The Book Cover - Key Insights

Several very important **core insights** are **right on the cover, easy to grasp. Seven** historic figures worked 83 years, from Rankine's first prop Analysis, 1865, to ultimately create **Betz's Classic Prop Logic,** by **1919**, and the **Goldstein-Theodorsen, essentially exact, rare genius math solution by 1948!**
We don't have to learn the math, in fact no one was ever able to see through the wildly complex math, and the heavily loaded, 3 D air flow, until my old college friend, Dr. Andy Bauer, and I took it on as an ultimate intellectual challenge, went through everything with gun and camera, played with it over a decade, until we were finally able to **see the core simplicities** no one ever had before, the **"easy enough" horse sense of what is happening physically!** The whole explanation is based on the core insights of **1. A Rotating Wing**, **2. Pulling in and Throwing Back Surprisingly Heavy Air, Newton**, and **3. An Airscrew**, which teaches **high Pitch Props are most efficient!**

See the perfect Helical Screw Airflow on the Cover, The Objective!

Simplicity can be a core of the best genius work, and Betz tells us to simply ***pull in*** **a perfect, Constant Pitch, Constant Slip, pure Helical Air Inflow**, ***throw back*** a **stretched, still pure, Helix, Archimedes Screws, 212 BC!** That **tells us how to set up the Air Inflow**, creates several fortuitous outcomes, one, a **constant ratio of Thrust to Torque, at every radius, if Drag Free!**

The Math!

Goldstein created **a rare genius solution** for the theoretical **3D airflow** by **1929**, **Theodore Theodorsen**, an **essentially exact**, real world, **rare genius, heavily loaded solution**, where the **speed increase at the blade** is **much greater than the average** of the **prop created stream tube** -- using **Goldstein**, by **1948!**

The Game!

The **core of the whole ball game** is simply to **counteract the aggressively wrong, excessive tip loading** of a rotating wing, **dumb as a Stump**, by **simply tapering the tips** much more than you usually see, **forcing the half tear drop radial loading** shown on the cover, right next to **the family of ideally shaped, and thus loaded, constant optimum angle of attack, coefficient of lift, C_L props**, simple, ***easy enough*** to grasp! **Low Pitch Props, the worst offenders,** are **more tapered! Hi Pitch, a Canoe Waterline is the Shape of the Perfect Prop!**

Make a List of All the Insights on this Page --- Start Nailing YOUR Insight!
Make That 10 Minute Effort and Begin to Launch Huge Insight

To my Lifelong Friend,
Teacher of Doctoral Level Aerodynamics,
and loyal, always ready, long time collaborator,
Doctor Andrew B. Bauer

As we both struggled through 83 years of the often Rare Genius Work of Rankine, Froude, Betz, Prandtl, Goldstein, Glauert, Theodorsen, it was Andy who saw that the Historic Masters had given us a simple Kx Blade Loading Chart, that, with Theodorsen's Equations, allowed us to Analyze, Program, Decode Propeller Art, Logic!

With Gus Raspet, number 8, who showed us all that overall Propulsion Efficiency, could be as bad as 58%, Andy well deserves to be number 9, the Professional, who made it possible to finally explain Propellers, 138 years after Rankine's First Prop Analysis, 1865, for the Wright's 100th Anniversary, Dec 17, 2003, when we first had it! It has been the Longest, Most Fundamental Gap in the Science of Flight, and Aerodynamics!

It was the ability to incisively collaborate, of two turned into more than two lifetimes of experience, that made the success finally possible, 138 years.

And to Milly, who Helps me in Everything!

Propellers

The First and Final Explanation!

The Professional, Incisive, Understandable, Logic of Propellers. The Explanation that has so very long, been so badly needed, by Aeronautical Engineers, Propeller Designers, Pilots -- the users.

That Should Have Been Available, at least a Half Century Ago!

The Longest, Most Fundamental Hole in Aerodynamics!

Jack Norris

Jack Norris Publisher

Propellers,
The First and Final Explanation

First Edition, Published July 2007
Northridge, CA

Price purposely kept low to spread the insight!

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Propellers

The First and Final Explanation

The Professional, Incisive, Understandable, Explanation that has long been very badly needed, Should Have Been Available, 50 Years Ago!

Though all Based on the Rare Genius Level Work of Betz Ideal Logic, Goldstein, Theodorsen Math, Perhaps the most Sophisticated Logic and Math Solution ever accomplished - Never Really Correctly Understood and Implemented in Ideal Form!

It is All Explained in the Understandable Logic of What is Happening Physically to a:

1. Rotating Wing
2. An Airscrew
3. Pulling in and Throwing Back Air, Much Heavier than you Thought

The kind of Insight and Logic we can all understand!

No Math, a few Simple Basics for Easiest Specific Clarity

All The Genius Level Math Works for us -- hidden in a Computer!

A Triple Ideal Prop Results - Actually 6 Ways Better, and QUIETER!

Jack Norris

Table of Contents

This Book is Different: It is not a Novel, not an Engineering Text Book. Its purpose is to teach the Logic, the understandable Physical Horse Sense Logic of how Propellers Work, previously the most complex, unintelligible Mind Swamp in Aerodynamics.

To help Pilots pick out, and tie together the many, many insights, the key logic insights are highlighted, ***superemphasized***, to make what you are trying to learn, **literally Jump off the Page at you!**

I've learned we **Professionals** need that more than I ever would have imagined, core issues, simple Aero 101 Insights in hindsight, that we **never saw in 138 years**. Leave all your hubris behind until you grasp the same logic that Novices need, then with the Superemphasis, the advanced reader can speed read, skim ahead!

This is a Different Kind of Book

It is Purposely Written a very Different Way - To Help You

It's Job is to: Explain How Airplanes, and Propellers Work

It probably has A Lot More Content, Specific Insights, Key Interrelationships -- Than you've ever dealt with before!

We've Superemphasized, all the Key Statements for You, Yellow Highlighted it for You --- Tied Everything Together!

It's apt to seem cumbersome, excessive, at first, but soon you'll see we make all the Insights Jump Off the Page at You

Hopefully, soon you'll realize you don't have to Pick Out the Key Statements, tie them all Together, we did it For You

You're in Training, to get Informed Enough, That You Can Grasp The Whole Logic of Props on Just 2 Pages, in an Hour

Sharp Guys Can Grasp the Logic, Learn to Speed Read it!!!

Novices, who Never Tried Anything Like This can be Helped

Dive In - Go For It - A Lot of Content - but all Sorted for You

Cryptic in Places -- We Break a Few Rules -

If You can Grasp Props in an Hour -

We Broke the Bank in Monte Carlo!

Laugh at it -- We'll try to make it impossible for you to fail - So we can succeed together!

Come Prepared to Laugh, and Learn, a Ton

You can **make this a fun, challenging, *laughable* event! - It can be the most memorable learning experience in your lifetime, a real kick in hindsight!** We're taking the most complex, challenging subject in Aerodynamics, Propellers, never explained in 138 years, and **reducing it to all the understandable logic and *insights* of everything that is happening physically. No Math, each of the insights is logical, understandable, not a real brain strain, by itself. The big WOW, the big surprise, is how many things are happening, all at the same time, a wild and crazy subject!**

We Repeat, Tie it All Together - Give you Plenty of Time!!!

But, that need not be a big sweat for you, simply because we have it all layed out for you. That's what this explanation is. It's all layed out for you, all correctly tied together, correctly showing you how it all ties together, in sequence! You don't have to do that, we did all that for you. All you have to do is to first get aware, then, *at your own speed*, start catching on, first, to all the individual insights, and then, in your own time, how all the insights fit together, in hindsight.

If you're a pro, lose all your hubris right now. In 138 years we never saw, never caught on to all the "easy enough", Aero 101, and logic insights here, me too. It was pretty much an ultimate intellectual challenge to see through all the rare genius level math and complexity, to make it "easy enough" here. Forget all about criticizing how I wrote this. **I didn't write this, prop logic very specifically writes exactly what must be said. It's underlined, superemphasized, bold, yellow highlighted for you, because we pros need that as much as Pilots, Novices. It's what we all missed for 138 years, Aero 101 in hindsight.**

The first several pages, simply start getting you aboard, start *feeding you valuable initial insights*, **getting you practiced on superemphasis**, getting to where it can help you see, grasp the key statements, not seem too busy and unnecessary. *In an hour*, **all the key core insights on propeller logic are on two pages with pictures, the Superemphasis showing the exact words that can explain propeller logic to you.** ***Get that, You've won!***

Laugh at it -- We'll try to make it impossible for you to fail - So we can succeed together!

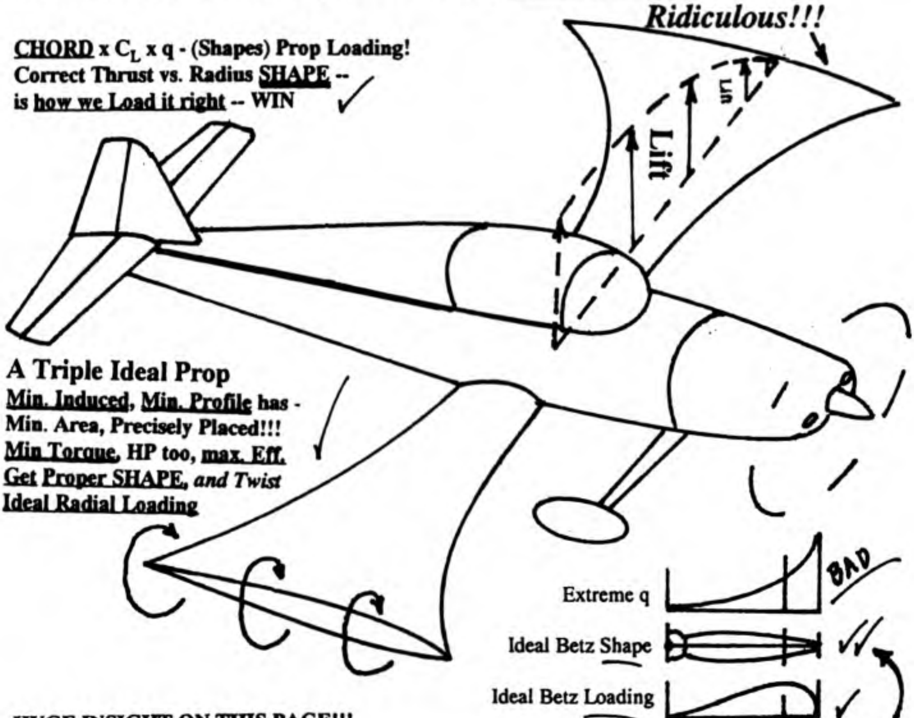
Making Propeller Logic Understandable

A **PROP** is ***trying to load itself INSIDE OUT*, DEAD WRONG, DUMB,** ***compared to what a wing needs!*** A **Wing** creates **Max Lift at the Center** and simply falls off, pretty much like ***an Ellipse***, no matter what shape it is, because **Wing Lift *Must, Will Fall to* ZERO AT the TIP**, a ***TIP VORTEX*** **Swirling from the *Higher Pressure Bottom*, to the *Lower Pressure Top*,** (even tip Dams only partly effective). But here's our Dumb Prop with very ***high Velocity Tips*, Huge Dynamic Pressure, q, Tips, (Proportional toV^2)** **trying to make max. Thrust and Drag AT the Tips, where Thrust will be LOST, must fall to Zero, creating an Extra Big Tip Vortex, *thus* Extra Induced Loss, *extra* Unrewarded Profile Drag, *at max. radius*, Max Lever arm, extra unrewarded Torque, bogging down the Engine RPM, Losing HP, Losing (4), four Ways, DUMB AS A STUMP!!! Creating NOISE too!!!** **It's our job to be smart enough to COUNTERACT that, Taper the Tips, Pull the Excess Loading Back Away From the Tips, *EASY KEY INSIGHT!!!***

HOW ABOUT AN EQUIVALENT *TIP LOADED* WING

CHORD x C_L x q - (Shapes) Prop Loading!
Correct Thrust vs. Radius SHAPE --
is how we Load it right -- WIN

A Triple Ideal Prop
Min. Induced, Min. Profile has -
→ Min. Area, Precisely Placed!!!
Min Torque, HP too, max. Eff.
Get Proper SHAPE, *and Twist*
Ideal Radial Loading



HUGE INSIGHT ON THIS PAGE!!!

This is the most Important and easy Insight You'll Ever Learn about Props!
It has been mostly missed, mostly not understood for the last 100 Years!
You don't win *playing games* with a wider tip, make Lift, where we just pulled it back!!!
(*Later we may be able to beat* the Betz 20th Century Ideal Loading and Shape!)

Propellers Explained - for Pros, Novices

50 Years Late!

It took 138 Years, a Third of A Century after my Spacecraft Small Rocket Maneuvering Control Components, went to the Moon and Back, **to get a Correct, Understandable Explanation of Propellers**. Two Key Summary Pages later in this Explanation were written on the Flight Home from the **Wright's 100th Anniversary, December 17, 2003**. All work since then was simply refining, checking, making it better, ever **Easier to Understand**, the subject that was **Always the Impossibly Complex "Black Art", the Biggest Fundamental Hole in Aerodynamics.** I waited a Half Century, for someone else to do it, finally had to dive in with my old College Friend, **Dr. Andy Bauer, an Ultimate Intellectual Challenge, just because it finally needed to be done, a great, challenging, fun, productive Collaboration, two lifetimes of Experience!!**

It's **all explained in the Understandable Horse Sense of what is happening Physically, to a Rotating Wing, An Airscrew, Pulling in** and **Throwing back Air, heavier than you thought!**

Very Purposely No Math! We've Needed to grasp the Logic!

But, make no mistake, everything you learn here, is based on Classic Betz Logic, the **Rare Genius level Goldstein - Theodorsen Math, maybe the Most Elegant Logic and Math ever, in any of the Engineering Sciences, the final product of 83 years work, by 7 of the Brilliant, Historic individuals creating the Aerodynamic, Hydrodynamic, Math, Sciences, Rankine, Froude, Betz, Prandtl, Goldstein, Glauert, Theodorsen, Giants**

Propeller Math was essentially Exactly Solved in 1948 in Theodorsen's Historic Text, "Theory of Propellers", we simply never Understood what it Meant, Directed, Taught! Laughably, they gave us a simple Blade Loading Chart, no one seems to have correctly understood what was there!

We Professionals have needed to understand how to really optomize Propeller Design, finaly get it right, QUIET, less Loss, amazingly Props Trying to Operate Dumb as a Stump!

Some good work has been done Augmenting their's, better blade loading for very high Pitch, Advance. We'll tell you where! Modern work mostly missed, didn't understand!

There is A Substantial Human Problem Here to Solve!!!

Different Level Individuals have quite different **Needs, Desires, Expectations!**

Since this is **the first real explanation of Propeller Logic**, that **took 138 years**, it will be read by Lifetime Professionals, and an even larger number of just good interested individuals, Pilots, in many cases, most cases, with no technical background at all. **There will be very Different Personalities, very Different Expectations**, and of course, all very human, **we will all think that we are the ones who have the proper, correct expectations**, and **see best how the job should be done.**

Now, you may not think that you're starting with an opinion, but the truth is that we are all quite human, more predictable than we'd like to think, **really. We would all like to think of ourselves as the hero in Sinatra's song, "I did it my way"!!!**

As you'll soon learn, we have the core of Prop Logic on just two pages that can finally be very understandable, that took 138 years to find. It turns out that I did Not write those two pages, the Logic of Propellers wrote those two pages. I was simply the guy who found them for you. Those two pages incisively state all that you need to know to grasp the understandable Horse Sense of how Props Work Physically!

I've seen innumerable, **really laughable examples of just how diverse the expectations of we mortals are**, and of course, **we all unfailingly believe in our heart of hearts that we know better than anyone else how this job must be done.**

Props Set what you Must Learn -- I've seen What Can Work - what can't!

The truth is that neither you nor I have much luxury of opinion here! The job that needs to be done here is to get you ready to honestly understand just 2 Pages that are "easy enough" as soon as we can get you up to the point where you are prepared to learn what would have been impossible for you to grasp an hour before!

HELP, by simply Understanding, coming Aboard, Laugh a little, make it easy!

My job is: one part Human, one part Technical, one part Writing, and one Big part Explanation, that can work for EVERYONE! I'll be **teaching, leading, corralling** all we diverse human beings into **being able "to Get" 2 core pages!!**

Loosen up, drop any Hubris! We Pros missed the Aero 101 Core Issue for 138 Years!

If You're Particularly Sharp

I'll bet you'll think I'm being Way Too Repetitive!

Perhaps, but as I'm giving the slower guy lots of time and extra chances to get it, I'm often saying it a little differently, many times expanded insight, very purposely hoping that the sharper guys are getting more, and more facile in their grasp, ultimately being able to flip the logic around in their head, the place I'd love to get everybody. The sharper guys, more curious, more capable will go on to Advanced Chapters, and be that much more prepared to grasp all the Advanced Insight, end up with More Factual, Practical Grasp -- that has Never Been Available Before!

You Must Realize, I am NOT writing this Just for You, but for EVERYONE, from Novice to Pro! You'll see, I expect everyone to soon enough learn to read this at their Level --- Pros, Sharp Guys Learning to Skim, Cherry Pick, After you Grasp the Logic --- Your Contribution, Your Help and Participation to Help Me make this Work for All Levels.

The First part of this Introduction goes Slower to Help Novices Aboard! The Second part Skims ahead to a lot of great Advanced Insight, Great Stuff! Novices will get it too.

I've Purposely Put a great deal of Insight into this Special Introduction. Many Pilots Will have more insight than they ever expected in this Introduction, and be satisfied!

At the End here, I show how to Cherry Pick the rest of the Book. We're trying to set this up for anyone, everyone!

Your Contribution - Your Part of the Job - Learn how to read this book at your Level - Your Speed!!!

READ THIS!!!

How We're Going to Explain Propeller Logic To You!

Propellers are without any question the most ridiculously complex problem in Flight. Since we Aerodynamic Pros could never explain propellers -- it took 138 years, and over a Decade to finally get this one - It's going to take real insight to figure out how to correctly, understandably explain them to Pilots with no technical background! **If we tried to do it the normal way, there are so many things that we'd have to teach you, the story would go on and on, you'd get totally confused, lost, give up, and we both would have failed**. There would not be the chance of a snowball in hell that we could succeed that way.

Over about an hour, we're going to get you aboard, feed you **a lot of basic insight**, hopefully get you **a lot more informed**, far better prepared, ready to learn. **If you soak up what we're feeding you, about 20 pages in, you're going to be a lot more prepared to understand, learn, grasp what's happening!!!**

At that point, on **2 pages, two single pages**, I'm going to show you **the bottom line insight, on the understandable core of Prop Logic, How they Work, How we can Understand Props!**

Now, there are a lot of things happening, interacting, all at the same time, all interrelated. So how do we avoid confusing you there, solve that one? That could kill things!

We're going to start Superemphasizing the key points, make them Jump Off The Page at You!!! It will look Wild, and we'll encourage you to laugh at it!!! My hope is that with an hour's insight and practice, it will be "easy enough" for you to separate --- or integrate all the things happening!

Actually, we have pictures, little sketches in the margin, and it's easy to see the problem of a rotating wing, and the solution -- even before you read the text. The Pictures - Easy!

My bet: If you can fly an Airplane safely, you'll be able to noodle out those 2 pages, and we'll win! I'll help, Go for it!

You'll learn a Lot Here!!!

How Much Does a 100 foot Cube of Air Weigh at Sea Level?

No tricks -- Not Floating in the other Air, Separated, on a Scale, Truth!

76,000# Wow!!!

About the Weight of an 80,000# Highway Truck!!!

A 1,250,000# Airbus A 380 is Throwing Down Enough Air Fast Enough,

To React 1,250,000# - That's What Induced Loss is, The Core Induced!

The Tip Vortex Induced Energy Loss is Extra. Maybe + 25% Extra.
(At the Speeds we Fly all Induced may be 20, 25% of Total Loss)

NOT a Wing, Props Have Much More Induced Loss, lots More!!!

Nominally Twice the Loss of a Prop's Profile Drag, 200%, 2/3, Not ~25%!

Most Props Have Ridiculous Tip Loss - Noise!! We Never Understood!!

Props, Dumb as a Stump, Work Aggressively To Create Tip Vortex Loss.

And we Never "Got It". We Never Saw The Core Problem There!
(That's the Most Important Insight you'll Ever Learn About Props)

How Far is a Reno Unlimited Advancing Each Revolution? 37 1/2 ft!!!

How Much Air is That Unlimited Throwing Back? 4 1/4 Tons/Sec.!!!

Not Faked Out ---You Can Have Fun With All The Insight Here!!!

Planes, Props, We'll Deal With a Lot of Induced Thrown Air Here!!!

And We'll Get the Wild Induced Loss, Down to a Dull Roar - Quieter!

$(100 \text{ ft.})^3 = 100 \times 100 \times 100 = 1{,}000{,}000 \text{ ft}^3 \times .076 \text{ \#/ft}^3 = 76{,}000\#$ Wow!

Yes, a Lot More Air, a Lot More Weight, More Induced Energy Loss, Than You Ever Realized!!!

Where Props Try to be Dumb As A Stump---Wasteful Tip Vortex Loss!
It's Our Job to be Smart Enough to Counteract The Tip loss!
We Just Taper the Blade, *Twist*, Pitch the Blade Correctly - EASY!
That's Been the Hidden Secret, a Big Reason We Needed an Explanation
For 138 Years!!! And it's All Here -- Understandable!
(It's All About How we Load the Blade - Blade SHAPE, with the correct *TWIST!!!*)

Laugh At It! We Did it Very Differently - On Purpose!

You'll Be Amazed At What You've Conquered, Learned - Proud, A Good Laugh!

The Game Here

To Make It Possible

For You To "Easily Enough" Grasp

The Most Complex Subject In Aerodynamics - Defused!!!

The Subject That Took 138 Years to Explain!!

That We Professionals Never Grasped!!!

If There Is Any Genius Here

It is in Converting The Ultimate Intellectual Swamp

Into The "Easy Enough Horse Sense"

Of What is Happening Physically

to

A Rotating Wing, An Airscrew, Pulling In, Throwing Back Air

It's Not For Speed Reading --- Grasp the Insights

The Game - Make It Possible For You to *Easily Enough See*

What You Could Not Possibly Normally See

The Core Insight is on Just 2 Marvelously Insightful Pages

My Bet is You'll End Up Smiling - Soon Laughing - Proud of Yourself!

We Try to Make the Key Insights - Superemphasized-

JUMP OFF THE PAGE At YOU!!!

Dive In, Laugh At It, You Can't Possibly Strain Your Brain

We Just Taper The Blades, Twist Them Right, That Easy!!!

You Can End Up Laughing, Plenty Proud Of What You Nailed!!!

You can Teach Your Friends The Easy Core - Laugh at it Together!

We'll Learn - Props - Fast Tips, Agressive Tip Loading - Really Dumb - Never Grasped!

The Impossible Subject, Propellers, Made Understandable!

How can we possibly take **the Black Art** subject that we pros could never understand and explain, now 141 years, and make Props understandable to Pilots, with no technical background. Well, we're certainly not going to do it with the rare genius level math that some of the most famous men in Science, Mathematics, Hydrodynamics, Aerodynamics took 83 years to create, **1865-1948**. The reason we've never had a propeller explanation: **no one could ever see through that rare genius level math, see what it Meant, Directed, Tried to Teach Us!**

The EASY Insight to Grasp: A Prop is a Rotating Wing, the British correctly call them **Airscrews.** Anyone standing behind a propeller, running up, or a helicopter landing, or lifting, realizes they're **Throwing Air,** and ***Newton*** teaches us his Equal and Opposite Reaction Force, and the ***simple, insightful, but a bit tricky way to understand what's happening there***.

Everything we teach you here is based on maybe the most **Elegant, Logic and Math** ever created in any branch of Engineering, over those often rare genius 83 years, but the game is to teach you that the **Understandable Horse Sense Logic** of **those three insights** into **what is happening Physically -- can exactly, correctly explain what the CORE of the genius level math is doing - never really nailed before!**

We've targeted this to help all the good, curious, most interested, most interesting guys who'll wade in and give it a good honest try - to try to make sure everyone can "Get It"

We had the guts to do this very Differently, Make it as Easy as Possible FOR YOU!

Since new guys can't pick out the gems of Insight from Bland Text, we **Superemphasize the key insights** to, as much as possible, make them **Jump Off The Page At You**. Since **most of us**, many pros included, **don't really catch on the first time** someone tries to teach us a lot of new insights, **we repeat, always tie together, as we broaden, deepen your insight.**

We **get you ready**, show you the **Bottom Line Conclusions in less than an Hour**, **FULLY AWARE early, much easier that way**. As we **repeat, expand your insight, tie it all together**, it **can all soak in**, and **you can grasp what we pros never did!!!**

We Pros Need to Grasp The Same Basic, Horse Sense Logic, Missed for 138 Years!

It can Look a little crazy, Laugh at it, make a Fun Challenge of it, Soon Smart!!!

IF YOU'RE A PRO - Don't Underestimate What's Here!!!

As a Pro, you'd recognize the names Rankine, Froude, Betz, Prandtl, Goldstein, Glauert, Theodore Theodorsen, T.T., NACA's marvelous Wartime Chief Physicist, Historic, often Rare Genius Level Names in our Science, Mathematics, Fluid Mechanics, Aerodynamics. Over 83 Years, from 1865 to 1948, they were the Historic, often Rare Genius Level Pros who created Classic Betz Prop Logic, essentially exact Goldstein - Theodorsen Math for us, brilliant, achieved an "essentially exact" Solution for Propeller Mathematics for us over a Half Century Ago, by TT's Historic 1948 Text!

Any fault was ours, we just never understood, what it all Meant, Implied, Directed, snowed, typically unable to Understand the Genius of their competence, we failed to grasp that the bottom line on their work was a simple Blade Loading Chart vs. Radius - for low to high Advance Ratios!

Prop Math, was essentially exactly solved over a Half Century ago!!! If you think that because you're smart, can do Math, have a Computer, know how to write code, you can start off and do better, smarter than those Historic men, likely very wrong! They were Brilliant! The trick is to finally Grasp what they created, far too long waiting for us!

What we teach is correct, based on maybe the Best Math Work ever!

Thinking it ridiculous, unacceptable, that we're into the Second Century of Flight, that my Spacecraft Controls went to the Moon, and back, a third of a Century ago, my old College friend, **Dr. Andy Bauer, and I decided it was time to Nail Props, explain them, not only to Pros, but Pilots, anyone interested!**

We went way past the Math to Find the *Easy Enough* Core Insights, Logic!

***The hardest thing of all is to make the most complex, daunting subjects "easy enough", understandable, but that's what Science really is, isn't it?* Nature, Science is always orderly, logical! Once someone solves it, sees through the complexity, we can all Understand, have Nature work for us!**

First - We pros Need to Grasp the Same Incisive Insight that Novices Need!

Over a decade, we went through all the Math, did all the Code, the Professional Studies, and as always, it all comes out the Understandable Aero 101 level Horse Sense, the understandable Logic of what is Happening Physically!

Drop the Hubris guys - You'll see we missed the Aero 101 Core Issue for 138 years!
Theodorsen is in the Appendices, the Math in a 19 Page Program!

The Task Here:

Take the Most Complex Problem in Aerodynamics

Propellers

Never Correctly Explained in 138 Years by Anyone

Find The Understandable Aero 101 Logic

Make it Understandable to Pilots, Professionals

Anyone Who'll Give it a Good Honest Try!!!

We Lead You In, Show You Some Basics

One Hour In, Getting You Aboard, Prepared

2 Very Special, Very Concise, Incisive Pages

Can Teach You The Whole Core of Prop Logic!!!

They Replace The Book That it Would Take -
To Teach Pilots a Whole Basic Aero Course!

By Essentially Starting With the Conclusions

It Becomes Much Easier, Faster, To Grasp, Learn!

You Can See the Logic, The Patterns Very Early!

The Normal Way, too Long, You'd get Confused, Lost, Drown, Give Up!

The Two Pages Look Pretty Wild at First, But

Since you Can See The Logic, *Bottom Line Answers*

It Can Quickly Start Soaking In, *gets Easy Enough!*

Laugh at it, Go For It, Make it a Fun Challenge, Smart Quick!

Pros, Propeller Designers, have badly needed this for a Half Century!!!

Designed Correctly, Props Get QUIET!!!

Anytime We Learn Something New ---

It **Tends to Seem Hard at First**, but then **Easy in Hindsight**, **once we catch on to the Logic**, **the Horse Sense of it**! That's what we'll find here, **Props** seemingly very, very complex at first, but **"Simple Enough, Easy Enough" in Hindsight!** The **Trick is to get you over the Hump, where it all makes sense -- show you that there are Aero 101 insights that nail Props!**

Pilots, Technical Novices, it would be dumb to expect you to pick technical gems out of bland text, especially when there's **a lot going on**, seemingly so complex, that professionals never found the understandable logic of Props, never an explanation in 138 years, **the biggest fundamental gap in Aerodynamics!**

Since there is **a lot going on, we need to be Creative**, **work out a way that we can sort out all the complexity for you, finally the bottom line decoding of the 138 year mystery!!!**

It will help a bunch if you're flexible, a little creative yourself, not an uptight, rigid person, someone who can laugh at something that looks very unusual at first, **that solves that core problem. The Task Here is to sort out the most complex problem in Aerodynamics, make it "easy enough" for you!**

The core math is at the rare genius level, we better not try that. There are a whole bunch of things happening, all at once, and interacting, so **the whole game is "can we be creative enough to show you that there are easy enough core simplicities", able to show -- but separate all the side issues -- or easily integrate them -- since they are useful, insightful, part of the final proper, correct grasp! Succeeding there is the key!!!**

We're going to use **Superemphasis, pretty much a hit you over the head with a 2 x 4 writing style**! We'll start off, feed you some key insights, give you time to grasp basics, get comfortable, building up. **About One Hour in we have the whole core logic of props on 2 Pages, wildly dense, but *simple enough* as it soaks in**, just **the Horse sense of what is Happening Physically**. **Laugh at it, go along with the gag, and see what we pros never did in 138 years! Wildly, We pros never saw the core issue!! -- and it's Aero 101 Simple!!**

OK, Here's Where We Start, and Where We're Going

Classic Prop Logic is based on simple, but Brilliant, Betz Insight and Logic - and Rare Genius Goldstein, Theodorsen Math. Impossibly complex, Math at the outer limits of what people could do, **No one was ever able to see through it, what it Meant, Directed -WHY! That's where the Insight Hides!** With a lot of very hard work, **we have it down to the Aero 101 Horse Sense of What is Happening Physically**, to **a Rotating Wing, an Airscrew, Pulling in and Throwing Back** ***(Heavy)*** **Air to Make Thrust**, **(Newton's Equal and Opposite Reaction Force).**

Most Important is to see What it - Directs - and WHY!

Easy Enough, there's a whole bunch of extra supporting things happening at the same time, with really important, and valuable insights. Great, but it becomes a problem of more things happening at the same time than Pilots, Technical Novices, have ever been faced with -- in **one big Gulp!**

So Here's Where We're Going! The only way that Pilots, or Engineers have a prayer **to grasp it Quickly, easily enough**, is to **put the Final, Marvelously Incisive, Bottom Line Insights of 138 years Work on 2 Wild, Superemphasized Pages**, that are **actually quite easy once it all soaks in, starts making sense**, but looks like a crazy head full the first time you see it!

But here's the clue. Rereading it a few times, vastly easier and faster than reading a whole Chapter, or a Whole Book for Novices, you can start seeing the core issues - separate from the supporting insights. Once you get to that point you can **see that you can read the core issues, with the** ***also Insights,*** **either skipped, separated, or then, fullly integrated**, **HUGE INSIGHT! In 10 Minutes you might grasp the really simple enough Insight that very smart Engineers never saw!**

If you don't Grasp it all, at first, You're Instantly Aware of the Final insight!

Don't fight the **superemphasis** that **separates** ***or*** **integrates the Total Insight**. Realize **the Logic, not me, writes the page. The whole trick is to be able to see, separate, then integrate the whole concise core**, the **final Insights of 138 years work, quick, easy.** **We give you plenty of time, help to get it!** **Long, normal writing,** ***the alternate***, **way too long, no chance, you'd drown!**

Norris's First Law

Nature, Science, is Orderly, Logical, thus understandable, explainable, and can potentially be made useful for the good of man, part of our ever expanding grasp of knowledge!

In fact that's what Science really is: once someone is able to see through the Fog, the Complexity, gets an orderly, logical, proper explanation, anyone who tries can usually grasp it!

Norris's Second Law

However, if you think it's completely simple, you'd usually be very wrong, you'd fail to see, understand everything else that is happening in the background, the whole universe, and all its laws, a marvelously interrelated, web of Insight!

THERE'S MORE TO LEARN AFTER THE BASICS

Galileo, 1564 - 1642, figured out how fast dropped objects accelerate, but we're still trying to figure out what gravity really is, trying to master the logic of the universe!!! Watson and Crick defined the Double Helix of DNA, in 1962, so now we're deeply into working on decoding it.

Look on the Cover

Betz defined the Double Helix of Classic Prop Logic in 1919, but Theodorsen's essentially exact, genius level math took 29 years, 1948, 83 years after Rankine's 1865 start of prop analysis, but we never saw what it was trying to teach us!

A Double Helix? See there's one from Each Blade, 180° apart! ✓

So here, 2003 to 2006, 55 years after Theodorsen, you'll find the first real explanation of what it all really means, how to understand it all, use it fully intelligently. But, this is about a Half Century Late - Always before, too Complex to Solve!

Hard Work, a lot of Determination is always at the core of breakthroughs. So we finally have an explanation. It seems no one else was ever going to nail it, a half Century is long enough to wait! So the trick is to actually make it truly *easy enough*, not snow everyone -- truly easy enough to grasp.

You'll see we have the core down to Three Simple Insights, of What's Happening Physically, easy enough horse sense. We go on, help you grasp Props to any degree that you wish!
If you have trouble at first, we give a lot of **Time**, ***Repeat***, **Help** ✓

This Book is Written to cover THREE Needs

Since there has never been a penetrating, correct explanation of Propellers, this book will be read by **Pilots**, a major audience, with essentially no background, or experience, sorting out tough technical subjects, and **World Class Technical Professionals**, with a lifetime of technical insight, who, like me, have been waiting for the intelligent, incisive, correct explanation of Propellers, (for an extra Half Century). So, It is basically an impossible writing challenge to write in preferred style for such a diverse audience, and we both need to see that right up front!

Some People Like, Want, ***incisive summaries!*** Others like, need **a more conversational narrative, repeating, tieing together, to help them along as they figure it all out, absorb it all**, especially if it's a many faceted subject. Complete technical novices, who might wade in with no experience, or technical grasp, can be **helped with a super emphasized, hit you over the head with a 2 x 4 style** --- (We technical pros can benefit from that too, because there were very specific **Aero 101 core insights that we never saw in 138 years, the most basic gaps in the Aero Profession!!!**)

It's FAIR, Proper, to ask Pros, easier for them, to ADAPT!

It's all here, and all you have to do is realize it going in, **learn how to read it at your level**, but that's no detail, **that's your part of the job, your contribution** to make this book reach everyone that it needs to. Full busy, having to fit this book into an already busy lifetime, I simply don't have the time to write two books. Realize this is **not a Pablum Book, it nails Props!**

Pros can learn to Skim, Speed Read, BUT only AFTER they grasp the Core Basics.

With two lifetimes of experience applied, my old college friend, Doctor Andy Bauer, and I, have labored through all the Rare Genius Math that took 7 Historic technical figures 83 years to create, done all the lengthy studies to find out who had it right, wrong, or close but no cigar, and have it down to the **understandable** ***Technical Horse Sense*** of what is happening **Physically**, to a **1. Rotating Wing, 2. An Airscrew, 3. Pulling in and Throwing Back Air, Newton's Equal and Opposite Reaction. The Introduction first goes slow to help Novices! In the second half, nails a ton of Advanced Insight!!! We go on with a Primer, a Chapter 9 in Book I, then a whole Book II, a Summary, Total Insight!!!**

There's a ONE PAGE, 8 1/2" x 11" SUMMARY at the end. Go Peek!!! But, Don't Short Yourself, don't skip the Basics, or the Advanced Insights. A Day to Grasp it!

A Couple of Great Big Problems!

It's ridiculous really, unacceptable. We're into the Second Century of Flight, a third of a Century since we went to the Moon, and we never got a correct, understandable explanation of Propellers, their Logic, how we can correctly understand them, and their operation, proper design, the hidden horse sense, always the Black Art Mystery of Aerodynamics. I know, I've been looking for one, waiting for someone to do it, explain them, since I was a kid, building, designing competition models.

Worse, a propeller, a rotating wing, always has nominally, 2, 3 times as much efficiency loss as a comparable Aspect Ratio wing, even when designed by classic theory, and math, 4, 5 times more loss if designed unknowingly, and no one ever seems to questions why! In a giga byte world, how can that be?

All that extra loss goes into NOISE, Correct Props Noticeably Quieter!!!

Astoundingly, no one seems to have ever written, or said what the core problem is, when in hindsight it's really simple Aero 101, all of us blinded, faked out by the apparent Black Art complexity, when props are trying to operate aggressively wrong.

All that is even more amazing when we learn that 7 historic figures created classic propeller logic by 1919, exact theoretical math, but not real world math by 1929, a good approximate solution by 1934, and Theodore Theodorsen's essentially exact (~ 1%), real world solution by 1948 -- with the 1929, and 1948 work having a simple chart that showed us how to load the blades correctly vs. radius, for high to low Pitch, or Advance Ratio, as you'll learn. Nobody ever really caught on, nailed it.

It's time we Understand, get props Correctly Understood, Correctly Designed!

No Hubris here, my old college pal turned into Dr. Andy Bauer, one of Douglas's key, core Aero Pros, and collaborating, adding in my very full lifetime of experience, and a whole lot of honest hard work, we nailed it - the old fashioned way - we earned it! So it's our gift to you, and the ***Flight*** that gave us an E Ticket to life. We even have it down to the horse sense logic of what's happening physically. But you have to let me teach you in a different way, because done the wrong, long, complex, normal way you'd drown. Come prepared to laugh at it, learn incisively!

Aero 101 on <u>One Page</u>, with a Picture Page!!!

Pilots: We all **know how airplanes work**, but we probably ***don't specifically* understand** as well as we might. We know **Wing Area makes Lift**. At a **higher Angle of Attack**, -- (*a higher Coefficient of Lift*), we **can takeoff slower**. The **faster** we go, higher IAS, the **less angle of attack it takes**. You may have heard of **q, Dynamic Pressure**. It's simply the **Pressure our Pitot Tube feels**, **stopping the air** rammed into the tube, the same pressure we'd feel **sticking our hand out the window** - **EASY!**

Realize q is the pressure, energy motivator of Lift and Drag!

Simply, Lift, $\mathbf{L = Area \cdot C_L \cdot (\rho V^2/2)}$ $q = (\rho V^2/2)$

q, the Ram dynamic pressure, is just the mass density of the air, ρ, times V^2 divided by 2, so if we go **twice as fast** - the **q** pressure making lift, and drag goes **up by a factor of 4**, (3x is 9x higher, 4, 16) **Basic**.

Grasp that formula, it's the ~ same one for Drag, C_D, q, V^2, *Not Hard*, Basic!

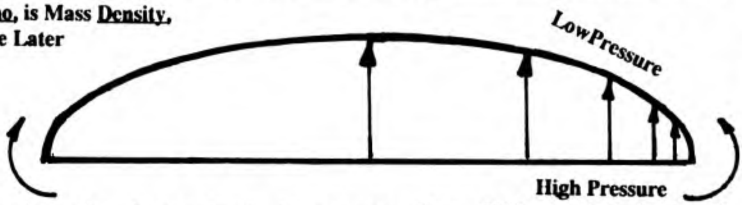
Heavy Water Penetrates Air More - than Air Penetrates Air, Next Page
But Notice the Hole Behind a Power boat, Both Skimming, Throwing, Induced Loss!

We all learn it's the speedup of air over an Airfoil, dropping the pressure, that makes Lift, but we'll learn that **Airfoils *also* turn** and **throw down air**, causing **a reaction force, throwing air**, another way of looking at the **same lift**, *not* a duplicate lift. We'll learn that's what causes **Induced Loss**, the ***Energy Cost, the Loss of Throwing Air*** to make **Lift**, or **Thrust**, hugely important on **props, the biggest loss on Props**. **Profile** Drag, air **Friction drag**, the basic drag, may be only half induced.

One Brief Page, a Ton of Insight, Grasp!

Try the Spoon, under the Kitchen Fawcet Trick, YOU CAN FEEL THE SPOON PULLED IN, SEE THE *BENT FLOW!*

ρ, rho, is Mass Density, More Later



+~25% Induced
2 Tips Vortex Loss

It's hugely important to grasp that **Wings tend to have Elliptical Lift Distribution**, fall off to a **Tip Vortex**, zero, maybe a +~25% Induced, **depending on Speed**, **Props Hugely Worse**!

There's huge insight in the Lippich Smoke Tunnel Pictures, **Look!**

We Do NOT do the Scary Math in this Book, Rather, Insight!

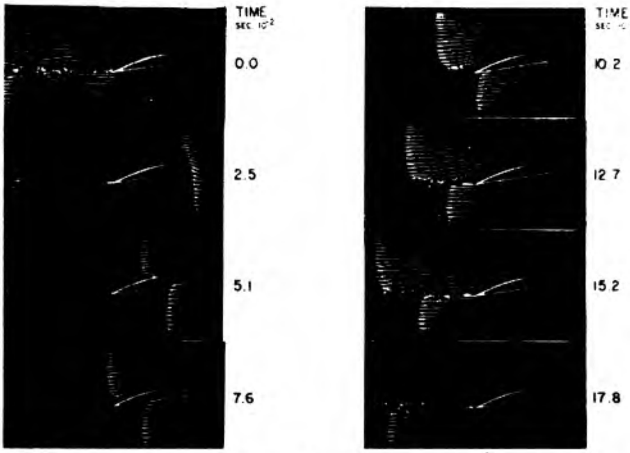


FIG. 13. Sequence photographs of time lines on a wing section with lift (reproduction from a high-speed film).

Notice the thickening upper Boundary Layer.
Actual Separation can create an extra Pressure Drag.

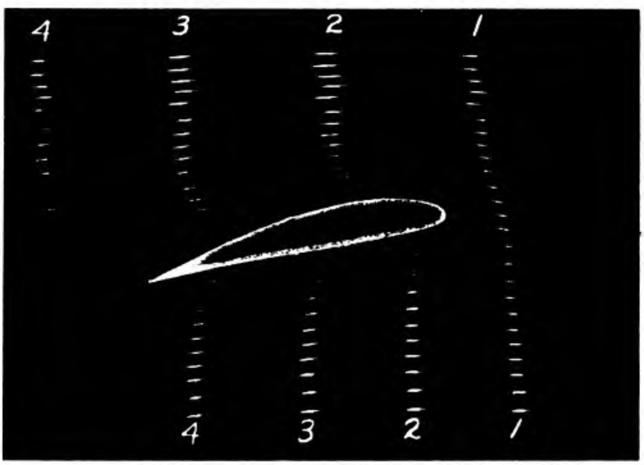


FIG. 15. Multiexposure of time line of a flow over a wing section. (It should be observed that the upper and lower branches of the same time line are largely offset. Equal numbers identify equal time line position.)

Marvelous Insight, from Lippich's Smoke Tunnel Work.

Fantastic Lippich Smoke Tunnel Visualization!

Lippich really understood Aerodynamics, really Smart, led Germany into Jets, before our team, **fantastic insight here!** The air over the top of an Airfoil does NOT meet the bottom's at the Trailing edge, **maybe ~133% faster**, as shown, **the mean camber line bending the Flow Downward, just a little, but vastly more Massive that you'd ever guess, or realize!!! Profile Drag, Friction retarding the Flow, a developing *thick* Boundry layer.**

Dumbed Down, or The Real Truth, *Easy Enough*

Everyone knows the drill: To sell a lot of books, make a lot of money, you "Dumb it down", write the Pablum Book. But we didn't do this to make money, but rather as **a gift, the real truth, a *Give Back*** to the **Flight that gave us an "E ticket" to Life!**

This Business gave me a leading edge Life most could only dream about!!! ✓

Besides, if I write the Pablum book, that's done on the premise that I'm smug, you're somehow dumb, I have to dumb it down --- and that's just not me --- and my bet is, that's not you either!

It's ridiculous, really, that this correct insight is 50 years late!!!

You'll soon see that my bet is that, if you can fly an Airplane for several years without killing yourself, got through High School, maybe had at least a few teachers who tweaked your interests in smarter insight, took a courses, or so, with more challenge than Gym., you're not at all dumb, and **you can *soon grasp* Just Two Pages that Nail The Core Logic of Props!**

Besides, 10 of us worked 138 years, 141 years to this day in late 2006 when I'm writing these *last first pages* to get a wild subject "down to just 2 pages that I'm betting you can *get*"!

Most of us Pilots have some Adventure in our soul, *confident*, think it's our right, love charging off into the **Wild Blue Yonder**. We're generally not techies, the nerd, geek type, don't want to be, and that's perfectly OK with me. I flew for years just for fun, a break, a get away from my work, flew at 18,500' in **the Sierra wave twice**, down the crest of the Sierras, in the upslope winds in a plane that wouldn't really fly at 15,000', through lots of Ohio Winters, Cold Fronts, wild winds, do ***power off landings from 10.5, 20 miles out*** - gliders can, we can too!

2 Miles High, a 12 to 1 L/D, 24 Miles Range, Gliding, 70 MPH, fast idle

My simple bet here is that there are actually a lot of you who love flying, have a fair bit of curiosity in your soul too, not a geek, but don't see yourself as a dummy, ***confident***, **not afraid!** So, simply, we've done everything humanly possible to get prop logic **down to 2 core pages, with simple direct words**. We've aimed it to give max. help to a guy who is *not* a geek, *may* sweat a little, **betting that you can and will get it! You might read those 2 pages twice, several times, finally see it really is *easy enough*, just *all the core, key insights* - collected!**

A Look Ahead, to p. 14 of the Primer

(Next, After this Introduction)!!!

Let me explain. There is nothing in the literature that tells us clearly, simply, that the objective of the math is to load the prop correctly vs. radius, to prevent excess tip loading, unnecessary, unrewarded induced and profile tip losses, that proper blade loading is accomplished by proper shaping of the blade with proper twist, that if you actually achieve a constant optimum angle of attack and C_L, you get min. profile drag too, min. area precisely placed, Min Torque, a Triple ideal optimum prop, not just min induced --- that you must accurately correct for nose velocity profile, slowdown, because we really need to predict inflow to all blade radii to .1 degree, yes one tenth degree, that a 1 degree, .1 C_L error will give us a 20 % error on a .5 C_L prop --- that the slowdown correction which results in less twist, lower blade pitch angles, especially inboard, can create a major Plus in fixed pitch prop operation slow, in take off and climb.

Betz is Min Induced - Norris's 6th. Law, Min Profile, Torque, Triple Optimum!

No Math! --- The Computer Does All the Hard Smart Work for Us!
We just Learn the Understandable Logic, The Understandable Horse Sense Logic --- of What is Happening Physically --- Finally, *Easy Enough!*

The kind of things we'll learn is that Speed vs. RPM, with due consideration for needed inflow and angle of attack sets pitch, which sets max. efficiency attainable, that use of B-G-T, Betz-Goldstein-Theodorsen Math, will then deliver max. efficiency, that it will also deliver a **Precisely Loaded, Shaped, Twisted** prop, **a constant optimum angle of attack and C_L, minimum area, precisely placed, a Triple ideal, min. induced, min. drag, min. Torque prop, if we're only smart enough to ask for it.**

Remember, with 21st Century Insight, we can improve on the old Optimums

A lot of long, hard, dedicated work has been done here, simply because Andy Bauer and I were experienced enough to recognize that the explanation was badly needed, long overdue, and that with two lifetimes of experience we could sort it all out, do it. **There is a lot to teach you**, be you a novice or pro, **a long string of incisive insights**. **We'll simply build on and expand 4 basic insights here, ever deeper, broader, more sophisticated**, ***superemphasized so anyone who tries can get it!***

A Little Preliminary Overview

Our Whole Modern Life is Based on the Rapid Advances of Science and Engineering --- Made Understandable, Useable.

Do You Love Flight? Come Find out How it all Really Works, Propellers too, an *easy enough challenge*, if you'll go for it!

Think Engineers are Nerds, Geeks? Lose the Thought! There's more guts in Engineering than people ever realize! The Apollo, a 36 Story Tall Vehicle, 7 Million Pounds, Lifted with 7 1/2 Million Pounds of Thrust, was lifted, *leaned over*, *grabbed*, to fly it out of the Gantry, both too big to move clear of each other -- a bet that we could Stack 6 Separate Vehicles, make them all Work, Go Round-trip, the Whole World Watching -- *World Class Guts* --- *Audacity!!!*

Flight Controls, for Big Jets, and Spacecraft was my speciality.

Personally: We moved, Milly and I, 3 small Kids, on the Bet that I could Move us to L.A., Start a Company on the Run, Build a Team, beat all the Local, Established Competition, win the Lion's Share of the Small Rocket Maneuvering Systems Control Components --- 107 of ours used on the Mercury, Gemini, And Apollo, in the Milestones of Flight Gallery, the Central Hall of the Smithsonian, National Air and Space Museum, the day it opened --- July 4, 1976, our Country's 200th Anniversary. *Nerds* -- hardly -- savvy -- *guts football required.*

A Little Guts, a fair Try, We can get you huge insight - *Easy Enough!*

Before this, Props were the wildest Subject in Aerodynamics, never explained in 138 years, a combination of Black Art, Math, and guessing. **We explain them** with just the **Aero 101 Horse Sense of What's Happening Physically to a basic: 1. Rotating Wing, 2. Airscrew, 3. Pulling in and Throwing Back Air, *a lot of it*, a lot heavier than you thought, *No Math* - but all backed up, accomplished through a computer, with perhaps the most Elegant, rare Genius Math and Engineering ever accomplished, the work of 7 rare Geniuses over 83 Years - that you don't have to deal with!** √

It's all Explained in the Specific Horse Sense Words of What's Happening Physically.

A Novice can't pick out the Gems of Insight, so we **Super Emphasize, Repeat, as we expand and go deeper - Thus, give you plenty of Time, and repetition to catch on - written to help you - your best chance ever to *really* end up understanding Flight, Props too! If you *scratch harder at first*, *learning*, you'll see it's *easy enough* once you grasp it.** √

This Introduction, Pretty Complete, Gets Pilots Aboard - the Primer - then Ch 9, Book I, then Book II -- takes Anyone, Everyone as Deep as You Personally Choose, You Choose!

You'll soon see I had the Guts to do this Very Differently!

The Whole Core of the Story on TWO Very Dense Pages!

Normal Writing Style - Too Long a Story - People Get Lost!

A Little Guts, Desire on Your Part
Able to Laugh at it
Hang In
Let it Soak In

You'll Finally Realize it's Far Easier than you Thought!

Easy Enough!

You'll understand what we Pros Never Did! Props 101!!!

A bit More Insight,
I might have Tumbled to it A Half Century Ago
When I looked for it the first time, as a Kid.

Competing in Model Contests

I Wanted to Know --
What is the Right SHAPE?
What is the Right Twist?
How do we Get Pitch Right?
Stubby Blades, or Long Skinny Blades?

As a kid, my Questions were Spot on!

Blade SHAPE, *Twist*, Blade Loading is the Key!!!!!

Laugh at it. Read Exactly What the Words Say!

Not Faked Out -- You can get Very Smart -- Very Quick

A Needed Insight on the Real World, and us -- Mortals!

Never, in 138 years, have Propellers been adequately explained! Since there has never been a really correct, understandable explanation of Airplane Propellers, this will be read by every level of Individual from Novice Pilots, fully green technically, to Lifetime technical Pros -- with the full Spectrum of Knowledge, Experience, *maybe* the complete Lack of either - every Opinion, Prejudice, personal Bias that we mortals have.

I've been taught, some pretty enlightening, laughable insights!

There will be pros who think that if this isn't written in their preferred wording, that assumes a lifetime of technical insight and knowledge, their exact style, that it just isn't properly done.

Graduates of one course in English 101, effective writing can feel that they are the final arbiter of *the* one proper writing style.

The Game Here is to Help Novices Grasp what we Pros Never Did in 138 Years!

I'm saying this because specific experience has shown me that I'm dealing with the full spectrum of the Human Race here, every strongly felt personal opinion, prejudice, bias on how the task at hand should be done, and on page 1, I've been taught that I need to intercept that full spectrum of the Human Race here, and settle everyone down to the Real World of the Task at hand.

The task here is to **Explain Propellers to Everyone**, from **Novices to Lifetime Pros** - when in the Real World, Propellers have Never Been Successfully Explained, by anyone, to anyone, at any level, correctly, never once in 138 years, because the subject has always been impossibly complex! No one ever saw through them incisively before, the genius level math, the complex heavily loaded three dimensional flow, always previously beyond human grasp, never a proper explanation.

We have successfully reduced a correct understanding of propellers to the practical, understandable grasp of the Horse Sense of What is Happening Physically, just 3 "*easy enough*" core insights, but there are so many allied things happening, that we need a "hit you over the head with a 2 x 4 writing style"! You can see it quickly - in an Hour, Grasp it!

Dive in -- Go along -- Laugh at it -- Even Have Fun -- Get a lot Smarter!

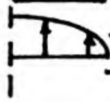
The Bottom Line Core Insights, Conclusions - First, Up Front!

One Page --- Pictures Too

Low Pres. on the Top - High Pressure Bottom, Naturally, *a Tip Vortex!* Wasteful, Costly ------

Induced Loss is simply the **Energy Cost, Loss of Throwing Air** - *Down or Back* - **to Make Lift, or Thrust**. **Profile Drag** is simply **Air Friction Drag**, a Loss. **Prandtl** teaches us the **Elliptically Shaped and Loaded, Minimum Induced, Min. Profile Loss** ***(Spitfire)*** **WING**, because any normally shaped wing loads itself very close to **Elliptical**, **Lift falling off to Zero at the tip** into a **Wasteful, Costly Tip Vortex**, maybe a 25% extra Tip Loss Induced Penalty, maybe, at the speeds we cruise, **Induced ~ 25% of total Loss**!

A Wing



A Prop

The **Core Issue in Propeller Design**, *Astoundingly, Never Clarified, Never Stated Before,* is that a **Propeller, a Rotating Wing**, Very Fast Tips, **Extremely High Tip Dynamic**
1 **Pressure, q, Proportional to V²**, is **Aggressively Tip Loading itself**, Dumb as a Stump, **Aggressively Wrong, Inside Out, Opposite to what any Wing Wants, Needs to be Efficient**, creating **2, 3,** ***done poorly,*** **4, 5** ***times*** **as much loss** vs. a Wing!!

The Problem

You just Don't Tip Load Any Wing - Dumb - Extra Tip Vortex Induced Loss!

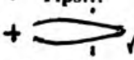
1. Losing the Lift, 2. Creating greatly excessive Tip Vortex Loss! 3. Excess, Unrewarded Profile Drag, at Max radius, Max Lever Arm, Max Torque, 4. Bogging Down available Engine Torque, H.P., LOSING FOUR WAYS, Propeller INDUCED LOSS is greatly Excessive, especially with an added Rotation Loss, Terrible, Never Identified before!!! A .55 C_L Prop, Induced 2/3 of the total loss, not 25% -- 200% of Profile - Twice the Profile!

Get It - This is Easy to See Horse Sense!

Classic Betz Propeller Logic, Goldstein-Theodorsen Math, BGT, Rare Genius Level Work, available to us for over a Half Century, since 1948, **counteracts that** by controlling, directing classic **Half Teardrop, Radial Blade Loading**, given to us in a **Simple Blade Loading Chart, vs. Radius** for all Props from Low Pitch, Advance, to High, **amazingly never explained, never correctly understood, never correctly used before**, until the 2004 ***WhirlWind*** **200 RV Prop**, we taught, a decade long professional effort to finally explain Propellers, **the lack of a valid explanation, the longest, most Fundamental Hole in Aerodynamics**. **A Half Century Late, into the Second Century of Flight without a Propeller Explanation, Ridiculous!**

Loading

Highly Tapered Tips!!!



SHAPE
The FIX
Counteracts **q**

A Family of ideally Loaded, SHAPED, ***Twisted*** **Props results!**
The Family of Shapes, The Loading, ***with optimum Twist***, **Shown on the Cover!!**

The Key, Core Insight, ONE PAGE!!!

Right up Front - We Immediately - Pretty Brutally,

Dump you Right Into the Core Propeller Problem,

and the Betz - Goldstein - Theodorsen Solution!

Just Blade SHAPE, *Twist*, Controlling Blade *Radia*l Loading!

(Always Tapered Tips to Counteract Excess Tip q, The #1 Core Issue!)

The Reason that's Best --- You're almost Instantly Aware!

That's Much Better than making it a long, Drawn out Story!

Get it Quick, If You Can -- *But*
***You Don't Have to Get It on the First Look* - Just Get Aware!**

We Repeat, as we Expand, Go Deeper, Always Tie together!

You'll Have Plenty of Time, and Opportunity to Catch On!

We Superemphasize, **(Novices can't pick out the Gems, at first.)**

Try to Make the Key Insights Jump Off the Page at You!!!

Give Novices all the Help Possible - Help get you Started!

You'll Find those Underlined Statements are Very Explicit!

The Explicit Words that Can Nail the Key Insights for You!

Laugh at it - Join in - Don't be Faked Out! -- Smart Quick!!

***If You Have Trouble* - There's a Cartoon on Page 6 - That can Help, a lot**

The Bottom Line Core Insights, Conclusions - **First, Up Front!**

No Math, we can completely **Explain Core Propeller Logic** by simply understanding, **1. A Rotating Wing, 2. An Airscrew, 3. Pulling in, Throwing Back Air**, *much Heavier than you thought,* **just understanding what's happening Physically, Logically!**

The Game is **Minimize Induced** - **Minimize Throwing of Air!** **3. Newton teaches $T = \dot{M} \Delta V$, Thrust equals Mass Flow Rate, $\dot{M}$, M dot, times the Delta V Speedup -- Get a Big $\dot{M}$, so we can Get a Small Delta V, ΔV, Speedup!!! EASY!**

Minimize the Throwing of Air!!!

So, we either need to Go Fast, or Have a Big Diameter Prop, Easy to Grasp -- Fast allows a Smaller Prop!!! Newton!!! Minimize the Throwing of Air - Minimize Induced, ***Easy to Grasp*!**

An Airscrew, the # 2 concept, brings it all together! We **Want HIGH PITCH!!! Simply, between two Props, the High Pitch Prop is the Faster one - that Minimizes Induced! High Pitch Minimizes Profile Drag Loss too,** so simple it's **Funny, a Shorter Spiral Path to Get to the Destination, a** ***low pitch spinning furiously*, way too far to get home,** ***wasteful*!**

THUS **- It's SPEED** ***vs.*** **RPM that sets PITCH, thus sets Max EFFICIENCY Limit!**

Now, if you can **Grasp those Core Concepts, Quick, Early**, get **Quick, Facile in your Grasp**, You have this Book Licked!

By Simply **using BGT**, *choosing*, a **Constant Ideal Angle of Attack**, α^o, alpha degrees, and resulting **constant, ideal C_L, coefficient of Lift**, **at all radii**, we get a **Triple Ideal Prop**, actually **6 ways best**, **Minimum Induced**, **Min. Profile**, ***Min. Area Precisely, Optimally Placed***, Thus **Minimum Torque**, thus **Min. H.P.**, **Max. Efficiency** --- **Norris's 6th Law!**

By **greatly reducing** the **Aggressively Violent Tip Vortex**, with **Optimum Loading, Optimum SHAPING**, ***Twisting***, we immediately **GREATLY REDUCE NOISE, excessive Noise, an immediate by-product of unaware, unknowing design!!!**

But There's a Lot Happening ---So!

To **Help Novices**, we **Superemphasize**, essentially Yellow hi-lite it for you, **make the key statements jump off the page at you - Repeat, as we Expand, Tie it all together for you!!!**

138 Years, 1865, to the Wright's 100th Anniversary, Dec 17, 2003!!!

Just TWO Pages to Grasp! **Reread** **Get them!**

Jack Norris 12/17/03

*A Reno Prop Throws 4 1/4 Tons of Air Per Second!!!

Everything here depends on giving you an **Introduction -**

that pretty much **says it all** in a few pages - **an hour read**.

There's nothing else like it anywhere!

A Lifetime of Aero Insight - Propellers Nailed - One Hour!

You Won't get it All - You won't be able to repeat it Yet -

But you will be **Marvelously Aware, Quickly** - Easily Enough!

By "Easily Enough" we mean -

It will seem Like a Head Full at First - the First time.

But as it soaks in you'll see it is *Easy Enough* - *Makes Sense*

It's just the Horse Sense Grasp -
of What's Happening Physically
The Kind of Logic we can Understand!

No Math!

1. A Rotating Wing, That tries to work Very Wrong (Fix **Shape, *Twist***)
2. An Airscrew, Fast, Low RPM, High Pitch Best, min loss.
3. Pulling in, Throwing Back Air ($T = \dot{M}\,\Delta V$)
*** Air a lot heavier than you thought!**
Get a Big $\dot{M}$ (Simply Go Fast, or Big Dia.), Thus Get a Small ΔV, Low Induced!
--- There's Nothing really very hard there! ---

The Game - In an Hour - You're Pretty Much Totally Aware

You can soak it up at your own Speed - Novice to Pro

(There's a 12 page Aero 101 Pamphlet to Help Novices who want it, get a good Start)

Getting an Introduction that could work determined the Publication Date.

So we just Skip all Formality - Just Start into it ---

Making Propeller Logic Understandable

Just Understand Aero 101 - What's Happening Physically - No Math!

Since there has never been a real, correct, understandable explanation of Props, this will be read by everyone from total Novices, to Lifetime Pros - an impossible writing task! ✓

We want Pilots to be able to see through the simple fact that Props try to work Very Wrong, try to Tip Load themselves, Dumb as a Stump, Aerodynamically. We fix that, (*to the degree that it can be fixed*), by simply Tapering the Tips, Ideal Overall Blade SHAPES, with the *Proper Twist*, to hold Ideal Blade Angles, *most simply*, ideal Blade Shapes, varying vs. Prop Pitch, low to high - *accounting for* - Speed vs. RPM.

The Family of Ideal Shapes and Blade Loading - is on the cover!!!

We need Pros to see the same insight, because that Core Issue has been *missed for the Whole First Century of Flight!* ✓

We Pros were so blinded by complexity, we missed the core of Aero 101! ✓ WOW

To help Pilots, *Novices*, we've provided a 12 Page "Aero 101 Pamphlet" to get you familiar with the Definition of the Basic Terms, start you into the swing of understanding the core terms, how things basically work in flight, start you into the core *Technical Horse Sense* of *how Airplanes work*.

It's not Brain Surgery --- It's just Grasping the Physical Horse Sense!!!

Since this will be all new to Pilots, and you'll want all the help we can give you, we've adopted a "Hit you over the Head with a 2 x 4 writing style, *Superemphasis*, to *as much as possible* make the key statements jump off the page at you! Novice and Pro alike, We've Yellow Highlighted it for you! ✓

Novices get HELP --- Pros can learn to skim, Speed Read it!!!

✓ **There are more Pilots than Pros, and the Pros, not sweating at all, it's logical and fair that we expect you to do the adapting to what is necessary, to help the new guys. Pros, don't feel you have to give me a writing lesson, I've been doing it in our Pro style all my life. The Challenge here is to help new guys grasp what we missed for 100 years!!!** ✓

✓ **Skip the Hubris guys. It's the open, adaptable mind that creates!** ✓

Since there is a lot going on, we very purposely repeat as we tie together - expand your insight, *repeat, expand, tie together*. ✓ **The game is to get you *facile* in your basic thinking, grasp, so that it becomes second nature to you - *finally* able to grow!** ✓

The Definitions Novices Need are here: p. I-12-Bk II, more after Ch I Book II.

Making Propeller Logic Understandable

Just Grasp Aero 101 Logic - What's Happening Physically - No Math!

Over a lifetime, one can build ***a penetrating insight into flight***, but to **explain propellers**, pretty much ***the ultimate intellectual can of worms***, we took it on as **the final challenge, a final dare!**

The **First Challenge** was to **go deeper, farther, more explicitly** than anyone ever had, ***get past the 3D flow complexity***, the rare genius level math, ***grasp the hidden core logic***, the ***Horse Sense*** of the ***never explained - most complex Aerodynamic challenge!***

The Challenge was to find the Patterns of the Logic For You!

The **Final Challenge** was to **figure out** how to **make this most complex of all technical problems, never explained, *never really fully, correctly understood*** by engineers in 140 years --- **something** that **could "easily enough" be explained, actually be understood by *anyone* willing to go for it** - ***smart in 1 hour!***

NO MATH, the core Horse Sense of a 1. Rotating Wing, 2. Airscrew, 3. Pulling in and Throwing Back Air, *simply*, What's Happening Physically --- It's finally this simple:

The Computer, *behind the scenes, a pro's tool, out of sight,* does all the hard, smart work for us - Just grasp the Horse Sense!

***Let the Inflow, the Outflow, be a perfect helical Screw Surface*, just like the picture on the cover, *just* Constant Pitch Inflow!**

Let the Computer Precisely Load the Blades, *just Shape, Twist* them just like the Family of Shapes on the Cover, always with Precisely Tapered Tips, the WHOLE BLADE SHAPE actually, because, SURPRISE, Props, Dumb as a Stump are *aggressively* trying to load themselves *Inside Out, Max at Tip, a big mistake, compared to what any Wing needs to be efficient!*

Yes, Simply SHAPING, *Twisting BLADES Ideally*, *creates the bottom line answer, took 140 years - and the computer does it all!*

We purposely wrote it *a wild way, Blasts you into Awareness*, "a hit you over the head with a 2 x 4 style", superemphasis, because that's what works, leads you to all the smart insights. *Dive in, Be Brave, Don't quit. Go for it. A wild hour* - Smart!

Go Back - Reread those 2 Pages - if you need to! Let them Soak in!

Making Propeller Logic Understandable

I like and appreciate good writing, good writing style, and my intent here was to write an excellent, professional, great looking computer generated book, that explained how easy it is to understand flight, how to fly airplanes with more insight and intelligence --- and then the never explained logic of propellers.

As they say, the best laid plans of mice and men go astray! Propellers have always been the impossibly complex, unexplained "Black Art" of Aeronautical Engineering, the lack of an incisive, comprehensive, understandable explanation, the longest, most fundamental, gaping hole in the Science of Flight.

Actually, there has been magnificent, incisive, technical logic and Math work done on propellers, truly Elegant, and long ago, an essentially exact mathematical solution 57 years ago, 1948, and we have successfully made them vastly easier to understand, but there still is a problem. If we just start in writing, with professional style, the story goes on, and on, too long, too many interesting things to teach you, all tied together, and you're apt to just get lost, throw up your hands and quit.

The **first challenge** was to see through the ultimate technical swamp, unexplained for 140 years now, a whole century of flight, to the Moon, and back, and still no explanation - ***find the core logic for easy enough explanation***. The ***second challenge*** was to figure out how to take this subject, never adequately understood by Engineers, and **successfully explain it to Pilots**, who don't usually try to unwind wild subjects - and Engineers too.

Right there, good writing style lost out, because the central need here is to ***superemphasize***, make a complex basic subject, that engineers never adequately understood, easily enough understandable to technical novices -- and engineers too! It turns out the proven most successful method is to ***blast you quickly into broad awareness***, make the logic so clear, everyone can get it soon enough, not quit. The core is this easy: ***Dumb props try to load themselves inside out.*** We ***counteract that*** by ***forcing ideal radial loading***, simply with **SHAPE**, ***Twist***!

GET THIS! ALWAYS TAPERED TIPS

Twisted

Do You See? It's really Very Easy - A Family of Ideally Shaped Props!

Making Propeller Logic Understandable

Props have never been really correctly, understandably explained, never really correctly understood, because they **have always been a mind boggling black art swamp** of **wildly complex math**, and **unfathomable, heavily loaded 3 D flow**, where what is happening right at the prop is greatly different than what is happening, on average, over the Stream Tube pulled in, and thrown back to make thrust, more action *at* the blade.

The genius math of the 3D flow, is not the way *anyone* can learn it.

Actually, 7 rare genius historical figures worked 83 years from 1865 to 1948, and created **Betz Classic Logic**, and **Goldstein-Theodorsen Math**, that gave us **perhaps the most Elegant Logic and Math ever created** in any branch of Engineering, **Marvelous! But Pilot, or first time Pro, you Do Not want to tangle with the obscure inner workings of all that** -- ***we did!***

Happily, loaded into a modern Personal Computer, it will spit out **essentially exact Ideal Theodorsen Props**, as fast as we can type in the Specification Requirements, and push the Go Button!

So, we can skip the genius level Math, secure in the fact that **everything we teach you here, *all correct*, is fully backed up by some of the most Elegant Engineering work ever done!**

What we teach is much easier, correct! The Math far too obscure!

To **succeed here together, Pilot, or first time Pro**, we had to get the previous *Black Art* down to the **Understandable Horse Sense of What's Happening Physically.** **That's what we all can grasp!**

For the Pros who want to go on, once you understand the Horse Sense Logic, it is vastly easier to tackle the math, especially after we show you that Goldstein - Theodorsen gave us a simple Blade Loading Chart vs. Radius, that *simply* changes as we go from Low Pitch, or Advance to High!

Tibery and Wrench have refined loading for Very High Advance.

Now, since there is **a lot happening**, and you'll want us to **sort it all out for you, make it as easy as possible, especially at first,** ***embrace the style*** - ***emphasizing the meat, the core logic:***

1. ***Superemphasize,*** so the **key points jump off the page at you**.
2. **Dive right into the core Problems and the solutions.**
3. **Clarify Insight, repeat, tie together** as we **expand, go deeper.**

Making Propeller Logic Understandable

The **way we've been looking at props, is very, very simple** vs. the ***intellectual swamp that pros have had to face for decades***. If you look at the math in the Historic books it initially looks like a swamp of complexity that only a first class math pro could even begin to understand. The final 3 D Potential Flow Solution is something that few Engineers could even dream of accomplishing. **Theodorsen calls Goldstein's 3D solution the greatest, most important contribution in the History of Propellers. He then went on to use it, modify it for Heavily Loaded Flow**, ***where the ΔV pulled in, and thrown back at the prop, is much greater than the average of the Stream Tube*** the Prop Creates, a rare genius himself. His book is a Historic Work! But the bottom Line was, **nobody could see through that and the snakepit of the physical 3D flow well enough to nail the Practical Insights,** until **Dr. Andy Bauer** and I put in **a huge effort to finally nail it all -- a once in a lifetime task!**

But, fortunately ***there is a way*** to make the subject ***easy enough***:

1. People *easily enough*, see a prop is "*kind of*" a ***rotating wing***.
2. Many see a propeller is an **Airscrew**, the British description.
3. Pilots, *easily enough*, see a **helicopter** pulls in, **throws *down* air to make Lift, Propellers** pull in and **Throw *Back* Air to make Thrust** - too few realize wings are also throwing down air to make lift, a Newton's *Equal and Opposite Reaction force*. **Said simply**, the ***energy cost, the loss of throwing air*** is the ***Induced loss***, the other basic loss in flight, with skin friction, ***Profile Drag***.

GET THAT -- INDUCED -- IT'S BASIC

Fortunately, if we just teach you the comprehensive insight in those **3 very basic fundamentals**, *all backed up* by the **Elegant rare genius level math**, we can **skip the math**, because, the simple logic teaches us ***What*** the math is doing and ***Why***, better than the rare genius math, which hides what's happening physically, but ***the math precisely affirms the horse sense logic.***

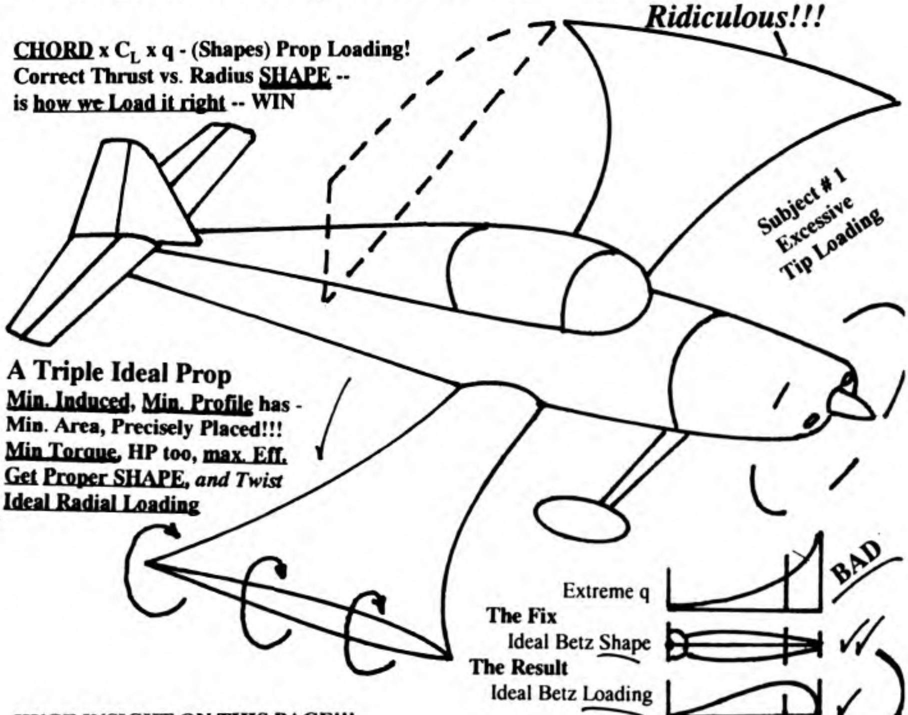
All **three** of those basic insights are very important **-- teaching us specifically what is happening Physically, Logically**, the kind of **practical insight we can all understand, our brains working on understood logic** - complexities then easier to see.

Geniuses created the Logic, the Math, the Computers for us.
We just need to Grasp the Horse Sense of What's Happening Physically!

Making Propeller Logic Understandable

A **PROP** is *trying to load itself* ***INSIDE OUT***, **DEAD WRONG, DUMB,** ***compared to what a wing needs!*** A **Wing** creates **Max Lift at the Center** and simply falls off, pretty much like ***an Ellipse***, no matter what shape it is, because **Wing Lift** ***Must, Will Fall to*** **ZERO AT the TIP**, a ***TIP VORTEX*** **Swirling from the** ***Higher Pressure Bottom***, **to the** ***Lower Pressure Top***, (even tip Dams only partly effective). But here's our Dumb Prop with very ***high Velocity Tips***, **Huge Dynamic Pressure, q, Tips, (Proportional to V^2) trying to make max. Thrust and Drag AT the Tips, where Thrust will be LOST, must fall to Zero, creating an Extra Big Tip Vortex,** ***thus*** **Extra Induced Loss,** ***extra*** **Unrewarded Profile Drag,** ***at max. radius***, **Max Lever arm, extra unrewarded Torque, bogging down the Engine RPM, Losing HP, Losing (4), four Ways, DUMB AS A STUMP!!! Creating NOISE too!!! It's our job to be smart enough to COUNTERACT that, Taper the Tips, Pull the Excess Loading Back Away From the Tips,** ***EASY KEY INSIGHT!!!***

HOW ABOUT AN EQUIVALENT *TIP LOADED* WING



HUGE INSIGHT ON THIS PAGE!!!

> ***This is the most Important and easy Insight You'll Ever Learn about Props!***
> **It has been mostly missed, mostly not understood for the last 100 Years!**
> **You don't win** ***playing games*** **with a wider tip, make Lift, where we just pulled it back!!!**
> **(*Later we may be able to beat* the Betz 20th Century Ideal Loading and Shape!)**

Jack Norris 12-17-03

PROPELLERS EXPLAINED

The easy core insight: Props naturally Tip load themselves, Bad! Just Tapering the Blade can *counteract* that problem! That Core Issue in Propeller Design, amazingly, seems to never have been specifically identified, stated, written anywhere that we have been able to find! If true, that is the greatest, fundamental oversight in the history of Aerodynamics, in 2006, over 140 years since prop Analysis started with Rankine in 1865.

(The Civil War "Monitor", others, had early Screw Propellers.)

Simply, **Propellers, a Rotating Wing, very fast tips, greatly amplified tip Dynamic Pressure, q, (Proportional to V^2), tries to Greatly Overload the Tips, *create Greatly Excess Tip Losses, actually "inside out, reversed loading"* vs., the Center Loading, any wing needs**, because the **Lift, Thrust of any wing surface MUST, will FALL to ZERO at the TIP**, the higher pressure below **swirling** into a **tip vortex induced loss** to the lower pressure above the airfoil surface ***wasting energy*** **- Aero 101 really!!!**

The Simple FIX is to *Counteract that very wrong q Loading* with tapered tips!

Simply, presuming we ***twist*** **the prop** to maintain an **optimum angle of attack, alpha, α°**, an **optimum coefficient of Lift, C_L**, we can **SIMPLY taper, SHAPE the Prop Blades**, into **a FAMILY of Triple Optimum Props, Min. Induced Loss, Min. Profile Drag, Min. Torque, Minimum Area Precisely Placed, Norris's 6th Law --- chord vs. radius, Shape varying vs. Advance Ratio, Pitch.** That's a **Betz Minimum Induced loss Prop, Goldstein-Theodorsen** rare genius level, essentially exact **Math**, available to us since **1948 --- with an optimum C_L to get the Minimum Area Precisely Placed - least Profile too!!!**

Try going for a higher C_L, less Area, and you get higher Induced, start losing.

Simply, since 1865, **Propellers have never been, correctly understandably explained**, never really properly understood, because a proper explanation has been missing, that long, the biggest, longest gap in Aerodynamics. I know because, a lifetime pro, with my products all over the world, I've been looking, waiting for that explanation since 1946, 1948 when I won the Senior National Model Championships, two of the three years I was there to compete my designs.

My college friend, and collaborator, **Dr. Andy Bauer, and I**, two Lifetimes of Knowledge, took it as - the *ultimate challenge!*

PROPELLERS EXPLAINED

Always, the never explained, most complex subject in Aero, I knew **we had to get it down to Aero 101 Logic,** ***Horse Sense***, so that **Pilots, technical pros too**, could finally grasp what was happening ***physically***, the **logic**, ***easy enough to see through it!***

It took years of professional work, of working all the math, all that everyone had done, **computer programming everyone's methods, running studies, cross-checking, finding who had it right, wrong,** *or close, but no cigar*. **Goldstein-Theodorsen had the math correct, essentially exact 57 years ago**, and all **we have to do is to be smart enough to honestly understand correctly, use it all**, ***their simple blade loading chart***, **let modern PC's spit out essentially exact answers for us** - ***easy!***

You, Pilot or pro, Do NOT have to deal with the genius math, ***we did***, **just understand the LOGIC, the Horse Sense**!

Specifically, because of the "Inside Out Loading" props always have 2, 3, (designed poorly, 4, 5) times the loss of a comparable Aspect ratio Wing!!!! If we simply use Betz Logic --- which demands the perfect Helical Screw Surface inflow, a stretched, still perfect helix thrown back, shown on the cover --- given to us by Goldstein-Theodorsen Math, we get the "Half Teardrop Loading" shown on the cover, the Family of Triple Optimum Shapes, shown, if we simply use an optimum angle of attack, α^o, and C_L - THAT EASY!!!

We can understand all the Logic of What's Happening Physically, the core logic of Props by just learning the Logic of - 1. A Rotating Wing, 2. An Airscrew, 3. Newton's Laws, Pulling in and Throwing back Air, ***heavier than you thought!***

We've succeeded, made the logic easily understandable, but there is a lot happening, all tied together, ***interrelated***, **a whole book full, finally, depending on how far you want to go, a quite good grasp simply in this Introduction,** ***maybe some cherry picking where I'll tell you to look***, **matching anyone's level of interest.** --- ***But enough to confuse you if we did it wrong!***

Making Propeller Logic Understandable

It's been **140+ Years**, into the Second Century of Flight, the **Astounding fact** is that, **no one ever stated this Central Core Problem in Propeller Design*!** Actually, B-G-T did the **Marvelous, Rare Genius Technical Work**, maybe in all, the **Most Elegant Logic and Math ever, in any Branch of Engineering -** but it was such an impenetrable Swamp of 3D Flow, Genius Level Math, it Faked Everyone Out. **No one ever** dug enough, **dug deep enough to grasp what it was trying to direct and tell us.** We Never Got the **Triple Optimum Prop**, ***Min. Induced Loss, Min. Profile Drag, Min Torque***, Norris's 6^{th} Law, the **true Optimum**, that delivers the **Needed Thrust, for the Least Torque, H.P.**, **turns easiest for the Thrust**, **Max Efficiency!**

* Actually we had this core long before 2003, Wright's 100th, continuing our work.

We don't even have to deal with the Math - Just let a Computer design an Optimum, Exact Betz Logic, Goldstein - Theodorsen Math, Minimum Induced Loss Prop, but ***Twisted*** **to achieve an Optimum Angle of Attack, Coefficient of Lift**, for ***Minimum Area, Precisely Placed***, Norris's 6^{th} Law, **all on a Computer, Easy!**

That previously Secret Key, Startlingly Simple, is to **just grasp the True Aero 101 Logic of a Prop:** That Fast Tips, often Extremely Excess Tip Dynamic Pressure, q, relative to the prop inner radii, works to Violently Overload the Prop Tips, *Losing Paid For Thrust*, creating greatly excess Tip Vortex Loss, NOISE, Excess Profile Drag, at Max Lever Arm, Excess Torque, Bogging Down Engine Torque, Losing RPM, Losing H.P., Dumb as a Stump, Easy, once you see it. Dr. Andy Bauer, and I, two old pros, nailed that and many other key Aerodynamic Insights, had the experience to solve it . We were willing to do the hard work, **as a Gift, an ultimate challenge, a "Give Back" for a fantastic life in Flight** ***in this Greatest Time and Country ever.***

We did it the old fashioned way, we Earned it. Honest Work Pays off!

The big Funny: we launched the 57 year old Math. It tapered the Prop Blade Tips, ***counteracted*** the **excess tip Loading**, got a **Family of Theoretically, essentially Exact Optimum Props!**

Looking for answers, Hard Truth as a kid in 48 - winning the National Championships, *T T's genius waited a half Century for Andy and I - wild!*

Propellers - *Just Understand What's Happening Physically!*

(It's all backed up, *Proven*, by genius level Math -- *that You can Skip!!!*)

Pilots,

If we simply look at Airplane Propellers as **1. Rotating Wings**, **2. Airscrews**, **3. Pulling in and Throwing Back Air**, that's a **lot heavier than you thought***, we can understand all the **core logic** of **how they work**, and **should be designed**! We thus get **understanding them** down to the **horse sense** of what's happening physically, and **you**, ***and engineers too***, **can understand most easily!**

It turns out this is a big ***breakthrough***, because, if *pros* dive into it as an Engineering, and Math problem, it quickly becomes a morass, that has defied understandable explanation for 140 years

WE HAD TO SEE THROUGH IT --- YOU DON'T!!!

As Pilots, this hidden logic can seem harder than it really is. ***Unexpected***, **we engineers, need time too. To help *everyone***, we purposely do things that **look pretty wild at first**, but **succeed!** **1.** We ***Superemphasize*** the Horse Sense Logic, ***make the key words***, **the logic** jump at you. **2.** We're purposely going to dump you into the whole core of the Logic in a pretty brutal, dense way, to ***Blast you into Huge Awareness, Quickly, not draw it out!***

You don't have to grasp it all, at first, we repeat, *just get aware, just start to get it!*

Experience has taught us there's very good purpose in both approaches. If we just start in explaining everything in a more gentle manner, the explanation goes on, and on, gets deeper, too drawn out, and pretty soon novices and engineers both feel confused, maybe overwhelmed, might give up. If you can live through a few wild looking pages, without going into shock, **blasted into Awareness**, you can start seeing that there is some pretty powerful logic, very quickly. Then, it quits looking crazy

It's not for Speed Reading. We want you to see all the phrases, how they fit together!

You will surely be shocked to some degree, but if you just hang in, you'll find we wrote it to help pilots get aboard on what is a pretty wild subject. We keep repeating, drawing you in, leading you. *I'm sure you'll feel out of control*, but ***hopefully***, it will start sinking in, start making sense to you. You don't have to figure it out, *we lead you to all the right insights*. Have guts. Dive in, hang in. Treat it like a game, a challenge, *a worthy Mystery novel*. You'll ***get aware, very fast***, maybe even laugh about it!

*** A Reno Racer Prop *Flows* 4 1/4 Tons of Air, 8500 #, per Second, at 480 MPH!!!**

A Special Early Page for Pros

As a pro, I've been really surprised to see that **a smart novice can sometimes "get it all", right now, quicker than a long experienced pro!** I've seen some pros tend to have a head full of ***barrier ideas*** they're very sure of, *don't really get it*, read, all that is said here, don't see all the implications, going off on their own thoughts before they get it. I've had pros immediately start telling me how to write it, (for them), **clearly before they understood what is here, also, not a clue** it has to be **written very differently for Novices**. I've seen we pros can need the Superemphasis, *at first*, as much as Novices!!! ***Sobering!***

One can see why it can be *the adaptable guy* who gets the new idea!!!

How did we pros never nail the core issue here, the bad loading? As pros we seem to maybe accept the high q prop tips, assume we'll deal with that correctly, maybe misunderstand that's the natural place to get high lift, not recognize that's **a very bad situation for any Wing** --- that **any wing is incapable of efficiently holding significant loads, *relative to the root*, anywhere near the tip** - lose the thrust we're paying for, a prop sure to create greatly excess tip Vortex and Profile Drag losses, at max. lever arm, bogging down the available Engine Torque, losing H.P., ***losing 4 ways, a prop always 2 to 3 times more loss than a comparable wing, 4, 5 times done poorly!!!***

How come no one ever asks why props lose 2, 3, 4, 5 times more efficiency?

As a kid, before I had the formal education, had a clue about circulation, horseshoe vortices, I had to figure out, understand the horse sense of Aero, and that can help, even be better. I first understood **High Aspect Ratio** as a very long sailplane wing where we ***wanted a lot of lift, a long way from the tip***, the long narrow tip itself with less loss --- a **60/1 L/D Sailplane**, a 1/60 loss, .0166, 1.66% loss, **98.33% efficiency for the whole plane. That helped me to tumble to the terrible prop loading!**

Aspect Ratio teaches - Don't tip load ANY wing - the Truth!

If you're a pro, learn how to best read this book, (Written for Novices, not you)! Don't bitch, think broader, understand. Smart enough, once you grasp the insight, you can **speed read skim the superemphasis! It's Yellow High Lighted for you!**

You want a **Long Span** for High Mass Flow rate, **min ΔV**, **min Induced - Tip Far Away too!**

Now, We'll Move On, Learn a Lot more

Some Aero 101 Basic Definitions --- and Insights

Very Important, Enlightening Basic Insights

Profile Drag - Is Simply **Skin Friction Drag - by the Air**, a **Basic Loss**!

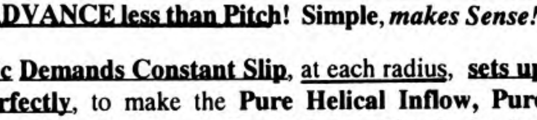
Induced Loss - We're taught **Wings produce Lift**, because of a lower pressure over the top of an Airfoil - but all less than infinite span wings **also throw air down**, *another way of looking at the same lift*, just like Helicopter Rotors, or Props throwing air ***back*** to make Thrust - Also a ***Tip Vortex Loss!*** Both, are an **Induced Loss**, the **Energy cost of Throwing Air**!!! **The core problem of Propellers** is a **Greatly Excessive Tip Vortex**, from **excess Tip Speed, V**, **magnified Tip q, Dynamic Pressure**, and a **Rotation Loss too**! **Induced is only a fraction, of Plane Profile where we fly Planes, ~ +25%**, but on a **.55 C_L Prop**, **Induced is ~TWICE Profile, A HUGE LOSS**!!

q, Ram Dynamic Pressure - Is simply the **Pressure Rammed, into our Pitot Tubes, Stopped**, used to **measure** Indicated Airspeed, **IAS**, but also measures **Energy at that V**. Thus, it is the **Pressure and Energy** used to create **Lift, Profile Drag, Induced Loss**, often thought of, used as a **Drag**. **q is Proportional to V^2**, V squared, so it's 4 times as big at 200 MPH, vs. **100 MPH, 25 times as big at 500 MPH** (a Huge Problem on a 100 MPH Plane with 500 MPH Tips)! **Excess TIP q on Prop Tips, causing Excess Tip Vortex Loss is the Central, Core Problem, and Source of Excess Loss on Props**!

Yes, Our Airspeed Indicator -- Extracts the Square Root of q!!!

Helical Pitch - Is Simply **how Far Forward a Prop Will Screw Through a soft solid, in one Revolution, No Slip**, acting as a ***Perfect Screw*** at **all Radii**, like the **Perfect Betz Helical Airflow on the Cover**. (A Prop won't end up with Pure Helical Pitch, after we correct it for Slowdown, the Slowed air in the Plane of the Prop, from the Embedded Body, decreasing, the steeper inner Prop angles.) But that can be very Good, Perfect at Design Speed, **Better Slow, at Takeoff and Climb**!!! **So, Props have *Less than Theoretical Twist, Better!* Pitch Measured at 3/4 r!**

Pure Helical Screw Pitch
Model Builder's Layout of Pitch



Circumference layout gives angles

Slip - Advance - **Propellers are *Overpitched* to Account for Air Inflow** Thus, **they SLIP**, actually **ADVANCE less than Pitch**! **Simple, *makes Sense!***

A Key Insight: **Betz Logic Demands Constant Slip**, at each radius, **sets up the Flow Geometry Perfectly**, to make the **Pure Helical Inflow, Pure Helical Stretched Outflow** of the **air Thrown Back, faster, *Simple Genius***.

Advance is very **important**, fundamental to **a Graph of Max possible Efficiency**, since **only High Pitch, High Advance Props can have Max possible Efficiency**. Advance is **often called Lambda, V/πnD***, very **Simple once you see it, just Forward Velocity / Rotational Velocity of the Tips. Think** and you can see that **defines the *actual* Angle of Advance** of the **Tips**!

***All measurements in ft., #, sec. V in ft./sec. n = rev./sec. λ =**

Some Aero 101 Basic Definitions --- and Insights

Very Important, Enlightening Basic Insights

Propeller Efficiency, Eta, η, is Simply: **Energy, or H.P. out / input of related Energy, or H.P.,** ***easy enough*, a ratio, shows "useful percent".** **Nominal Efficiencies** on **High Pitch Props** range from **90%,** a little better on fast Optimum Cases, to **85% max. on *slower*, Low Pitch Classics at 100 MPH.** On old, Aerodynamically poorer planes, with wider Tip Props, not correctly designed, it's possible **to *lose 10%*,** a **75% Prop, *not*** a proper **85%,** and **often another 10%,** on extra **scrubbing Drag,** and **poorer flow,** maybe some flow **separation,** η x .9, ***only 67% overall Propulsion Efficiency,*** η_P. In the 60's, Gus Raspet, found only **58% overall on a Bellanca Cruisair, charging Engine Cooling to the Engine, not the Airframe, *an eye opener!***

1/.58 *requires* 172.4% more HP, Powered, vs. Gliding, WOW!!!

The Lift, or Drag Formula **Area* x C_L x q = Lift** **Drag = Area x C_D x q.** Naturally, **Wing Area is used for Lift,** but **also for Drag,** (which makes less sense, because the whole Airplane is involved, but that's convention). **For Props,** of course, **Blade Area is used. q, Dynamic Pressure,** as above, **is the pressure available to be put to work,** (interestingly, as above, it's also a measure of Energy, per cubic foot of air). **C_L maybe ~ .5 on a Prop,** to ~ 1.2, or more at Stall. Let's Call it **a Fudge Factor** that **defines how hard the Area x q, is working,** maybe 2,5 with Flaps!

→ * Using Chords for a Prop, local q, gives local Thrust, for integrating vs. Span!

Angle of Attack, α° **Simply** the **Angle between the Wind Line, and the straight Line connecting the nose of the Airfoil and its Trailing Edge.** Significantly, with ***a cambered airfoil*, Zero Lift C_L may be at minus 4°,** thus, **to get a .5 C_L** we may only need a **~1 degree positive angle of Attack,** since ***typically* 1 degree angle of attack nominally changes C_L ~ .1** ***Handy.***

LATER YOU'LL LEARN INFLOW CHANGES *EFFECTIVE* ANGLE OF ATTACK!

Coefficient of Lift, C_L It's really just a dimensionless **coefficient that simply ratios, how hard the airfoil is working, thus the "Lift per sq. ft.", little at a low angle of attack, a lot at high α°, simply ~ +.1 C_L per 1α°, until that nice easy relationship quits being linear near stall!** **A Small, or Slow, Low Reynolds number chord, *may* stall at a C_L of 1.2,** a **fast, huge wing at 1.6,** with max. **flaps ~ 2.5.** Notice anything over 1 could look like it's getting **more than 100 percent of q, *not true,* huge Flow Rates of air, *of q, energy!***

Aspect Ratio. Very Big **Span/Chord,** or **Span²/ Area, Long Wings, narrow chords, is what drastically reduces Induced Loss on a Sailplane** wing. Physically, **a lot of efficient Lift** is made **far away from the Tips,** far **less loss rolling into a Tip Vortex ←- More Important, on a Prop !**

A LONG SPAN WORKS ON A BIG Ṁ, THUS LESS ΔV, THUS LOWERS INDUCED

Blade Shape As we've seen here intelligent **Shaping of a Prop Blade, (with proper *Twist* and Pitch, to fly all Airfoil stations with proper, α°, and C_L)** is far more important on a prop than a Wing with Hugely exaggerated Tip q.

***Further*, Complete Definitions at the end of Book II Chapter 1**

Remember, the Book Was NOT Written Just For You, but for Others Too!

Prop Loading vs. Radius - Pictures Worth a Thousand Words

A Dense Summary - The Core of the Whole PropLogic Story

In 1919 Betz Conceived the Ideal Minimum Induced Loss Propeller, *initially* done on a *Profile Drag Free Basis*, a **key basic core** math optimum. It creates **pure helical inflow**, **throws back a stretched pure helical backflow**, in a **"Streamtube"**, thus creating **a reaction force Thrust**, per **Newton's Laws**. It's overpitched a little to *account for the inflow*, thus **slips a little, advances a little less than the pitch**, creates the pure helical flow *ideal* by **designing the inflow for constant Slip**. The **excess tip velocity, greatly excess V^2 tip Dynamic Pressure, q**, of a **Rotating Wing, greatly overloads the tips**. The **Excess Thrust is Lost rolling off the tip into an excess tip Vortex Loss**, extra, unrewarded **Profile Drag Loss** at a max. lever arm, **bogging down the Engine**, losing H.P., **losing 4 ways**!!!! By **precisely loading the Blade vs. radius**, by precise **SHAPING** of the blade with **proper matching *Twist***, Betz ***counteracts*** the **Excess Tip Loading Losses**, **prevents excess losses**, **minimizes losses**, **actually achieves the Ideal Propeller**, **even a constant ratio of Thrust vs. Torque, or H.P., constant efficiency at all radii** -- all, if first considered Profile drag free -- ***Amazing Insight!!!*** We learn **only** (**Fast**, *or geared*) **High Pitch, High Advance per Rev Props can have Max. Efficiency, Min. Induced, min. Profile Drag Energy loss** (a short Spiral path home). **The Ultimate Prop is a Graceful Canoe Shape**, (**low Pitch props more Tapered**), **by Theodorsen Math.**

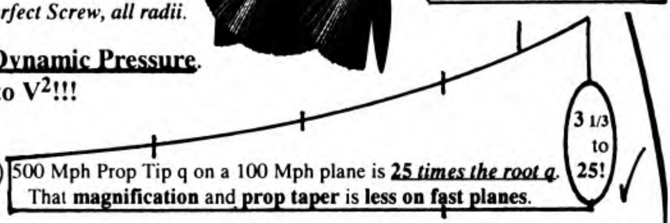
Betz Helical Inflow, ***pulled in***
Stretched Outflow, ***shown*** -
***Downwash*, Backwash.**
Inflow helix + ideal α^o = Twist β^o's

Helical just means a perfect Screw, all radii.

Tapering Tips
Pulling Back Loading
Is the Crucial Key Step!

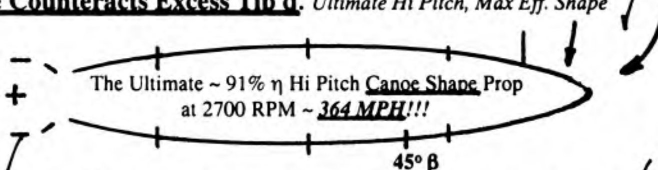
Exaggerated Tip Dynamic Pressure.
"q" proportional to V^2!!!

*q magnification on **this ultimate prop** (1) is **only 3 1/3**, but is **25 on a Luscombe!**



Ideal Blade Shape Counteracts Excess Tip q. *Ultimate Hi Pitch, Max Eff. Shape*

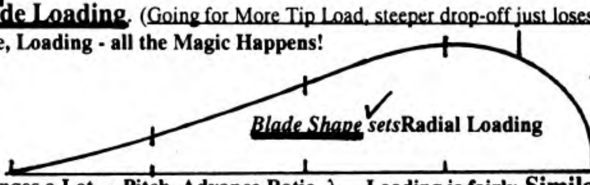
Hi q magnification props, ***are far more tapered***, narrow tips, almost triangular, at *very* lo pitch, ***moves*** the ***max. chord inward***.



Betz Optimum Blade Loading. (Going for More Tip Load, steeper drop-off just loses!)

The Right Blade Shape, Loading - all the Magic Happens!

See page 147 for all the complete insight on Shapes, Loading.



Ideal Prop Shape Changes a Lot vs. Pitch, Advance Ratio, λ. **Loading is fairly Similar**

An Interesting Overview of Propellers

The British never went to broad tip Props, not in WW II when our guys did, (to absorb the high H.P. of BIG engines, also to avoid excess Mach tips, *limiting diameter*, with High Activity Factor, tip loaded props), not after*, because it's **a Bad Idea**, fails to understand the basic engineering logic of propellers, the essential horse sense of how to make props work well, or poorly. ***Brits*** call them ***Airscrews***, and that's a proper term, but we get really key insight by learning what's bad about a **Rotating Wing**. They went to more blades, kept blades closer to the correct shape, **the four bladed Spitfire, a smart WWII example**.

* Some British Planes had American Props. I saw such a Spitfire On TV.

It turns out **only High Pitch, High Advance** per revolution props can be **most efficient**, **Faster vs. RPM**, they have the **least Induced loss, throwing of air to make a Reaction Force Thrust, and the least Profile Drag Energy Loss**, simply a shortest path to get home, so easy its funny! **Fast**, **low RPM**, thus hi pitch, is the easy way to get a high efficiency prop, a higher cap on the possible efficiency. A fast prop can be smaller in diameter, than a slow prop, because **Newton** teaches us the **game is to get a big Mass Flow Rate**, $\dot{M}$, so you can get a **small Delta V**, ΔV, **thrown air speedup** for any given thrust, because ***throwing air is what causes Induced loss, lost Energy***.

SLOW PROPS MUST HAVE BIG DIAMETER, WANT LOW RPM, HIGH PITCH!!!

It turns out that props want to be **a steep, effectively 45° Helical Screw**, and the **final efficiency ball game** is all about **loading them ideally vs. radius**, and presuming we use proper twist to hold a constant ideal angle of attack, and C_L, that simply means **SHAPING** them optimally, since ***chord places Area***, **Load Distribution**. We've learned **dumb props** are trying to work **inside out, *opposite* vs. a proper wing loading**, our job is to be smart enough to correctly ***counteract the inside out!!!***

Where you let the MAX LOAD happen, the Distribution, *is the game!!!*

Despite magnificent technical work that took 83 years, but got us a Classic Prop Logic and essentially exact math by 1948, we ***never got a comprehensive, understandable explanation*** of the *logic*, **the horse sense of it all**. **That's what this book is all about!!!**

Beginning to Expand our Insight

It is absolutely essential that we first show you how to grasp the Basic Horse Sense Logic of Props **Quickly,** ***superemphasized***, because, explained the wrong, long, complex way, it's just too easy to get lost. **We nail it, repeat, expand!** We very purposely use ***this Introduction to get you to understand the big picture***, then slowly take you into a quite sophisticated grasp in bite size steps, repeating, helping, summing up, ***so you can go as deep as you wish!***

Here's the way we do it, ***superemphasized to help novices get it:***

1. This **Introduction** to get you started with ***great overall*** **Insight.**
   The 1 page X-Ray, Incisive, Magic Basic Core Insight. page **I - 21.**
   The slightly more sophisticated **2 page, very concise Grasp.** p. **I-22, 23.**
2. The ***Helpful*** **~1 hour Book II Primer** to get you well into it all.
3. **Chapter 9 of Book I**, the Airplane Book, targeted for the "Thinking Man Pilot", *p.147, ultimate Blade Loading Family of Shapes, Twist.*
4. The ***Smooth Read*** **Chapter I, Book II**, really the **Advanced Introduction to Book II, Propellers.** ***Advanced a ~1 day read!***
5. The **Pro's Insight, all of Book II**, no math, but more incisive insight than has ever been available anywhere before.

We use a few key Graphs, PICTURES, of how things work --

Despite some of the most Elegant Logic and rare genius level mathematics work ever done, there has never before been a comprehensive, incisive, understandable explanation of props, their logic, and **what all the math means, instructs, and implies**, in a way that even pros could fully grasp.

The great misfortune is that despite some absolutely magnificent technical work by 1948, the lack of an incisive explanation has resulted in even Aerodynamacists ***not*** correctly understanding the real core engineering logic, the understandable horse sense of prop logic, almost no one, even among propeller designers, correctly understanding the ultimate way to go.

It was only with the advent of **early smaller computers in the 70's** that (only) the best companies got started on Betz caliber design, but complex, **the accurate, simple insight here was pretty much missed. We never got an ultimate Triple Optimum Prop, our 2004 *WhirlWind* 200 RV 8 *a first!***

You can spot a Triple Optimum Prop, Min Area Precisely Placed, by its Shape!!!

It's all simply proper loading vs. radius, and that means Shape, with correct Twist.

The **Objective** here is to ***get Propellers correctly understood for the second Century of Flight***, ***accurately designed***, no more seat of the pants guesses, **precise designs easy enough!!!**

(We may now even beat the Betz Ideal - simply a modified SHAPE, *correct* twist!!!)

Beginning to Expand our Insight

Getting Twist Right - *The* Betz *Minimum Induced Loss* Prop

Getting a Major Fundamental Nailed -- Easily!

In Gottingen Germany, at the University, Prandtl concluded that (at a constant angle of attack and C_L), the **Elliptically Shaped and Loaded Wing was Ideal**, because that lift naturally fell to zero at the tip, gave Minimum Radial Flow, **Minimum Tip Vortex**. His friend, **Betz**, concluded the much more complex Propeller had the **Minimum Induced**, if it ***pulled in*** a ***Perfect Helical Pitched Air Inflow***, and ***threw back*** a ***stretched still Perfect Helically Pitched Outflow***, downwash, backwash, perfect **Archimedes Screws**, (212 BC), **four**, a pair from each blade, **two separate rotating wings, 180° apart** in their **Stream Tube**, *nominally* ***half the speedup in front, half behind!*** See the cover picture.

To **Advance Forward**, the prop should logically be ***Overpitched a little to account for the Inflow***, (not the outflow, it turns out), and if we make the resulting **SLIP the Same at Every Radius**, it would ***act like* Even Inflow Velocity**.

Logically, we might expect that there is an **Optimum angle of Attack** and **C_L**, (and there is, *nominally* **.5 C_L, ~1.1° angle of Attack, α°**). Do you see the hint on where we're heading? If we use an **optimum α°, and C_L**, we should be able to get **min. Profile air friction Drag**, **if we distribute the minimum area optimally!**

Now we've thrown quite a bit at you, *perhaps too quickly*, but we're right up to **an insight of Major Importance**. If we simply **add a constant optimum α° to our perfect helical screw inflow, we have accurately, and pretty easily defined our propeller *blade twist* and Specific Pitch Angles, β°, at any radius!!!!!**

Plane Speed, + Inflow, + α°, *vs* **Rotation Speed, sets the Pitch Ramp Angles!!!**

So **our prop blade does not have perfect helical Pitch, just a tad different**, but actually, **simple enough, once you catch on! The prop is Pitched a little extra to account for pulling in air to throw back, so it Slips, *Uniformly*, Advances a little less,** but you have **Major Insight in one page, *Twist Understood!!!***

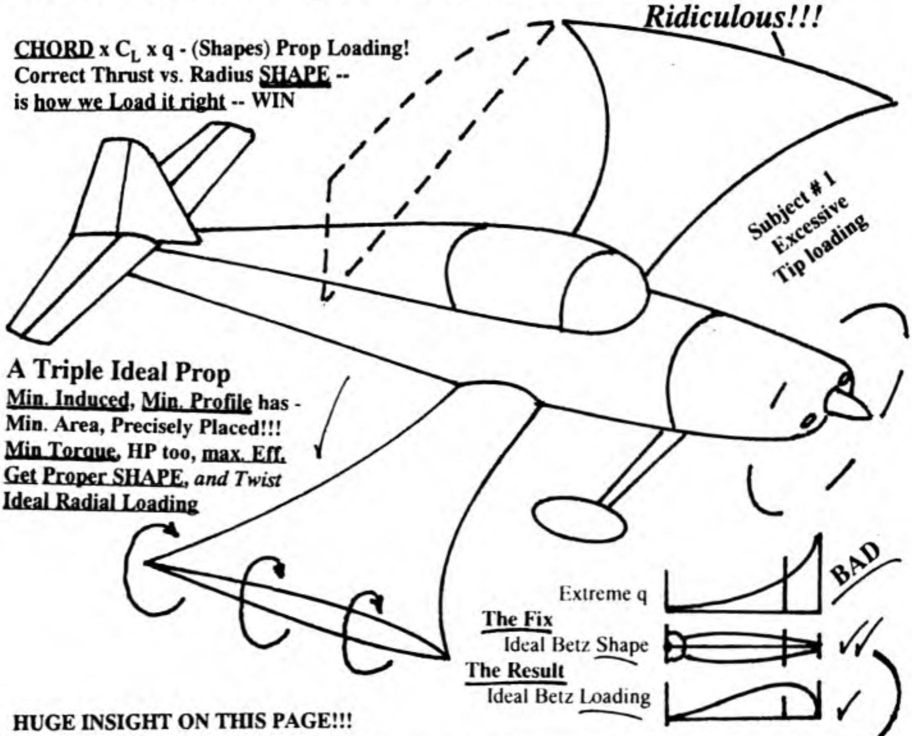
Much later, we'll correct angles for *Slowdown*, the *nose Velocity Profile!!!*

This is pretty typical of Prop Logic - tricky details, but OK, soon Understandable!!

Making Propeller Logic Understandable

A PROP is *trying to load itself INSIDE OUT*, **DEAD WRONG, DUMB,** *compared to what a wing needs!* A **Wing** creates **Max Lift at the Center** and simply falls off, pretty much like ***an Ellipse***, no matter what shape it is, because **Wing Lift *Must, Will Fall to* ZERO AT the TIP**, a ***TIP VORTEX*** **Swirling from the *Higher Pressure Bottom*, to the *Lower Pressure Top*,** (even tip Dams only partly effective). But here's our Dumb Prop with very ***high Velocity Tips*, Huge Dynamic Pressure, q, Tips, (Proportional toV^2) trying to make max. Thrust and Drag AT the Tips, where Thrust will be LOST, must fall to Zero, creating an Extra Big Tip Vortex, *thus* Extra Induced Loss, *extra* Unrewarded Profile Drag, *at max. radius*, Max Lever arm, extra unrewarded Torque, bogging down the Engine RPM, Losing HP, Losing (4), four Ways, DUMB AS A STUMP!!! Creating NOISE too!!! It's our job to be smart enough to COUNTERACT that, Taper the Tips, Pull the Excess Loading Back Away From the Tips,** ***EASY KEY INSIGHT!!!***

HOW ABOUT AN EQUIVALENT *TIP LOADED* WING



HUGE INSIGHT ON THIS PAGE!!!

This is the most Important and easy Insight You'll Ever Learn about Props!
It has been mostly missed, mostly not understood for the last 100 Years!
You don't win *playing games* with a wider tip, make Lift, where we just pulled it back!!!
(*Later we may be able to beat* the Betz 20th Century Ideal Loading and Shape!)

Moving on to the Advanced Introduction

We'll do a Little Mid-Stream Review

To Solidify Your Grasp of the Core Logic

(The More Facile Your Grasp, the Easier, Better Going On!) √

Then, We'll Bring in Other Expanding Insights

Give you a Very Good Grasp in Just this Introduction!

We'll also Show you How to Cherry Pick -
Many of the Other Interesting Insights in the Book!

Some Pilots may be Satisfied with just the Introduction

So we'll Help, Show You a Way to Maximize That! √

If you tried to Learn 25 insights, on one Pass, You Wouldn't Remember!

But the More We can Build This into an Integrated Story,
Repeat the Basics, *continually Tie Together*, as we expand Your Insight,
Make a well Integrated, Logical Story, You Might win a Great Grasp!
So That's the Way We're Building This!

(If we could Discuss Props for a Day, we could get you a Pro Grasp)
So there's a Day's Worth of Meat, Discussion Here!

Using the Classically Perfect Prop to Understand Prop Logic

Because, with ~ Perfect Math we can teach you Thoroughly, Accurately!

Later, we'll show you how to do even better!!!

Rankine did the first prop analysis in 1865. Betz defined the Ideal Minimum Induced Loss Propeller in 1919, and by 1948, Goldstein and Theodorsen had created rare genius level math for an essentially exact, Elegant Math Solution. But we never got a comprehensive, understandable explanation that went way past the math to fully understand **What** the math was doing, and **Why**, fully understanding the Logic, the Engineering Horse Sense of the Engineering Swamp involved. That's what this book is all about, **showing you the understandable horse sense that has been hiding in the Genius level Math since 48.**

We learn that a prop **Pulls in and Throws back (heavy) Air** to make a Reaction Force Thrust that ***causes induced loss***, that it's an **Airscrew**, and ***only High Pitch, High Advance per rev props can be most efficient***, that as a **Rotating Wing**, a prop is being "Dumb as a Board," trying to ***greatly overload the tip*** area, causing greatly excess and unnecessary Induced and Profile Drag losses, turning those *losses* into objectionable **Noise**, ***drag*, losing engine RPM**, thus **Power**. And we learn that we can stop ***both*** unnecessary losses by loading the prop Ideally vs. radius, **by just Shaping it, Twisting it Ideally vs. radius, an Ultimate Triple Optimum, Min Induced, Profile, Torque Prop, precisely defined by what is maybe the most Elegant Logic and Math you'll ever find.** The math and a lightning fast computer, working in the background, allows us to give you **precisely correct, Horse Sense clear, X-ray Insight!!!**

But there's a lot to teach you, all interrelated, so we repeat, expand, tie together, *Superemphasize it*, make it super clear. We need to get it Super clear to see all the possibilities.

The *core* that the logic and math is doing is pulling excess loading back away from the tip to prevent *both* excess losses, *~optimally!!!* But that mathematically optimum blade loading is max. at the 70 to 80% radius, **still very high at the 90% radius!!!** As we use the logic and math that has been available for a half century, but never fully understood well enough to get Triple Ideal Props, ***teach you***, we'll see that even more tip unloading may beat the theoretical ideal with a lower, more elliptical outer blade loading.

First we'll learn the classic Betz logic Prop - Then Look Beyond - A New Century.

3 Physical Insights can Help us Understand Propeller Logic

This is the *1 Page Magic, Specific Core Insight*

Propellers **1. Pull In** ***and*** **Throw Back Air** to **Make a Reaction Force Thrust**. They are **2.** an **Airscrew**, **3.** a **Rotating Wing**.

- **Magnificent Math** ***can precisely*** **Computer Design Betz props!**

3 Core Basics Teach us the Underlying Physical Logic of Props!!!.

- **Betz taught us the core Logic of the Ideal Min. Induced Loss Theoretical Prop in 1919**, first done Profile Drag Free, *basically* **creating pure helical Screw Inflow,** ***stretched*** **Outflow**.

1. A **Fast Prop** has an **amazingly high Mass Flow Rate of Air** going through its Disk area, and **thus it can make its required thrust with a Lower Delta V, ΔV speedup**, and since **throwing air to make lift or thrust is the root cause of Induced Loss, we want to go Fast to minimize Induced Loss.** √1

GRASP THAT THROWING AIR -- IS THE BASIC CAUSE OF INDUCED LOSS!!!.

2. A propeller must be understood as an **Airscrew**. Since a **FAST**, low enough RPM, **High Pitch Prop**, has ***both*** a **minimum ΔV thrown air Induced loss**, and a **Shortest Spiral Path to the Destination, minimum Profile Drag Energy Loss**. **Only High Pitch, High Advance per Revolution Props, can have max. Efficiency --- pretty simple once you see it!!!** √2

SPEED and RPM -- SET A CAP on MAX EFFICIENCY!!! √√√

3. A Rotating Wing has a serious, basic flaw: The Prop ***tip*** is going so fast, its V^2 Dynamic Pressure is so much greater than the root, that it trys to **Greatly Overload the Prop Tip**, where the **Thrust must, and will fall to Zero** in an extra big **Wasteful Tip Vortex, Losing Thrust, much higher Profile, air friction Drag**, at **max. lever arm**, *(high torque)*, **bogging down the Engine RPM**, **losing H.P.**, **losing 4 ways**. If we **simply taper the tip**, pull the excess loading back away from the tip, we can ***counteract***, **prevent the excess loss** - ***grasp that!!!*** √3

Precise Radial Loading, A family of Ideal Shapes, vs. Twist, sets the Ideal!!!

- **Goldstein,** *then* **Theodorsen**, by **1948** had created an *essentially* ***exact heavily loaded 3D flow solution, magnificent!*** √4

We learn a **Modern Computer, Elegant Math** can give us a **Mathematically Triple Optimum,** ***min. induced, min. profile,*** min. torque, **ultimately Minimum Area Precisely Placed,** ***fantastic insight!*** √5

We can **Learn the Basic Horse Sense Logic** with 5 Overview Insights, 3 Core Logic Insights, expand, broaden, deepen that insight, **let the Computer create ~perfect Designs for us!**

The Propeller - *Understandably Explained* - after 138 Years

The 2 Page Incisive Summary

A Propeller is **1.** a **Rotating Wing**, **2.** an **Airscrew**, **3.** it **Pulls In** and **Throws Back Air** to make a **Reaction Force Thrust**. That's all accurately constructed by some of the most **Elegant, Rare Genius Level, 3D Optimizing Math** ever created. Happily, it is those **three simple insights that can teach us the Logic**, **the understandable horse sense insight of WHAT the Elegant Math is doing, and WHY it is doing it!** Thus, the Elegant math and the lightening fast computer can simply work in the background to **give us a precisely calculated, Triple Optimum, Minimum Induced, Min. Profile, Min. Torque Propeller**, a task any computer buff with the program can do!

See the Cover Picture of Betz's Perfect Helical Screw Inflow, Stretched Outflow

The computer will **precisely Shape, *Twist*** the prop blades to create **Betz's perfect screw air inflow and stretched outflow of the thrown air**. If requested, a constant angle of attack, α^o, a constant chosen optimum Coefficient of Lift, C_L, can be used, **correctly Pitched**, marvelously accounting for the **required extra inflow** for **Heavy Loading**, where what is happening right at the propeller is significantly different, and ***greater than the average speedup*** over the **stream tube the outflow creates!**

The core key to making all this Optimum Magic actually happen is in Optimally Loading the Blade vs. Radius, by simply Shaping the Blade vs. Radius, along with the Matching Precise Twist, Pitched for a Constant Slip vs. Plane Speed, which acts like perfectly uniform axial inflow, actually created by highly varied axial inflow and rotation, perfectly, geometrically combined for the Constant Slip!!!

See the Family of Perfectly Shaped Props on the Cover.

Actually, it is the Engineering Horse Sense of the Logic that teaches us that the Dumb Prop is trying to work Inside Out, OPPOSITE to the logic of a proper wing which wants max. load at the center, because the lift or thrust will fall to zero at the tip - and here the very high speed tip, extremely high *Velocity² Tip dynamic pressure*, q, is trying to create extreme overloading of the tip, a greatly excess, wasteful tip vortex loss, *noise*, losing the thrust, which **cannot be held,** also

extra profile drag at max. lever arm, bogging down the engine torque, the **RPM, and thus H.P. -- losing four ways!!!**

See the Ideal, Half Teardrop Loading, next to the Ideal Blade Shape.

It is actually the precise, systematic, accentuated tapering of the Outer Prop Shape, the whole shape, that precisely, **optimally counteracts** this **wasteful natural tendency of the rotating wing propeller.** The whole, **simple, hidden secret of the Ideal Propeller,** is a **Family of Ideal Shapes, varying vs. Pitch, or Advance Ratio,** the low Pitch, Low Advance Propellers, being more highly tapered - **The Ideal, Fast,** ***sufficiently*** **Low RPM,** quite **High pitch, High Advance prop** ***wanting*** **a perfect Canoe Shape, max. Chord at Half Radius.**

A 2700 RPM *sleek craft* at ~ 364 MPH seeks this Optimum Shape!!! **See p. 147**

They all are, in fact, a **fully integrated family of Optimum Designs, mathematically essentially perfect, all done by the computer and the genius level math, sight unseen to those who wish to ignore the math, but quite understandable to the professional trained to appreciate the *calculus* Elegance!**

The Fast, High Pitch, Short Spiral Path prop can be Most Efficient!!!

The designs are finally ideally corrected for the actual average velocity profile at each radius at the nose of the embedded body. That ***final key step*** **makes the prop better *slow*, *T.O. and Climb.***

Reduced angles at slowed inboard radii can avoid stalling - slow!!!

It's perhaps the most Elegant total solution in all of Engineering, but it's ***easy enough for an informed amateur to grasp and use***.

The key is to Superemphasize the magic Insights, make it easier!!!

It is as important for an Amateur and Pro to grasp the Logic, the Understandable Horse sense Insight, as it is for a pro to grasp the Elegant Math, because it is the Logic, the Horse sense, that tells Why it is all needed, How it works out!

Two separate rotating wings, 180° apart, there's a root vortex too!

The Simple Bottom Line: It gets the **SHAPE, TWIST, BLADE ANGLES, PITCH, DIAMETER, the ASPECT RATIO,** the blade width distribution, all **Precisely Correct** for the Specification Requirements, exactly the **Understandable SPECIFICS** the professional or amateur wants to know!!!

It is an Elegant Masterpiece of Logic and Math took 138 years!
It is as comprehensive, incisive a Science Insight as you are ever apt to find -

Rankine, 1865 to Dec. 17 2003, 138 Years!
The 100th. Anniversary of Flight.

Jack Norris 12-17-03

A Complete Outline of *Classic* Betz *Min Induced* Prop Logic

Betz Core Objective: Getting Ideal Minimum Induced Loss!

(Basically Achieved by Pure Helical Inflow, *stretched* helical Outflow)

- **It's purposely First Done on a Drag Free basis, the simple case first ---**
- **Drag can then be easily added, Min Induced, *then* Actual Drag *(separated)*.**
- **It's an Archimedes Screw into, out of each Prop blade** (see Cover Photo).
- **Achieved by designing for Constant Slip, *holding constant Pitch Inflow*.**
- **Slip is the difference between inflow speed and Airplane Speed, *constant*.**
- **(Mathematically that is done by holding r tan ϕ constant. (ϕ inflow angle).**
- **The Geometry teaches how *highly variable* inflow and rotation combine.**
- **Amazingly, a Constant dT/dQ results, a constant ratio of Thrust vs. Torque.**
- **That means a constant efficiency at every radius, *steep root angles too!***
- ***But remember, it's first done Drag Free, then Drag Added*, separated.**
- **Bottom Line: that results in "Ideal Betz Loading", Thrust vs. Radius.**
- **Betz Loading is like a half tear Drop**, weak root, stronger, hi q outboard.
- **A Family of Ideal Blade Shapes *and* Matching Twist *results, if constant* α, C_L.**
- ***Most Significantly*, Tapered Tips *vs. Advance Ratio*, Pulls Back Excess Tip Loading.**
- ***Not Allowing* Greatly Excess Tip Induced and Profile Drag at hi q Tips.**

That final Hidden Imperative is the SECRET, Never Adequately Seen!.

--THEN--

We teach the Logic of Props *by just looking at* 3 Physical Insights.

But, it's all Backed Up by Elegant, *rare genius* Goldstein Theodorsen Math.

Pulling in, Throwing back *Heavy* Air - a Reaction Force Thrust

(We teach Props without Math, but two little formulas here, give us the easy key insight.)

- **Induced Loss *is just the* Energy Cost, Loss of Throwing Air.** *It drops to calm.*
- **Newton's 3rd Law teaches us how to understand Reaction Forces.**
- **Thrust $T = \dot{M}\,\Delta V$, M dot, *just like it looks*, Mass flow rate, *x speedup* Delta V.**
- **Axial Efficiency loss is half Delta V, $\Delta V/2$ vs. Speed, V, -- *thus*, $\Delta V/2V$.**
- **There is actually 3D Induced Loss, Rotational and Radial, (Tip Vortex) too.**
- **Rotational, Radial are substantial, but it's Axial that teaches us the logic.**
- **(Airplane Logic teaches us Induced is a $1/V^2$ loss,** at twice the speed, 1/4 loss).
- **(*Props the same*. If V doubles, ΔV can drop to half,** thus loss 1/2, divided by 2, 1/4.
- **Thus the Objective is: go Fast, *have a* big $\dot{M}$, a Doubly reduced Axial Loss!!**
- **Slow, to be efficient, requires a Big Diameter - Fast *allows a Small Diameter*.**
- **(Radial Induced, can be as big as axial, too big! A clue, it can, should be less)** !

After a simple enough start, there is finally a lot of insight that we can teach you. Reading onward you might get into overload, get confused. A *complete* list like this can keep you straight, *cut off confusion*. Read on, *use it for that*. The final objective is to *have the whole list make sense to you*, and this helps.

Understanding a Prop as an Airscrew

• A Prop wants to be a FAST, *Low Enough* RPM, Hi Pitch, Hi Advance *Airscrew* pulling in and throwing back a Betz pure Helical Screw Inflow, a stretched pure helical Outflow, *for a* Big Ṁ, *min.* ΔV, *min.* ΔV/2V Induced axial loss, *and* total 3D circumferential, and Radial Induced Loss too, but also a shortest helical path, for least Profile Drag Energy Loss, as well.
• A Prop wants to be *effectively* a 45° Airscrew, nominally a 45 degree Blade at ~ 2/3 + radius, because that steep screw is the most efficient, yields the Optimum Blade Planform, a Canoe Shape, Max Chord at ~50% r!
• There is a constant mechanical screw ratio of Thrust to Torque, dT/dQ, at low or high blade angles, constant efficiency, at every radius, if first considered Drag Free, but profile Drag loses efficiency at both shallow and Steep β angles, *a classic rounded crown corner* hat shaped curve.
• Airplane Speed, Engine RPM are the Primary Controllers of Propeller Efficiency, η, both setting, limiting Pitch, Advance, the Max η Cap possible.

Understanding, Correcting, Optimizing a Rotating Wing

• Excess tip V^2 Dynamic Pressure, q, loads a rotating wing inside out, 1. loses thrust, 2. creates excess tip vortex Induced, 3. Excess *unrewarded* Profile Drag loss at max. lever arm, 4. excess torque limits RPM, HP. Pulling back tip loading by tapering tips, is *the core of intelligent design*.
• The Classic Betz Min Ind., half Teardrop loading gives key Insight!!! *Forcing Basic* Wing Elliptical Loading offers higher η for 21st Century!
• The Betz Pure Helical *Inflow* + Constant Optimum α° *easily* sets basic *blade Twist* and β angles -- later *accurately corrected* for body nose Velocity Profile.
• Using Optimum α° and C_L on a Betz Prop, we get *a Triple Optimum Prop, Min Induced, Min Profile, Min Area Precisely Placed, Min Torque!*
• The Family of Double Optimum, Betz- Goldstein- Theodorsen Props shown on p.147 of Ch. I, which varies from *almost triangular* at low pitch, low λ Advance, to Canoe Shape at High Pitch, High λ Advance, is the proper bottom line objective of Classic Prop Logic. Using *High Drag wide tips*, is a negative!
• Loading a Prop Blade correctly vs. Radius, By Correct SHAPE, *Twist*, also optimum α°, C_L, is the heart of intelligent Propeller Design!!!

Goldstein- Theodorsen Math

• Goldstein solved the 3-D flow Math in 1929, *but* for evenly loaded flow.
• Theodorsen, using Goldstein, solved 3D Heavily Loaded Flow *in 48* by considering the needed greater full ΔV, his w, Far Back, with a slightly smaller D. His Kappa relates his $\overline{\overline{w}}$, to the Stream Tube average ΔV.
• *Their* Kx factor, (vs. Radius and Advance Ratio) *sets* Radial Prop Loading!
• Simple Charts of Kx, Computer *interpolated, greatly simplifies the Math!*
• Appendix T, shows Theodorsen's Math to design Props, using Kx, *etc.*

The Ideal 45 Degree Blade Angle, and **where it's located**

When I was a late teenager competing and winning Nationally, I had very good plane designs, but was really frustrated trying to find correct prop design specifics. What was the **really *correct* *shape*, *twist*, *pitch*? It seemed that those high angle prop root radii, pulling sideways against engine torque, more than forward, could not possibly be good.** ***But***, we've learned here, that **drag free, a Betz prop can have a constant Thrust vs. Torque Ratio, every radius equally efficient, productive,** ***(if first considered drag free).*** We'll look more at high inboard blade angles shortly, see that they're perfectly OK, **working as a screw** on very high pitch props. We'll also see a **Blade Angle of ~ 45° is optimum**, thus it's insightful to see ***where*** the **45° blade angles are vs. Advance.**

Also --- Where is the Max Chord vs. 45°?

The study below looked at **J/π**, (Lambda's, **λ**'s), of **.2 to .88, (of low to very high pitch props). (J/π, λ Lambda, is the advance ratio of Prop Tips.)** The chart below and the chart and Shape Plot vs. load distribution on the next page give great insights into the characteristics of ideal propellers and are worthy of your study.

	Reasonable Advance			Extremely High Advance			
J/π, λ	**.2**	**.3**	**.4**	**.5**	**.6**	**.7**	**.8**
Overall η	.8607	.8940	.9068	.9125	**.9149**	.9144	.9112
45° β, % r	23.25%	33.60%	44.15%	54.82%	**65.74%**	76.70%	87.82
Local η	.8781	.9018	.9104	.9141	**.9159**	.9158	.9135
Max Chord.	25% r	38% r	43% r	47% r	**49%** r	53% r	56% r

Amazingly, a Reno Racer can have a .88 λ, almost a 45 degree Tip!!!

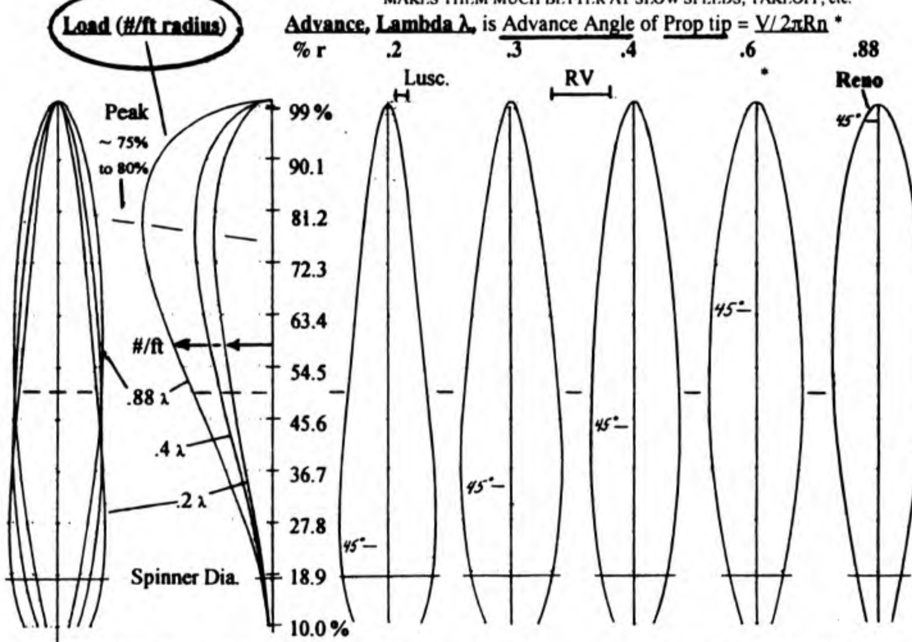
So we see the most efficient **45°** blade can fall way inboard to way outboard - but is **most efficient at the ~2/3+ Radius** at **.63 λ**. Now if the ~**45°** Blade Angle is most efficient, it might be that the splendid Math might put the **Max Chord** there. Well, if you look close at the data above, the interesting insight is that's trying to happen, at the lower **J/π, λ's** where fixed pitch props operate --- but are pulled outward a little at the low **J/π, λ's** away from the inner root vortex **--- much stronger inward at high J/π, λ's away from the stronger tip vortex!!! Now, isn't that *smart*! It fits right into the logic, not overloading tips!!**

Interestingly, the max Chord is at ~50% radius on the max η ~.63 λ Prop!!!

The Change in Blade Shape and Twist --- Low Pitch vs. Steep Pitch.

We know it's the **Slow planes, Low Pitch, Low Advance**, that have **the *huge magnification of Dynamic Pressure, q*, tip vs. root**, thus **need the most highly tapered blades**. ***Conversely***, the **Steep Advance props will be less severely tapered**. Below, see the blade outlines for this blade study, **λ** from **.2**, low, to a steep **.88λ**, (a Reno Racer class prop, though this study of all 6' props for comparative consistency is a miniature for Reno). Note how the **steep λ props *taper in greatly inboard***. (**Slowdown** ***lowers blade angles, especially inboard, widens blades.***)

MAKES THEM MUCH BETTER AT SLOW SPEEDS, TAKEOFF, etc.



-- RV 8 Cowl Width -- Locations of 45° β°. Ideal ~.63 λ * ~364 MPH.

To keep all props on the same apples vs. apples comparison, starting with a 6 foot prop we end up with low thrusts and H.P.'s for the fast planes, like a miniature, slick Reno Racer finally, but this shows shapes and twists well, the intention here, so just imagine and understand.

*THEODORSEN ACTUALLY HAS A MORE COMPLEX DEFINITION OF λ THAT INCLUDES $\overline{w}$

***Prop Blade Study basis*: 6'Dia, α° 1.1°, .5 C_L, AR 15, 2700 RPM, 8000', Area 1.944 ft²**

Ref. Data pages 99.56 -1 to 99.56 - 8.1 BLADE ANGLES ARE *BEFORE* SLOWDOWN CORRECTION

λ	Vmph	HP8000'	Thrust#	Eff. η	β°, 18.9% rad.	β°, 99% rad.	ΔTwist°
.2	115.6	56.5	155.3	.8607	50.365°	13.600°	36.765°
.3	173.5	94.4	179.7	.8940	60.583	19.046	41.536
.4	231.3	140.5	203.6	.9068	67.053	24.263	**42.790**
.5	289.2	195.9	228.5	.9125	71.382	29.142	42.240
.6	347.0	260.5	253.8	**.9149**	74.440	33.634	40.806
.7	404.8	334.5	279.1	.9144	76.715	37.760	38.955
.8	462.7	418.4	304.3	.9112	78.482	41.556	36.926
.88	508.9	494.2	324.6	.9058	**79.653**	**44.411**	35.242

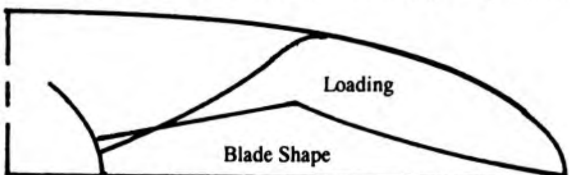
This Page is really the Bottom Line on 138 Years Work --- 1865 to 2003!

A Look at Elliptically Loading a Prop Blade

At a constant angle of attack, constant C_L, **Prandtl's** theoretical Ideal Wing Shape, and Ideal Wing Loading is ***Elliptical***, max. at the center, falling to zero at the tip, ***minimum radial flow, min. tip vortex, no extra unwanted tip induced loss***. Of course, very much unlike a prop, all radii are going the same speed, **same q!**

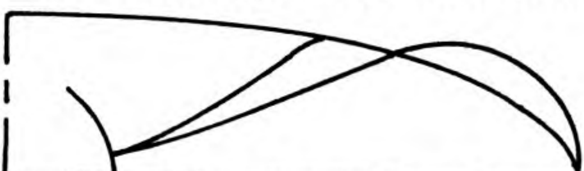
Elliptical Leading and Trailing Edges would still be Elliptical Loading

Now, if we **try loading** a constant angle of attack, α^o, and C_L, **prop blade, elliptically** vs. radius, like a wing, with far higher dynamic pressure, q, outboard, we get very narrow chords outboard, **a wild shape curving to excessive chords inboard**, due to rapidly falling q -- can really only do it to 40, or 50% radius, must then taper the blade to a practical root, with lift falling dramatically. If we tried to hold blade forward thrust elliptical, not blade lift, it would be worse, (at steeper inward blade angles).



A Propeller Blade Shaped to hold Elliptical Blade *Lift* Distribution, (not Thrust)

But if we superimpose this elliptical lift distribution on the half teardrop radial lift distribution of an Ideal B-G-T prop, we can see that in moving the blade loading more inward, we would **logically lose less off the tip,** ***better than the B-G-T Ideal!!!***



The Betz and Elliptical Blade Loading Directly Compared

With a wild looking prop, we can beat the Classic Betz Ideal!

A Look at Elliptically Loading a Prop Blade

There is a lot of potentially important insight to be gained here. We'll learn that Ideal B-G-T propellers tend to have potential efficiency caps of nominally 85% for a 100 MPH Luscombe, to 90%, or a tad more, for a Fast, High Pitch, High Advance RV, but if it were an efficient elliptical wing, a 20:1 L/D, only 5%, or less, loss would be easy to achieve, actually better than that. When we look deeply into Theodorsen's book, we find Radial Flow, Tip Vortex Loss, an auxiliary, add on loss, can actually be bigger than the axial loss we must have to make Thrust, certainly not a good situation, we'd like to have to live with.

So, the creative new thought, after a Century of Flight, of making a prop act more like a wing, has real merit that was never seen by anyone in Aerodynamics before, so let's look closer.

A high Aspect Ratio Sailplane Wing has very low Induced loss, because there is a lot of Center Wing maintaining max lift, undiminished, far away from the tips, can have small narrow tips, an Ideal Situation! Now, that prods us into a very important insight. Looking more closely at the prop teardrop, or outboard elliptical lift distribution, we tumble to the important insight that, either way, **a prop has almost NO Center Wing working**, it's **effectively all tip**, **almost only two outer halves working**, **much more vulnerable to excess tip vortex loss**, **a major insight!**

So, simple bottom line, even if we switch and start forcing a prop to act more like a wing, we're not going to get down to very small percentages of loss, but, with a creative, but wild looking prop, **we can potentially do even better than a classic optimum prop** - and do it by just doing what the horse sense tells us to do, **get the load pulled back away from the tips!!!**

Now, we can get over 90% efficiency, η, maybe 92, 94, a task for Century 21.

We have to be careful, because a metal prop like this, might fail much more easily in vibration, potentially kill you in a crash, perhaps giving more advantage to a composite prop. Requiring new math, this creative new idea by Paul Lipps of Arroyo Grande California is the new idea for the new Century of Flight!

The Simplest, Best Summary Insight on Propeller Logic

For the smaller, slower, non jet, personally owned airplane, the slow, or very long range military reconnaissance planes, the **propeller should always be the most efficient, lowest cost, lowest fuel usage method of propulsion**. With duct losses, no form of Fan Jet, Ducted Fan, or other method of propulsion *should* ever be able to match the maximum 90% plus attainable propeller efficiency. With amazingly high compression ratios, over 40:1 on the GE 100,000# Thrust engine for the Boeing 777, the advancing Fan Jet is amazing, but propellers, especially with optimum radial loading, especially if it is possible to optimally gear and pitch them, should, it seems, stay in the lead.

The Fatal Flaw in Propeller Logic is that with greatly faster tip velocities, even more greatly magnified V^2 dynamic pressure q, at the tips, vs. the root, the dumb prop really is trying to work inside out, just exactly ***opposite*** from the way a wing is going to work, max. lift at the center, where lift must, and will, fall to zero at the tip - in a losing radial flow tip vortex. Automatically magnifying that, the prop case is the worst possible situation, and the best we can do is to **counteract** that unfortunate tendency by **significantly tapering the tips to significantly pull back the loading radially inward, to a more manageable lift or thrust distribution**, that can better be retained, not lost.

This is the HUGE Fundamental that was Never Adequately Recognized!!! .

The **Betz, Goldstein, Theodorsen Classic Logic and Math** clearly is a marvelous integration of creative, multifaceted, **Elegant Logic and rare genius level Math**, aimed at minimum Induced Loss, initially done drag free. Actually, profile Drag, even correct for applicable low Reynolds Numbers can be added, the prop subsequently corrected for the embedded body nose average velocity profile at each radius -- or analyzed for off design point, are beautifully possible -- **Elegant, a tribute to amazing human intelligence, and the modern personal computer.**

Unfortunately, we can see that the Half Teardrop radial thrust distribution of the Classic B-G-T Minimum Induced, Optimum Prop, is still biased heavily outboard, max. at 70 to 80% radius, nominally 75%, still high at 90%, that it is logically farther out than is best. Other than bringing in the Modern PC, creative, genius level work on the propeller stopped in 1948. **We never even got a comprehensive, understandable explanation** until now, a half Century later. That did hurt, propeller designers never did really understand the true final logic, **we never did get the Triple Optimum Prop, Constant Optimum α^o, C_L, Min. Induced, Profile, Min. Area Precisely Placed, Min. Torque!**

The 2003 WhirlWind 200, RV 8 Prop, is the First Triple Ideal Prop ever!

Worst, maybe never actually realizing all the ultimate Engineering horse sense, bottom line grasp, the fact that the B-G-T radial thrust distribution is still heavily biased far outboard, no one in the first 100 years of flight backed off, thought outside the box, as they say, and saw that if we simply pulled in the distribution more, went for the ideal elliptical thrust distribution of a wing, that a practical improvement of a few more percent, certainly desirable, if safely attainable, is available. **Paul Lipps, of Arroyo Grande, California, a highly intelligent Radar Pro, and Private Plane refiner, clearly deserves to become the 11th. benchmark achiever in the history of Propellers, for creatively providing us this path to ultimate efficiency, for the Second Century of Flight**.

Now, that takes care of **completely explaining and correcting the harmful effects of a rotating wing, excessively loading the tips, creating excess losses.** All the other key insight that we can learn from the basic logic and understandable engineering horse sense of propellers is equally applicable to any prop design

---

Pulling in and Throwing back a heavy, high Mass flow rate, $\dot{M}$, allows us to minimize the ΔV speedup required to generate the required Thrust, minimize the ΔV/2V axial induced loss, actually complete 3D Induced loss, thus FAST, is the easy way to have an efficient prop, Low RPM, as well,

gives High Pitch, a High Advance per Revolution, both Min Induced Fast, and Min Profile Drag Energy Loss, with a short, steep, least energy path to the destination!!!

A Slow Plane, a Geared Down RPM, High Pitch, Advance -- Works too!!!

Thus, the **1. Steep, Hi Pitch, Hi Advance AIRSCREW, 2. Maximizing 3D Efficiency of Pulling in, Throwing Back Air to make thrust,** ***(decoded by Newton's 3rd Law),*** **3. Tapering the ROTATING WING Prop Shape, crucial outboard, to pull excess loading back away from the tip, where it would be excessively lost,** ***NOISE,*** completely decodes what can look like a frighteningly, massively complex 3D flow situation, all backed up by the Elegantly integrated Betz Logic, and Goldstein-Theodorsen Math, which does completely deal with, and essentially exactly solve, the heavily loaded, 3D flow complexity, with us completely free of the details, *if we wish.*

Regarding Betz: It should be said that his core objective is to **pull in a pure helical inflow**, and **throw back a stretched, twice speeded up pure helical outflow**, two separate **Archimedes Screws**, (212 BC), one to each blade, blended at the center, finally stretched. This is done by over pitching the inflow and prop to account for the speeded up inflow, (not outflow), to **hold a constant pitch of that inflow at all radii**, a **Constant Slip**, **vs. Airplane Speed**, which acts like constant axial inflow velocity, (even though you'll ultimately learn that a close look at the inflow and rotation diagram of the actual airflow is quite variable, but magnificently combines in constant pitch, constant slip to act like uniform inflow)!!!

Equally **magnificently**, simple High School math, Algebra, Geometry, Trigonometry, can prove **a constant ratio of Thrust to Torque, dT/dQ, exists at every radius,** (*if initially drag free*)!!! If an **optimum constant angle of attack and C_L is used**, for ***Triple Optimum, Min. Induced, Min. Profile,*** **Min Blade Area Precisely Placed, Min. Torque,** ***Min HP, Max*** η, **the blade twist is simply the perfect helical inflow, plus the constant angle of attack --- *Voila, a 140 year mystery put to rest!!!***

All up, **the entire Betz Logic, Goldstein solution of the partial Differential equation based math for 3D flow, Theodorsen extending Goldstein's Math for real world heavy loading**, where the full ΔV, right at the prop blades, much greater than the average of the resulting Stream Tube, is **perhaps one of the most Elegant integrated Logic and rare genius level Math Solutions in all of Science and Engineering, a tribute to the towering intellect of man at his best.** ***But alas, human Hubris is disallowed, there is a flaw!!!***

The high humor in the situation is that we never got past the rare genius level math, to see the basic horse sense insight, apparently never saw the family of ideal Blade Shapes, the half tear drop loading of it all, that the teardrop loading was still too heavily biased toward the tip. Not in the half Century after Theodorsen did a professional decode and go past the marvelous work, completely understand it, get it down to specific drawings of the hard actual results, ***a picture one could grasp***, **the understandable horse sense of it all**. **Math can clarify, but not carried out, studied, really understood,** ***complexity can obscure, prevent the understanding that is there!***

The Computer, of course, was the Final, and NECESSARY Tool!!!

Betz and Prandtl, ***might*** have seen that the true proper objective of propeller design was to force it to act like Prandtl's optimum, elliptically loaded wing, with a wild shape, not let it act as a propeller with extreme tip overload, but the math solution of Betz's great insight was a decade, 1929, and 29 years in the future, 1948, before the true picture could be seen. Who's guilty? No one, the Aero Profession maybe. No one ever finished the job, got it down to real understanding before.

A Half Century later, Andy and I just decided to finally get Props Understood!

A huge credit goes to ***Paul Lipps*** creatively thinking outside the box, not encumbered by knowing, buried by the Classic logic. Not in the profession, not encumbered by all the complexity and detail, but very smart, creative, knowing that Prandtl sought **elliptical lift distribution**, he **went for that simple ideal**, ***great work***, *a big belly laugh after 100 extra years*, **Good going Paul!**

It's Repeating, Expanding, Saying it Different ways,
That Makes you *Facile in your Grasp* -allows you to go *Easily, the Goal!*

Props are **1.** a **Rotating Wing**, **2.** an **Airscrew**, they **3. Pull in and Throw back Air** to make a **Reaction Force Thrust** per **Newton's 2nd and 3rd Laws**, but that's what causes **Induced Loss**, the ***Energy Cost Loss of Throwing Air*** to Make Thrust. In Props there's **a *3 Axis Induced Loss***, not just axial, the air finally just settles back to static again, finally the energy lost to friction.

The Game is to make a Triple Optimum Prop, Min Induced Loss, Min Profile Drag, Min torque, HP, Max η!

Slow, Demands a Big Diameter Prop, Fast, Allows a Small Diameter, because the game is to work on a **Big $\dot{M}$, Mass Flow Rate**, so the Delta V, **ΔV speedup** can be ***small***, **Low Induced! High Aspect Ratio**, just like a long sailplane wing is ***thus*** **Best.**

It's Finally exactly correct Twist, and SHAPE, Tapered Tips, the Key, Min Area, Precisely Placed!!!

Very High Pitch, High Advance per revolution is **Most Efficient**, a **~ 45° Blade Path** best, a **45° Blade Angle**, way out near the max. blade loading point, **~ 2/3 to 3/4, radius**, farther out the higher the **Pitch, Advance**. Surprise, it's thus **RPM vs. Speed** that **sets your efficiency cap**, ***Speed most Important***, but **RPM** more important than you realize, ***since it's*** **fundamental to Pitch!**

A Short Spiral Path Home, Min. Profile Energy Loss, -- Fast, Min. Induced too, SIMPLE!!!

Betz showed us the **Sophisticated Logic** of the **Minimum Induced Loss Prop** way back in 1919, and he thus established **Classic Propeller Theory**. **Goldstein** gave us the *Basic*, Partial Differential Equation, 3D Potential Flow Math Solution in 1929, but **Theodorsen** showed us how to get the **Real World Heavy Loading, High Advance ratio essentially exact, 1948**, all **Rare Genius Level work**, correct answers, a gift to us all!!!

We make it Much Easier, but there's a lot to teach you. We ***Super Emphasize*** to ***help!***.

Always before, an unexplainable dismal swamp of complexity, **never comprehensively, understandably explained before**, even for pros, the **breakthrough here** is that we can show you the **Engineering Horse Sense** of the **4 subjects**, **1.** a **Rotating Wing**, **2.** an **Airscrew**, **3. Throwing Air**, **4. Betz**, the **Basic Logic of Props** down to **Understandable Engineering horse sense Logic, a few key Pictures!** It's this **easy**: you **load it optimally** vs. **Radius,** by simply ***twisting it***, ***Shaping it correctly!***

It's looking at it as a Rotating Wing that teaches us to taper the tips.

The stupid prop is trying to work inside out, trying to load itself Inside Out, max. load at the very fast, extremely high dynamic pressure, q, tip, where thrust must fall to zero!!! Dumb as a board, our job is to be smart enough to counteract that by tapering the tips!!!

So, How are we going to Teach you?

There's **more to learn in the Classic Betz Theory**, but you can **thus learn a lot more going through it**, and with **essentially exact math** developing our data and incisive studies with clear conclusions, ***we can both be sure what we teach you is correct!***

Tibery and Wrench 1964 have later, better Blade Loading, at High λ.

Paul Lipps used his own math to design his props. Full credit to him, he went about it quite professionally, but depended on the ability of modern P.C.'s to iterate calculations where such things as induced angle of attack are not known, the computer looping to finally, supposedly, eliminate errors from assumed inputs. Such basic approaches have no way to cope with 3D flow and induced loss, whereas, radial, tip vortex loss is the core issue we're trying to refine and evaluate. No put down, because his math and computer seems to give excellent design predictions with results that agree with the computer outputs.

On the other hand, his initial work was not corrected for slowdown, a major correction, but we can show him how to do that easily, professionally, accurately, and plan to as we write this, as we're checking the validity of doing it with Glauert's quite good approximate method (~ 1 1/2 % pitch error, etc.), as we also look at possibly adapting Goldstein, Theodorsen math.

All that aside, **the obvious right approach is to teach you the B-G-T logic and math**, ***quite valuable in itself***, because it's all logical, understandable, with **essentially exact math, accepted, respected by the very best pros, thus completely creditable** answers, so you can be **sure you're learning it right**, hugely ***valuable for us both***, no Mickey Mouse, good incisive learning.

All we really do for the (partial, outboard only,) ***elliptical lift distribution is shape the narrow tips even more severely than the Betz prop***, pull the load in even more, just what we did with B-G-T, just do it a little more severely, **the same basic game**!!!

In the Betz Chapters, next, we'll still call B-G-T *Elegant, call solutions Optimum*, because they are -- until, and *if*, Testing, we finally go for the new, potentially next 21st Century way, going for more elliptical Radial Loading. ***If you're interested in props***, **BGT is the way to learn it all**, ***correctly!!!***

How to Cherry Pick!

As I built the story here, I purposely repeated, **said the basic logic several ways vs. the other factors,** *because* my objective was to get you as close as possible to being able to flip the logic around in your head, be **facile in you ability to grasp it, use it**.

Many Pilots may have satisfied themselves by now, and I purposely created a pretty incisive Introduction to fit that - and if you wish it, **here's how to Cherry Pick the rest of the Book**:

The Family of Ideal Props - p. 146, 147 of Chapter 9, Book I, p. I 26, 27 here, really is **the Bottom Line on 138 years work!**

Inflow Geometry - p. 128 Ch. 9 Bk. I, then p. 82, 86 Bk. II, shows the first, then "all up" insight into the key inflow geometry! The creation of a **Constant Slip Geometry is basic to Betz.**

Chapter 1, Book II might be considered the more normally written, **"easy read" "Summary Introduction to Book II"**, but with less content, less Superemphasis. It has the very fundamental, important **Advance Ratio vs. Efficiency Graph**. p. 9, (also more extensively covered on p. 48 II), **an RV and a Luscombe Prop** design and characteristics, (a bit of extra Thrust on each), and, at the end, a pretty complete **Definition of Terms List**.

Chapter 2, Book II

Super Magic Chart, p. 45 II, **Sea Level Thrust, Efficiency, ΔV, $\dot{M}$, α^o, C_L -- Zero Speed -- to Zero Thrust Speed** - where Prop runs out of sufficient Pitch to make Thrust, **at actual RPM vs. available H.P.,** for a **.55 C Prop designed at 12,500'**

Magic Chart, p. 50 II, **Sea Level Efficiency vs. Zero Thrust Speed**, without a Slowdown Correction of **Various P/D Props**.

Baldeing Efficiency, Profile Drag Efficiency vs. β^o, p. 60 II, Profile Drag effect, **low at normal angles, worse low and high**

The Five 800# Gorillas of Prop Design, p. 19 II

Chapter 2 Conclusions, p. 62,65 II

Chapter 3, Book II

More on an RV and Luscombe Prop, a little extra Thrust, p. 90,92 II, the page 92 data with considerable detailed insight!

Slowdown, p. 106, 109, **A Source Sink Analysis**, getting the **Velocity Profile**, in the **Plane of the Prop**, at the nose of an **Embedded Body**, a **method by Rankine**, taught by Prandtl.

Overall Propulsion Efficiency, η_P, Gus Raspet's Discovery, p. 110, 115, the **extra losses over and Above Prop η losses.**

Design Study, C_L vs. Diameter, p. 120, 126 II. An Important, Interesting Study that shows the **effect of Changing Cl**, it's **huge effect on required Diameter**, and **Induced vs. Profile** Drag Loss, but most significantly finding **.5 Cl to be most Optimum across the Performance Spectrum**, an Alt Cruise Design, at T.O., Climb at S.L. and Altitude, V_{Max}, .55 Close!

Theodorsen's Special Factors, p. 147, **w, Kappa, κ, Epsilon, ε.**

Airfoils, Low Reynolds Number Drag, p. 148, 149

Of Course There's a Lot More Insight than this provided in the Chapters, well worth seeing all the insight provided.

A Word of Caution: being a good engineer, I'm always careful to keep my statements sound, not get involved in optimistic claims. Having been the guy who founded and ran the Spacecraft Controls Company, one works on Hard Fact, that meets the payroll, not an engineers fond Hope.

Everything we've seen so far says Goldstein - Theodorsen Math is Spot On, Essentially Exact, the Props doing just what the Computer Program predicts, but use Tibery and Wrench Loading for very High Pitch. **When off spec Performance is Calculated, however, of necessity, we are dealing with normal Engineering Trigonometry, and Math Calculations, less Sophisticated, and exact than the BGT rare genius core solution.** As such, my appraisal is that **studies, etc.**, are valuable, insightful, helpful, but will **simply not be of the same caliber as the core, heavily loaded math,** ***can't be.***

Off Spec. -- Better than you might think

Of course, if you design a prop for a specific condition, **altitude cruise**, for example, **a very good choice**, because that's where you should spend your time, fuel, and money, fly there every time you can, it's not going to be perfect at other conditions. But, of course, **if you have it essentially perfect at its design point, loaded, shaped, twisted, ideally, you have a basically excellent prop**, a bunch better than someone's amateur try, and the rest of the story, fortuitously, is surprisingly favorable, with a properly designed prop, so, **we're heading for a good place**.

The first surprise is that later, **at low altitude, Vmax**, if you just must play macho with your buddies, it turns out that it's apt to be **even more efficient**, going faster, at a lower angle of attack, **a bigger mass flow rate, $\dot{M}$, less ΔV speedup** of the air in proportion, a dandy surprise the computer teaches us.

The really big piece of good fortune is that when we correct a perfect prop for the nose velocity slowdown, far bigger inboard where the embedded body is pushing the air ahead, and outward, the **slowdown correction**, which we can do quite accurately, **results in significantly less twist, and the prop is significantly better flying slower in climb, and takeoff**, because slow, the uncorrected, grossly steep inner blades would be stalling, so either fixed pitch, or constant speed, variable pitch props are much better slow, than they would have been.

The **correction at the 19% radius on an RV 8** with an 18% radius, or diameter spinner, **is a wild 17.65 degrees**, and remember, we're trying to hit blade angles to ***.1 degree accuracy***, **2%**, a **1°, degree, .1 C_L, being a 20 % error on a .5 C_L prop!!**

The correction is still a hefty **7.56 degrees at the 35% radius, still a .953 degrees at the 75% radius**, the difference between a climb and a cruise prop, **.383 degrees at the tip**. Not only do you get a bunch of good help doing it with the master's math, you can see how much better off you are using the master's math, compared to some hubris type thinking that, because he is smart and has a computer, he can start cold and get it right! Our **forebears** were **very smart men, and did 83 years work!** √

Everyone Needs a Day to Assimilate Prop Logic

We can show you the **core of Prop Logic in 10 Minutes**, but I've found ***everyone***, pros included, ***needs time "to really get it"***, really grasp it, soak it up, make it their own. The three core insights, **1.** A **Rotating Wing, 2.** An **Airscrew, 3. Pulling in, Throwing back air**, are simple enough, but there is **a long enough list of insights, and implications**, that it comes down to **a whole new way of thinking about props**. ***You need a day***

Since we can't talk. I give you a day's conversation, a day's reading.

Trust me, if you start out cold, trying to understand all the math, the heavily loaded 3D flow, with no real insight on the logic, it's a world class technical swamp, a morass, a nightmare! It's really a snap by comparison, the way we explain it, but my point here is quite the opposite to that. **Anytime we learn something new, it's a challenge**, especially if it has a lot of complexity, as props do, even simplified, especially if you're a greenie, a technical novice, and this is your first try, at logic!!!

No one ever got this simplified before, no one ever took the very long time it took to see through it and get it simplified. Andy and I took it on as ***the never solved Intellectual Challenge***, ***did it over years!*** If you're a novice, relax, pros need time to get their head lined up with the new way of thinking about props, seeing, believing, that **the simple horse sense teaches us what no one ever learned from the genius level math**, just too hard to see what all the hidden implications are in the math. **Making hard things simple, is the *final*, hardest task of all!** √

A retirement hobby intellectual challenge, over years, the big funny is that *very gradually*, my *subconscious would sort out - the pearls of insight, that I could say, must say to nail it, make the complexity clear, easy*, as I woke up in the morning!

Knowing it will take you time to get it, soak it up, make it your own, **I purposely repeat, expand, add insights, give you time, lead you to what you'd take years to see through. Just *stay going***, *as far as you wish.* **and *you'll end up with a pro's insight*** √

Pro's: Understand, This book is to help Pilots! Learn how to Cherry Pick it!!!
That's your contribution. I expect you to be smart, wise enough to see that! √

Teaching You Classic Propeller Theory and Logic

Rankine, Froude, Betz, Prandtl, Goldstein, Glauert, Theodorsen were the 7 Historic, Scientists, Mathematicians, and Engineers, who created the Benchmark, Milestone steps in the Development of Betz Classic Propeller Theory, *Elegant, with essentially exact* Goldstein-Theodorsen Math -- from 1865 to 1948 - 83 years of often rare Genius level work.

We teach it to you, not only because it is the Classic Theory, but because it is **orderly, and logical, understandable, simply explainable, with clear Engineering Logic**, that we can present to you as just **good understandable Horse Sense**, *clearly, logically correct*, but **backed up with essentially exact math**, maybe **some of the best, most sophisticated math work ever done -- unquestionably accepted as the Gold Standard by top Aerodynamic Leaders.**

With the use of an **Optimum angle of attack, α^o, and C_L**, it all ends up in an **orderly family of Triple Optimum Props, Min. Induced Loss, Min. Profile, Min. Torque, Minimum Area, Precisely Placed, Norris's 6th Law, now all explained, all with the natural Elegance and beauty of form and function, the "Good Art" that we so often find with Nature explained.** ***What could be more beautiful than a Sea Gull riding the bow wave energy of a breaking wave coming in to shore, the finger feathers of a soaring Eagle converting a rectangular wing tip Vortex into thrust, an equal and opposite solution to the Gull's pointed tip, our human work only a fond hope?***

The **"Introduction" Blasted You *Quickly* into Sophisticated early Awareness, but then repeated, expanded, *justified*, hoped to cajole you into really grasping the new insight, really making it your own! Now the "Primer" will carry that further, begin to add more, deeper insights to help make your knowledge ultimately whole!!!** ***You need time, more and more insight to make it your own!!! Onward!!!***

PROPELLER PRIMER

THE PROPELLER

PROPELLERS FOR A PILOT'S *FIRST INTRODUCTION* .

We can look at Props in several ways: **1.** as simply **pulling in** and **throwing back air - to make thrust - a reaction force**, per **Newton's Laws**, **2.** as a **Rotating Wing**, **3.** as an **Airscrew**, the British term, **4.** as **Betz's Minimum Induced Drag Theory** and **Logic**, pulling in and throwing back a **perfect helical screw shaped downwash, backwash**, by **controlling the loading vs. radius**, set up by very carefully, and accurately controlling the **Shape**, thus loading, with matching **Twist** and **Pitch**. We're going to want to look at and understand propellers from each of those standpoints, because we can learn very much from each view, and learn how it all fits together into a quite sophisticated, but understandable overall grasp, that has never been satisfactorily explained in the 138 years since prop analysis started in 1865.

Have some fun with your friends. Ask them **how much a 100 foot cube of air weighs at sea level**? Not a trick question. Presume you can cut out that block of air, put it on a scale, not floating in the other air, **real weight, no trick**. Ask yourself, pilots, Engineers, a sophisticated group at a cocktail party. Have a good laugh together. The real answer is **76,000 pounds**. Air only weighs .076 pounds per cubic foot, 3/4 of one tenth of a pound, but there are **a million cubic feet in a 100 foot cube**. Try it, a **1** followed by **six zeros**, x **.076**. A long airplane wing, even a propeller disk is processing, ***moving*** far more volume and weight than you'd ever guess. It shocks experienced engineers as much as a cocktail set. A 747, 700 to ~900,000#, almost a million pounds, is throwing down *enough* air, *fast enough* to hold itself up, just as ***prop thrust is throwing back air***.

Sailplane pilots know the game is to have a long, skinny, high aspect ratio wing, **low span loading, involve a lot of air**, as much as possible, because Mr. Newton teaches us the game is to involve a lot of air, a **High Mass Flow Rate**, in his terms, because then you can hold up the plane with **a *surprisingly small speed up of air*, throwing the air down in an amazingly low angle downwash.** That will hold up a sailplane with just a gentle whoosh of air as it flys over, and a 747 with a lot more whoosh, but still a quite small angle of downwash.

The 747 has a second trick, it's **going fast horizontally**, in addition to a big wing span, also moving a vast flow rate reaching up and down vertically. Think of a vast symmetrical water melon encasing the wing, (see how the big chord gets involved too), not taking off until ~**170 IAS**$_{MPH}$, with **flaps**, flying ~ **270 IAS**, *540 Alt TAS*, the numbers can all work out, enough mass flow *rate*, enough speed up. You not only don't want to get behind a 747 in a light plane, you don't want to in another big jet. There can be **massive tonnage still swirling minutes later**. Fish Salmon got upside down in a Bonanza on final at Burbank years ago, but as Lockheed's chief test pilot, got it right side up and lived.

That old story may be wrong. It may have been Tony Levere, with Sammy Mason.

Throwing air, using extra energy to hold the plane up, or make prop thrust, is why **Induced Loss** happens, air thrown down to make lift, or back to make thrust, or into those great big swirling tip vortices that Aero Engineers account for with a fudge factor, called the Oswald efficiency factor increasing the theoretical induced drag calculation, that basically accounts for throwing the air down to hold the plane up - the tip vortex extra.

Now we make a big point out of this because the way we end up designing a prop, the **induced losses can nominally be twice the skin friction profile loss from the prop blades**. Now realize **we can reduce induced loss on a prop by having a big diameter, high aspect ratio blade, but also by just going fast.** ***Just going fast is a key to high prop efficiency***.

1. A Prop Throwing Back Air - Grasping Newton's Insight

Learning from the *Axial* Induced Loss

Pilots, Civilians are usually faked out if they see even a simple little math formula, but let me show you simple **math can be** the **EASIEST way to see the Horse Sense of this subject**. Newton teaches us Thrust, **T = $\dot{M}$ ΔV**, Mass flow rate -- times the Delta V speedup, dead simple, if you don't let yourself get faked out. If we can get a **big Mass Flow Rate** through the prop, by either having a **Big Prop**, or even better, **Going Fast**, we can get by with a **small Delta V, ΔV speedup** --- **Dead Simple**, **really.**

$\dot{M}$ is called M dot, just like it looks. Delta, Δ, just means difference to engineers.

Now that basic, **simple insight is of huge importance**, because the **efficiency game is to minimize the axial ΔV wind you make**, **DON'T MAKE EXCESS WIND**, because the efficiency loss is **half the ΔV wind speed increase --- compared to the plane speed**, or big wind coming toward the prop. Can you see that **going fast gets you a good double whammy, favorable result on efficiency**? **Fast** gets you **a high Mass Flow rate, thus a small ΔV**, and ***half that* divided by a big V_1** gets you **a twice lower *axial induced* efficiency loss. That's why GOING FAST is the EASY WAY to GET GOOD PROP EFFICIENCY.**

3 induced losses happen, Axial, Rotational, & Radial - feeding the Tip Vortex

Now, if you can grasp that little drill in math, and Logic **you have learned the most *basic* Horse Sense Logic of Propeller Efficiency.** Yes you have to be gutsy enough to not be faked out by a little math formula**, but the reward is you can easily grasp the most *basic* Horse Sense of Prop Efficiency Logic.**

Of course, we cover Profile Drag Efficiency Loss shortly, also

Our basic objective in this Primer is to write it without math, just the basic technical horse sense logic, but that one simple little math formula is actually the easiest way to show you the *specific* little ***axial*** efficiency logic that underlies everything in propeller logic, in the fewest possible words. We actually show you the ***axial induced efficiency loss formula**** in the next section, which looks more scary, but isn't really, because again it's easy and basic, for those who aren't faked out. **Next, fast is Good, Slow can cost.**

 ***Total 3D Induced losses simply have a higher percentage loss.**

Gearing - Used Very Slow or Very Fast

Very **Slow** and very **Fast** planes are each **special cases** that **need to be geared for quite opposite reasons**. To be efficient a prop ***wants*** a high mass flow rate passing through it, so that it can have a low Delta V, ΔV speedup to make its required thrust, since *axial induced* efficiency loss is ***half*** of **ΔV** *compared to, ratioed to,* that is divided by the speed of the air coming at it, **ΔV / 2 V_1**.

The full 3D Induced losses simply have a higher percentage loss. Don't be confused.

Slow: A very slow plane like a Wright Flyer, a man powered plane, or an ultralight, being slow have a low Mass Flow Rate passing through their **D**iameter, ***Disk Area***, so they tend to need a relatively high ΔV, and when that is compared to a low, slow V_1 a *double whammy loss,* *both unfavorable*, it comes out to be low efficiency. If the normally high RPM of an Engine is **geared way down**, like in the Wright's chain drive, we get **High Pitch**, which we'll learn is desirable, a tell tale of good Efficiency, and a **Big Diameter**, a Big Mass Flow Rate, finally a **low ΔV**, good efficiency even compared to the **still low V_1**, when run through Prop Math. That can fix the basic problem if the gearing is sufficiently low. The Wrights ended up with two **Big 8'6" props** (12 HP), the **Daedalus** man powered plane had a **giant 11.3' prop** (.2+ HP). Ultralights start with a terrible situation, slow speed and maybe 5000 RPM, very flat pitch which we learn is bad, the sign of an inefficient situation. Ultralights are often only partially fixed, insufficiently geared to limit prop size.

Slow, *you need Geared*, Lo RPM, Hi Torque, Big Diameter, High Pitch.

Mach, Fast: Prop tips must be kept below .9 the Speed of Sound, nominally 1000 Ft./Sec. at standard temperature, slower cold, at altitude. If you gear down, slow the RPM, *but* don't let Diameter expand as much as the efficiency suggests, **use more blades**, the vector combination of rotational and forward speed can be kept below .9 Mach at Prop driven Fighter Plane speeds, at some efficiency penalty, right up to the stretched limit at Reno max speeds. **Slow and fast are the special cases. Normally, we want the light weight, simplicity, low cost of an ungeared engine**.

2. What's Very Wrong about a Rotating Wing Hi q Tip?

A Prop Tip Shape, its Loading, is Far More Important Than a Wing! √

How is a Wing Tip Made Right, Much Less Loss than a Prop? √

As a Pilot, you probably already realize that the **Lift of a Wing** ***must*** **fall to Zero at the Tip, a big swirling vortex created as the higher pressure air below the wing swirls around to the lower pressure top**, no dam there to stop the swirl -- the reason we tend to taper wings, a smaller tip vortex -- the reason **Prandtl** taught the ***Ideal*** **Elliptically Shaped** (Spitfire) **Wing**, that is thus elliptically loaded, the **lift naturally falling to Zero in an equivalent half ellipse, max. at the center span, zero at zero tip chord**, the math optimum **least Induced,** ***and Profile*** **Loss**.

Constant α°, C_L, ***Elliptical, has a constant Downwash Angle,*** **tip loss a min. extra.**

The Seagull and the Sea Birds, the Land Soaring Birds, Buzzards, Eagles, Condors have found two very opposite, even more sophisticated ideal solutions, **both varying the wing tip twist as conditions demand** --- the **sea birds then using a pointed tip, the land birds an almost rectangular wing** with **twisted finger feathers that convert the swirling tip vortex loss to thrust**, *the genius of* natures's perfect adaptive evolution, a natural wonder, our **tip sails a poor man's copy**. (We don't get the soaring bird's full effect, ***no added thrust***, ***if*** there's no twist!)

The **birds** are even more sophisticated, **twisting for least muscle load**, man copying these days for **least structural load and weight**, a Jet with typically a huge root chord and thickness, which also conveniently houses the landing gear, a tapered, very narrow tip chord to minimize wing and root bending loads, while still achieving high aspect ratio, big span, minimum induced loss, our best, most sophisticated shot at emulating what the birds do naturally, hardly a thought, a reflex. √

A Boeing 787 Dreamliner Ad shows a long, Swept, Seagull like, Pointed tip! √

When you see a Jet flying low overhead, start noticing the often gross root chord, the sometimes very small tip chords, notice that some tips are narrower than others, nothing like an ellipse these days, and you can start building insight into the Structures Group and Aero Group noodling out the Weight-Aero Optimum. √

(The tips stall quicker, if too narrow - untwisting, **less α°**, the usual fix.)

So Here's Our Propeller, Dumb as a Board, ***Inside out, dead wrong*****!**

With **very High Tip Speeds**, 5 times the root velocity on a Luscombe, the V^2 Dynamic Pressure that controls Lift and Drag is 25 times greater at the tip, compared to the root, **trying to make max. Thrust and Drag at the tip -- where Thrust *must* fall to Zero**. Begin to appreciate the wrong headed, inside out, dead wrong way the prop is trying to operate, max. thrust and drag at the tip, minimal at the root, at low dynamic pressure, low q, ***exactly inside out, opposite, compared to a proper wing***.

With huge tip q, vs. the root, Prop Tip Shape is far more crucial than a wing tip!!!

The dumb prop is **going to lose most of the extra thrust it is trying to produce out there, rolling off the tip** into an **extra Big Tip Vortex Loss, extra Drag way out there at max. lever arm, trying to bog down the engine torque, thus RPM, lower the available H.P. You not only pay for extra thrust in extra induced and profile drag, you lose much of the thrust, while reducing the available engine H.P.,** ***losing 4 ways!***

Realize props try to act about as inside out, opposite, as you can do it!!!

Now fortunately there is an easy, simple, **good technical horse sense fix for that problem, simply tapering the tips, but significantly more than the elliptical wing!** The chords represent wing or prop blade ***area*** as you integrate out along the wing half span, or prop radius, so we can control the prop blade loading vs. radius, in pounds per foot, or inch of radius, by just tapering the shape as we choose. **This is the easiest and most important insight you will ever learn about propeller logic**

Do you see the simple enough horse sense of that? We can *counteract* the excess tip loading that exaggerated Dynamic Pressure, q, tries to produce at the prop tips, pull the max. loading inward away from the tips to an Optimal Radial Thrust Distribution that we can control and choose.

P. 147 shows **Optimum Blade Loading and Shape, vs. Advance Ratio,** (or Pitch)!

In a few more pages Betz will show us how to do this Ideally, Optimally, for Minimum Induced Drag Loss, genius level insight, that gives us ***Ideal Prop Shape, thus Loading!***

3. The Prop as an Airscrew - Screwing Home Efficiently.

The English had it right, a prop **truly is an Airscrew**, and must be, its job much more than just a rotating wing, its objective to **Screw you to your destination as efficiently as possible**.

There are ***two remarkably simple insights*** that teach us that a **High Pitch, High Advance per revolution prop is the most efficient Screw Propeller**. Simply, a High Pitch, High Advance prop screws the **shortest, least energy consuming path to the destination, a low pitch prop simply spinning an excess distance to get home**, simple as can be, the **least profile drag energy cost with steep pitch**. **(45° is best!!!)**

It's almost as easy to see that a **High Pitch, High Advance prop has the Least Induced Drag Loss,** from what we've already learned. A high pitch prop is going to be going relatively faster for any given case, **Fast, a bigger $\dot{M}$, Mass flow rate, thus a lower ΔV, a lower $\Delta V/2$ divided by a bigger, faster V_1, a lower efficiency loss.** I hope you can grasp this, see that this is really pretty easy once you tumble to it all. If you can grasp this OK you're getting really great insight, the real meat, pretty quickly, that demystifies the most complex basic subject in all of Aerodynamics, the **Basic subject that never got coherently, Incisively explained before**

A Tricky Little Logic Conquered!!!

Let's Review, and Sum up to this Point:

We've learned that a **prop naturally tries to greatly overload both the Thrust and Drag at the Tip**, **(where thrust must fall to zero, the excess lost)**, simply because the Dynamic pressure can get way excessive at the tip, vs. the root -- that **we can fix that flaw by simply tapering the shape, pulling the radial tip loading inward** - that we **want high pitch, *if* Speed vs. RPM permit** to get a **big $\dot{M}$, Mass flow rate**, a **low ΔV speedup, low vs. the plane speed V_1**, to **get a low *axial induced efficiency loss*, a low $\Delta V / 2 V_1$**, if math symbols don't scare you, **a Short, Low Profile Drag Path too**.' It's *simple enough*, the core logic.

 It's SIMPLE: Taper the Tips --- Hope Speed vs. RPM allows High Pitch!!!

GET THIS.

4. Albert Betz's 1919 Genius Level Insight

The beautiful thing about **Science**, the **explanation**, the **logical application of** the principals of Physics, Chemistry, Biology, **all of Nature**, is that (although there can be mind boggling complexity), there is almost always **finally beautiful simplicity, orderly logic**, like God, ***smiling***, gave us the challenge, but the Brain to sort it all out.

Albert Betz was a contemporary of Ludwig Prandtl in post WW I Germany, just after the age of the Spads and Fokkers. Prandtl saw the logic of the ideal elliptical wing, and Betz, amazingly, saw through the ideal propeller, a far more difficult problem.

He must have seen that **controlling the radial loading of a prop is the key to Ideal Operation and Efficiency**. In marvelous insight he saw that the ideal solution is simply to **pull in a perfect helical screw surface *of air***, perfect **constant pitch at each radius**, and **throw back a theoretical stretched, still perfect Archimedes screw downwash, backwash from each blade, just like the picture on the front of the Book!!!** √

It's the Air that's a perfect Helical Screw Surface, *not* the prop.

He first considers this **drag free**, because the simple case yields the **Minimum Induced Drag Loss**. He seems to ignore the Tip Vortex, which in the real world swallows up this Ideal, Perfect Math Model. **He doesn't ignore this, however, and the subsequent, 3D Flow Math Approximate Solution by Goldstein in 1929 and Theodorsen's essentially perfect solution in 1948 allows us to design an essentially perfect Ideal, minimum Induced Loss Prop on a Computer, as fast as you can type in the parameters and hit the Go Button.**

The 3D Radial Tip Vortex Loss *is* accounted for, rotational flow too.

Concurrently, the proper Low Reynolds number drag coefficients can be added, for X-ray insight on a ~ perfect Prop. There are magnificent parallel insights from Betz, shown on page 129, as incisively as you'll ever find it, **constant Slip the hidden insight** that optimally balances radial flow, Thrust, and Loading. **Page 147 shows optimum Shapes, Loading, vs. Advance.** √ √√

5. Seeing the Whole Propeller Logic Picture

Of course there's more to learn, a lot more, but if you understand this **Primer**, you've grasped **the core of Prop logic, easily worth reading these 11 pages over (if you need to), because this is the heart of the subject, and if you got this Ch. 9 is licked!!**

A **computer** uses an **amazingly simple Goldstein-Theodorsen Kx blade loading factor *chart* vs. Radius, and Advance Ratio,** to interpolate, ideally load a ~ perfect theoretical prop, give two or three pages of Data, for ~ exact definition of an ideal Betz, drag free prop. But Low Reynolds number drag can be added to the program, if you're a pro, as my partner Dr. Andy Bauer has.

SHAPE, thus CONTROL of LOADING is the KEY!!!

There is a highly varied velocity profile at the nose of a plane, the imbedded body pushing a bubble of air ahead, especially if there is a bulbous cowl, that acts like a Slowdown, that is **a very important correction, adaptation** of the basic theoretical prop. We really **want to predict inflow angles to +/- .1 degree, yes, 1/10°**, a normal shop tolerance, for prop product consistency, so anything but the real math is fooling yourself if you want real answers that match real results.

Home Grown Computer Programs are *Anti* Productive!!!

A separate program analyzes an Ideal Prop design off of its normal altitude Cruise design point, for example, Sea Level and Altitude Climb, Vmax on the Deck and at 8000' Altitude, for those who want to fly at max continuos power, 75% of Rated.

We set this book so you can read each subject at any level you wish, this very insightful 11 page primer on props, Chapter 9, more, progressively deeper, a good bit more, after its core 20 pages, Book II the whole Magilla, pro insight for anyone who cares to go after it all, more and more insight, the first comprehensive, understandable explanation ever. It takes **an hour or two for Ch 9, a day or so to truly get it all. We purposely Superemphasize, repeat, lead, tie together, sum up -- *all* so Novices can get a pro's insight.**

Summary Insights and Conclusions, Insights to Realize:

1. <u>**Definitions**</u> of **Propeller terms** found **after Chapter 1,** Book II

2. **Pitch: Simply, Perfect Helical <u>Prop Pitch</u>** is the **inches** or feet a **Propeller would Screw through a soft solid,** *per rev.*, with **no Slip.** (If the twist is not pure helical, especially after correction for slowdown, it is taken as the pitch of the 3/4, **75% radius.**) Realize that since a propeller is **pulling in and throwing back air** to make thrust it is ***typically overpitched*** a small amount, to pull in the air, **there is some Slip** <u>thus</u> the actual <u>**Advance**</u> per Rev. is <u>**less than the Prop Pitch**</u>.
Ideally, <u>*Air Inflow Slip*</u> is held <u>constant</u>, Betz's <u>constant pitch *Air Inflow* V_2 *minus* V_1</u>.

3. <u>**Propulsion Efficiency**</u>**:** Realize <u>**Propeller Efficiency**</u>**, eta, η,** is <u>**Traveling Efficiency**</u>, and thus <u>**at static Runup**</u>, burning fuel, straining, **going nowhere, propeller efficiency must be <u>Zero</u>! As the plane speeds up,** more slowly throwing back air, going faster, thrust is logically dropping, but **efficiency is improving,** still **reduced during climb,** only reaching cruise design efficiency at cruise, typically highest at Vmax. If there is an **extra interference (in)efficiency,** scrubbing drag, faster air blowing across the fuselage, etc., any extra separation, any extra pressure drag, propulsion efficiency, η_p drops farther, prop efficiency, η, and Interference efficiency, η_i multiplied together! In a **shallow dive,** faster than the pitch capability, ***thrust*** drops to ***zero, efficiency again drops to zero,*** ***graph on next page.***

4. <u>Newton's Laws</u> **Fundamentals: <u>3rd</u>, <u>Thrust</u>,** an <u>**Equal and Opposite Reaction Force to air Thrown Back**</u>**, <u>2nd</u>, <u>Thrust</u>,** <u>**Equal to Mass Flow rate $\dot{M}$, times** the Delta V, **ΔV *Speedup***</u>**,** <u>*Axial Induced Efficiency Loss*</u>*****, Half the <u>**ΔV**</u>**, <u>ΔV/2</u>, vs.,** that is <u>**divided by**</u>**,** <u>**Inflow Velocity**</u> **V_1, --- (ΔV / 2V_1** in math terms, if that does not scare you), is <u>a real fundamental of propeller logic</u>, can be seen operating all through Propulsion Efficiency, above, and if you can grasp the horse sense of it you have made a giant stride. The actual 3D airflow used for actual propeller design is much more complex, but grasp this simple, basic logic and you've won.

 ***3D Loss, Axial, Rotation, Radial, (TipVortex), is Simply a higher % Loss.**

5. A Rotating Wing, has a **Bad Basic Flaw.** With very High Speed Tips, **Much Higher Dynamic Pressure, q, at the Tip vs. the low q root,** a prop is **trying to make excess thrust and drag at the tip,** where **Thrust Must Fall to Zero,** physically **rolling off the tip, making extra induced loss,** a bigger Tip Vortex, unproductive **extra Profile Drag,** *at max lever arm,* max radius. The **propeller begs for the good technical Horse Sense to highly taper the outer prop Profile Shape** to **pull the max load point inward, allow a natural drop off profile** of **thrust vs. radius** to **prevent excess, unproductive tip losses, better efficiency,** just good sense, once you see it. See p. 147. Ch. 9.

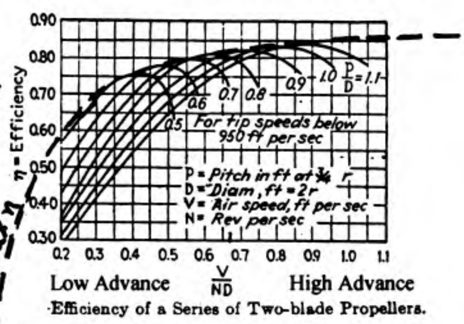
6. A Prop is an Airscrew. Thinking of a Prop as an Airscrew is very Important, Fundamental. **High Pitch, a shorter Spiral Path** to the destination is the key to both **Low Profile Drag loss** and **Low Induced, high pitch** ***going with*** **high V, big Ṁ, low** Δ**V.**

NEXT, SEE BETZ'S PURE HELICAL AIRFLOW PHOTO ON COVER

7. Betz, p.129, teaches us how to get a **Minimum Induced Drag Prop,** (first considered profile drag free), **by Ideally Shaping,** thus loading, a blade, **constant pitch** air inflow, **pure helical inflow, constant slip,** vs. plane speed, ***stretched pure helical backwash.*** More p. 129

8. Theodorsen, has **a ~perfect math solution** for a **Betz** prop!

9. Advance Ratio, Pitch/Diameter, P/D Ratio. A look ahead. Low Pitch, low P/D, props have **low efficiency, high Pitch, hi P/D, high** η**, each fixed pitch prop has a limited speed range!**



·Efficiency of a Series of Two-blade Propellers.

This old graph from a 1941 Marks, Mechanical Engineer's Handbook*, though inaccurate, ~5% low on Max Efficiency, shows how a series of various P/D Props have a limited speed range, starting at zero efficiency, at zero speed, but nest together to form what we will learn is the **Advance Ratio Curve of Max Efficiency of *ANY* Prop** — Valuable Insight. By permission of *McGraw-Hill Book Co. Inc.

Advance Ratio, J, V/nD, like J/π, V/πnD, ratios forward to rotational velocity, an insightful picture. This is an old, outdated Graph with poor plots, the efficiency ~5% low, but marvelous insight if you can grasp it this early.

Wow!!!!

Of course I realize that's a whole new world of logic to lay on a civilian, a pilot, not experienced in technical thinking. In fact that's never been explained to engineers before. Pro's have never had a starting explanation of propellers that is that **coherent**, that **incisive**. We don't have correctly designed props with properly tapered blades because that introduction to propeller logic was never correctly put together before for pro's or civilians. **Few pro's have really understood that correct loading of the blade, correct SHAPE, with matching proper twist is the final basis of properly efficient propeller design**.

Understanding this Primer on Props is Pivotal, a challenge, it's your entry ticket!

So now understand what's going on here. Airplanes are relatively easy to explain, but propellers have been so mystically complex they've been impossible to correctly understand or explain. The pros never had a proper explanation before, 138 years, 1865 to Dec. 17 2003. But now, we finally have one, and **if you have a little guts**, don't get faked out, **you can understand all the things that never got nailed before!!!**

Props are the special case, the previously impossible challenge.

No, I'm not some weird techie who's too dumb to understand that you'd like the simple, dumbed down, easy explanation of everything, written in good simple normal writing style. This book started out to just explain planes, and matching engines to them intelligently, easy enough, but then it became possible to teach you what has always been impossible, understanding props

If you can understand the horse sense of this Primer, you can learn Props!

So here's the deal. **Recognize your awareness just went up by a huge factor!!!** It's really not possible to strain your brain, and maybe you only spent an hour or so to get through this Primer. **If you simply understand that I lead you through the morass of propellers, superemphasizing, I can lead you to all the nifty insights and you can understand what would have been impossible for you to know before. Have guts, have faith, hang in, and you'll be amazed at what you learn!**

Realize we keep leading you to the Truths. You don't have to figure it out, we lead you!

A Real Engineering Breakthrough --- Understanding Props

For the first time in 138, years we can understand and explain both the big picture and the incisive details of prop logic, design, efficiency, and operation --- both as the engineering horse sense involved and the rare genius level math, and what the math really means, and what it dictates. And happily, we find that the horse sense supports and better explains the logic of the math, making it more clear and understandable to both the novice and the professional engineer -- as the math completely supports and verifies the horse sense logic, the mutual agreement supporting that we do, in fact, finally have it all correctly understood!

Before computers there was no really adequate analytical methods for using Theodorsen's marvelous math efficiently in a cost effective way for non government, low cost private flight. Talking to the old timers, in one key company, it was an old pro from NACA with real feel replacing analysis. In hindsight my 1947 model propellers were much better than the prop on my 47 Luscombe. I got a specific, accurate speed answer every time on a speed model, better test data than pros.

In the very best companies there is always someone sharp enough to get to the technical truths, and as soon as earlier computers became available that started, but some got it less correct than the best, and it was proprietary, secret, and vibration often took precedence. The best did very good work.

The brilliant few who created the logic and the math, Betz, Goldstein, Theodorsen certainly had to understand, but there is an interesting insight there. People at that level of brilliance, locked on to the genius level math, are almost unable to come down two notches and say and teach all the practical insights on what all the math really means and dictates. The technical horse sense that we have here has been the missing link, can teach novices and non genius level pros what the resulting logic really is, what is dictated that has not been clear enough before.

Let me explain. There is nothing in the literature that tells us clearly, simply, that the objective of the math is to load the prop correctly vs. radius, to prevent excess tip loading, unnecessary, unrewarded induced and profile tip losses, that proper blade loading is accomplished by proper shaping of the blade with proper twist, that if you actually achieve a constant optimum angle of attack and C_L, you get min. profile drag too, min. area precisely placed, Min. Torque, a Triple ideal optimum prop, not just min. induced --- that you must accurately correct for nose velocity profile, slowdown, because we really need to predict inflow to all blade radii to .1 degree, yes one tenth degree, that a 1 degree, .1 C_L error will give us a 20 % error on a .5 C_L prop --- that the slowdown correction which results in less twist, lower blade pitch angles, especially inboard, can create a major Plus in fixed pitch prop operation slow, in take off and climb.

There is no criticism whatsoever of the truly magnificent, rare genius level math and technical work done by our marvelous forbears, who gave us superhuman solutions, ready for easy use.

The problem is that with no explanation, what it meant was not understood! ✓

The kind of things we'll learn is that Speed vs. RPM, with due consideration for needed inflow and angle of attack sets pitch, which sets max. efficiency attainable, that use of B-G-T, Betz-Goldstein-Theodorsen Math, will then deliver max. efficiency, that it will also deliver a **precisely loaded, shaped and twisted** prop, **a constant optimum angle of attack and C_L, minimum area, precisely placed, a Triple ideal, min. induced, min. drag, min. Torque prop, if we're only smart enough to ask for it.**

Remember, with 21st Century Insight, we can improve on the old Optimums

A lot of long, hard, dedicated work has been done here, simply because Andy Bauer and I were experienced enough to recognize that the explanation was badly needed, long overdue, and that with two lifetimes of experience we could sort it all out, do it. **There is a lot to teach you**, be you a novice or pro, **a long string of incisive insights. We'll simply build on and expand 4 basic insights here, ever deeper, broader, more sophisticated**, ***superemphasized so anyone who tries can get it!***

I'll take this page as the bottom line on a lifetime of experience + insight – Jack Norris 8-16-06

 We had to go years past the math to get you the incisive clarity here.

An Important Advanced Insight

***If* I can do a little calculator math without scaring you ---**

Airplane Math Hides Some Pretty Bad Prop Design!!!

Going faster, plane drag goes up as the Velocity Squared, **~V^2**, but **power Cubed, ~V^3** -- because in going faster you have to put in the higher Thrust, and Energy, **(pounds x feet traveled, # ft.)** for that higher speed, *at a faster rate*, **ft. # / sec.**, because that's what Power is, rate of putting energy in, **ft. # energy per second.** (It's actually a little less than V^3, because faster, induced loss is dropping, but let's keep it simple, to look.)

To go 1% faster, you need $(1.01)^3$, 1.030301, **3+% more power**, to go 4% faster, you need $(1.04)^3$, 1.124864, ***~12.5 %*** more power!

Now let's say a **220+ MPH Triple Ideal RV 8 Prop**, min. Induced, Profile, Torque, **can be 90% efficient**, because it can be that efficient --- but we **really Klutz up the design and get 50% unnecessary, extra loss, lose 15% not 10 %,** we have an 85% efficient prop, not the 90% that we can and should. But that only cuts our available HP in the ratio of 85/90, .944444, or 1.0588, inverted, and the good prop only goes $(1.0588)^{.333333}$ faster, **1.019**23555, using all the decimal places, less **than 2% faster**, maybe a typical difference, fair vs. perfect. **With few valid tests,** ***poor props have hid for decades,*** the perfect prop gypped.

***If* you can cope with a good calculator, play with this, get a lot smarter!!!**

Now, let's say we design it really poorly, and get **twice the min. loss, 20% loss, not the ideal 10%**, 80% efficiency, not the 90% we deserve, a 80/90, or 90/80 power ratio. We only go $1.125^{.3333}$, **1.04**0042, **4% faster** vs. a really poor prop. **WOW!!**

The numbers hide quite poor props, but there is no reason to not get them right.

Guess What? On Dick Van Grunsven's, Van's Aircraft, recent tests of available commercial props for the RV 8, the best prop, **Hartzell's latest,** ***basically*** **designed to Theodorsen Math**, with some extra area at the tip, went 208.9 MPH at 2500 RPM cruise, the worst European prop only went 200.7 MPH, a **1.04**086 speed ratio, **the klutzy prop had double the ideal loss, bad!!!**

It's time we get props correctly understood, correctly designed!!!

We're after **2 objectives** here: **1.** ***Accurately, Understandably, explain prop Logic***, **2. Get props correctly designed**, **easy with *Betz-Goldstein-Theodorsen math*, available for 50 years.**

Throwing Air - Really understanding What Induced Loss is

There are two basic types of loss, **Profile, Skin Friction Drag,** just based on ***surface area skin friction***, just like it sounds, and **Induced Drag**, or **Loss**, just the **energy cost loss** from ***throwing air, to make Lift, or Thrust***, as a **reaction force**. Mathematically, it acts like another drag, but I very much **prefer the term loss**, not drag, which ties in to a much more simple, smarter, incisive way of looking at it, because you **simply throw air to get a reaction force lift, or thrust, spend energy to do that throwing**, the **energy simply lost** to **friction, turbulence**, as the air settles back to static, ***but a fundamental need***. -- Yes, you can get separation, interference, bad high drag designs, but we're talking basics here.

You never hear it referred to that way, but, you see **it really is the core essence of the subject.** The day that first dawned on me, it was like someone just turned on the sunlight, and I really understood for the first time. **I hope that, maybe, it can be an equivalent awakening for you!!!** Anyone can make these things complex, **the magic is to see the simple, basic insights**.

That's very important for propellers, because if we design a prop for **a .55 C_L the basic losses are nominally 2/3 Induced, 1/3 profile, *Induced the bigee!*** You'll learn that if you design for a very low C_L, you can interchange those losses, and have a prop almost as good at the design point, ***but* much bigger, heavier, less good overall**, not what we do, **.5 to .55 C_L best.**

Ideal Props are all about minimizing both Induced and Profile, KILLING TIP LOSS.

Profile increases as V^2, twice the speed 4 times the drag, 3-9, 4-16 etc. But we learned in the Airplane Book I that **Induced is a $1/V^2$ Phenomenon** that **drops with speed**, 1/4, 1/9. 1/16 etc. **Propellers disguise that, but work exactly the same way**, the Induced, the reason ***fast***, *high pitch* props are best.

The tricky $T = \dot{M}\ \Delta V$, and $\Delta V/2V_1$ logic is easier to see through here!!!

See Through $T = \dot{M}\ \Delta V$. Big speed, **big V**, **big $\dot{M}$**, only need a smaller ΔV, a **twice lowered $\Delta V/2V_1$**, a **big V lowering the $\Delta V/2$, dividing it by a bigger V, *a $1/V^2$ phenomenon disguised.***

Try very hard to get this if you're a novice, if this is tough for you.
It can be a huge fundamental breakthrough, that can clarify the tricky basic logic!!!

Book II

Advanced Propeller Insight

Following Propeller INTRODUCTION, and PRIMER,
Read Chapter 9, Propellers, of Book I, The Logic of Flight.
Then return to this start of Book II, Advanced Propeller Insight.

Propellers -<u>Starting a Professional Understanding</u>
A Lifetime of Insight in an Hour, a Day, *as much as you choose!*

There has **<u>never been an understandable, comprehensive, incisive explanation of propellers and their logic</u>, not for the 138 years since Rankine started water Propeller Analysis in 1865**. It's been t**he ultimate dismal Swamp** of the Engineering profession. Quite simply, **no one ever got their head around the whole subject well enough to make sense of it all, <u>explain it in a way that either novices or pros could</u> <u>see the horse sense of it all</u> -- as well as <u>the key technical specifics</u>**.

With a lot of long hard work we've conquered the 138 year challenge!!!

Actually, 7 historic, benchmark technical masters achieved **an *<u>Elegant</u>*, essentially exact solution for the Ideal Betz, Minimum Induced Loss Propeller by Theodorsen's 1948 book**. But it mostly scared even pros away, not realizing that his book showed **a very practical, easy enough way to solve the Ideal Prop**. I saw that yawning gap in Aeronautical Engineering as a kid model competitor in the later 40's, and it still existed at the Millennium. **Dr.Andy Bauer** and I took it on as **a dare, a retirement <u>final intellectual challenge</u> a decade ago**. It was **a worthy challenge, a final gift** to the **time and profession that gave us an E Ticket to life**. We could **fly**, help **design and build Jets, even manned Spacecraft to the Moon and back**, ***<u>what a fantastic, fun, satisfying life we've had</u>!!***

We found **<u>Rare Genius Level Work</u>, Rankine, Froude, Betz, Prandtl, Goldstein, Glauert, Theodorsen, the seven masters**. Our good intent was rewarded by finding the opportunity to finish and explain **some of the greatest, most challenging, Elegant engineering work ever done**, the chance to make it understandable **to pros --- and novices too -- <u>Put It To Work</u>!!**

There was a lot more to finish, <u>Adapting an Ideal Prop</u> to the <u>Highly Variable Velocity Profile of an embedded body</u> nose, adding <u>low Reynolds Number Drag</u>, <u>analyzing it off spec Speed, RPM, Altitude ρ</u> --- *<u>Making it understandable</u>!!!*

There is so much here to be taught that, done wrong, we could drown, confuse, lose even good pros, no progress there. **Betz, Goldstein, Theodorsen** were **not just brilliant**, they were the **once in a century, rare genius level wonders who came along in the right sequence, spread out from 1919 to 1948**. They could see through and solve what normal pros, mere mortals, could not. We had to dig through all their work, **understand what it all really meant, do analytical studies, get way past the math to finally see all the hidden, obscure technical subtitles -- finally see the real horse sense of it all.**

The marvelous thing about Nature, Science, is that amidst unfathomable complexity, there is finally orderly logic, Betz's Double Helix, one from each blade, no less a discovery challenge than Watson and Crick's later Double Helix DNA.

You and I, mere mortals **understand and remember what makes sense to us**, so our job here was to dig and dig, not quit until we had been through everything, **not quit until we saw *ALL* the horse sense of it all**, checked everything twice, went around, consulted with, taught, **checked with every prop expert in the country, wrestled it down to the irreducible technical horse sense of it all, nail *all* the technical specifics**.

Novice or pro, there's enough here that it takes everyone a little time to actually absorb it all, all the new thinking. **To succeed we had to get it down to technical horse sense, the 4 element Horse Sense of the Primer, 1. Newton logic, 2. a Rotating Wing's Flaw, 3. the need to understand a prop as an Airscrew, 4. the Elegant, *multifaceted* total logic of a B-G-T Propeller**.

We purposely set up the Book for each reader to go as far as he chooses.

We ***teach*** the logic in the **Primer**, ***expand*** **it in the Primer Chapter 9**, ***overview*** it to **start this Book 2**, a nice smooth read, ***many pilots satisfied, and hopefully honestly understanding in 3 shots*. There's a ton more, a really insightful education, a pro's grasp for those who choose to go all the way through Book 2, *a day***.

A STARTING POINT TO A TRULY ELEGANT LOGIC

Let us presume that you have read, and generally understand the **11 page Propeller Primer for Pilots**, and **Chapter 9 of Book I, Propellers for a Pilot's First Grasp,** Book I having covered Airplane Logic. ***Maybe***, you have **first read** the **Overview here**, were **able to start the Primer with the very helpful benefit of knowing where the whole subject is going,** insight that can make a complex subject like propellers far easier to learn and understand. **We want you to get the horse sense of Props so we build it all on the same base, lead you ever deeper!**

You can start with 12 pages here, or the Primer, but read them both and Ch.9.

Propellers have always been the **unexplained, unexplainable subject**, just too many things happening, all interrelated, affecting each other, **pretty much the ultimate technical swamp**, the subject that even experienced engineers couldn't understand, or explain to each other. It's taken two of us, two professional lifetimes of experience to **tame it**. We took it on as a **retirement intellectual mystery challenge, taken on just for the challenge, like Everest, because the dare was there, the job that never got solved, and wasn't going to be solved!**

Often engineers can resolve usual problems to a math equation, maybe a couple of equations, and when you can do that, see what's happening there, engineers can see the logic of it all. Props were always too much of a morass, too many things happening, interrelating, affecting each other, everything else. It took a long time to learn everything that has been learned, to figure out the logic, to figure out how it could all be explained. **To succeed here, my challenge was creating an easy enough start so people can grasp the technical horse sense here, fast.**

Compared to the usual morass this overview explanation is pretty tame.

It's all here. We show you the logic of it all. ***Props still try to be complex, tricky, so we superemphasize***, repeat, bring it all together, **do everything possible to help you get it**. If you're **interested enough to try, care, you can get it. It's up to you now!!!**

CHAPTER 1 BOOK II

THE PROPELLER

AN OVERVIEW INTRODUCTION - TO A PROFESSIONAL GRASP

The **brilliant work** of the **7 Historic Giants of the field**, over **83 years, Rankine, Froude, Betz, Prandtl, Goldstein, Glauert, ultimately the *rare genius* of Betz, Goldstein, Theodore Theodoreson,** we have **a truly Elegant, Classic Propeller Logic, essentially Exact Math for our Computers!**

Theodorsen's 1948 book brought together the very practical, and **essentially exact mathematical solution** for the ***Heavily Loaded, High Advance Ratio, Ideal Minimum Induced Loss Betz Logic Propeller.*** It's *first* done on a **Profile Drag Free basis**. Theodorsen credits **Goldstein's 1929 basic solution for the Mathematics of the (3D) Potential Flow Problem** as, "unquestionably the greatest single step in the evolution of Propeller theory". ***Theodorsen finished it, for heavy loading!***

It is possible to show with **simple technical horse sense** that there is a **harmful basic flaw** in the **operation of a propeller as a rotating wing!!!** There is **a fundamental need to significantly taper the tips of a propeller!!!** The **Shaping, twisting, therefore *Radial Loading* of a propeller, logically, is significantly more important than the shaping of a wing!!!**

Simply, **the tip velocity of a propeller, so much faster than the root**, at an **even more magnified tip Dynamic Pressure, q,** proportional to V^2 --- **tries to greatly overload the thrust and drag at the tip, where the thrust must fall to zero!!!** ***Excess Thrust swirls into the tip Vortex --- and is lost,*** **causing extra unrewarded wasteful tip vortex induced loss,** ***noise*** - **extra tip profile drag at max. lever arm** - ***excess torque, bad design!!!****

 ***Now we can *nail*, Min Induced, Min Profile, Min Area Precisely Placed, a Triple Ideal Prop. We'll ultimately learn how to beat that 20th Century Ultmate!**

Fortunately, there is a **simple, good technical horse sense fix** for that very fundamental basic flaw, ***simply taper the tips***, **thus the radial blade loading,** *pull the excessive tip loading back to a more sustainable, mathematically ideal radial shaping of the blade loading*. **Betz-Goldstein-Theodorsen, Math** simply optimizes the tip loading, indeed the **loading of the entire blade into a mathematical optimum, Minimum Induced Drag loss, a unified propeller theory with several advantageous, ancillary, insights and features,** one of the most elegant, all encompassing logics that you will find in all of engineering -- constant pitch pure helical inflow, constant slip, stretched pure helical outflow, constant dT/dQ, a constant ratio of thrust vs. required Torque at every radius, every radius equally efficient - *if* first considered free of Profile Drag. ***Elegant***

PERFECT SHAPE VS. TWIST GIVES IDEAL RADIAL BLADE LOADING

Profile Drag can be added concurrently in a subroutine program, in the same basic overall propeller design program. Since propeller blades tend to have the speed of Jets, but the chords of model planes, **low Reynolds numbers**, well below to above 1,000,000, it's **proper to use drag coefficients that have proper higher drag coefficients vs. Rn's, also earlier Stall**.

Norris's 6th Law, teaches the useful insight that if you simply design an ideal BGT prop, that **actually achieves a constant, optimum angle of attack, α°, and C_L,** you will have a **Triple optimum prop for the design condition**, because you'll have **ideal minimum area, precisely placed**, ***Ideal Shape***, ***Loading!***

Min. Area, Precisely Placed, gives Min. Induced, Profile, Torque for that C_L

The whole, **very simple, very understandable Bottom Line** on **Ideal Propeller Design** is simply that the game is to **SHAPE the blade, (with matching, proper TWIST), thus ideal LOADING** for the design conditions, which, **with ideal constant α° and C_L produces a Triple ideal, Minimum Induced, Min. Profile Drag Loss, Min. Torque Prop Design!**

It is subsequently **necessary to adapt a theoretically ideal BGT prop, for the slowed velocity profile at the body nose!!**

 For Century 21, we can try to force Elliptical Loading, do a few percent better!

We initially learn prop logic by looking at them in 4 ways.

1. As **pulling in and throwing back air**, to get **a reaction force** per **Newton's Laws** - Which **teaches us basic prop logic**.

2. As a **Rotating Wing** which **exposes the need for tapered tips**

3. As an **Airscrew** which teaches us that a propeller is **more than a rotating wing - must be considered as an Airscrew**.

4. As a *Triple* **Ideal Minimum *Induced* Drag Betz Propeller** designed for **constant optimum α^{o} and C_L - min. *Profile, Torque too*.** ✓

Pitch of a perfect helical screw prop, is simply **the inches or feet that a prop will screw forward in one revolution** through a soft solid with **no Slip**. Since a prop blade is not apt to have perfect helical pitch, especially after it is retwisted to match the slowed velocity profile in the prop plane at the nose of an embedded body, the **pitch at the 3/4, 75% radius** is used.

Advance. Since a prop must be **overpitched a little bit to pull in and throw back air to make thrust**, and have **an angle of attack too**, a prop will **advance a little less each revolution than its pitch**. **The Difference is the SLIP**. We will learn that a core characteristic of an Ideal Betz prop is to have **Constant Slip at every radius --- a basic of Minimum Induced Loss.** ✓

With Constant Pitch Air, Constant Slip, it has Constant dT/dQ, if drag free.

We will learn that **only High Pitch, High P/D, High Advance Ratio Props** can be **Most Efficient**, because the technical **horse sense** will teach us **all three go with Minimum Induced, Min. Profile Drag Loss, *Min Torque too***. We will find three similar, but different ways to define **Advance Ratio**, the most useful, most easily understood one being **V / πnD**. **Look**, and you can see that **V** is simply **forward Speed**, or **Velocity** (in ft./sec.) **vs. the circumferential velocity of the prop *Tip*** in ft./sec., **n** simply being the **rotation** in revolutions per second, **D** the diameter in feet, ***the Tip Advance Angle***, which **acts much like P/D Ratio, both tied to max. efficiency possible.** Realizes there's **a few % Slip there.** ✓

High Pitch, High P/D, High Advance Equals High Efficiency

In the Propeller Primer and Ch.9, Propellers, in the Airplane, Book I, we learn that Isaac Newton teaches us the way to **minimize Induced efficiency loss** is to **minimize throwing air**, **minimize** Δ**V**, and.$\Delta V/2V_1$ the ***Axial*** **Induced Efficiency Loss**. There is also a ***Rotational*** and a ***Radial*** flow Induced Efficiency loss that makes the total Induced efficiency loss **significantly bigger than just the *axial*** $\Delta V/2V_1$ loss, but just looking at the axial loss, at first, **most easily teaches us the tricky basic logic**.

It's Really a ~1/V² Induced, just like aWing, *a double effect of V, just disguised!*

Newton teaches us **the way to minimize, (all three) Induced Losses** is to **have a BIG Mass Flow Rate** flowing through the **Prop Disk**, since Thrust equals Mass Flow Rate times the Delta V, ΔV speedup of the air, simply, $T = \dot{M}\,\Delta V$, for a flowing fluid. Simply, a **big $\dot{M}$, M dot**, allows a **small** Δ**V** for any given required thrust. Now logically the way to have a big mass flow rate is ***either*** have a **Big Diameter Prop, or Simply Go Fast! Simply going Fast** is the **easy way to get high prop efficiency**.

Fast lowers the Optimum Diameter, both Profile and Induced!!!

Now, that sets us up to **very easily see** that **only High Pitch Props can be Efficient**, that **high blade angles** are the pro's math based, and horse sense **clue to high efficiency**. It's easy, a cinch to see that a **high pitch** prop has the **shorter Spiral Path** to the destination, **less profile loss cost**, low pitch wasteful. Since **High Pitch correlates with Fast**, at usual RPM's, it correlates with **Big $\dot{M}$, Low ΔV, low $\Delta V/2V_1$, low axial Induced loss** too - tricky yes, but pretty easy once you catch on, especially once you realize that's the easy enough answer to decoding the logic swamp that befuddles smart guys, before it's explained.

Now, we'll be teaching you the **classic Advance Ratio Graph** of **Max Potential Efficiency** for ***any prop*** shortly, done **including Profile Drag, full sophisticated math**, but, you see, **High Pitch, High P/D, High Advance, High Blade Angles**, all correlate with **High Efficiency**, **just *a little slip insight hiding in there* —**

Gearing Slow Planes for Low RPM, High Pitch , Big Diameter

Gearing for Lo RPM, increases the ***Torque***, can turn Hi Pitch, Big Diameter.

We've purposely been teaching you the much more simple **basic technical horse sense of propeller logic, (wonderful to finally have what has been a 138 year morass down to horse sense),** because horse sense is what technical novices can understand, and this book is for **Pilots who properly want insight that makes sense**, not intellectual elitism. But pros should understand that the only way we were able to make it this simple, was going through and past all the marvelous Historic BGT Math, two old pro's with **two lifetimes of experience**, enough to **finally clarify the logic**.

The Sense, the Logic, is what pros grasp when they really understand.

Either the **sophisticated math** or the horse sense can show us that High Pitch, **High Blade Angles**, High Advance is the **fundamental tell tale of High Efficiency**, ~ **45° the optimum**, you'll see, but that tells us that we can gear down the RPM on a too Slow, too High RPM case and ***always*** be able to get a max ~ 91% prop efficiency - and that's true, the math proves we can.

Aspect Ratio can nudge the ~ 91% up or down.

But, as always seems to be the case with props, there is some trickiness hidden in the shadows. If you gear down, slow down the prop for **lower RPM, Higher Pitch**, it's going to take a **bigger prop** to make the required thrust at now lower q. **Good,** that will get the **mass flow rate up**, the $\Delta V/2V_1$ **induced loss down. But,** when the diameter goes up, for the same speed the **tip angle**, tip **advance angle goes down**, ***counterproductive***. Notice two pages back, at the bottom that **V / πnD**, that best defines Advance ratio, is really just the **prop tip Advance Angle**. √

Now, what happens is, gearing slow planes for efficiency works, but **Diameters get a lot bigger, props heavier, RPM's a lot slower**, a process that takes ***a Lot of change*** **to get *a very Low ΔV vs. a V_1 that starts low* --- to actually get high efficiency.** √ The man powered ~ **.2+ H.P. Deadalus used an 11.3' prop**, the **Wrights** were **smart** enough to know they needed **(2) 8.5'** props for ***only*** **12 H.P. I'm impressed** they were that smart in **1903!**

 Paul MacCready used a 12' Prop on Gossamer Albatross.

Propeller Efficiency, eta, η, Overall Propulsion Efficiency, η_P

If you're either lucky or smart, you may have realized that **basic propeller efficiency** doesn't depend on the propeller, but rather on **Airplane Speed, V, and Engine RPM**, because **that's what controls Pitch!!!** You'll see **High Aspect Ratio helps**, a **bigger Diameter**, for a given blade area, **more $\dot{M}$, Mass Flow Rate,** and, of course, **BGT Logic and Math** to get **perfection, the last few percent.** But it's **Speed vs. RPM** that determines what ball park you're in, **85% max for a Luscombe, ~89% max for an RV 6**, is the **best possible, the BGT max**.

The Advance Ratio Graph Teaches us that.

Efficiency is really Traveling Efficiency.

It really helps people to teach them early that **Prop Efficiency, eta, η, is really Traveling Efficiency**, **Zero at runup**, roaring, shaking, **going no where**, **hurt in climb**, throwing back extra air, making extra thrust to **hoist the plane too**, going slower, **finally up to design efficiency at cruise**, if designed there, actually **better at Vmax, actually at a lower angle of attack, less ΔV, divided by a now bigger V_1**. Grasp it that way and you have **a pro's insight, just 6 pages** from the start of Book II.

Super Magic Graph, Ch. 2 II, will show how everything varies vs. Speed.

Overall Propulsion Efficiency

I never met him, but **I just love and respect Gus Raspet**, a **creative maverick**, I'm led to believe. He did propellerless glide tests, from a towed altitude, found normal drags, but terrible overall propulsive efficiency on light planes when compared to required H.P., only **58%** overall on a Bellanca Cruisair, **172% more H.P., vs. the Drag x V gliding H.P.!!!**

Gus had sealed the cooling ducts, taped leaks for min Aero Drag.

Zero Thrust Glide Testing my Luscombe we found only **67% η_P overall propulsive efficiency** with **cooling charged to the Airframe**, ***(~10%),*** at efficient altitude cruise, 85 IAS, 100 TAS, equivalent to the Bellanca. Presuming bad ***75% η prop**, that's an **89.33%** η_i interference efficiency to equal .67η_p. **More to come!**

Realize a .67 η_p *inverted*, demands 150% of Gliding Drag H.P.

 An RV 8 Prop Test, showed a poor prop could be 10% worse than a proper Prop!

Implications of Blade Angle Accuracy Requirements

McCauley uses **a shop tolerance of +/- .1** degree, yes **<u>One Tenth Degree</u>**, to ship **a consistent Prop Product**. I certainly would not expect that their old props, designed decades ago, before computers, were designed anywhere near that accuracy, but let me show you with **our usual technical horse sense** that **we need to predict the inflow to all our prop radii that close** to have props that agree with our computer calculations.

Nominally a 1 degree angle of attack change, changes the coefficient of lift .1, 1/10. Now, simple horse sense can tell us that **if we design a prop to .5 C_L, a 1° error, .1 C_L error** we have a **20% error in our calculation!!!!!** Thus, with a **+/- .1° shop tolerance McCauley would be shipping a +/- 2 % variation, quite good**, when you realize they've been **hand grinding and twist bending,** ***accurately tweaking*** **2025 Alloy fatigue resistant Aluminum forgings for over a half century.**

The **Goldstein-Theodorsen Kx Blade Loading Chart**, **(vs. radius and Advance Ratio)** printed to three decimal places, i.e., .xxx, is said to **be good to 1%**, actually therefore **twice as good as McCauley's shop tolerance**, just what you'd like to have from an analytical method. Actually, Ribner and Foster, University of Toronto, did **a modern computer analysis confirmation** in the 90's, generally found the basic loading chart was about **1%**, **excellent, when you fully understand the complexity here.**

The Wild Flow We're Analyzing Here ***<u>Grasp This One</u>*** ---- √

We're pulling in and throwing back a big Mass Flow Rate of air to make thrust, with **minimum ΔV**. It's **rotating too, much more at the steep inner blades.** The **<u>ΔV is not even close to uniform</u>** out along the radius, but with rotation, you'll see we form it into a **perfect helical <u>constant pitch inflow</u>, <u>constant Slip</u>,** which **<u>acts like uniform inflow</u>**, you'll learn, **stretched perfectly helical downwash, backwash, <u>the picture you can see on the cover</u>**. There's **radial flow feeding the tip vortex, out on the bottom of the blade, in on the top**, opposite, but there is **a root vortex too, radial flow opposite to the tip. With Heavy Loading, the ΔV at the prop is much bigger than avg.**

 ~1% accuracy with that complexity! You tell me how Smart BGT were. √

Elegant -- Theory, Logic, Mathematics -- ***Rare Genius Work***

Top Scientists use the word **Elegant** when they grasp the ***magnificent order and logic of Nature*** which is so often **simple**, while being **complex and sophisticated, all at once**. As you come to fully understand, let me suggest that you will see that, in total, **propeller theory is as elegantly simple and beautiful in its complexity as any logic you will ever find.**

The Genius of Betz, in 1919 taught us to **simply guide inflow into a *perfect screw surface*, a pure helical Archimedes Screw inflow of air to each blade**, then **throw back a still perfect stretched helix, downwash, backwash emanating from the blade trailing edge, as the second $\Delta V/2$ is added**, a good art form if you add **the vari-hued beauty of varnished wood** in a simple stack of ice cream sucker sticks, the model on the cover.

Archimedes died 212 B.C., and his screw is still pumping Irrigation Water in Egypt

Hiding in that **sophisticated constant pitch simplicity**, is a **"Constant Slip" at every Radius**, when **compared to Airplane Speed,** which acts like constant inflow speed at each radius, when axial inflow is ***not*** constant, a perfect blending of axial and rotational inflow, you'll learn, for **balanced inflow out along the radius, no added radial flow loss, the least induced loss!!!**

To create perfect, Constant Pitch, Helical Inflow, the Blade Shape, Twist must be Perfect

Appendix T-Q, proves a **constant dT/dQ**, a **constant ratio of Thrust vs. required TorQue, or H.P. at every radius, equal efficiency at every radius, no penalty for prop twist**, if first considered profile drag free, all provable with simple high school Algebra, Geometry, Trig. **Elegant Simplicity from gross Complexity**

It's all Topped off with an Elegant, *Rare Genius level* Math Solution!!!

It's all accomplished by **perfectly Shaping and Twisting**, ***thus*** **precisely controlling the radial distribution of Loading** to **deliver precise, pure helical inflow, stretched outflow** --- the **magnificent Goldstein-Theodorsen "Potential Flow" Math Solution *directing* each air molecule in the precise 3D direction to solve it all - even for heavy loading** where the ΔV **is much greater at the prop**, vs. the Stream Tube. ***Elegant!!!***

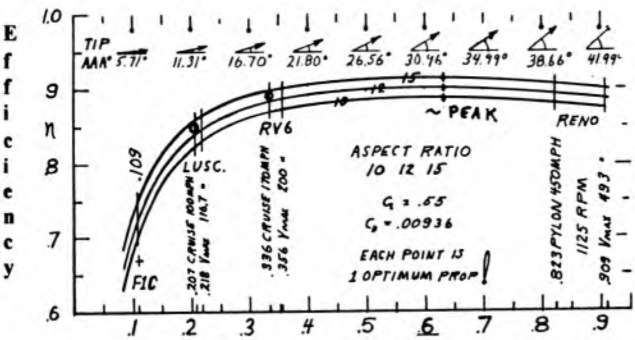
Elegant Simplicity - Pure Helical Inflow = Optimum Prop

Propellers were always impossible to explain, too many complex things happening, interplaying, a too complex technical morass, too much for engineers to get their head around, ridiculous for Civilians and Pilots. **The solution is to show people we have an essentially exact, *canned*, Elegant 3D math solution for Betz's Elegant perfect helical inflow and stretched outflow, easy, indeed beautiful to visualize.** Then **with people *not* snowed**, we went off to **teach everyone the 4 different ways of looking at props**, all the little individual things that are happening, **their logics, how they fit together, *superemphasize* so novices can really get all the hidden points, and pretty soon it can all start coming together for people who want to try, who never tried anything like this before.** Go for it ---

----

Let's take a simple, quick look at the famous **Advance Ratio Graph**, that shows low pitch, Low Advance props have poor efficiency, High Pitch, High Blade Angle, High Advance, High Efficiency. Simply, The **horizontal Axis is V / πnD**, as before, simply the **Actual Advance Angle of the Prop Tip at D**. The **vertical Axis plots Efficiency, (vs. tip Advance), angles shown.**

(The full coverage of Advance Ratio is on p. 48II, but more complete, is more complex.)



Tip Advance Angle vs. Efficiency η (optimum ~32°)

Actual Advance Ratio **J/π = V / πnd** (often called Lambda, λ)*

Next, let's look at an **actual Ideal Luscombe, and RV 6 Prop,** their **Ideal Shape and Loading, then on to a pro's explanation of props.**

 * Think of Tip AAA, Actual Advance Angle -- Shown on Graph, 32° optimum!

Really Understanding --- The Elegant Betz Propeller Logic

The **Betz Propeller** is **truly Elegant** in the **sophisticated, yet simple** way that it **ties together several subtle but hugely important features.** It's **hugely important, most important of all, that you *finally* understand this core of all the logic. This page will help you see where it's all going!!!!**

The **pure helical Inflow** is the **cornerstone of the logic**, simply because it is **Constant Pitch Inflow**, which results in **Constant Slip at every radius**, simply vs. the **Airplane Speed**. It's the **Constant Slip that acts like uniform inflow speed**. *Imagine **loading each radius uniformly, a balanced radial loading***, not causing unbalanced extra radial flow, **avoiding extra induced radial flow loss, (right at the heart of min. induced loss logic).**

We set this **Constant Pitch, Constant Slip inflow** up in the geometry we **teach you in Chapter 3-II, (p.94-II, 98-II)**, that you **first saw** in **Ch.9, p.128**. It results in the **blade shape**, which, with the constant C_L twist, results in the **ideal blade radial loading** you see on the **facing page**, produced by the **Elegant 3D potential flow BGT Math** solution. Now, **(in reverse order)** if you learn that the **Characteristic Betz SHAPE (tapered tip, root, *twist*)**, and thus **Ideal LOADING**, that pulls back the excess tip load, **(we learned a rotating wing needs)**, we **produce an Ideal Prop**. Constant pitch, constant Slip also produced **constant dT/dQ, a constant ratio of thrust vs. required Torque, equal efficiency at every radius** if first considered drag free. **(proven in Appendix T-Q), that cuts like a knife through all the complexity!!!**

Realize Radial Flow is Tip Vortex Flow, not shown in the Picture

When you finally grasp it all, and then finally grasp its elegance, you see **a pure helical Archimedes screw inflow to each blade, a constant Slip, (elegantly produced by the Trigonometric combining of axial and rotational inflow), acting just like constant axial inflow, minimizing radial tip vortex flow, minimizing induced loss, by preventing excess *radiial* induced loss - ideal shape, ideal blade loading (excess tip loading pulled back to a sustainable loading profile). (In addition to the facing page, see the ideal load distribution and shapes on p.147, the Betz page, p.129, the flow geometry taught on p. 94-II through 98-II.**

Look ahead to the grasp of the integrated logic you can end up with!

Betz's Rigid Vortex Sheet

<u>Shapes</u> and <u>Resulting Loading</u> of Constant C_L Betz Props

(These examples are *<u>not</u>* modified for Slowdown) ✓

Luscombe 1400# GW

73.8" Diamater vs. 71" normally

151.5# Thrust (140# T at new η_2 OK)

.55 C_L 1.612 degrees alpha

2280 RPM 48.15 H.P. Alt Cruise

100 MPH TAS 85 IAS

10,500 ft. Density Altitude

Ref Analysis 99.36 - 21-23 & 99.75 - 67,68

RV 6 1600# GW

70" Diameter, (or 72" is good)

164# Thrust, (156# T at η_2 OK)

.55 C_L 1.612 degrees alpha

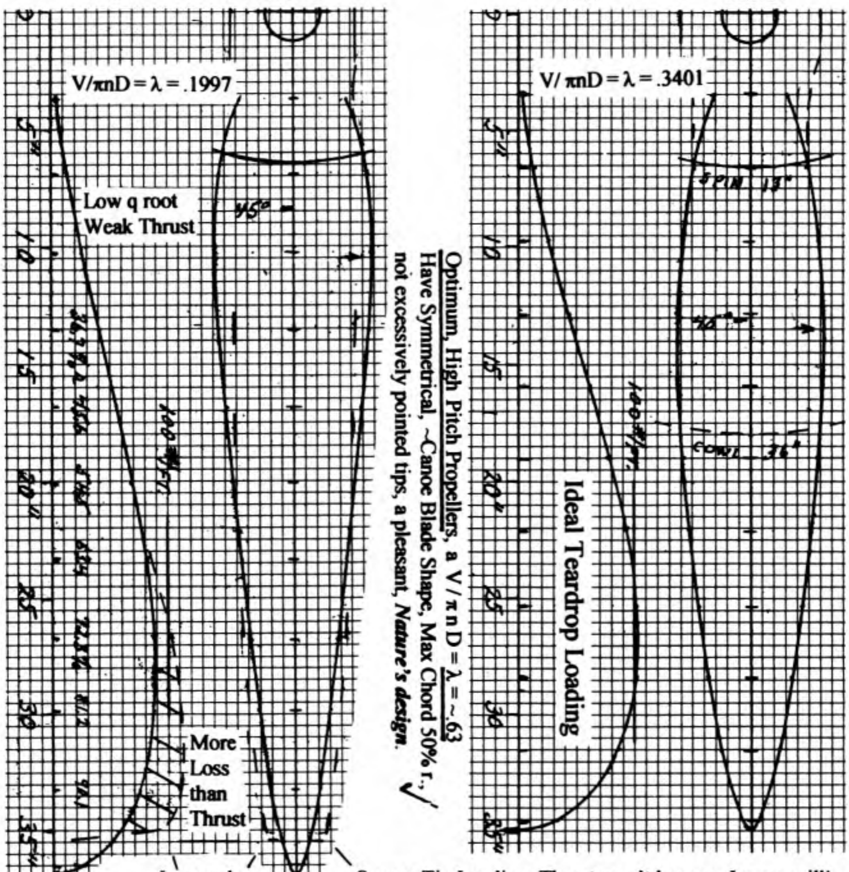
2400 RPM 82.9 H.P. Alt. Cruise

170 MPH TAS 140 IAS

12,500 ft. Density Altitude

Ref Analysis 99.36 - 24-26

Realize Betz SHAPE, thus LOADING vs. radius are shown here. ✓



Luscombe — Square Tip Loading, Thrust won't happen, Losses will! ✓

High Tip q, but Zero T# result *wants* Outer Chords Narrow for efficiency!!!

Ultimately Realize the Good and Bad of *half* Teardrop Radial Loading -- ✓

It's <u>Precise Betz SHAPE</u> and twist that gives <u>Ideal Loading vs. r.</u>, min Induced Drag Loss

Is a Betz Prop Really Better*? What Happens Off Speed?

Models and private planes prove **poorer props that load the engine fairly correctly will work, just not as good as they should**. Knowing that we want +/- .1° inflow accuracy control, and most props have only a wild guess for slowdown, flow field correction, shapes far from ideal, we have a world full of less than great props, ***but hidden by Arirplane V = Power³ Math.***

I'm not pushing fancy theory, or math. I'm after the Facts here, TRUTH!!!

Looking at the just better engineering horse sense of a properly shaped and loaded tapered tip, and a professionally designed prop with an intelligent correction for the flowfield, slowdown, I'd expect a proper prop to be 5, 7, maybe 10% better than what we have, not huge, but **now we can both understand it all correctly**, and **know we have the Optimum Classic Prop**. If a perfect Luscombe prop can be 85% efficient, a bad one only 75%,* 15%/25% loss, we've cut our prop loss to 60% of what it was, **166.66% better**, *a lot, but only* **.85/.75, 1.1333% more H.P. available**, *and* **Speed is** *only* **the cube root of Power --- 1.0426!!!**

Many props miss Chord and Blade Angle distribution badly, 5, 7, *10% off!!!

What we'll do is get rid of the poorly designed props, wildly varying C_L's, senseless chord and load distribution, flow field corrections far off, wildly varying vs. the +/- .1° inflow accuracy we should shoot for. **We can now understand the logic exactly and what we should shoot for, and we have the math to do it credibly, accurately**. ***We finally understand!!!***

Getting rid of Poor Props, finally knowing what we're doing is my objective.

Off Speed, fixed pitch, understand the angle of attack goes up as we slow down, finally way up at static runup, the **good high pitched props worse**, ***stalled a lot, most inboard***, ***but* helped by BIG slowdown correction**, *lower inboard angles, less twist*. Realize **fast, even at higher RPM *the angle of attack continues to decrease***, **α^0 goes to zero, finally zero average C_L's in a shallow dive, no thrust, back to zero efficiency**, But we ***do better starting from a known, a Classic Ideal, accurately designed prop, especially with big slowdown angle corrections!***

 Surprise - We're finding BGT Props are QUIET - Proof Positive of Losses Eliminated!

* A good RV 8 Prop Test showed a European Prop had *Twice the Loss*, ~80% η, not 90!!!

An Early Incisive Overall Evaluation of the Math Method

We're **purposely** trying to give you a **good, quick, insightful grasp of overall BGT Logic to start Book II** Propellers, so you **grasp early where it's all going**. We're purposely writing the text to quickly teach people that we **finally have a correct Logic to understand, and *essentially exact* math,** because all checks tell us the **Betz logic is correct**, indeed ***truly Elegant!***

We do also have ***essentially exact math***, a proper claim because it does address and solve the very, very complex **(3D), Heavily Loaded, High Advance Ratio Potential Flow Problem,** but we must now properly qualify that, not overclaim, because that is the fundamental no no in engineering **where credibility is everything, *absolutely* must be maintained.**

I've always thought of Theodorsen's basic core accuracy as close to 1%.

Theodorsen notes that **Goldstein solved the Potential Flow Problem**, but **strictly speaking** only for the **multiblade, thus lightly loaded, low advance ratio part of the problem. Theodorsen,** I believe, accurately **solves heavy loading** by treating the math **far back**, for a **higher Advance Ratio,** to account for the greater ΔV effect right at the blade, **and a slightly reduced effective Diameter, D_o.** Then Theodorsen notes that his (Kx Blade Loading Chart *(multi blade)*) work **depends on his (pre computer) very accurately done analog, voltage field Potential Flow simulation.**

Theodorsen's method makes Goldstein's basic chart directly, accurately usable!!!

With Computers now available **Ribner and Foster**, of the University of Toronto, checked Theodorsen's work, publishing in 1991, a **Cray X-MP/24. Their work was extensive**, adding **3 bladed props**, up to **12 blades**, checking not just the **basic Kx Circulation Blade Loading vs. Radius and Advance Ratios** but the **lesser efficiency and energy loss plots of associated variables** used by Goldstein -- and Theodorsen's extended work.

It would be as big a mistake to underrate the answers, as to think exact!!!

Ribner and Foster made **a few changes in the math details**, that they felt were appropriate and presented **many pages of carefully plotted data** in their **64 page report**, only providing 2 numerical chart checks of Goldstein's basic work, generally much **closer than 1%,** 3 local exceptions of 1.2 1.7 and 1.8%, along with a few charts of associated variables showing a few % errors in some less central numbers. The **graphs show excellent agreement and support of the core numbers**, **a digital comparison not possible** from the plots, **a hint of a bit heavier loading proper outboard** and **at very high Advance**. In all, **as close to *coveted* 1% basic core answers on such a complex problem as we could ever hope to have**. With modern Computer Power, **future checks can clearly refine the answers even more.** ?

Later work by Tibery and Wrench at David Taylor Model Basin confirms loading a t Lambdas, λ of ~.5 and below, but higher above, Applied Math Lab Rpt.1534, 1964.

 Now, we'll sum up, start going deeper, discussing more, in Book II

A Summary Overview

After you understand the basic logic of Propellers there is a **wealth of more incisive Insight Available**, going back in more depth, and **that is what we'll do in the rest of Book II.**

But first, a comprehensive ***Summary Statement*** can ***nail a lot***. The trick is to get **a grasp, "a feel" for how props really work.**

By now you should realize a prop is really two separate rotating wings 180° apart, in a stream tube that it activates, moving the whole tube backwards, pulling in a pure helical inflow sheet, a slightly reduced pressure in front, throwing back a stretched faster, pure helical downwash, backwash sheet, two Archimedes screws, one feeding and stretched from each blade, nominally half the speedup as inflow, half as outflow, two almost equal $\Delta V/2$'s. (Theodorsen's Math can divide that precisely.)

As two separate rotating wings, they each have both a root vortex, and a tip vortex, of course the root weak, the tip much stronger, relatively weak q, dynamic pressure at the root compared to an exceptionally stronger tip q, proportional to V^2, with the much higher rotational velocity at the tip, making a diagonal spiral path with the forward speed. **Intelligently managing the spiral velocity effects is the central key to intelligent prop design, *nailed below.***

But first, realize that a low pitch prop rotates an excessively long distance getting to the destination, very wasteful of profile, skin friction drag *energy consumption*, so easy to see, once you see it, high pitch props far more efficient vs. profile drag *cost*. But, also from what we've learned from Newton, a fast, High Pitch prop naturally has a big $\dot{M}$, and that allows a small ΔV for any required Thrust, minimizing the thrown air velocity, minimizing Induced loss too, high Pitch, hi P/D, high Advance per revolution, high Tip Advance Angle the key to efficiency!!!

But now, just like a Wing, where Induced loss drops as $1/V^2$, simply going fast is the easy way to get high Induced Efficiency, but on props $\Delta V/2V_1$ is the specific math, low $\Delta V/2$ allowed by a big $\dot{M}$, divided by a big fast V_1, two good effects!

It's still is a $1 / V^2$ effect, dropping fast, but acting indirectly through $\dot{M}$ and ΔV

But with Hi Pitch, Hi Advance, the key to both Profile and Induced loss reduction, Hi Efficiency, **Speed, V** becomes the most important factor in prop efficiency, but surprise, **low RPM** which allows High Pitch, Hi Advance, is almost as important!!!

Speed, V, and RPM set the max limit of your efficiency!

Now, having established that basic insight, it sets us up to show now that the use of Betz-Goldstein-Theodorsen Logic and Math is the Sophsticated Professional Classic "Master Stroke" to intelligent Propeller design, because with sophisticated radial Loading, through sophisticated SHAPING and Twisting, we make the Classic Ideal radial distribution of loading, don't create an extra radial flow over the mathematical minimum, minimize both root and tip Vortices, get the Classic mathematical minimum Induced loss from throwing air back to make thrust!!

The whole game there is simply recognizing that the Dumb prop trys to work **Inside Out, Dead Wrong, trys to make max thrust and drag** at the undammed, **ridiculously high q tip**, ***where thrust must fall to zero***, **manufacturing excess tip vortex loss, NOISE, WASTED ENERGY, high drag at max lever arm, bogging down the engine Torque, RPM and available H.P**. and **losing thrust it tried to make** there, *dumb as a stump.* In addition to proven performance tests, BGT props are **QUIET**, proof positive **the significently excess tip loss is gone!!!**

The final Coupe de Matre, Master stroke, is Theodorsen's Math accounts for **Heavy Loading**, the fact that Betz's stretched "Rigid, Vortex Sheet" is moving back through the stream tube faster than the stream tube average, actually nominally 2, 3, 8 times faster on a Luscombe, RV, a Reno Racer. **Theodorsen is the *only way* to get the Pitch, all the calcs precisely correct*!**

 Now, we're trying a More Elliptical Tip Loading, for a few % better!

But we've learned, and are going to learn much more -----

On a Sea Level Buzz Job, a 200 MPH RV 6 can make 280# of Thrust with only a 10 MPH full ΔV, only a 5% full ΔV, half that, 2 1/2%, for $\Delta V/2$, the axial efficiency loss. But surprisingly on a high pitch prop Theodorsen's magnificient math shows us the radial vortex loss can be a tad bigger, another 2 1/2%, 5% together, maybe 2% or so rotational loss, 7% total. That makes sense because an RV 6 Prop can be 89% efficient, an 11% loss. That would leave 4% for Profile Drag loss, and that makes sense because if a ,55 C_L is used the loss is 2/3 Induced, 1/3 Profile Drag, a .5 C_L prop roughly as shown here, Great Insight.

On a bigger .5 C_L prop a ~4% profile is more than 1/3, logical.

Long narrow, High Aspect Ratio Blades reach out farther, a bigger stream tube, a bigger $\dot{M}$, more efficient, less Induced loss, just like a long Sailplane Wing, but a long prop blade can be more vibration prone, a lowered natural frequency. We must temper our quest for efficiency, because a fatigue failed blade can rip the engine out, your plane uncontrollable, kill you!

***But*, a Luscombe Prop needs a 14:1 AR to *lower* a critical RPM below Cruise RPM!** √!

Page 146 and 147, may be the two most valuable, practical pages you'll ever see, because they show the **ideal teardrop loading**, unfixably weak at the root, low q, **max at 75% r to 80% r**, **a fast drop off to the tip**, ***not smart to try to get more tip loading*, *once you see that plot***, the ***perfect BGT SHAPES that generate that optimum loading***, highly tapered tips, tapered roots too on the very hi pitch, hi advance optimum props with those naturally graceful ~ Canoe shapes, the low pitch, advance props surprisingly triangular, the max chord at mid span on the optimum .63 λ, Lambda, prop, optimum 45° blades from root to tip on low to high pitch props, Reno racers near 45° tips, WOW!

The basic Sophisticated Game is just **be smart enough** to realize you need to ***taper the tips***, perfection proven by math, understandable by horse sense. ***Now let me show you how to sort out, make sense, understand the logic of all the variables:***

Understanding all the Variables in Prop Design for T# reqd:
* **Speed**, **RPM**, **Altitude Density**, ρ are usually set by the application, **3 items set by the Specification, 3 Spec Items**.
* **Aspect Ratio**, **Coefficient of Lift**, C_L, **Coef. of Drag**, C_D, are **3 Choice Items**. Physics really sets C_D, ***but it takes judgment vs. Rn.***

I purposely down play the Airfoil, bugged leading edges killing super foils.

Now, we really want to find **Diameter**, **Area** and **Shape**, but with the **extremely varied q vs. diameter**, those 3 very basic variables are ***interdependent, can't be separated***, but once **Aspect Ratio** is ***chosen***, **BGT math just scales them all up and down to perfectly meet the Thrust required,** ***SIMPLE!!***

Of course what **BGT math** does is get **SHAPE** and **Twist**, thus **LOADING, *precisely correct*** -- ***min. area precisely placed*** for a **Triple Ideal Prop**, if you're smart enough to use an ***Ideal*** C_L.

We learn how to set up the key Inflow Geometry in Chapter 3, Book II

We rough out prop design with an NACA 4412 airfoil, 12% thick, 4% mean camber chord line - ***then vary t %, but hold camber,* the easy way to vary thickness with minimal effect!**

How's that for making complexity easily understandable!?!

The core concept to understand, remember, **visualize** in your mind is the **great layout** of **p.131**, the **extreme magnification of tip q, a tapered blade that *counteracts* excess tip loading,** the **half teardrop blade loading - a mistake to try to load the tip more** because you'll **just waste energy, attempted thrust that will just roll off the tip, manufacturing extra Induced Loss, making** NOISE, **unrewarded drag at max. lever arm bogging down engine torque, RPM, H.P.,** not smart.

It's ***simple*** **TAPER the TIPS, *hope* Speed vs. RPM = Hi Pitch** ✓✓✓

And now for those who wish, we'll go deeper in the rest of Book II, get some really professional insights. Think of it as a Mystery Novel, not a difficult chore. Even if you miss a lot, you'll learn a ton of insight, and you can't strain your brain!!!!! ✓

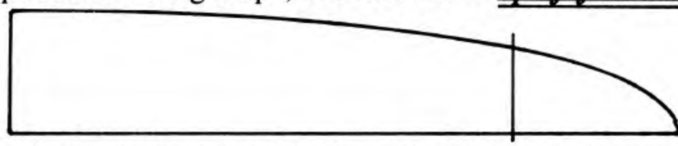
It's all available because two young WW II modelers, got a lifetime of pro experience!!!

So You Can't Possibly Fail to Understand - The Tapered Tip

It's almost funny, after going through all the complex math and gross complexities of propellers, decades where people argued prop shape was not important, to find that **<u>SHAPE, with correct *Twist*, is the Central Issue of Ideal Radial Loading of Ideal Props</u>, missed for a half Century**. In hindsight, it's as simple as seeing broad tips flunk Aero 101 horse sense, that we missed, were **blind to - the easiest key insight in Prop Logic!**

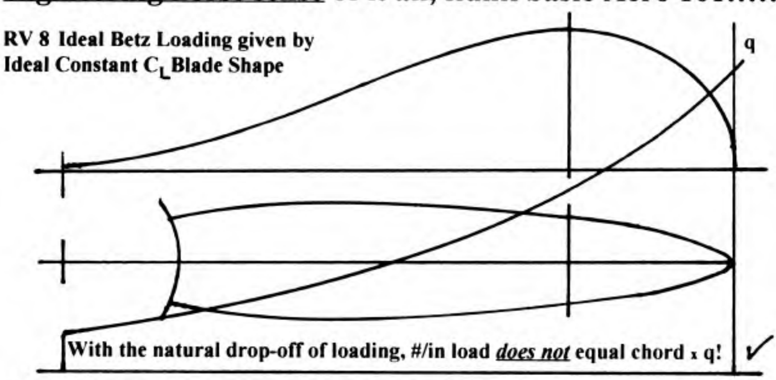
You simply <u>Can't Maintain High Loading at the Tip</u>, *<u>you create Extra Losses</u>!!!*

The **<u>Elliptical like drop off</u> of <u>Wing Lift</u>, at <u>constant q</u>**, fairly independent of wing shape, **DECREES --- *<u>tip lift fades to zero</u>!***



Even a Hershey Bar Rectangular Wing Drops off pretty much like this, no stopping it!

<u>The Tip Thrust Drop-off of Perfect Prop Thrust Distribution</u> vs. radius is <u>already Quite Severe</u>, due to a very, very excessive tip dynamic pressure. To not strongly counteract **q** with a fairly severely tapered tip, **to leave a tip wide, to try to get more tip Thrust in any way, is to <u>just manufacture unrewarded extra losses</u>, <u>completely miss the basic engineering horse sense</u> of it all, flunk basic Aero 101!!!!!**



An *<u>overloaded tip will simply dump the lift</u>*, <u>rolling off the tip</u>, thereby <u>manufacturing excess tip Vortex Loss</u>, NOISE, excess unrewarded profile drag, at max. lever arm, thus bog down the engine Torque, thus RPM, thus H.P., lose 4 ways!

 This is the Easiest, most fundamentally Important Insight in Prop Logic!!!

The Five, 800 pound Gorillas of Prop Logic

As you begin to get a feel for Prop Logic, you'll come to realize there are -- FIVE 800 Pound Gorillas -- that **control the results!**

1. Dynamic Pressure, q, proportional to V^2. The fact that the **Prop Tip** is going **so much faster than the root**, *especially on slow, high RPM planes*, and that **q is : V^2**, is the ***key fundamental*** that makes props, their theoretical ***constant C_L Shape***, and ***Ideal Lift-Thrust Distribution vs. Radius, different than wings***

This Key,Tapered Tips for Ultimate Props has gone Unrecognized for 50 Years! ✓✓✓

2. Diameter: is obviously ***hugely important***, because it controls the **size of the stream tube** and the **mass flow rate, $\dot{M}$**, (*also considering Speed*), the **lever arm of the blade drag**, especially when you learn it's **D^4** in the thrust coefficient, **D^5** in the power coefficient, but surprisingly **C_L**, the next Gorilla **can trump it.**

Stream Disk Area needs D^2, bigger D and V needs a second D^2 for Thrust & Drag

3. Lift Coefficient, C_L. Surprisingly, a **.6 C_L** shrinks the needed RV 6 prop **D**iameter to **69.1"**, a **.3 C_L** balloons the **needed D"** to **83.7"**, proving to be **an even more powerful basic than D!!!** A real surprise is that the **profile drag** on a **.55 C_L** prop grows from ~ **1/3** of the total loss to **62%** at **.3 C_L**, **~78% heavier: ~$(D_2/D_1)^3$!**

C_L actually controls the ratio of Profile Drag loss vs. Induced Loss!!! ✓✓

4. Speed, is Hugely Important because it **raises the $\dot{M}$, Mass Flow Rate**, reduces the **ΔV** **(required to make thrust),** ***twice*** **reduces the $\Delta V/2V_1$,** ***twice*** **reduces Iinduced Loss, rasies the Pitch** and **Advance Ratio**, thus lowers the corkscrew path length, the **profile energyy loss**, all **raising the Cap on Efficiency, eta, η.** **Speed** also **directly reduces the optimum Diameter.**

Speed and RPM Controls the Cap on Efficiency, BGT *gets that* Ultimate!!

5. RPM is much more important than realized, because with Speed, it **directly Controls Pitch**, **Advance Ratio**, thus directly controls the **Cap on Efficiency**, **(with Speed)**, and of course, the **Induced loss** and **Profile Drag corkscrew path**. Engines want high RPM for max H.P. vs. Weight, **a direct conflict** with **props that want High Pitch for Efficiency!!!** ***FIVE GORILLAS!!!*** ✓

 This is a Very Important, Valuable Page to Grasp Early!!! ✓

Symbols, Definitions, Clarifications

Realize Engineering calculations *in the English system* are *always* in consistent units - foot, pounds, seconds, - ft. # sec. (never in MPH, inches, RPM, HP) for the *very good reason* that the *units then all cancel out* to give *the correct units of the answer*, say rps, or #, and the correct numerical answer, if no wrong constants are used. Engineers check long calculation, to see if the answer comes out in the units they intend, ***to check that they set it up correctly*****, a hugely important double check. You'll see it's the dynamics calculations with Mass and g that get weird, (but as simple as possible below*), *or* skip it for now.**

Power is expressed in ft #/sec, 1 HP = 550 ft #/sec.

MPH x 22/15 = Ft/sec   Ft/sec x 15/22 = MPH.   Simple.   60 MPH = 88 Ft/sec.

~ The "similar sign" used to show where things are *not* exactly equal, say, a detail effect.

α^o alpha Greek a -- *Angle of attack* to airstream.

β^o beta, Greek b -- Propeller *blade angle(s)*.

κ kappa Greek k -- Cuts Theodorsen's w to avg. ΔV of stream tube.

γ^o gamma, Greek 3d letter -- Airfoil *drag to lift angle*.

Δ Delta, Greek Capital D -- Meaning *difference*, ie. ΔV.

ε epsilon Greek e -- Theodorsen's 3D losses for each axis.

ϕ^o phi Greek f -- Wind *inflow angle* vs. prop plane.

η eta Greek h -- Propeller *efficiency*, regarding energy, power.

ρ rho Greek r -- Mass density of air, .002377 slugs/ft^3 at S.L. (see M)

Σ Sigma Greek Capital S -- Meaning a summation, "summing up".

Ω Omega Greek w, Capital and lower case ω -- Rotational velocity in Radians per sec. $\Omega r = 2\pi rn$ -- both are ft./sec.

a Glauert's *ratio* of the *inflow velocity*, half the total ΔV, ΔV/2, to the airplane speed, or the *slowdown speed V_1*, thus $\Delta V/2V_1$.

a' Glauert's *ratio* of *half the prop caused stream tube rotation Speed at any radius*, $\Delta\pi$nd, to the *rotational velocity* πnd, thus **$\Delta\pi nd/2\pi nd$**

AR Aspect ratio, span/average chord, or span^2/area, for a wing, but here we use 90% of D, the hub not effective, later 80%, 19% to 99% D.

C_L The coefficient of lift, based on the the air inflow angle of attack α^o.

ΔV The *total axial velocity difference caused by the prop*, ie, ΔV/2 in, out

D, Propeller Diameter in *feet*. d = partial diameter. (~ Radius R, r).

g *Acceleration of gravity, 32.174 ft per sec, per sec*, ie., ft/sec^2.

J *Advance ratio* of propeller = V/ nD. (Forward velocity vs. rotation).

J_π J/π, often called Lambda, λ. With V vs. πnd, the more easily grasped rotation *velocity*, actual *prop tip* advance angle, or ratio, AAA°, AAR

Easy: V is the forward velocity, πnD the circumferential velocity of the tip, Tan AAA = V/πnD.

Kinematic Viscosity, ν, nu, is .0001576 @ S.L. .0002015 at 10,000 ft.

Lift, L = C_L Area ($\rho V^2/2$) pounds. Similar, Drag, D = C_D Area ($\rho V^2/2$)

M Mass, in slugs, which is weight / g, # / g, # / ft per sec², = #sec² / ft, !!!
Newton's Dynamics calculations need weird units, slugs to get correct numerical answers --- and come out in pounds, a smaller number of more massive units. SEE NEWTON BELOW!

$\dot{M}$ Mass flow *rate* in slugs / sec, which is # *per sec* divided by g, the acceleration of gravity 32.174 ft/ sec² which comes out # sec/ft, which seems weird, except that makes $\dot{M}\Delta V$ come out in pounds, T#! Dynamics calcs using Mass, Mass flow rate $\dot{M}$ and g are weird until you catch on. *Ignore all that engineering complexity if you wish.*

$\dot{m}$ The natural mass flow *rate* through the prop's disk area from the plane's speed, no speedup from the prop -- no prop there.

n Revolutions per second, rps. = RPM/60.

\# The pound symbol used for both force and weight.

P Propeller *Pitch, (no slip), in feet* for calculations, P/D OK in inches.

q Dynamic Presseue, $\rho V^2/2$, #/ft², 25.565 psf, 100 MPH, S.L. ~ .1776 psi.

Rn Reynolds Number = Vc/ν = Velocity x Chord / Kinematic Viscosity.

V Velocity in ft./sec. V_0 is plane speed = V_1, *if no slow down*.

V_1 Plane air speed V_0, but slowed by the body pushing air ahead.

V_2 Velocity *at the prop disk*, after the *first* prop $\Delta V/2$ speed up.

V_3 Velocity far back, after the *second* prop $\Delta V/2$ speed up.

V_4 Final Velocity farther back, from the initial slowdown pressure, p_1.

ΔV The *full speedup* caused by the prop, = 2 times $\Delta V/2$

W Wind *inflow velocity* to prop blade, (at angle ϕ to the plane of rotation of the propeller. See the prop geometry sketch).

w Total Displacement Velocity: Theodorsen's heavily loaded flow total ΔV, much greater right at the prop. w/2 sets the constant pitch inflow angles ϕ, that all radii of a prop blade must maintain due to the inflow, rotation, the pitch angle geometry, that sets ideal, minimum energy loss props for Betz's loading. See geometry sketch, Ch. 2. $\overline{w} = w/V_1$ See κ

*Newton's 2d Law *for solids*, F = Ma, is the equivalent of F = Wt. (a/g) That is amazingly simple once you see it, Force = Wt. times *the ratio* of the acceleration, to the acceleration of gravity. *The force is a simple proportion to the two accelerations*, but it complicates the units by using W/g = M, makes a simply thing seem hard, confusing units to all, at first.

T = $\dot{M}\Delta V$ the *fluid flow* version of Newton's Second Law. Simply, the *"per second"* is removed from the "a", in the acceleration of Newton's F = Ma for the *reaction force* for *throwing solids*, and applied to the M, making $\dot{M}$, a flow rate per sec. the formula now $\dot{M}\ \Delta V$. (a becomes ΔV)
Velocity V and ΔV are ft./sec. Acceleration, a, is change in velocity per sec, ft./sec.²

Downwash - Backwash. In addition to creating a pressure difference lift, wings make equivalent lift from the reaction force to throwing air down, the downwash, comparable to props throwing air back, backwash, their full ΔV to make Thrust.

Getting Fully Comfortable, Deeper Into Newton Basics
A Special Lead in to Chapter 2 II -- Nailing Newton Insights.
Pros, *as below, Cherry Pick this*, set up to help Novices Really Get Newton!
Novices seem to have the most trouble with Newton, so we go slow, show it all!

PROP LOGIC is BASICALLY THIS EASY!!!

Prop Horse Sense Logic - is really pretty easy once you catch on. You simply ***need adequately tapered tips*** to **stop excess q**, **dynamic pressure, from forcing excess tip lift, dumping that excess lift off the tip, causing excess tip Vortex induced loss, noise, unrewarded profile drag out there at max. lever arm,** ***torque dragging down the engine RPM***, thus **H.P. - actually just properly SHAPED, TWISTED, PITCHED vs. radius, *thus IDEALLY LOADED (vs. r), a Triple Ideal Prop*, min. Induced, min. Profile drag loss, *Min.Area Precisely Placed, min Torque.***

Next, Look at it as an Airscrew

You want **High enough Speed**, **Low enough RPM** to get **High Pitch, High Advance, because that's what sets your Limit on Max Possible Efficiency, Caps It. Then the computer, Betz, Goldstein, Theodorsen can give you an essentially perfect Triple Ideal Detail Design -- right up to that Cap on eta, η!**

You must **think of a Prop as an AIRSCREW**, wanting **High Pitch, High Advance. Obviously, a steep, high pitch prop travels a much shorter, less wasteful profile drag energy consuming path to the destination. But a little surprisingly, it's Newton's flat Actuator Disk concept that teaches us we want a fast, Big V, (or big Diameter) Big $\dot{M}$, *thus* Low ΔV, twice lower $\Delta V/2V_1$, *(if fast)*. That shows us why a *FAST*, High Pitch Airscrew prop has min. axial *(and total 3D)* Induced loss too!!!**

Now we Look at it as Newton's Laws

As we begin to go deeper, you want to clearly, easily grasp Newton, $T = \dot{M}\Delta V$, and $\Delta V/2V_1$, hopefully be *facile* in your grasp of all the basics. But since those look like formulas, math, they scare many beginners! -- We're going to do a deeper lead in to Chapter 2 II, help beginners get better insight on the Stream Tube, *not* be afraid of Newton's math.

This Page is GOOD -- GET IT!!!

YOU may want to Read or Skip this Special Lead in to Ch. II-2.

It was originally intended to Help Novices Having Trouble with Newton's little Formulas: $T = \dot{M}\,\Delta V$ and $\Delta V / 2\,V_1$ --

We say it different ways, repeat, go deeper to help Novices.

The Formulas are not hard once you catch on, but can look hard if you tend to be afraid of Math, even a little formula, never tried one before, and need more time and some extra help.

But going deeper, it can look TRICKY, Pros may want to read it

Novices may want to Skip it --- You Choose!!!!

If you grasp Newton well enough, just go to 38 II and 39 II.

BUT:

Everyone should read p. 30 II, and 31 II, Really Important Insights on Stream Tube Specifics:

My biggest challenge, it seems, is to ***not*** have $T = \dot{M}\,\Delta V$ fake out, stop, and drive away technical beginners, too many Pilots, scared stiff of even a simple math formula --- so I go as light as possible at first. There is more to be learned about $\mathbf{T = \dot{M}\,\Delta V}$ and $\mathbf{\Delta V/2V_1}$ so after going as light as possible at first, now we'll ***go a little deeper***, get a pro's insight with minimum brain strain.

We *learn more insight about the stream tube, looking closer.*

Getting Props down to our 4 Insight Logic, is **good for pro engineers too** - but too often they think this must be light weight if I'm not immediately into explaining Theodorsen's Math. The fact is, ***we have the key logic insight here, that was not grasped for a half century***, that **a novice or pro BOTH NEED**. *The broader thinking pro can understand* that if he just accepts **a format that helps more novices get it**, he can learn all the great insights, many of which have been missed for a half century, ***only one* precisely triple ideal prop out there *now***.

Smart Guys, *be willing* to help the novices trying to get all this ---

Novices get scared of *EASY* math, like $T = \dot{M}\,\Delta V$ and $\Delta V/2V_1$ don't see it's **pretty easy**, once you catch on, but they certainly **don't see it that way, especially at first!!!** So, **relax,** here in this lead in. I'm **purposely going to be repetitive** enough to **give new guys, novices, *extra time and help to catch up, catch on!* *Realize*, we're dealing with a very diverse audience here!!!!**

Amateur or Pro, if you just go through this, **let us lead you**, in an hour or so, **in a day**, you can know important insights about designing an essentially exactly correct, and slowdown corrected **Betz-Goldstein-Theodorsen** propeller, insight not really correctly, fully understood in the past. We have yet to have a perfectly shaped and loaded propeller from the propeller industry that really, accurately and completely understands **B-G-T logic and math**, and gets **a Triple Ideal, Minimum Induced, Min. Profile, Min. Torque ~Perfect Propeller.**

The **Whirlwind 200 RV prop** for Van's RV 8, designed with **Jim Rust, the founder of Whirlwind**, is that **first** somewhat historic, benchmark **Triple Ideal Prop**, that understood **all the math, all its implications**, *the full logic of everything*. No, we're not bragging, don't have a distorted ego problem, we just put in the long hard work, after **a 55 year gap** to finally nail prop logic and math. We did it the "old fashioned way", we earned it with long, hard, comprehensive work, **the hero, Dr. Andy Bauer**, who **comprehensively finished the problem after 138 years**.

Now, to help struggling Novices, we'll use the same format, repeat, but **go deeper, and then broader**, **keep on summing up**, **bringing together**, so if you miss something you can still end up knowing how things come out, a quite sophisticated final grasp. Pros, intelligently skim, cherry pick, as you must be doing. From **p.147 I**, you all know what the perfect props look like, their loading, the core keys. ***So Go for the whole grasp!***

Since I've learned that it does take at least a day for most of us mortals to grasp a whole new set of prop logics, I do very purposely repeat, say it different ways, always tie together, sum up, because I found the smarter guys can get more facile, the less gifted guys can actually get it if we talk about it for a day!!!! A day is not too long to solve a 140 year void. I'd like to see you end up with an easy grasp of these basics. Then you'll more easily gain a grasp of all the pro insights.

Newton, and the "**Rankine-Froude Actuator Disk**".

Looking Deeper, we want Novices and Pros to have a solid grasp of basic prop logic. Newton holds the incisive insights.

Novices - we lead you deeper - we repeat - it's Important. You *Can* Get It.

The **Basic Logic of Props, can be Tricky**, but it's actually quite **helpful and insightful**, and **Newton makes it easy enough!!!** This is **so basic and helpful, important** to understanding the **basic horse sense of props**, that I want to **say it concisely**, but **helpfully enough** that you **really get it --- make it your own!!!**

Yes, I repeat, but I'm taking Novices Deeper, so you can finally get it all.

A prop is **a *Rotating wing Airscrew*,** is computer calculated using amazing math, but it can also be seen as **simply pulling in and throwing back air that is far heavier than you'd think**, and the **simple little formula for Newton's 2nd Law makes it a real opportunity to grasp the basic horse sense logic of props**.

The Key Insight is Very Simple!!! The Detail Insights get Trickier!!!

If you try to throw a Medicine Ball, **a heavy blob** of sand in an oversize basketball, you find **you can't throw it very fast**, and it **pushes back on you hard**, just as hard as you try to throw it, **Newton's famous 3d Law** --- **Equal and Opposite Reaction**.

Of course we want a BIG $\dot{M}$, a SMALL ΔV ---

The **Fluid Flow version of Newton's 2nd Law**, **$T = \dot{M}\Delta V$**, is **Thrust in Pounds** = **Mass flow rate, $\dot{M}$, M dot,** *times* **ΔV, delta V, in ft/sec.**, (*not* MPH). Now, in case you're not a math guy, don't let that simple little formula fake you out. ***It's this simple:* The thrust simply depends on how big the Mass flow rate is, and how much you speed it up,** *easy, simple multiplication!*

M and $\dot{M}$, are ODD UNITS, Slugs and Slugs/sec. See DEFINITIONS p.21-II

The reason that is **Big Time Important**, is that the **mass flow rate is far heavier than you'd ever guess**, and the **ΔV, delta V speedup needed is much lower than you'd ever guess** --- and **thus you can quickly get a whole different feel for prop thrust than you'd ever figure out for yourself**. You'll soon see an **RV6 at Vmax can make a 280# Thrust**, only throwing back a **10 MPH ΔV average wind**, because it has **614.5#/sec. of air flowing through its disk,** *like* ***1 1/4 cubic feet of steel/sec!!***

A **Reno Racer at 480 MPH** has ***4 1/4 Tons of air per second***, 8500 #/sec, may ***only*** make a **7 MPH average ΔV wind**, numbers *no one would guess anywhere near correctly*, **big time insight!**

WOW!!! Even Engineers are Blown Away by Those Amazing Numbers!!!

That's known as the **Rankine-Froude Actuator Disk**. Rankine the famous Scottish Scientist-Engineer who first figured out **the correct Steam Engine Thermodynamic Cycle was doing the first rudimentary water prop calculations by 1865**, Froude a famous Hydrodynamicist, (the Froude Number) had it named by 1889.

$\dot{M}$ is Explained More at the top of p. 21 II

The **actuator disk concept can teach us several important insights, below**, so it's **absolutely basic to understanding the horse sense logic of props**. (There are *oversimplification*s that make it **inadequate for real prop design calculations**. It **assumes a constant axial ΔV**, as the term Actuator Disk implies) You'll learn in the Flow Geometry of Ch. 3 II that the axial ΔV varies a lot from blade root to tip, and with heavy loading the helical vortex sheet actually moves back 2, 3, 8 times faster than the average ΔV of the stream tube, but **the simple concept can teach us a ton of insight, so we want to grab that insight**.

With a small pressure reduction in front of the prop, and a small pressure increase behind the prop, nominally **half the ΔV, ΔV/2 happens as inflow**, *half as outflow*. **Now the prop is logically designed and pitched to account for *only the ΔV/2 inflow!!!***

Next, it **pulls in air**, *speeds it up*, **from a larger diameter** than its disk --- and that **increases the *natural* $\dot{m}$, mass flow a little bit** to $\dot{M}$. Per Bernoulli, ***the stream tube shrinks again*** as it speeds up, the second ΔV/2 behind the disk, but that ***does not*** **increase the mass flow rate again, *because* it's still the same tube flow rate that came from the larger diameter in front of the prop!** At cruise that's a ***small*** increase, *more in climb*, big at runup.

Natural $\dot{m}$ is the Heavy Flow Rate thru the Prop Disk, *no prop there*, from Plane Speed.

Now what you're learning **here, and next**, is **Hugely Important, fundamental**, so I want you to **read this all very carefully, take time and really get it, because props are licked *if you do***.

A Little Fair Warning - I Drag you Screaming to Success

Novice or Lifetime Pro, I've learned it **takes a day of talking, or reading** to **really catch on to the real technical horse sense** of props. Surprisingly, pros sometimes catch on slower, a head full of **preconceived** *(wrong)* **ideas, fighting** the "easy enough" **real truth**. But **a day is a hell of a bargain**, compared to a lifetime! The missing insight is: it's **Shape** *vs. Twist*, that **loads it correctly**.

I give you BOTH this Narative, and Very Dense, Concise Summations!!!

Novice or pro, people just don't grasp what they don't expect, the first time they see or hear it, so my approach is to be constantly **repeating, building and expanding the basic story, so by the time I'm done, even the guys who didn't get it at first, have caught on and are working on the more insightful expansion.**

What's happening is that we have a **fantastic modern computer**, and **rare genius level math** that took the smartest, **rare geniuses** that ever came along, **83 years to finally get it right**, a gift from heaven far **beyond the capability of all mere mortal engineers**, that **you *don't* have to learn**. **We simply show you the engineering horse sense**, that is essentially **directing the math**, and in turn is directed by the math, the **insight that's been missing for 138 years**, the product of 10 years of lifetime experienced digging, checking, decoding, ***a gift!***

You earn your right to use that gift in this **unusual introduction** to this Chapter 2 II. I must warn you that it's going to **seem Ridiculous, repetitive to most of the audience**, for sure the pros, and the less smart guys, who care less than the eager guys, **but there is good reason, slower, eager guys get it!**

Dense Summations - Longer Narative - Read this the way it works for You!!!

Were going to dig deeper, all the way, to see all that $\mathbf{T = \dot{M}\,\Delta V}$ and $\mathbf{\Delta V/2\ V_1}$ can teach us, **professional depth insight on those**, but we're going to be doing it **in a way to help**, and drag along, where necessary, new guys who are struggling, ***repeating, going deeper, broader***. Your job, **don't bitch, just get it, *pro insight!***

Now there is **this simple little fraction**, that **looks complex, but is not hard at all,** $\Delta V/2$ **vs.** V_1, $\Delta V/2V_1$ **in math form.** That and $T = \dot{M}\,\Delta V$ are the ***only*** **two little formulas we'll ask you to grasp** to **understand *all* of propeller logic, *not a sweat!***

That V_1 is just plane speed, (or thinking of a case with a ***slowdown profile***, we could think of it as the slowed speeds coming at the prop), so that little fraction that might look complex to you is simply the **ratio of half the full ΔV, $\Delta V/2$ vs. V_1 the air speeds. EASY!!!**
Now **in our RV example above,** it's simply 10 MPH/2 vs. 200, **2 1/2%, .025**

A prop also pulls in air from a larger diameter, increasing Mass flow Rate, $\dot{m}$ to $\dot{M}$.

Now that is of Huge Importance, because we can use it twice:

- It's the **Fraction, Decimal or Percent that the *natural mass flow rate* (thru the prop disk), $\dot{m}$, (*mostly from the plane's speed*), gets increased to get $\dot{M}$, from a bigger diameter, (increased just a little, 2 1/2%)!**
- **It's also the nominal *axial* energy or efficiency loss, 2 1/2 %** which is the **axial, *in and out* component of induced loss.**

We learn the logic from *axial*, BGT Math nails radial, rotational too, all 3d Losses.

The Insightful Logic that comes out of $T = \dot{M}\,\Delta V$ math is:

You want a BIG $\dot{m}$ and $\dot{M}$, a SMALL ΔV --- for Efficiency --- ✓

- **Fast, high pitch props are efficient, slow, low pitch props can't be efficient, (they create high Induced Loss, *and* Profile too*).**

*** A Long Shallow Helical Path Wastes Profile Drag Energy Traveling Too Far.**

- **Plane Speed, and Engine RPM, set and cap the limit on a prop's efficiency** - as shown on the classic **Advance Ratio Curve** p.48 II!

Realize High RPM Lowers Pitch --- BAD!!! ✓

- **The Prop Blade is *Not* in Control of its Own Efficiency:**

--- ***Only*** **able to help itself with a high Aspect Ratio Blade.**
--- ***Only*** **able to match the Max Ideal Efficiency Cap with Betz-Theodorsen Ideal design!! The eta, η, on the Advance Ratio Graph!!**

- **Max Efficiency, Min. Induced Loss, achieved by Hi Speed, Big $\dot{M}$, Low ΔV Wind, Low $\Delta V/2V_1$,** per **Newton's 2nd Law.**

We gain Huge Insight from grasping $T = \dot{M}\,\Delta V$, and $\Delta V/2\,V_1$.

$\dot{M}$ is slugs/sec, ***simply $\dot{W}$ #/sec divided by the Acceleration of Gravity*, g, 32.174 ft./sec. per second,** **$\dot{M}$ a smaller number of bigger units of Mass.**
$\dot{M}$ Slugs/sec. *Flow Rate* Gives answer in pounds, and not 32.174 x too high!!

IMPORTANT!!! If you have to read the last page 5 TIMES to REALLY GET IT, I want you to do it - ***because*** **Newton's whole basic horse sense logic of props is there as concisely and completely as I know how to say it. If you get that page, you have Newton's basic prop logic licked!** ***Read on*****.**

In Ch. 2II you'll learn a ton more about props, The **Super Magic Graph**, that shows *how everything changes As Speed Changes*, The **Advance Ratio Graph**, *the classic basis of prop efficiency*, The **Magic Graph** that shows *efficiency vs. P/D ratio vs. Speed*, ***All*** **in Chapter 2II.** The fancy **ideal helical flow is in Ch. 3II, design Studies, much more**, but ***if you really get the last key insight page, you have the Basic Logic of Props Conquered!***

Now, Going at the Speed of Explanation for New Guys

We very Purposely led into this Nitty Gritty Chapter for very good Reasons: We don't want to lose Novices or Pros.
1. Moving concisely, covering **a lot of ground fast** can quickly **give everyone, (including non technical Pilots), a quick overview!**
2. Moving too slow would badly frustrate pros, engineers, more advanced amateurs seeking the real facts, Prop Truths.

We certainly don't want to loose the advanced audience, because this is **the first time there has been a comprehensive, yet understandable explanation of prop Logic**. We want it to be **possible for everyone to quickly get a true grasp of how props work**, ***even great for pros who can then tackle the Math***.

But this Book is First and Foremost for Pilots, generally **new to taking a serious look at the engineering secrets**, especially a wild case like props, with **a TON of content for a civilian**!

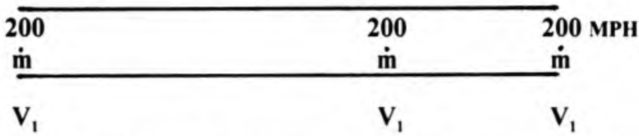
In the rest of this Introduction and in the Chapters we're going to purposely go slow enough, repeat enough, say the same things in different ways to give the new guys who will be struggling more time to catch up, catch on. To help them, the central audience, ***I expect the pros to astutely cherry pick!!***

A NOMINAL RV 6 PROPELLER STREAM TUBE

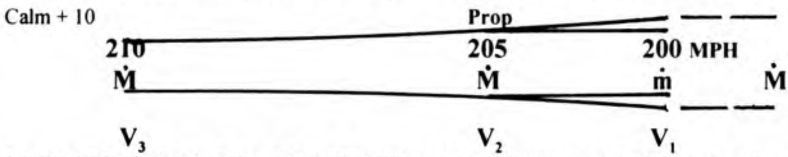
Simple case, no slow down of the air from the body pushing a bubble of air ahead

Propellers make thrust by pulling in and throwing back a stream tube of air passing through the prop disk area. **$T = \dot{M} \Delta V$ #**

There is a **heavy mass flow rate**, **$\dot{m}$**, ***fed to the prop disk area***, ***just from the plane's speed***, without the prop even being there.



A prop airfoil makes a lower pressure in front, a slight pressure behind, thus when it's working, making a Δ**V**, making thrust, half the ΔV, $\Delta V/2$, happens as ***inflow***, from *a slightly larger diameter*, then $\Delta V/2$ again, as a faster ***outflow***, the *stream tube shrinking* a bit more per Bernouli, and at the final full ΔV that makes thrust.



Leaves a 10 MPH ΔV wind behind. 5 MPH Average is a loss to turbulence, back to calm.

The **$\dot{m}$** is increased only a small percentage to **$\dot{M}$** in cruise. **A big $\dot{m}$, or $\dot{M}$, is hard to throw fast, but that's good, because half the ΔV, ΔV/2 becomes a loss settling back to calm**, and only a **surprisingly small ΔV is needed to make thrust at cruise**, with a **big $\dot{M}$**. It's ***axial* loss ratio is $\Delta V/2V_1$** in math form.

We **calculate $\dot{M}$ at the prop disk** where **only half of ΔV, ΔV/2 has happened**, ***pulled in from a larger diameter***. The ***$\dot{M}$ does not increase downstream***, the second **ΔV/2** diameter shrinking!

Why? Pressure drops, the tube shrinks as it speeds up --- per Bernouli --- just like pressure drops over an airfoil!

$\dot{M}$, slugs/sec, can be calculated as simply the area of the prop disk, in square feet *times* the proper axial ($V + \Delta V/2$) velocity at that point, in ft/sec, to get cubic feet/sec --- then multiplying by rho, ρ, the mass density we taught you early in the book, .002377 slugs / cubic ft at sea level. Mass is a pain when you first learn it, but it ***gets the correct answer***. (The nominal air density is .076 #/cubic foot, simply $\rho \times g$, .002377 x 32.174 = .076477 using exact standard numbers.)

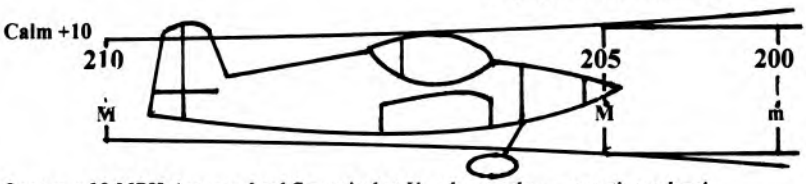
You can check yourself -- a full calculation of thrust is on page 31 II, *next*.

A Picture with Actual Numbers

Simple Case -- No Slowdown

In the graduate course we'll show you stream tubes with slowdown --- Recognize the prop flys through *calm air* and *leaves only ΔV behind!!!*

70" prop / 12"/ft = 5.833 ft.



Leaves a 10 MPH Average backflow wind at V_3 above calm — creating a loss!

	V_3		V_2	V_1
MPH	200 + ΔV (Far Back)		200 + ΔV/2	200
MPH	**210**		**205**	**200**
Ft/sec	308	(MPH x 22/15 = Ft/sec)	**300.66**	293.33

Thrust Calculation with No Slowdown for Simplicity

(At the Prop Disk)

$\dot{M}$ = V_2 ft/sec x Disk Area ft^2 = ft^3/sec, x (Mass Density ρ Slugs/ft^3) = (Slugs /sec)

$\dot{M}$ = **300.66** x $(70/12)^2 \pi/4$ = 8035.4 x (.002377) = (**19.1***)

ΔV = 10 MPH x 22/15 = **14.66 ft/sec** x 14.66

Thrust = = **280.1#**

*** Note that 19.1 slugs/sec x g, 32.174 ft/sec^2 = 614.5 #/sec!!!**

ρ, mass density at sea level, .002377 x g, 32.174 = .07647 #/ft^3, air density at Sea Level.

Sure, most pilots are afraid of tackling Physics, even a simple little basic Physics formula, T = $\dot{M}$ ΔV. (It *is* confused by the $\dot{M}$ in slugs/sec, *divisions by two* on the $\dot{m}$ to $\dot{M}$ increase, and the energy and efficiency loss). Forget that *if it gets above you*. Just grasp the T = $\dot{M}$ ΔV, get the horse sense of it, that big speed gets big $\dot{M}$, small ΔV, small loss, good efficiency!!!

High Speed = Higher Pitch, Big $\dot{M}$, low ΔV, Low Loss, High Efficiency!!!

Soon, we do the Basic Chapter 2 II on props, actually easier, and there is a wealth of valuable easier insight. And in this basic chapter, we show *great conclusions that go way beyond the technical difficulty of the chapter*, so you have *a great chance to learn more than you earn*. I hope you can get it, because it *can give you great insight, finally, now in print!*

***If you can grasp what's here, let it soak in, you're apt to find you can get all of the graduate course!* This *Intro* is hardest!**

Summing Up NEWTON'S KEYS TO PROP LOGIC

Solidifying your Basic Grasp of Newton

Here's how to understand the key basic, **$T = \dot{M}\,\Delta V$**, ***completely***. **Thrust in pounds = Mass Flow Rate, $\dot{M}$, (M dot) times ΔV,** Delta V, in ft/sec., not MPH. $\Delta V/2V_1$, increases the ***natural*** *mass flow rate $\dot{m}$*, through the prop disk, a small % to $\dot{M}$. (Air pulled in from ***a bigger D***).

Imagine we can fly fast with the prop removed!!!!

1. *Without the prop even there*, there is a big, surprisingly ***heavy natural mass flow rate*** we'll call $\dot{m}$, (m dot) through the ***prop disk area***, ***before the speedup***, just ***from the plane's speed.*** **That's important.** It gives the prop **a *big* mass flow rate $\dot{m}$, to throw!**

2. The easiest, minimum math way to see how a prop *Thrusts* is to recognize that it **pulls in and throws back *an already heavy* "mass flow rate" of air! - Fast planes have a big advantage!**

3. Now, that's very important, because you can see from that simple formula that if you have a **big $\dot{m}$**, and final **$\dot{M}$**, you only need **a *small* ΔV for a given thrust!!!!** That's very important - ***ΔV creates an extra wind loss - but only $\Delta V/2$ counts as a loss!***

Why? It's the average speedup, $\Delta V/2$, that sets the distance traveled and energy loss!!!

4. Now, it turns out that the **increase from $\dot{m}$ to $\dot{M}$ is small,** ($\Delta V/2V_1$), because the **ΔV** is small. The big thrust comes from **a small ΔV *times* a big $\dot{m}$ and final $\dot{M}$.** It is ***not*** the small increase from $\dot{m}$ to $\dot{M}$ that makes the big Thrust, **but rather the multiplication of a big $\dot{m}$ increased just a little to $\dot{M}$, *times* a rather small ΔV. $T = \dot{M}\Delta V$. Get that and you're home free!!**

5. Now, **mass flow rate $\dot{M}$** is **like** Pounds flow rate per sec. **$\dot{W}$**, **except $\dot{W}$ is divided by g,** the *acceleration* of gravity, 32.174 ft. per sec. per sec., (ft./sec^2), thus **a smaller number of bigger units of mass, slugs, and here slugs/sec.** since it's a flow rate. That little drill makes the Thrust answer come out in **pounds,** and numerically correct, not 32 times too big. **Mass** is a pain -- **but it gets the correct answer!** (Why? See M & $\dot{M}$ in the Ch 1 II definition list)

Go ahead, be brave --- Read this key page again --- Get it!

GET ALL THAT *early*, AND YOU'VE ALREADY WON -

A Little Review Narative with Overall Insight

Props, full of Surprises – *different logic, insights* than you expected!

The **few, key, great, classic books and papers on propeller theory**, are **all heavily into getting the complex mathematical analysis correct**, a few basic characteristic graphs and formulas for key coefficients, but **what has been missing is - *an incisive clarification of what all the math means, an understandable, technically correct, comprehensively complete, logic structure in words*, *not impenetrable math!*** **That is our core objective!**

A propeller is *stuck with* overcoming *the drag of the plane* in all its different flight modes. *Flying at the speed of the plane*, the *RPM of the engine*, *a fixed pitch prop is at excess angles of attack at slow speeds*. There can be ***a major efficiency loss, over and above the prop efficiency loss, particularally on slow planes requiring extra thrust and power*** as the ***prop interacts with the plane***, often much more unfavorably than is realized. That has never been dealt with adequately by Aerodynamicists, simply because they've *never had a practical flight test method, a valid way of testing for it, separating it, in actual flight*.

(Our Zero Thrust Glide Testing has given us ***real data*** to work with.)

It took a multi-year effort to review all the past experts, figure out what they did do, and could ***not*** do before computers, *what was never made clear*. We did all the complex math, computer programming, analysis, to learn how to ***make it comprehensible.*** A pro's rotating wing blade element analysis, proper geometry, didn't work. Real three dimensional flow, only solved by NACA's chief Physicist, Theodorsen, a true genius gave correct answers. Props are as complex a subject as any of us will ever deal with. They're full of hidden surprises, unexpected logic and convoluted interplays. Fortunately the logic ***can*** be made clear. There are really ***wonderful insights and clarifications*** that make it **truly possible to actually grasp the logic *in a few hours.***

OUR mutual problem is there is *so much new insight available*, ***a teacher is apt to drown you with just too much, too quick!!!***

Because of that, the absolutely necessary way to teach it is to ***first teach the basic logic to pilots - get each new guy aboard on the core logic*** *that is* ***hiding in the basic Physics. Then expand his insight, but not drown him,*** *teach what's needed* ***to understand even better, with much greater insight,*** *finally offer* **great conclusions that go way beyond the basic insight, *min effort, max. smart! But FIRST, we must successfully teach you the key to the basic Physics, the correct CORE logic*.**

Once you grasp this basic logic, let it soak in, it becomes much easier to go on, to read, understand the advanced explanation in Chapter 3 II -- ***for those who wish to get it all***, -- ***as usual - reading the book to the depth you wish and choose***.

We teach you the basic logic with the Rankine - Froude concept, the "**Actuator Disk**", 1889. That's ***Newton's*** $T = \dot{M}\Delta V$, ***the core of the basic Physics. In hindsight, it's simple enough! Just grasp how a big*** $\dot{M}$ ***reduces the*** ΔV ***required and*** $\Delta V/2V_1$ ***loss!***

The game is to simply minimize the ΔV, the extra wind you make!!!

Amazingly, **Betz conceived the ideal prop concept in 1919, and it's still correct**. We clarify his concepts early, and teach his airflow geometry in the advanced chapter, 3 II, to not go too fast. Glauert got the air inflow and rotation pretty correct by 1934, Theodorsen, the genius solution by 1948, and we teach it all as you progress. ***Our task is to get you through the first steps into understandable logic, logical horse sense***, ASAP.

There are just a lot of brand new ideas that we need to get you aware of ***so you know enough to go on***, to start appreciating, understanding enough to start seeing the logic and patterns of it all, so **charge, have faith and trust, and you'll be rewarded**.

Only **a computer can nail a specific design**, we'll teach you a ton about propeller logic, ***but most basically grasp: FAST, low drag, low RPM planes with high pitch angle props, high P/D, are efficient - but low pitch props aren't.*** Slow, high drag, high RPM planes, **anything that gets you low pitch is bad, *EASY!***

But if you ***gear*** a slow, high drag, high RPM plane like an ultralight for ***low RPM, high pitch, much bigger diameter, you can get back to max. efficiency theoretically.*** (**But, *it's usually impractical, too big a diameter*, too low an RPM, *the math self defeating to get high enough pitch - because as the diameter goes up a lot, the angle of the tip goes down again!!!* Geared fighters, low RPM, have reasonably small diameters --- *only Because They Go Very Fast!*)**
Slow, you must and will have **low power density, low H.P. *per* square foot of prop disk area**, like ultralights have, part way to optimum. ---- You'll learn that **SPEED, RPM, C_L** are all far more important than you'd ever guess, **all 800# Gorillas! It's great understandable logic, *but chock full of real surprises!***

q, Dynamic Pressure, much higher at the tip, --- is a 4th 800# Gorilla, D a 5th!

One of the big surprises is that since it's really ***the plane Speed and drag, and the engine RPM*** that **controls and limits propeller efficiency**, ***prop efficiency is really not prop efficiency at all, but rather* "a *traveling* prop system efficiency"**. All the prop can do is to be accurately computer designed, ***actually meet the max. limit of efficiency imposed by the plane-engine system!!!*** *The prop blade has a very important, but definitely limited role.* **Pitch**, **Advance**, **Aspect Ratio**, sets max efficiency ***because*** the ***prop is not in control of its basic efficiency***, the plane-engine is.

A Luscombe, ~ 85%, a Fast RV, ~89, 90%, ~ 91.5% a Classic Max!!!

There are *four kinds* of basic propeller losses, three relating to the propeller **stream tube**, the ***axial ΔV speedup*** that basically creates the thrust, the ***rotation***, ***worse*** for otherwise efficient high pitch props, (a questionable reason for counter - rotating propellers), the ***radial flow feeding the tip vortex***, and finally *the fourth, **profile drag skin friction***, that is always there.

Blade Drag is Penalized *Because* Small Chords give Low Reynolds Numbers, Rn.

We're very purposely going to center this initial advanced chapter mostly on the *axial ΔV speedup*, *simply because that's where the sneaky $\dot{M}\Delta V$ logic and multiple surprises are*. The other three losses are there, add up to more loss than the ***ΔV speedup*** loss, but that's ***not*** where the tricky logic is. You can see they logically exist, so we can leave them until later, to keep this basic chapter with the greatest gain in insight, the easiest picture to grasp, free of excess detail and excess complexity.

One of the greatest new insights is when you realize, grasp that --- the *radial root and tip loss*, *the rotation*, and *half the axial ΔV speed up* are *the induced loss! Like a wing*, that loss drops to a low level at high speed, leaving the irreducible *Induced and Profile* about 8 to 9%, a 91+% max. efficiency*, EASY --- *huge insight that helps make it all much easier!*

Like a sailplane, Aspect Ratio sets the final upper efficiency limit!!!

I'm very purposely going to skip a lot, leaving it for the advanced chapter, ***because it will be far easier to grasp after you grasp the key core logic!!! Grasp the Math:*** **Props make thrust by pulling in and throwing back, speeding up**, *the natural ṁ **mass flow rate of air** **through the prop disk**.* **$\dot{M} = \dot{m}\,(1 + \Delta V/2V_1)$**

A big *free* natural ṁ is fed through the prop disk by big speed, with no prop there!!!!

Do not allow yourself to ***get faked out***, because we use basic Physics, the **T** = **ṀΔV** core logic. **It is *not* brain surgery, *not* deep math**, it is *simple arithmetic*, **Ṁ times ΔV, that simple, a simple two element logic *where ΔV gets smaller as Ṁ gets bigger!!! Get that. It's very important***, because **ΔV/2V₁ is the loss that costs!! Big speed, big V, which gives you a big *natural ṁ* and final Ṁ, gives you *lower ΔV, high efficiency*!!! You'll thus learn *a pretty tricky, but simple enough logic that you'd learn and grasp no other easy way*, the real key, the real hidden secret to fairly easily decoding all the 100 year hidden secrets of propeller logic!!! That's the most confusing basic.**

We purposely keep saying it slightly differently so novices finally get it.

Propellers can otherwise be a huge frustration and task to learn, *or to teach*, because *done the wrong, long, math way, they are just too much*, something that will drown even pros. We **emphasize the axial loss**, blandly say there are three other losses, *that are actually just as important*, but *it's the axial logic where the secrets are hidden*. Trust me and you'll get it, easiest and *very completely if you go all the way through both advanced chapters*. I expect many will find this Introduction difficult, **it's the hardest part**, but you can end up ***proud if you got it***. Compared to the years props can cost professionals, ***you may end up deciding this is the best time bargain you've ever found.***

 *** Ultimately, we'll show you how to beat the Classic Ideal.**

A Concise Look at Prop Design Logic

You can end up with a *Feel for the subject*, much faster than the Math will teach!!!

A **fixed pitch** propeller can be described pretty simply, so we'll do just that and then expand it, so you can grasp very much very quickly. First, a prop must be **pitched (& twisted) correctly** for **plane speed** vs. **engine RPM**, (+ air inflow & rotation), so each blade airfoil flys at a ***low optimum angle of attack*** at ***design speed***.

But it will be way over pitched at all slow speeds --- runup, takeoff, climb!!!

Next, it needs a **proper blade diameter-area-shape** to give the **required thrust** at the ***Speed, RPM***, C_L, and (alt.) air ***Density***, ρ. Now *get all that*, because it's pretty ***simple, concise* and *specific!***

Correct Twist and Shape can make it IDEAL!!! Blade Pitch is held to .1 Degree!!!

When you're designing a prop, the diameter is extra important, because the ***tip is going so much faster***, is so much more important than the root or mid radius, **you cannot disconnect the Diameter, a powerful factor, from the Area--Shape calc!** Secondly, a **larger diameter, higher aspect ratio, reaches out to work on a larger mass flow rate**, which directly cuts the induced drag loss, by **directly cutting how much extra ΔV it must throw back the natural stream tube passing through the prop disk.** Like a sailplane wing, a prop wants max aspect ratio, max span. Diameter cuts induced loss in exactly the same way that a long sailplane wing works on more mass flow rate, cuts induced drag ***by having less resulting ΔV downwash, which is a loss, less disturbance of the static air, huge insight.***

MINIMIZE ΔV, don't make extra wind to leave behind as turbulence, a loss. **EASY!!!**

Blade shape is significant, the faster **outer blade** ***wanting*** much **narrower chords**, and thickness to ***create "a rigid vortex sheet", helical pitch of the airflow, the ideal foreseen by Betz in 1919***, **huge insight**, (the variant of **Prandtl's perfect elliptical wing, but *not* constant downwash**). Back to pitch and twist. If the twist is set to ***hold a constant*** α^o & C_L, and chord widths are made correct to actually hold that C_L, you can actually get "Betz loading", ***get constant pitch helical inflow***, (***but* then, *blade angles must be reduced, more inboard***, for the fuselage pushing a bubble of air *ahead, slowing the air feeding the prop*). This is ***huge grasp early!***

A propeller ***must* be *computer calculated for precise 3D flow*, to do a proper detail design**, but the math for that took our smartest analysts almost seven decades, from 1865 to **1934** for Glauert to get a *good approximate* solution, actually until 1948, 83 years for **Theodoresen** to nail ~exact **3 D flow**, with realistic **heavy loading**, and **high advance ratio** to get ***accurate inflow!*** We ***won't*** try teaching you the "rare genius level" math, ***pros drown***.

SO HERE COMES THE CONCLUDING TWO PAGES – WITH THE REAL MEAT SUMMARY!!!

It's much easier to see a prop makes thrust by ***pulling in, and throwing back air***, per Newton's Second Law which teaches us to ***calculate the thrust reaction force to throwing back air***. The formula is $\dot{M}$, (M dot) times Δ**V**, $\mathbf{T = \dot{M}\ \Delta V\#}$. The thrust is in pounds, of course, as shown by the # symbol. The *total* Δ**V** (delta V) speedup must be in **ft./sec.**, not MPH, to get the correct answer. $\dot{M}$ is ***mass flow rate in slugs/sec.***, [sounds like a scary new term, but it's just like pounds/sec. divided by g, (32.174 ft./sec. per second, the acceleration of gravity), again to get the correct answer, not one 32 times high]. That ***two item basic formula quickly buys you huge insight***, bypasses 83 years of wild math that most could not possibly understand in this lifetime. And surely don't want to ----

A **fast** plane has a **huge natural $\dot{m}$** ***through its prop disk*** - **free** - from its speed - **without the prop even being there!!!!** It's **increased just a little to $\dot{M}$** by the ***ratio*** of *half the* ΔV, ΔV/2 vs. V_1 the *slowdown* speed, ***half*** since nominally half the speedup comes from the prop making a small vacuum in front, half behind from a small pressure increase behind, **half the ΔV at the prop disk**. That ***ratio*** is made much easier to understand next.

WE PURPOSELY DO THE PROP CALC AT THE PROP DISK WITH HALF THE ΔV SPEEDUP.

Prop Airflow weighs a lot more than people realize, remember 76,000# for a 100 foot cube at sea level!!! **Specific numbers** offer **a feel for the facts**. A **BIG $\dot{M}$ allows the ΔV to be surprisingly small**. Again, an RV 6 with a small 70" prop at 200 MPH passes **614.5# of air per *second***, the equivalent of throwing back **1 1/4 ft^3 of steel** every **second!** With that, only a very small **10 MPH *extra* ΔV wind** makes 280# thrust. 19.1 slugs/sec x 14.66 ft/sec.

Now let's **ease** the item that might cause you the most confusion: Take **a ratio of half of** ΔV, $\Delta V/2$, **vs.** V_1, **in math form** $\Delta V/2V_1$, where V_1 is the airplane speed feeding the prop, (or in advanced cases, the slowed speeds caused by the body pushing air ahead.) *That is absolutely going to look pretty scary to many pilots, but let me show again how easy it is.* In the RV6 example we're using with a 10 MPH ΔV, it's simply **5 MPH vs. 200, 2 1/2 %**! ***Grasp how easy it is, because it's the 2nd central factor in understanding props, and once you've got it, props are licked!***

1. It's used to **increase $\dot{m}$ to $\dot{M}$.** $\dot{M} = (1 + \Delta V/2V_1)\,\dot{m}$, **1.025** $\dot{m}$. We do that because *we calculate* ***$\dot{M}$ at the prop disk*** where only 1/2 ΔV has happened, having pulled in the $\Delta V/2$ from a larger diameter -- and $\dot{M}$ does not, *can not* increase behind the prop disk, the stream tube diameter simply *shrinking some more*, (all per Bernoulli) - *speeding up more* - ***as the pressure adds $\Delta V/2$!***

2. We use the same ratio, $\Delta V/2V_1$, 21/2 %, to measure the **axial energy loss ratio**. You might think of it as $(1 - \Delta V/2V_1)$, 97 1/2%. (There's a really obscure reason for using half the full ΔV here that you can promptly forget. In Physics, the basic energy equation of motion, $MV^2/2$, one V of the two is the average V, V/2, because the distance over which energy is added depends on the average speed up!) Forget that pro reason.

So now, to really see the core logic of props, just grasp:

1 ***Fast planes have a big natural $\dot{m}$ & $\dot{M}$, thus need less ΔV, twice helped*** **with a small ΔV, a big V_1,** $\Delta V/2V_1$ ***shrunk twice!!***

2. The **$\Delta V/2V_1$ factor,** *a lot easier to use than it looks*, is used to **increase $\dot{m}$ to $\dot{M}$**, only a small percentage for a fast plane.

3. And that **same factor,** $\Delta V/2V_1$, is used to measure the **energy and efficiency axial loss,** the **2 1/2 % down to 97 1/2 % here!!!**

4. A **BIG $\dot{m}$ from a fast plane means a BIG $\dot{M}$,** (but only up a small percentage), and **that allows a small ΔV**, and that's good, because it's the **$\Delta V/2$ that becomes a loss! (But think, $\Delta V/2V_1$, the loss factor tries to be ~ 4 times bigger, (2 / 1/2) *at half speed* for the same thrust - (*except* a bigger, worse ΔV increases $\dot{M}$ more!) Think it thru!!!**

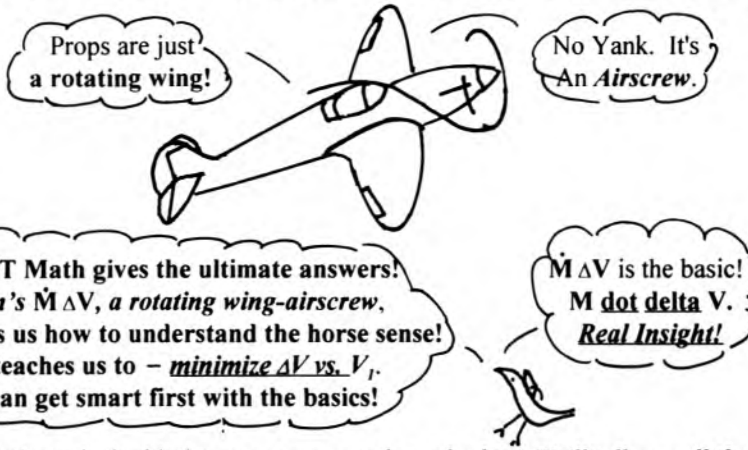
A LUSCOMBE IS LIMITED TO 85% EFFICIENCY MAX, AN RV CAN GET TO 89% vs. 91 IDEAL.

Yes, this lead in *is* terribly repetitive! Green Novices need time, practice!

GET THIS PAGE AND HAVE PROP LOGIC LICKED ---

√ √ √

The Wise Ole Bird ***IF YOU GET THIS PAGE, YOU'RE OK TO PROCEED.***



You need ***not*** deal with the *rare genius math*, ***we*** *had to!* *We'll tell you all the hidden conclusions*. **This dense summary condenses the core Newton logic**.

WE ALSO DESIGN A PROP KNOWING IT IS A ROTATING WING, AND AN AIRSCREW!!!

1. **Props work on** $\dot{M}\,\Delta V$. ***Thrust = Mass flow rate*** through the prop disk times the ΔV ***speedup***, in ft./sec. They thrust by **pulling in air, throwing it back**, *also increasing* ***the natural mass flow rate*** $\dot{m}$ ***provided by airplane speed a little to*** $\dot{M}$***!*** At **twice the speed,** ~ twice the ***final*** $\dot{M}$, you get the ***same thrust with ~ half the*** ΔV***!! That's efficient, because*** $\Delta V/2$ ***is a loss!***

Not exactly half ΔV, ***only because*** **a smaller** ΔV **increases** $\dot{m}$ **to** $\dot{M}$ **less ---**

2. $\dot{M}$ is *like pounds/sec.* **flow rate**, *except* divided by the acceleration of gravity, 32.174 ft/sec^2. That gives ***a smaller number of bigger units of mass***, with a weird name, **slugs, slugs / sec** here, *but* that gives the ***answer in pounds, and numerically correct, not 32 times high, plenty important!***

WE REVIEW THIS CAREFULLY BECAUSE IT'S THE HARDEST SUBJECT FOR NOVICES!!!

3. The key **axial energy loss ratio** in the ***stream tube*** is $\Delta V/2V_1$, ***half*** the ΔV ***ratioed to the slowed air speed,*** V_1. V_1 is plane speed V_0, *slowed down* by the plane's nose pushing a bubble of air ahead, *highly variable vs. radii*, (which changes the twist and chord). Later we'll learn about other **3D losses**.

The same small ratio, $(1 + \Delta V/2V_1)$ **is used to increase** $\dot{m}$ **to** $\dot{M}$.

4. **High pitch indicates high efficiency and vice versa. High V lowers the needed** ΔV**, a twice lowered** $\Delta V/2V_1$ -- and **high** V_1 **needs high pitch!!** ***Slow***, gear for low RPM, high pitch, larger diameter, and be just as efficient!

BUT The RPM Tends to Get Too Low, The Diameter Too Big, Heavy Too.

5. *Surprisingly*, ***Plane*** **V and drag,** ***Engine*** **RPM set the max. efficiency** possible without gearing. *The prop design job is to actually meet that target*.

BETZ LOGIC, GOLDSTEIN-THEODORSEN MATH SOLVES EVERYTHING ~ **PERFECTLY!!!**

That's more *new thinking* than I'd like to throw at you, but grasp it and *you've won*. *Let it sink in*. BIG insight is based on this *key core logic!!!*

BOOK II --- CHAPTER 2

THE PROPELLER

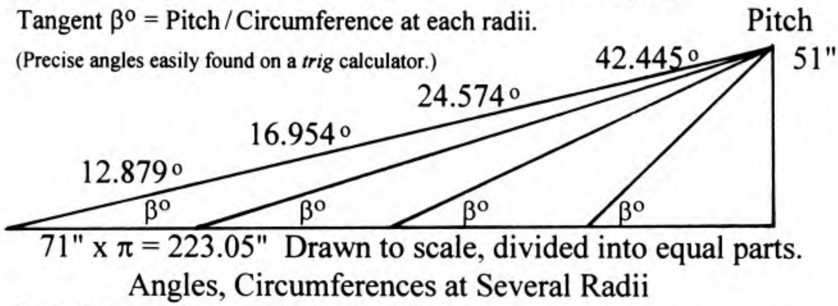
THE BASIC, ADVANCED PROP CHAPTER

Props are chock full of surprises! You've already seen many in the Primers. Everyone *kind of* understands how propellers work, but <u>*you've seen the real logic is hidden*</u>. Many see 1. *a rotating wing* or, 2. the English concept, an *airscrew*. Let's start there. Think of a *helical pitch*, a *twisted blade*, so *each radius* tries to <u>*screw ahead the same*</u> <u>*distance*</u> each revolution. **Pitch** is simply *the* <u>***inches or feet a prop would screw ahead***</u> each revolution, <u>**with no slip**</u>, like through a weak <u>**solid**</u>, say perhaps, a stiff Jello.

Helical Pitch --- For a 51" P, 71" D Luscombe prop

Tangent β° = Pitch / Circumference at each radii.

(Precise angles easily found on a *trig* calculator.)



71" x π = 223.05" Drawn to scale, divided into equal parts.

Angles, Circumferences at Several Radii

EXAMPLES;

Dia Pitch		TIP	3/4	1/2	1/4	Δ deg	P/D	RPM	Max. Speed
71 x 51	**Lusc**	12.879	**16.954**	24.574	42.445	**29.566**	**.7183**	2545-	116.4 MPH
70 x 79	**RV6**	19.760	**25.594**	35.696	55.165	**35.405**	**1.1286**	2700+	202 MPH
162 x 450.56*	**Reno**	41.518	**49.729**	60.543	74.231	**32.712**	**2.781**	3000/1125	480 MPH

* 450.56" is actually the Dreadnought's <u>Advance</u>, <u>37.546 ft</u> at 480 MPH, 1125 RPM!!! Pitch is more!

Props *advance* <u>***less***</u> *than pitch*, to ***pull Inflow***, there <u>***is***</u> <u>***some slip!***</u> You've seen <u>***advance ratio***</u>***"*<u>*J*</u>*"***, <u>***forward***</u> vs. <u>***rotational***</u> <u>***velocity***</u>. <u>***Important***</u>***!*** *Realize "*<u>***J***</u>*"* sets <u>*and limits*</u> the prop's <u>*max efficiency*</u>! **Great Graphs** will show you that ***J*, Advance Ratio**, <u>*and*</u> **P/D**, pitch/diameter, both tied to ***blade angles***, <u>***indicate***</u> ***efficiency!!!*** ***TRUTH --*** <u>***hi speed***</u>, <u>***lo drag,***</u> <u>***lo RPM***</u> = <u>***hi pitch***</u> = <u>***efficiency***</u>***!!!***

The reason props appear to ***slip*** is simply that in pulling in and throwing back air, they must be ***overpitched to account for α°***, and ***inflow,!!!*** So let's *conclude* **Isaac Newton's better way to grasp prop's, their thrust, logic and efficiency**. There are even more intriguing logic surprises. ***After*** *you grasp the horse sense of the technical logic*, ***if*** you wish to pursue propellers all the way, you'll *then* find the graduate level explanation in Chapter 3 II ***much easier*** to understand, with the basics grasped.

We'll want to get you smarter on *advanced logic* soon, but *first*, let's nail the final overview of Newton's basic insight.

A PILOT'S GRASP OF NEWTON'S LAWS OF MOTION

Props ***pull in and throw back air,*** and **"Newton's Third Law"** states what you should now grasp, there is ***an equal and opposite reaction***. Thrust results from pulling air in, throwing it back, just like *you* would be *pushed throwing a big heavy mass*.

Spread your new insight on atmospheric weight! Ask friends how much a 100 foot cube of air weighs at sea level, (if you could actually put it on a scale for honest weight, ***not*** a trick)? **Surprise, shock**, the answer is **76,000 pounds!!!** Air needs to have serious weight or those near million pound 747's would all fall down, and so would *your* plane, and your prop would ***not*** thrust!!! **Wings create *downwash*, throw a serious flow rate *down*, *supporting*, *equaling*** the wing's ***pressure difference lift***. Props ***speed up a stream tube***, *each act as* ***the reaction force!***

There's never an infinite span, so DOWNWASH NEVER GOES TO ZERO!!! √

There *is* a *little* trick there. There are a million cubic feet in a 100 foot cube, 100 x 100 x 100 = 10^6 = 1,000,000!!! Sea level air weighs ~.076 # / $ft.^3$, and that 3/4 of .1 # times a million is a plenty significant ~76,000#. The point is quite valid, ***not*** a trick. You've already seen that a 70" RV 6 prop at 200 MPH is **getting fed 8035 $ft.^3$/sec., 614.5 # / sec.**, *because* the 200 MPH plane is feeding a **big *mass flow rate*** of air into the prop disk, and the prop, you've seen, only has to **add *a small 10 MPH ΔV "speed up"*** to make **a sizable 280#** thrust. ***That's the secret!!!*** √

Newton's Second Law - gives us simple little formulas for calculating the reaction force, thrust. F=Ma, Force equals Mass times **a**cceleration, is for throwing *solids*. F or **T = $\dot{M}$ ΔV**, force, **Thrust**, equals ***mass flow rate*** $\dot{M}$, times **ΔV**, is for ***flowing fluids***. Mass, in Slugs, is just Pounds divided by g, the acceleration of gravity, 32.174 ft./sec.^{2}, so mass is ***a smaller number of bigger units***. **$\dot{M}$, slugs/sec. *flow rate*** times **ΔV** in **ft./sec = T#.** That little drill **makes the answer come out in pounds, and correctly, *not* 32 times high!** If you're not a math person, *don't* let that fake you out, *some will want the full insight.*

That's getting more technical than most pilots would like, but see the **principle is really simple**. **Thrust** is just **$\dot{M}$ ΔV**, **Mass flow rate, times ΔV**, *simple arithmetic*, and **it's the simple key to making props far easier to understand! GO FAST**, get a **BIG $\dot{m}$ and $\dot{M}$**. a **SMALL ΔV**, a **SMALL ΔV/2V$_1$**, ***lo loss***, **EASY!**

Thrust and Efficiency Think **what's happening at "run up"**. Your propeller is ***not*** acting as a propeller at all, but rather as **a stationary fan**, causing a big blast, a hurricane, *big thrust even with the prop forcing **all** the $\dot{M}$*, none from plane speed. **But all the energy is wasted,** ***you go nowhere!*** Grasp that **efficiency** is always ***useful energy or power out, divided by required energy or power in.*** *All the energy that you put into that stream tube is wasted*, useless turbulence, ***finally*** **settling back down to zero, static, a 100% loss** -- so you *must be* and *are* at **zero efficiency!**

Here comes the Super Magic Graph ---

Watch how we've just started you on a path that will give you a really sophisticated, yet simple, grasp of prop logic, that people can otherwise have a terrible time learning. As you start off *on **takeoff roll**, your prop is still more a wasteful fan than a prop, churning out a **big ΔV, big thrust** you do want for takeoff,* ***but*** *wasting almost all of the energy making a big thrust.* ***Still going slowly***, the thrust times distance, ft. lbs. ***useful energy***, (or T x V, ft. lbs./ sec., ***useful power***), ***is far less than is being put in!*** Making a big thrust, a big **ΔV** becomes a big loss, because that big **ΔV** just falls to static, ***sacrificed energy just to make thrust.***

Lifting off, starting to climb, **extra thrust** is **required** to ***both hoist and fly*** **the plane**. Realize your thrust maximizes, **with less ΔV! As you go twice as fast, the natural $\dot{m}$ doubles, and you get a given thrust with ~ half the ΔV! You're more efficient**, ***because*** the ***plane's speed is feeding a rapidly growing $\dot{m}$ & $\dot{M}$***, less **ΔV** required ! Fast planes can easily be more efficient! ***But***, do you see that the **very act of making thrust, forcing a ΔV, making extra wasted ΔV wind, is using energy, lower potential efficiency**. MAKING EXTRA WIND, EXTRA THRUST, especially at low speeds, ***low $\dot{m}$***, ADDING **ΔV**, USING ENERGY, COSTS, **lowers** the POTENTIAL EFFICIENCY!!!

But, NOW FASTER ---

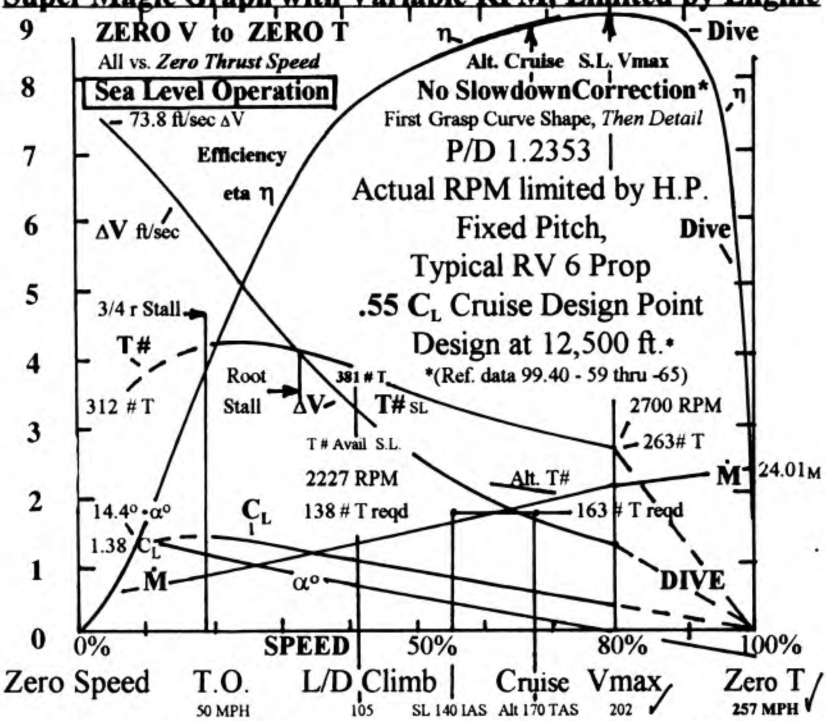
Your *prop also is now* ***less overpitched***, ***less stalling***, ***better C_L***, C_D, ***closer*** to flying at an efficient low angle of attack like a wing. **More $\dot{M}$, less ΔV**, efficiency increases! **But**, fixed pitch, ***still too slow for your fixed pitch***, you're still at *too high an angle of attack*, ***overloading torque***, ***thus less available RPM, and HP!***

That basic logic keeps right on working, right up to and through ***cruise, where the prop was designed to fly just like a wing, at a nice max efficiency, low angle of attack***, and ***lower*** **selected optimum C_L**, now making **a low, efficient ΔV**, a smaller, far more economical thrust, ***designed there, max efficiency at V_{max}!***

Realize, efficiency is *good only* near *design speed!!!*

Super Magic Graph Andy Bauer's incisive Super Magic Graph is a key learning tool. It shows how a prop starts at **zero efficiency at zero speed**, starts improving through takeoff and climb, $\dot{M}$, mass flow rate going up, ΔV coming down, better and **better efficiency through the cruise design point**, even **a bit better at *Vmax thrust***, but *drops toward zero again* as you *start overrunning the pitch*, *diving*, **finally back at zero efficiency at zero thrust!** The logic is simple, ***ΔV decreases, helped by $\dot{M}$***, mass flow rate growing naturally with speed. By now, hopefully, you've grasped it's really half of **ΔV**, **ΔV/2** vs. V_1, the ***slowed*** airspeed, **ΔV/2V₁** that shows % **axial** energy loss, ***not hard***. (The Super Magic Graph **accounts for *all* losses**, 3D and Drag.)

Super Magic Graph with Variable RPM, Limited by Engine



Sea Level wide open throttle --- ***actual RPM vs. available HP*** **is used --- at all speeds** from **Zero to Zero Thrust**, (in a slight dive, at 2700 max RPM) --- this shows **Efficiency**, **Thrust**, **Ṁ**, **ΔV**, 3/4 radius α°, **C**L, (all vs. *% of Zero Thrust Speed*), **wonderful insight for learning the logic!** Stalled α falls, Thrust peaks, then falls, Ṁ grows, **ΔV** falls. Climbing at a max L/D 105MPH, high prop CL is needed to both fly and hoist the plane, Thrust, ***above Treqd*****,** •*138 #, then drops*, still above the *design cruise thrust* of **163#**, 140 IAS-SL, 170 TAS-Alt. • Vmax, thrust shown, **263#**, ▪ requires the rated 2700 RPM --- which is subsequently held as thrust falls to zero. Interestingly, **altitude cruise design**, works ***perfect*** at **sea level**!

The *extra* Altitude Thrust Curve, shows Available Thrust vs. 163 # Design Alt. Cruise

A ***(variable pitch), constant RPM prop***, an ideal, infinitely variable transmission for the engine, *peak HP at any speed*, **is at *even lower efficiency at lower pitch***, that ***allows*** higher RPM, HP, and Thrust. ***Pitch, like J, Advance Ratio, is the eta, η indicator!!!***

 *Inner Radii work much better with Slowdown Correction

Andy Bauer's Super Magic Graph offers Wonderful insight! Before we press on, **STOP** long enough to **actually grasp** all the **wonderful basic insight** offered here by Andy's great work, ***the kind of incisive insight you simply cannot normally find!***

LOOK -- DON'T BE AFRAID of the GRAPH --- **IT'S A PICTURE , EASIEST WAY TO SEE EVERYTHING!!!**

First, don't be confused. The ***horizontal scale*** is just ***the percent of speed*** vs. the fixed pitch prop speed, 257, where thrust drops to zero diving, pitch too small to make a ΔV, thrust, at 2700 RPM.

An RV Prop would be stalled at T.O., but is far better after Slowdown Correction.

Angle of Attack, α^o, shown, is **for the 3/4, 72.3% radius**. Slow, on a relatively high pitched prop, that appears to be stalled. Realize the computer calculates at least 11 different radii, and integrates everything to get the overall answers. Recognize three very important points: ***1. Efficient high pitch are much better after slowdown correction 2. Steep inboard segments stall more than* shallow outboard segments**, *slow**. **3. *As V increases the situation naturally gets better***. Simply, every radius has excess pitch at zero speed, has trouble pulling air in fast enough to not stall. A 51-71 Luscombe prop, P/D **.718**, manages to hardly stall, a 79-70 RV 6 prop, **P/D 1.128**, is more efficient fast, but has to be dragged through the air, at hi α^o, slow at T.O. (The **1.235** RV P/D case shown has *excess P/D only because* slowdown was ***not*** used here, ***yet***.)

***Slow, Geometrically, Max stall moves outward, decreases, as Speed Increases!!!**

The Coefficient of Lift, C_L, which **generally grows about .1 for every 1° of α, breaks and falls above about 13 degrees, slow, depending on surface roughness and Reynolds number**. Notice that the $\mathbf{C_L}$ plot weakens at stalled speeds. This causes a *major problem calculating propellers slow*, *because* the exact $\mathbf{C_L}$ and $\mathbf{C_D}$ are *not* accurately known above stall, so slow speed calculations are naturally more in doubt. We'll look more at $\mathbf{C_L}$.

Wide Open Throttle gives Extra Thrust for Climb. *Note extra at Alt. vs. S.L!!!*

Delta V, ΔV Whereas, it's a wasted hurricane at runup, the very interesting thing to realize is that it's nominally **only 9.2 MPH** at **170 MPH**, **12,500'** ***cruise***, at **163# thrust** for an RV, **only 9.4 MPH** for **263# at 200 MPH**, **sea level**. (At altitude cruise the thin air reduces the $\dot{M}$, so ΔV stays close to the sea level Vmax, high thrust case.)

There are actually **four kinds of losses**, three stream tube, *axial inflow*, unwanted* *stream tube rotation*, (the reason for counter rotating props), the natural *radial flow* feeding the tip vortices, and, of course, the fourth, *blade drag* -- which is always present!

***But, you'll learn the air rotation is used to set up ideal helical airflow!!!**

For the graduate course guys, there are two interesting and important basic issues that are worth grasping here. **1.** The prop, like a wing, creates a lower pressure in front, a higher pressure behind. **Inflow $\Delta V/2$ is nominally equal to outflow $\Delta V/2$, each nominally *half* the total ΔV.** **2.** Then, an interesting insight on Physics is that the energy and efficiency loss is based on **only half the ΔV**, ***because*** the energy involved is based on the *extra distance* over which the speed increases, which is based on the *average* velocity increase, thus *half* the total ΔV. *Thus*, pros *only* consider the *inflow* $\Delta V/2$ to calculate the energy and efficiency loss, $\Delta V/2V_1$!!! You, as a pilot, can just skip such graduate fine print extra insight,if you wish.

Notce, only $\Delta V/2V_1$ inflow affects $\dot{m}$ to $\dot{M}$ increase, actually $\dot{m}\,(1 + \Delta V/2V_1) = \dot{M}$.

If you wish, learn these key fundamentals. ***Axial*** **loss** is **$\Delta V/2$** vs. the ***slowed*** axial velocity **V_1** ***before it's pulled in, at the prop***. **V_1** is the plane speed V_∞, ***but*** *slowed by the plane's nose pushing air ahead*, a bubble, less slow, as radius increases. ***Rotation*** loss, is half **$\Delta\pi dn$**, **$\Delta\pi dn/2$** vs. the circumferential velocity **πdn**, **$\Delta\pi dn/2\pi dn$**. The ***radial*** flow loss affects each calculation, a complex task in Theodorsen's math using the knowledge built up since 1919 when Betz defined min. induced energy loss logic. Theodorsen, solved heavy loading, hi advance, 3D flow by 1948.

We calculate each radius. Small d is *any* diameter, capital D, the full Diameter!

There's a lot to learn here, but *once you've grasped it, **the horse sense is quite simple***. $T = \dot{M}\Delta V$. Making ***ΔV* costs *energy*, *fuel*, *efficiency***. Minimize ΔV, you win, especially if the **V_1** ***slowed speed*** the prop sees is ***high***, you have a small loss percentage, $\Delta V/2V_1$ -- thus high efficiency! *The game is to keep ΔV small but also get V_1 thus $\dot{M}$, up*. ***Grasp that, and you have props basically licked, you've successfully grasped the central logic.***

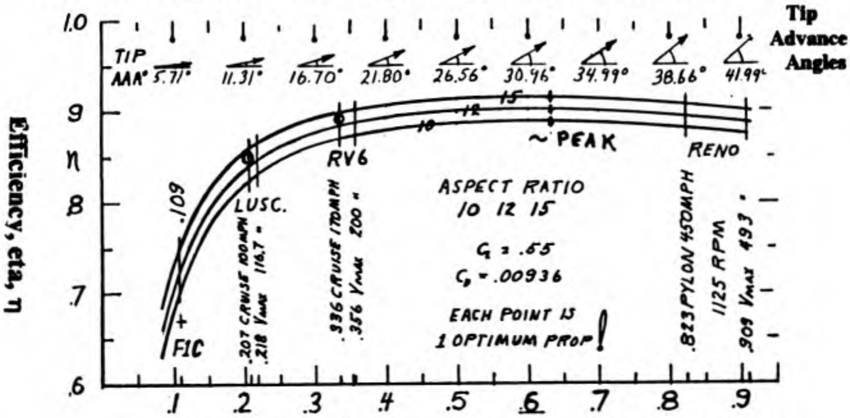
But, realize, a constant speed prop does *not* prevent this efficiency loss at low pitch!!!

Grasp *why* **low drag, thus low thrust required, low ΔV**, ***fast plane speed, thus high $\dot{m}$, $\dot{M}$***, **even lower ΔV, l*ow engine RPM, thus high pitch***, (or gearing), **is what *yields* high efficiency!!!!**

<u>ADVANCE RATIO</u> <u>J=V/nD</u> The Classic Efficiency Graph

The **classic Advance Ratio curve** shows **high J, high pitch is efficient**, but **low J, low pitch is inefficient**. ***<u>Efficiency swoops up as advance, or pitch, increases</u>***. (Dividing each side by π, J/π = V/πnD **makes it *<u>easier to see</u>*.** **V** is ***<u>forward</u>*** ***<u>velocity</u>***, and **πnD** is **<u>the circumferential tip *velocity*</u>**, both in ft/sec.) That's **a *<u>triangle</u>*** **showing <u>actual tip *advance angle*</u>**, (*<u>not</u> the tip angle*). **V/πnD *<u>is</u> the <u>tangent of</u>* <u>the blade tip</u> *<u>advance</u>* angle**. **(D = ft., n**, rev/sec) Below it's labeled **J/π, AAA°**, the ***<u>tip</u>*** **<u>Actual</u> Advance Angle, (or Ratio)**. The curves *flat peak* about .64, and **J**, the **<u>Advance Ratio</u>, simply π times bigger**, flat peaks about **2.0**. **LOOK, to help, *<u>actual Tip advance angles are shown</u>*, *<u>EASY!</u>***

Advance Ratio, J = V/nD, (J/π = V/πnD, is much easier to see)



J/π = Actual (Tip) Advance Angle, AAA = AAR = V/πnD

The message is simple, ***<u>Low Advance, Flat Pitch is Inefficient</u>***. Super F1C gas models, 29,500 RPM, 7" D, **<u>3" flat pitch</u>**, are an efficiency disaster, ***below 70%***, but super at getting 1+ H.P. out of a small .15 in^3 engine, about **7 H.P./in^3!!!** The Luscombe is ***hurt***, ***85% max***, the RV6 in fat city, ***89+%*** without gearing, the Reno Racers more pitch than ideal, would you believe ***a geared <u>37.5 foot advance</u> at only 1125 RPM***, but in sonic trouble, racing. **<u>Flat pitch causes High Induced Drag and also excess Profile Drag loss, a shallow corkscrew, too far to get to the</u>**

destination. ***High pitch*** **goes with a *big V*, *big* $\dot{M}$, thus a *small* $\Delta V/2V_1$ stream tube loss ratio**, a proper **low Rn C_D, a steep, short, economical corkscrew path to the destination, Profile is ~ 1/3 of the overall loss at .55 C_L, *induced ~ 2/3!!!* *Starting terrible at low pitch angles, ideal efficiency swoops up. Above the RV6's AAA, approaching .4, a J near 1.25, you start approaching optimum efficiency, near 90+%.* AAA flat peaks about ~.6+, J ~2+**. ***(Caution - You'll learn using a wrong high or low C_L can and will distort D, thus J, and also P/D. .5 to .55 is best)!***

Do notice that low Aspect Ratio will also limit efficiency!!!!

Now look, clearly we've thrown a bunch of new thinking and logic at you in just a few pages. I certainly expect that you might reread it to really get it. No one will pick it all up in the first reading --- ***but also notice the core is not hard to grasp!!!***

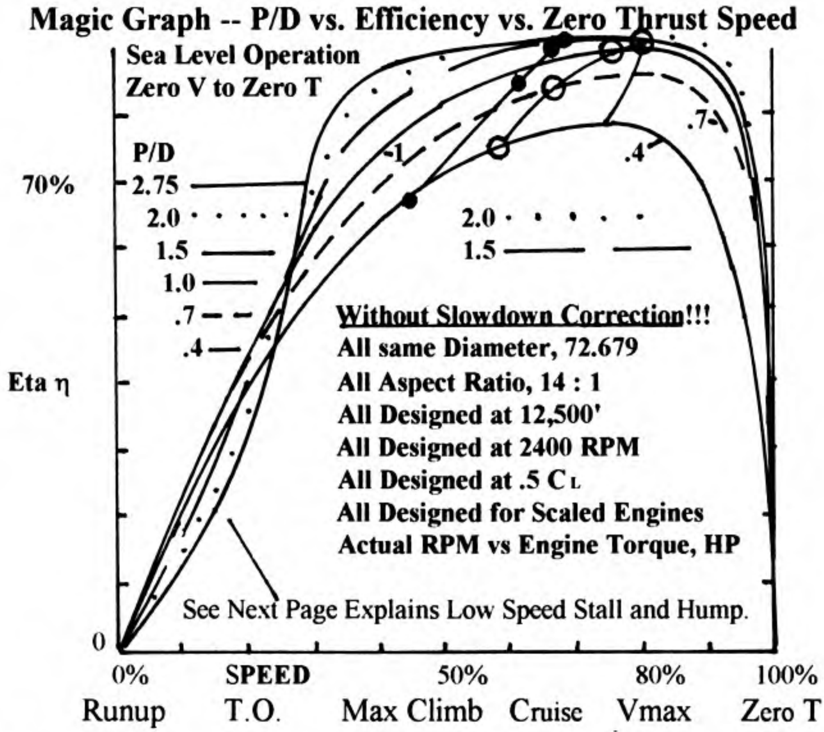
1. Creating ΔV, extra wind, to make thrust costs, ***hurts efficiency.***
2. **Fast V --- increases $\dot{M}$, reduces ΔV, lowers $\Delta V/2V_1$** ***twice!!***
3. **High pitch *indicates* high propeller efficiency!!!**
4. Surprise, propeller efficiency is really *a "traveling" system efficiency* that ***wants*** **high plane V, low plane drag, low engine RPM**, all of which **result in *high pitch, high blade angles!!!***
5. The computer's job is to **design the prop blade** ***to actually meet the ideal efficiency limit*** set by **Plane's V, drag,** and **RPM!**

Remember --- AR also limits efficiency!

It all makes sense: High pitch goes with high V, thus high $\dot{M}$, thus low ΔV, a steep corkscrew path, thus high efficiency!

Thus BOTH INDUCED and PROFILE Drag Energy are LOWERED.

Pitch / Diameter, P/D Ratio -- A Shorthand for Blade Angles. Whereas *Advance Ratio* deals with the *velocity ratios*, forward vs. rotational, the advance angle or ratio, which ties fairly directly to blade angle considering V, ΔV/2 inflow, slowdown, and α° -- **P/D simply directly nails actual blade angles**. An F1C model prop, 3" P / 7" D = **.4268**, is poor, below 75 % *max* efficiency. A 51" P / 71" D Luscombe prop, P / D = **.7183**, still compromised at 85% efficiency max. ***The RV6 1.128 P/D ratio, (79" pitch, 70" diameter) allows a fine ~89% efficiency.*** **Go for a P/D of 1+** ***~1.3 to 2 P/D maximizes at ~90 to 91%!!!***



This Graph provides marvelous insight into the Potential Efficiency, and ***No Slowdown*** **Stall Characteristics of normal and abnormally high and lowP/D props**. (Like the Super Magic Graph, RPMs are those allowed by engine Torque And H.P, until finally limited by Max allowable RPM — at each speed, a percent of the Speed where they fall to Zero Thrust in a shallow dive, at 2700 RPM).

Props usually range a little below or above **a P/D of 1**, a **51" P/71" D Luscombe Prop .718**, a **79/70 RV prop 1.128**. Early Spitfires actually used a fixed pitch prop, let's say 2.75 P/D where a *non constant speed* Reno prop would calculate, see p. 51 II, something you'd never do today. A 29,500 RPM, 3"P/7"D F1C model prop would be .428 P/D, for a low range example near .4.

Computer runs show **actual efficiency** and **stall characteristics.** (If, for example, we used a constant RPM, say 2400, **the graph would lie to us at low speeds** because at low speeds where 2400 RPM was *more* than the engine could drive, a false excessively high angle of attack would calculate a false premature stall as speed slowed, *a worthwhile insight to correctly understand what happens here physically*.)

If we were to list the angle of attack at each radial station on the high pitch props, as the plane slows down we would logically find the **high β angle inner radii stalling first**, the stall moving progressively outboard as the plane slowed more, finally causing the **overall efficiency to drop into the S curve you see on the slow end of the efficiency plot**, **worse at high P/D**.

The somewhat impractical, extreme 2.75 P/D case shows a very insightfull characteristic on the computer data. The whole inner part of the prop stalls so badly slow that the **RPM is actually higher at runup than part way into takeoff as the inner blades progressively unstall. The attention getting insight is that those very high Beta, β angle blades are lifting, not forward, but significantly counter to the engine Torque, so the engine RPM actually drops as you speed up**, the blades unstalling, fighting the available opposing engine torque ***more!!***

You can see how 1.5 and 2 P/D fit into that logic --

There, ***slow (but faster)***, the **RPM,** ***is so decreased that the RPM is a much closer match to speed***, lower α°, less ΔV, less thrust slow, but this **allows the efficiency to swoop up abnormally quickly, looking quite favorable** until you figure out that it's happening because **the abnormally low RPM lugging prop** is doing ***a poor job of providing takeoff thrust***. Those early Spitfires would have been dogs on takeoff! Old comments say those **1930's Schneider Cup races** were **for Seaplanes *because* of ridiculously long takeoff runs, airport runways too short**!

The opposite effect is found on very low P/D props, high RPM maintained at low Speeds *because* the blade angle is *not* pulling against the engine Torque as much as at higher pitch, and RPMs remain much higher as Speed slows down.

The three locus lines at the top of the curves are **the peaks on the right**, the **Vmax 2700 RPM case in the middle**, the **actual design point (at altitude) on the left, (not actually on the curves.) Notice low P/D with greater induced drag and excessively long corkscrew path is penalized operating well below peak!**

Gearing, ***often impractical****, **you can *always* create an ideal 91+% prop efficiency, a high J, if you gear your engine for low RPM, hi torque, hi pitch,** ***a much larger diameter prop,*** **more Ṁ, to give the required thrust at the lower RPM!**

With Larger Diameter Prop Tips Fall To Lower Angles,** ***Counterproductive vs. J!!!

Another way to think of the high pitch correlation with high efficiency is to simply grasp that a prop blade passing can only impart a limited ΔV at a proper lower α°, C_L, efficiently, and at high pitch, high speed, it's adding less in proportion at a high V_1, another view of a favorably lower ΔV/2V_1, thus a low loss ratio, thus high efficiency, *not* hard!

T he "Twice effect of V", is exactly comparable to the V^2 reduction of Induced loss!!

Yes, this is a headfull the first time, if you've never dealt with science and Physics, but ***if*** you hung in and got it, compliment yourself. Do recognize it is ***not*** possible to strain your brain!!!

We could start right now to teach you what a pilot needs to know ***to operate*** a prop more intelligently, but that is easier to do, and better, *after* you have a good bit of your new insight nailed, so let's wait a bit longer, and you can get much smarter.

Blade Angle Accuracy -- An Example, +/- .1° Required

The key insight is there is ***only .95° difference*** at the 3/4 radius, between a 48P-71D climb prop and a 51-71 cruise prop. That's ***not a tolerance,*** *but* **the whole range** from a *free turning climb type to the opposite kind, lugging the engine!* Thus, only ***.1° is a proper design and manufacturing tolerance to hold manufacturing consistency of thrust and engine torque load!***

I brought my 1951 McCauley 51-71 Luscombe cruise prop to a client's factory to do a granite table "plate check". My 51" Pitch cruise prop had clearly been twisted from a 48" pitch climb prop forging, ~ 48", less at the root, ***a constant 29° in front of the cowl for slowdown***, ~ 51" at the crucial, working outer radii. Checking, I found **McCauley's shop tolerance is only +/- .1°**, good reason and need for that accuracy!!! More later --

Blade C_L, An 800# Gorilla -- A Rotating Wing Calculation.

We do also calculate propellers as rotating wings -- Area, C_L, q. (Remember q is the ram dynamic pressure, $\rho V^2/2$.) The big complication here is that ***bigger D creates faster tips, (and bigger $\dot{M}$ too). D, and Shape is thus firmly tied to the Area calculation,*** and controlled by your aspect ratio choice! Imagine, if you calculate a prop as a rotating wing, logically ***a definite Area-Diameter-Shape is needed to get a specified thrust at a given RPM, Speed, ρ, and C_L.*** Now, *if* you **arbitrarily change a .4 C_L to a .5, that's *a big 25% increase*, and you've grossly changed the Area-Diameter-(Shape) required.** *-Realize C_L is an 800# Gorilla!*

Since ***only*** **1° is equivalent to .1 C_L**, prop ***angle tolerance needs to be quite accurate, simply to hold the design C_L and an accurate match to the engine torque and airplane drag combination!!!*** My ***cruise*** prop, **.95°**, more than a climb prop loads my engine enough that it won't quite reach rated RPM, Vmax at sea level, 2545 not 2575. ***.1° manufacturing tolerance is really appropriate.*** **Overall angle errors can completely destroy the intended engine-prop-plane design balance!!!!!!**

(*However*, the twist error of a constant speed prop, maybe 5°, ± .25 C_L changing from design to flat pitch *average out, not a big effect on η.)*

Specific numbers: A computer design study, (without slowdown), near the end of Ch. 3, next, in the book, shows a **.3 C_L demands an 83.7"** prop for an RV 6, whereas a **.6 C_L drops the required diameter to only 69.1", AMAZING! A .55 C_L requires a 70.8" fixed pitch prop, about what is usually used.** That was a huge insight for me the first time I saw it!

C_L selection, and holding accurate control of blade angles turns out to be *absolutely fundamental* to *both* hitting a design match for your prop, engine, and plane, and getting consistent results from a production run of propellers. Otherwise, engine load, needed diameter, or speed lose balance! ***How's that for an insight different than you might expect?***

Aspect Ratio -- Maximizing $\dot{M}$ - Minimizing Induced Drag.

Just like a sailplane wing, a propeller blade likes to have the ***highest practical Aspect Ratio*** (Span/average chord). ***Big diameter*** has the **least induced drag**, but now you're prepared to recognize **the maximum $\dot{M}$**, thus the minimum **ΔV, the *minimum ΔV/2V, and tip induced loss for the max efficiency***. It would seem to be an easy decision to use a high aspect ratio, but **prop vibration can be very complex and *treacherous***, and can quite literally kill you, so be cautious, no rash moves. We used the outer 90% to calculate Aspect Ratio, **the Luscombe is 14:1**. ***The inner radii are very ineffective***. A spinner reduces core drag.

LATER, WE NOW USE 10, 8% SPACES, 19% TO 99%. A 14:1 A.R. = 12.6 NOW!

Blade Twist - Modifying a Helical Pitch Blade for Ideal Twist

The objective of the classic propeller analysts has been to simply cause ***an imaginary Rigid Vortex Sheet, of constant pitch*** -- by geometrically creating ***constant pitch helical wind inflow angles phi, ϕ, stretched outflow*** at each blade station, ***constant (simple case) prop blade angle of attack, thus C_L, and proper chords*** to match, (to actually make that C_L happen). That takes a fairly complex geometry accounting for plane speed V, the inflow **ΔV/2,** the stream tube and prop rotation. That's all shown in Ch. 3, the graduate course. **But recognize it is *fairly close* to the simple helical blade** shown a few pages back, **just a little different to hold a constant angle of attack alpha, α, simple enough in concept, *not*** hard to grasp, really. (You'll learn in the geometry in the advanced chapter that in accounting for **ΔV/2** and rotation, Theodorsen's, or Glauert's math accounts for the ***half downwash, (inflow) at the prop***, thus the change to effective angle of attack, that lift creates, making it easy to grasp) That needs to be ***modified:*** The pitch needs to be ***unwound more and more as you move inward***, because of the bubble of air the fuselage pushes ahead, causing ***a highly variable slowdown vs. radius***, amounting to **17 1/2 % at the 13" radius** on the Luscombe prop, about **4.64°**, **4.8 % slow at the tip, .597°**

Calculating a Propeller's Area, Diameter and Shape ———— **Remember, we're** keeping this the more simple explanation for. pilots, indeed everyone, **to get everyone a good first grasp of the super important logic overview**, purposely avoiding the excess detail that we might mistakenly try to cover before you grasp the basic logic. *This is a subject that becomes much easier to grasp once the light bulb comes on, and you tumble to your first grasp of the overview.* But begin to realize, recognize, ***appreciate the wonderful capability of the modern personal computer*** *that can* ***accurately*** *deliver the complex flow field angles shown in the last section to* ***.1°! It's a modern wonder!***

Now realize this: **The game is to calculate a prop that will deliver the specified thrust, at a given RPM, speed V, altitude density ρ, and C_L Once you select the highest blade aspect ratio that you dare, you have, by that choice, set in concrete the *relationship of needed blade area to diameter*, and, in fact *the blade shape also*, *because* the math will give the planform shape, the cord widths, to give the C_L and *ideal lift distribution which comes from constant pitch airflow!***

Though wildly complex inside the computer, do you see that it. has become something acceptably simple to grasp, to understand? The computer does the wildly complex task of determining *the wind inflow angles, the ϕ's at each radial blade station*, **proceeding just like it was doing a straightforward wing area calculation, *except the desired area-diameter-shape aspect ratio is held***, and all for the twisted wing like prop blade! **Just grasp that you need a certain *"size"* blade to deliver the needed thrust at the given RPM, V, ρ, and C_L -- just like it was easy**, when it's an essentially impossible calculation by hand.

We **understand the logic using $\dot{M}\Delta V$**, because that most easily. allows us to see the hidden logic. Rotating Wing, Blade Element Calculations don't really give correct answers. But we use Theodorsen's 3D precise method. ***Grasp the easy view here.***

A SMARTER GRASP OF PROP OPERATION

Your Engine's Transmission, ***Fixed Pitch vs. Constant Speed*** Have you recognized yet that your propeller is your engine's transmission, and that ***a fixed pitch prop is, in fact, a single gear transmission***, with *a quasi adapting fluid coupling*. But **the variable pitch, constant speed prop**, is, in fact, the near perfect **infinitely variable transmission**. There is a *twist error at low pitch*, ***slow***, ~ 3° to 5°, (presuming a cruise design point).

THERE IS LESS TWIST, LESS ERROR, WITH SLOWDOWN CORRECTION

The ***surprise*** here is that the **constant speed prop *also* has low efficiency, slow**, *because* it's doing an even better job of making **ΔV, extra thrust, extra wind that is going to be wasted**!!!! It's a far better transmission, because *it allows max rated RPM, thus max HP* at any speed, offers *max thrust availability*, but slow, at low pitch, you've learned that ***still gives low eta, η!!!***

AS ABOVE, THERE IS ALSO TWIST ERROR, LESS WITH SLOWDOWN CORRECTION.

Fixed Pitch Recognize from Andy's Magic Graph, that right from runup, through climb, cruise, Vmax, and finally to the "zero thrust RPM and diving speed", **the angle of attack is always decreasing** --- from what can be a terribly overpitched condition at run up, worse on otherwise efficient high pitched props, even worse at the higher angle root radii. Especially on the efficient high pitched props at run up, the air cannot be pulled in fast enough to not stall, and even outboard it's operating at inefficient excess angles of attack at high drag. If you just grasp the horse sense of it, it's no big surprise that you can only turn 2000 RPM, or so, at runup, the engine torque way overloaded, and at a lot less RPM than you'd like in slower max climb. I cruise climb, get more RPM, HP. The prop is more efficient as speed increases, and at more reasonable α° vs. radii.

Our thinking here presumes Wide Open Throttle Operation

You automatically fly at lower efficiency every time you try making extra thrust, because you're making extra ΔV, which gets wasted, and ***fixed pitch***, **slower than design cruise**, you're ***flying the prop at high angles, lugging the engine at poor RPM***.

<u>The Constant Speed Prop</u>. Every engine needs a transmission to match its ***<u>RPM</u>*** and ***<u>torque</u>*** curve to the individual application. The *Constant Speed*, though it ***does <u>not</u> hold low RPM, hi pitch, hi η***, is the near perfect, infinitely variable transmission, ***<u>from the engine's standpoint</u>***, no confining gear ratios, ***<u>any variable load</u> you need to <u>always allow max rated RPM, thus max H.P.</u>***

The **downside is from the propeller's standpoint**, where **high RPM**, desirable from the engine's standpoint, is ***<u>highly undesirable</u>*** from the propeller's standpoint, ***the related <u>low pitch still inefficient at max thrust</u>*** **<u>for takeoff and slow max climb</u>!!!!** The good news is max power is only used for a few minutes, **the dollar cost of that prop inefficiency negligible**.

<u>Cruise Efficiency</u> The **constant speed prop is still a hugely important contributor to propeller and flight efficiency**, in a way that is ***<u>insufficiently understood in the pilot population</u>!!!*** The low pitch, max H.P. case is ***<u>not</u>*** the really important usage. **The really important need and usage for the constant speed prop is to be able to <u>pull back to low RPM</u>, <u>lower H.P.</u>, *<u>higher pitch</u>*, <u>limit the H.P. output</u>, <u>get your engine wide open at the lowest possible altitude, for the highest possible engine efficiency</u>, lean the engine at well less than 75% H.P. --- <u>get the plane and the engine ideally matched, the central objective of this book</u>. Remember, <u>the lower the altitude you can get your engine wide open, the more efficient your engine can be</u>, because altitude hurts engine efficiency, but you <u>must get it wide open and leaned first</u>, and *<u>at the IAS and/or angle of attack for the plane's best speed vs. drag</u>!!!!***
You don't know actual blade angle, but it's always as steep as the engine can turn. Pitch variable, a .5 C_L gives a bit more diameter!!!

That's a bit more efficient, but Heavier

<u>Gearing is a Separate Subject</u>. Don't miss the point that **a geared, low RPM, larger, high pitch prop would give *<u>more</u>* <u>thrust at higher efficiency</u>, (*<u>but</u>* <u>more weight</u>), on *<u>any</u>* <u>low pitch case</u>!!!!** ***BIG, fast planes need a BIG, geared, <u>low RPM</u> prop to develop BIG thrust, and <u>stay below .9 Mach tips</u>!!!!***

The Propeller, A Different Kind of Machine

Propellers are the unusual case, different than other machines in a fundamental way, and that, you'll see, is a fundamental reason why we have to teach you a seemingly unusual logic of why they work the way they do. In say, an electric motor, there is friction and heating, and those ***peripheral*** losses, that you can't get rid of, account for the efficiency losses, as you pull torque, and rotary power out for useful work. The torque, the power is the product. The efficiency losses are ***peripheral*** to the output.

Of course, more load, more power does generates more peripheral heat loss

In a propeller, the situation is fundamentally different. A **propeller must make ΔV to make thrust, and *that ΔV itself*, the product, *the necessary product to make thrust*, is a *central part of the efficiency loss!!!* That is *fundamentally different* than machines where the losses are peripheral. *You don't see through that looking at it as a rotating wing!***

Next, ***a propeller is quite different, in that, it's the Plane's Speed and Drag, the Engine's RPM that sets and limits the prop's max efficiency*** η, (if it can't be geared to restore the ideal high pitch math relationship). ***The prop is only able to reach the max ideal eta set by the plane-engine. It can't raise the max!*** √√

Only gearing for lower RPM, higher pitch, big D, or **high AR**, can raise the efficiency limit.

When engineers talk to each other, they discuss the math, the very complex leading edge problems on how to get the very challenging analysis correct. **We never got a true explanation of the logic, because that's *not* the challenge to them**. There's another problem. When you've done all the math correctly, made the computer print out correct answers, you're ***not*** done. **The numerical answers processed inside the computer do *not* make the logic clear. You have to go far beyond that to define and write out the logic**. That's very difficult because there are a ton of subtle and very complex interrelationships. **It's the *next step harder* to sort it all out, and say it correctly in logic and plain English**. Much of the ***advanced insight purposely skipped here, is in the final chapter and conclusions***. √

Overall Propulsive Efficiency -- A Second BIG Loss.

The biggest gap in Aeronautical Engineering is failing to understand and comprehensively deal with the *other half* of propulsive efficiency loss! *But now we're getting to the facts!!!*

Gus Raspet, a somewhat legendary Aero Professor.at Mississippi State, did towed, **propellerless, glide tests** of several private aircraft in the mid 50's. ***He found proper drag numbers!*** *That was **not** **favorable**, **because compared to the power required to fly the planes, it proved disastrously bad propulsive efficiency**!!!* The Bellanca Cruisair, a plane most thought well of, was a disastrous **58%, ducts sealed, vastly worse than any possible propeller efficiency loss**. Cubs, Cessnas, also did poorly. He provided the needed breakthrough insight, and hard, ***absolutely irrefutable data***. But the industry never picked it up and did anything comprehensive with it. They were *stopped, no way of getting safe, valid glide test data*

* THERE CAN BE ~10% COOLING DRAG, THUS ~ 68% WITHOUT COOLING LOSS!

Andy and I took that on as a challenge in the 80's, first with crude tests, then with credibly accurate analysis of zero thrust RPM's and glide tests, accurately accounting for slowdown. ***Finally, we did very accurate glide testing*** *accurately sensing the movement of the prop from thrust to drag, as it moved back in the crankshaft bearing* ***endplay***, with a vibration proof, high natural frequency model airplane wire feeler, lighting a sensor bulb. That solved the most basic, longest unsolved problem in flight, ***how to test for accurate drag of a fixed pitch prop plane?***

There tends to be two losses, that multiply to a **bigger overall loss**!!!

We confirmed Gus's great pioneering work on my Luscombe, with **Zero Thrust Glide Testing**, overall eta, η, from the low 70%'s at low power, to the low 60%'s at high power, an RV6 and a Whitman Tailwind, at the CAFE Group in Santa Rosa, at 80 %+ overall at Vmax, ***much better***, a poor Luscombe 75% η prop, vs 67% overall loss, there can be ***EXTRA SCRUBBING DRAG***. We now need some loose Lycoming engines on worthy planes to carry the initial work forward in a next phase.

Blading Efficiency - ~ 45° β Best - **Profile Drag Isolated**

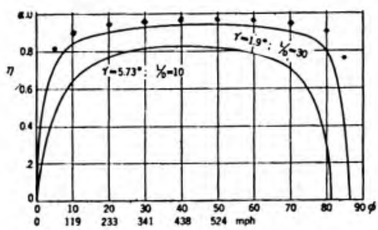
For $2.50 in 1944 Wartime dollars, at age 17, my Dad bought me a copy of Wilbur C. Nelson's "Airplane Propeller Principles"*, a great text, even if it didn't show the essentially final incisive insights that we have here, compliments of Betz, Goldstein, Theodorsen.

A basic Vector Analysis of prop Lift and Drag vectors shows:

$$\text{Efficiency} \quad \eta = \frac{\tan \phi}{\tan (\phi + \gamma)}$$

where: phi, ϕ, is the air inflow angle; gamma, γ, is the drag angle C_D / C_L

Thus, efficiency depends only on inflow angle, and drag angle, γ. A little Calculus, differentiating that vs. phi, ϕ, equating to zero, we find **optimum blade angle is 45° - γ/2, half the drag angle**, which for **.5 C_L**, ***.01* *low Rn* C_D**, is 50 : 1 L/D, **λ/2, .02/2 = .01.** Arc tangent of .01 = .573°, thus 44.43° β° optimum, ***nominally*** **45°**. Now look at his plot, but imagine a **50 : 1 L/D, just for profile**.



Simple Blade element efficiency variation. - **Imagine Profile *only*, at 50 / 1 L/D** · ·

Where Nelson does a simple derivation, doesn't distinguish between profile drag and Induced loss, thus plots lower L/D's, doesn't specifically include air inflow and rotation, but shows an imaginary, oversize angle of attack, Glauert uses a more complex derivation and final formula **just for profile drag** and gets higher η, similar curves, **valid at a *profile only* 50 : 1 L/D.**

The very ***important key, basic insight*** here is to see that **profile losses are low**, but are ***larger at very lo and hi blade angles!!!*** Andy's accurate program using **low Rn C_D's** works comparably.

 *Proper Credit is Due John Wiley and Sons, great texts!

A **Super Magic Graph** for a **Prop Corrected for Slowdown**?

The Super Magic Graph on page 45 II gives great basic insight on a theoretically perfect Theodorsen prop for an **RV 6** at various speeds, slow, all the way through shallow dives at zero thrust, 2700 RPM, 257 MPH, the prop running out of adequate pitch that fast. Great insight, but it's **misleading at slow speeds**, because **proper slowdown corrections are large enough inboard** that they **work significantly better**, ***not stalling inboard as early***, with the significant blade angle corrections, greater inboard ---

The first theoretically exact prop, **Triple Ideal,** Minimum Induced, Minimum Profile Drag. Min. Torque, **for the RV 8, designed for 220 MPH, 2700 RPM, 150 HP, 75% power at 8000', corrected for slowdown, it can work much better slow** than the uncorrected comparable RV 6 prop. We planned to give you a slowdown corrected Magic Chart for ***comparing***.

SORRY: We Intended to give you a Slowdown Corrected Super Magic Graph, as our Last Goal Line Task, but the computer program didn't want to run with both Slowdown Corrections and all the "Off Spec. Conditions" of the Graph. With no time to solve that we had to Pass. But below, see the ***RV 8 Slowdown Beta Angle Corrections*** for the Various Radii. This can give you a pretty good feel for the significant changes!

% Radius	Beta Angle °	Reduction °	Final Angle °	
19%	65.888	-17.649	48.239	
27%	57.315	-11.810	45.505	**Remember!**
35%	50.164	- 7.559	42.605	We're trying
43%	44.282	- 4.800	39.482	To **Hold .1°**
51%	39.453	- 3.081	36.372	Blade Angle
59%	35.471	- 2.023	33.448	**Tolerance!**
67%	32.161	- 1.367	30.794	
75%	29.383	- .953	28.430	For **+/- 2%**
83%	27.029	- .685	26.344	Consistency
91%	25.015	- .506	24.509	of Product
99%	23.277 **42.611Δ**	- .383	22.894 **25.345Δ**	

CONCLUSIONS

We have purposely ***not*** **covered all the material in this, more basic Chapter**, because in market testing, we found it would **drown you with way too much too quick**. If you first *grasp the logic, the new thinking, in this Chapter,* ***let it soak in*** *until you're comfortable with it*, it is ***then*** *much easier to tackle the* ***Graduate Chapter 3*** with all the **final Professional Insight**. ***Then it doesn't seem too tough***. ***The goal is to make it easier***.

We can give you a great set of conclusions that even go past what you've earned so far, get you quite far with min. effort!

1. A **~91+%** efficient prop can always be designed by gearing it for optimum advance, high pitch, (low RPM, high Torque, big Diameter, but diameters often too big, impractical). Gearing is common on excess RPM, slow, high drag, otherwise low pitch, inefficient ultralights, and large fast planes that need **high H.P., BIG, low RPM, multi-blade props**, for very **BIG thrust, while avoiding sonic tips**.

Very high fighter Speeds, make Prop Diameters Reasonable!!!!

2. **NACA postwar testing**, targeting 1% accuracy, showed **91 to 92 % efficiency**, *even with constant speed prop twist error,* ***until low pitch, or exceeding .9 Mach tips degraded performance***. Significantly, however, ***those tests were with limited diameter, symmetrical drive housings***. **Real airplane tests with large embedded bodies**, unsymetrical, inefficient cowlings, can produce **larger losses** than those predicted by *extra stream tube velocities*, thus, *not* just extra scrubbing drag!

Ham Standard charts show a 91.5% sweet spot!

3. **Fixed Pitch,** without gearing, **maximum propeller efficiency is set** ***and limited by*** **Plane** ***Speed V***, ***(and drag)***, **and Engine** ***RPM***. Propeller efficiency is ***actually a Traveling System Efficiency*** in which the ***blade plays a limited, but finally very important role***.

4. **The Classic Betz Prop and Computer Design of propeller blades Targets the maximum efficiency limit theoretically possible!** ***(But, now we see Elliptical Lift Distribution can do better!)***

5. Plane **V, RPM, and prop C_L**, are ***Three key Unrecognized Giant Gorillas***, of propeller design logic, ***because they exert very powerful, and generally unrecognized, control of thrust, efficiency, and required propeller size --- as follows.***

High q tips, needing counteracting, and Diameter are also powerful Gorillas, 5 Total

6. **High speed, high V, thus high mass flow rate $\dot{M}$**, through the propeller disk area, **directly lowers ΔV, the *extra wind* required to make a required thrust**, and provides ***a larger V_1*** as a ***divisor to produce a lower axial efficiency loss,*** $\Delta V/2V_1$. Though ***axial loss is but one of the four basic losses, axial, rotational, and radial stream tube losses, and blade drag loss***, ***doubling speed, cuts the ΔV based loss ~ in half, and in half again as the percentage divisor --- dropping the induced loss to ~1/4 if the drag and thrust are not changed, key basic logic***

(*Finally, higher V produces a smaller D, showing the complex interplay!!!*)

(~) Less $\dot{m}$ to $\dot{M}$ increase with a lower delta V, thus *not* exactly in half, and 1/4.

7. **RPM vs. V is *the* primary controller of propeller pitch! *Thus*, it is the primary controller of propeller efficiency**, *with V*. It's thus, ***far more important than is generally recognized!*** **Engines want *high* RPM, for high power at light weight**, but **props want *low* RPM for high pitch, high efficiency**, exactly ***opposite, directly conflicting requirements***. ***Gearing can, might help!?***

Understanding C_L, next, is complex, one of the secret insights on props!!!

8. **C_L, Coefficient of Lift**, ***can directly distort required propeller Area-Diameter***-(Shape). With a change of just ***1 degree α, .1 C_L representing the difference between a cruise prop and a climb prop***, ***C_L is capable of great mischief***, major effect, and ***by distorting D, changing assessment of J = V/nD or P/D.*** BUT,

Props act forgiving, --- But Realize a missed design, a low α° and C_L allows, *but demands* more engine RPM, more fuel usage. Excess α° and C_L lugs the engine, less RPM, HP, Speed! Design Study shows a .5 to *.55 C_L is a proper cruise-climb choice,*. *.5 C_L* Constant Speed

9. **Blade Accuracy Required, +/- .1°** Because any blade angle errors can directly distort the actual C_L, thus the required prop Area-Diameter, and the engine load, required angle accuracy is much tighter and much more important than is generally realized. ***However in repitching, it's the owner's way to fundamentally change engine load and propeller characteristics, if desired!!!***

10. **Pitch must be accurate to hold C_L** (vs. speed, RPM, inflow, rotation, slowdown). *Then*, **Blade Angle is *the simple indicator* of *potential* propeller efficiency**. (The **ideal is a *45° blade angle near the 2/3 radius*, a J of 2+, a J/π of ~.6+, a P/D of 2+, *very steep, 91% eta, η, but, like the RV6, near the 1/3 r, J/π .34, P/D 1.13, only costs ~2%, then drops as pitch flattens!)*** **On an efficient RV**, slowdown can equal inflow ΔV/2, plus angle of attack. *Thus,* **Vmax in ft/sec can be ~equal to a direct calculation of revs/sec times the needed pitch in feet**!! A slow, draggier Luscombe is ***only 95% of that!***

With the flat top of the Advance Ratio Curve, efficiency gets poorer below a P/D of 1+, a J/π of .33, stays good above

11. **Blade Twist** To obtain a theoretically ***ideal blade loading*, airflow angles, φ, are arranged analytically to have simple helical pitch,** ***a Rigid Vortex Sheet*, to which, typically, a constant angle of attack, constant C_L is added to obtain blade β angles**, and matching chords shape to really get that C_L. ***To account for fuselage caused slowdown, Luscombe 35% radius blade angles need to be unwound* 6.14°**, the tips **.435°**. (Blade angle and chord can be traded, but more drag if wider. ***We teach constant α and C_L as*** the standard simple, and best case.) A constant speed prop's low pitch twist error averages out -- though analysis targeta a ***rigid vortex sheet, precise Betz blade loading*** **vs. radius.** Flight tests can show large interaction losses, covered in Chapter 3 II. Separation can also exist, with stream tubes distorted from large, very unsymmetrical cowlings upsetting flow coupled with energetic blade tip spiral vortices, key insight.

12. **Aspect ratio** As previously described, **the highest safe AR is proper technically to optimize efficiency**, but risk of deadly vibration or structural problems cautions against any ill advised moves, that can, in fact, kill you! **Half the Axial ΔV stream tube loss, and the full tip loss is exactly comparable to wing induced drag losses that sailplanes minimize with long spans, high AR, max Ṁ. -- It's fundamental, *but* be cautious!**

Props do have Rotation Induced Loss too, that wings don't ---

13. **Blade Area-Diameter** The proper thinking here, wildly complex inside the computer, is dead simple. ***You simply need the proper Area-Diameter-Shape to deliver the required thrust at the V, RPM, altitude ρ, and C_L intended***. ***Caution on C_L distortion.***

14. **Blade Shape** That beautiful Spitfire elliptical wing has that shape to **deliver *minimum induced drag*, *constant downwash*, *optimum elliptical lift distribution*, *constant C_L's with ideal elliptical chords*.** Now, think of turning that Spitfire wing shape into a rotating prop, the ***tip now rotating twice as fast as the mid radius of the wing half, 4 times the q*** - *if not also moving forward. **The prop-wing will logically become highly tapered***, if it is to have ideal Betz loading, ideal lift-thrust distribution!!! See the highly tapered shape of ideal computer calculated chords on page 147 I, and realize that **broad tips, (high activity factor) are for power absorption, *not* for efficiency**. Broad, loaded tips are thicker, stronger, *more reworkable*, but manufacture excess losses and noise, *almost like reverse taper wings*! Older NACA tests show broader tip props can produce **more static thrust**, ***but they require wasting power to do that***. ***Unwinding a wider tip can hold proper loading, but costs drag, RPM, unless into Mach V's!***

15. **Sonic Limits** Mach 1 on a standard 59°F day, (518.7°R) is 1116.46 ft/sec, 761.243 MPH, and **decreases at altitude proportional to the square root of the absolute temperature**, ***unaffected by pressure***, to 968.09 ft/sec, 660.06 MPH at -69.7° F. at 36,089', the beginning of the supposedly constant temp. stratosphere. Even relatively thin airfoils may have a 30% speed up, which can cause standing shock waves, like you can see on a jet wing surface on an East or West trip when the light is correct, but they are *weak shocks*. **Tests show the drag rise really starts at .9 Mach, 1004.84 ft/sec, 685.119 MPH at sea level, 871.28 ft/sec, at the stratosphere**, and ***the vector*** of forward and circumferential V ***must be kept below that .9 limit***. ***A 6' prop at 2700RPM, 250 MPH, is at a 924.1 ft/sec vector V***.

So how's that for an understandable, penetrating insight, and conclusions on Aero's most complex subject, propellers, without having to deal with the hugely complex math and computer programming, the technical, horse sense logic put to words? There's more but it properly comes in a next step.

TEACHING PROPELLER LOGIC

My experience with explaining propellers has taught me to ***not*** feed people the whole McGilla in ***one gigantic dose***. It can be just too much. Most people **need time to become comfortable with all the surprises and new logic**. I believe you'll find the subject much easier, if you perhaps reread all, or part of this, **let it soak in**, **make it your own**, then do the advanced chapter.

When engineers discuss complex subjects like propellers, they do it in technical papers, with complex math, feel justifiably fulfilled when they conquer, refine one next step facet of the complex riddle, but because of all that, ***almost never deal with the overall explanation***. I believe their necessarily targeted focus is the reason we never got a comprehensive explanation of the overview, because the lesser guys, not at the leading edge never were able to get their mind around the myriad of complex interrelationships. ***We've been through all the expert's work, the complex math, checking it all, dissecting it, to try to nail it***.

For Engineers, the core of Theodorsen's math is in Appendiox T --

There are three reasons you don't see the heavy duty math here. Regular people don't want math, can't understand it, are just put off by it. Second, ***the objective here is to get this never adequately explained subject into words, a few picture graphs, a simple core formula, or so, to nail the heart of the technical logic, make it understandable horse sense logic***, so a regular guy can grasp it, if he's willing to try hard, hang in and actually get it. Third, don't misunderstand, getting it into correct words is just as hard as the math, in some ways harder, because only the human brain can do what even the computer can't, grasp the hidden logic, and put it into words. If any of you engineers out there doubt that, try it. You might be surprised to know that after we got the words nailed well enough, we had multiple instances where the words, corrected the math and the computer! Multiple times the logic showed us the math and the computer were temporarily wrong, an obscure error not caught.

Propeller Computer Analysis - One way of looking at it: **Betz** in **1919** conceived the "**rigid vortex sheet**", optimum logic. You'll learn the highly ***variable axial and rotational air particle motion combine to form a perfect helical screw surface***. The trick is to get the computer to design the **blade angles** β, **chord, and angle of attack** α**, to make that miracle happen** for each blade element, to get the **least induced loss**. It's a rotating wing, somewhat akin to ***Prandtl's optimum loaded elliptical wing***. **Glauert, 1934**, got the ***inflow and rotation essentially correct for somewhat simplified equations (using Prandtl's F Factor)***. It's ***simple helical pitch***, not of the prop blade itself, but rather of ***the air flowing into the prop blade stations***, *at helical angles, phi*, ϕ, logically adding a *constant angle of attack*. With proper blade chords that gets Betz's ideal inflow and loading *(ΔV/2 in, slightly stretching, helical + ΔV/2 out.)* One pro's solution uses sixteen basic equations, algebraically reduced to four, the computer almost instantaneously **iterating a trial and error solution** for the multiple blade stations, finding **the wind inflow angles for** a twisted wing calculation setting α, C_L, to get all the data and integrated answers. ***The angles are then unwound to lower pitch to account for body/nacelle slowdown***. A refined program code yields full data, *separately, an off optimum speed analysis*. **Theodorsen in** 1948 solved **3 D flow, axial, circumferential, and radial, *for heavy loading*, high advance, for ideal props!**

But it turns out that only Theodorsen's Math gets really correct Betz Answers!!!

The Axial and Tip Vortex Loss is Really the Induced Loss!

Here is the great insight that brings together the unique prop stream tube logic, and the wing induced drag insight you learned much earlier in the book, because they're really the same thing! Remember that when you ***double the speed V***, you also double the natural mass flow through the prop **ṁ**, and as a result, cut the needed **ΔV** in half, ***if drag not increased, ignoring ṁ to Ṁ increase*** Now you can see that ***the ΔV/2V$_1$ axial tube loss is cut to ~ 1/4 its previous value, because the V divider is doubled as ΔV is cut in half, cutting the axial loss to ~ 1/4!!!*** That's the secret!

67 II The Double effect of V is like 1/(V squared) Induced loss.

Now, remember way back, much earlier in the book, that a profile drag curve is a V^2 curve, whereas ***an induced drag curve is a $1/V^2$ curve that drops to 1/4 if you double speed***. The same thing is happening in a stream tube due to prop thrust*, as is happening in the downwash from a wing, ***they're both just the same old induced loss, perfectly equivalent****. In both the prop and wing case, the tip vortex loss is part of the induced loss.

***As ΔV/2V affects the ṁ to Ṁ change, it's not exactly 1/4, a fair amount different, but similar.**

The equally valid stream tube logic and explanation, however, is the way we can most easily get you aboard to grasp all the sequential surprises of prop logic that even smart guys have trouble getting through their head. *Don't feel alone out there* --

Realize, the **rotational loss** is **unique to propellers!!!** ✓

Now that logic happens just exactly as explained, but ***in the real world, more happens***, but the computer program handles it properly. As you go faster the complex algebra also shrinks the prop diameter. Props are a mine field of interrelationships, such that you must be very cautious of extrapolating what we teach you, or you can quickly be awash in wrong conclusions. Don't be afraid however, ***those 15 Summary Conclusions have already given you a wealth of insight on propellers you didn't have a few hours ago, and never would have found in any other book!***

A Summary Insight of the Efficiency Losses. At higher speeds, as you can see above, ***the $\Delta V/2V_1$ axial loss effect almost collapses as the key propeller energy and efficiency loss***. A *lower level of both axial and vortex loss at reduced ΔV* is married with *an increasing stream tube rotational loss* associated with higher pitch, and a normal surface friction drag loss. ***The characteristic Advance Ratio efficiency curve results, rapid improvement, leveling off to a very flat peak!!!***

The beautiful final way to look at this, is that *the induced loss collapses with speed*, all losses finally totaling a min. of 8 to 9%, which means about 91% ideal efficiency vs. AR!!!!
THAT IS A FANTASTIC INSIGHT - APPRECIATE IT!!!!
Realize, you only hit your peak at optimum speed, worse slow! √

A real world example of all this logic is that an RV6 won't go twice as fast as a Luscombe at equivalent drag, but it will do altitude economy cruise at 170 MPH TAS, 140 IAS at not too much more drag than a Luscombe at 100 TAS, 85 IAS, and with a more efficient prop, and much better overall propulsion efficiency, **at better MPG, 27.4, vs. 26.6, slow in a Luscombe**. An incisive insight here is that the **160 HP engine** uses only a ***70" D*** prop vs. the 85 HP ***71" D***. ***Notice that at much more speed, much more HP is required at almost equivalent drag. A much bigger engine is required to put that traveling energy in at a faster rate!*** **You've seen required prop diameter decreases at higher speed, so here's this much bigger engine driving a 1" smaller prop than on the Luscombe, much faster, more efficiently**!!! Props are an intriguing challenge.

Chapter 3 II Takes You to an Advanced Level

The Prop Primer, through Chapter 4 II, Propellers, are separated as Book II, to not complicate the basic Airplane Book, and **the book's objective of teaching how to match and maximize the Plane - Engine combination**. Chapter 3 II has a wealth of additional insight valuable to anyone who wishes to go for an even broader, deeper grasp of props. **The whole geometry of Betz loading is explained early as a major objective**, so you understand that key fundamental. **The whole McGilla seems too much to most people if given in one giant dose, but if you've grasped this more extensive basic presentation, review it, help it to soak in, really make it yours. The Graduate Course may then even read fairly easy to some**, because it will be filling in many of the details we purposely skipped in this basic chapter, and is apt to answer many questions a sharp guy will have seen, and be wondering about. ***To really become a propeller expert takes a considerable effort, because they really are as complex as any subject you will ever deal with. But see how much insight you've gained here in a very short time. It's our job to get you a great start!***

ADVANCED PROPELLER LOGIC - AN INTRODUCTION

Propellers are **a rotating wing**, ***but imbedded in a stream tube***, ***a very complex case*** **needing world class math to get usable detail design answers** ***to accurately get*** the **engine loading torque, thrust, all the key performance characteristics and shop lot control intended**. Since there is nominally **only one degree pitch difference, .1 C_L, between a cruise and a climb prop**, ***you can see that a necessary design and manufacturing tolerance is .1°, point one degree*** for a proper controlled result. An **inadequate program**, **inferior math**, flawed, inadequate logic ***will get you poor design answers***, *not* ones that will give you what you intend - ***more likely misleadingly wrong!***

Once you've set a prop's ***Size,*** **Diameter, Area, Chords-shape, if you don't have the inflow angles correct**, a proper solution to the **complex 3D, heavily loaded flow**, including an **accurate correction for body caused slowdown**, you can **miss your intended Thrust, and engine Torque Load** by a bunch, back to cut and try. **But an accurate program and a *wonderful modern PC* will print out an *ideal prop in just seconds!!!***

The problem is that doing all the studying that you need to do to truly, accurately, understand all the advanced, very complex math, all the technical logic and insights is a real brain bender, right out at the limits of intelligence of the most brilliant, rarely occurring analysts we've had in the 20th century. It took **a multi year hobby challenge effort**, two very experienced lifetimes of advanced engineering knowledge to get you the **wonderful insight** that you get here **in just a few hours - a huge bargain**.

Teaching pilots ***the math is not even close to a real option***, and you would not want to be drowned in it. ***But we can teach you the incisive, professional level insight and conclusions that come out of it all***, **again in just a few hours, a huge bargain!**

In hindsight, you might *now* be better able to see that what we did *after* the **Primers, in Chapters 1 II** and **2 II** was to **decode** the ***tricky, basic*** **propeller logic --** ***then*** **teach professional level conclusions on much more**, actually far more than you had to earn of your own personal sweat, a ***minimum of frightening math.***

I'm sure that many novices were either ***unnecessarily*** scared away, or temporarily confused by throwing you into **T = $\dot{M}\Delta$V**, something they'd think was scary basic Physics, a strange Greek letter and scary math. Those who saw through it OK are apt to see in hindsight that the equation is only *a simple enough, two item formula* ***that shows*** **the efficiency game is no harder than getting the speed up, the natural and final mass flow rates, $\dot{m}$ and $\dot{M}$ up,** ***so the ΔV extra wasteful wind can be small, the loss small, the efficiency high***. The logic it decodes is tricky, but once you see through it, the math is just ***simple horse sense***.

You didn't actually have to do the math, just grasp the logic. We did **a basic RV6 example**, so those who got it OK, **could see the details**. It turns out that *in hindsight*, that's ***the easiest way to teach you the tricky little basic logic of props***, that ***the loss gets small if you just go fast***. **BUT -- If you gear for Low RPM, High Pitch**, **Bigger Diameter**, on the slow, excess RPM cases, ***you can theoretically get ideal efficiency***. **BUT -- diameter can get excessive!** Like a wing, **the downwash, tip loss, (and rotation) - is the induced loss**. If you just ***go fast, that loss collapses***, and your prop is more ***efficient with less induced loss***.

Planes teach us Induced Loss is a 1/V² type loss, V lowering Induced TWICE!!!

The second little formula that fell out of it all, **ΔV/2V$_1$** again would at first look pretty scary to a new "non math guy", but since things are always far easier in hindsight, hopefully you can now see that it's just ***a ratio*** **of half the axial speedup (done to the stream tube, by the prop)**, to V$_1$, the speed of air coming at the prop ***before*** the prop suction affects things. That ***fraction*** establishes the ***decimal or % axial energy loss*** -- ***and*** the prop caused increase to the natural mass flow rate ***$\dot{m}$ to the final $\dot{M}$***.

Now, if you got all that, all the **insights in the prior chapter**, the **15 key Summary Conclusions**, you should have a pretty good grasp of basic prop logic, and be ***prepared to attack this advanced chapter***. To a large degree this chapter will simply be expanding your grasp and knowledge with many insights that, if given to you in one chapter, before the basic conclusions, just comes out to be *too much in one dose*. **Time helps it soak in!!!**

We're going to presume that you got the basic logic and move on. We'll, explain constant dT/dQ, its significance, give you ***a lot more insight into the vector diagrams that show you in picture form how the air flow works***, *how thrust, torque and power are distributed vs. radius*, ***ideal blade loading, vs. shape***, **the shape changes vs. advance ratio, steepness of pitch**, ~45° **best**, insight into the **slowdown caused by the engine cowling, interference losses**, very important *graphs*, ***pictures*** that show you that you can **tell a huge amount about a prop by simply seeing what its P/D ratio is, if it's over 1, or not, and by how much**, give you **greater insight into the stream tube**. The **blading efficiency graph** teaches the ***small drag changes on blades over wide blade angle ranges,*** but *worse at very low and high angles.* A **BIG Surprise, design studies**, show how C_L **can be swapped for diameter, at near equal efficiency!!!!** We cover ***thrust required***, **activity factor, airfoils, blade thickness**, better skipped at first, **but necessary as you expand your grasp.**

The airflow geometry drawings, the vector diagrams are particularly important to the basic insights offered in this advanced chapter so they'll be an early and very important part of this advanced chapter. *I expect you will find they'll be the most mentally challenging part of this advanced chapter*, just as you probably found T = ṀΔV to be challenging at first. ***You can of course skip the challenging geometry*** as you could skip T = ṀΔV if it's too much for you, ***but*** it's very much at the heart of really understanding props, so it's *very worthwhile if you can get it*. ***Go for it***. **As usual we'll help, key's nailed, emphasized.**

Please understand the risk we take in this book, *and why*. It was tempting to do the cartoon filled, "dumbed down" broadest market book, which I knew would be the biggest money way to go, but we *purposely* didn't do that. We didn't care about money, profit was not the game here. We wanted the book that **gets you the straight, factual, professional insights**. There are plenty of books, some actually very good and helpful broader market books that properly go after the biggest market, the most dollars. The problem is that there are **no other books that take you right to the really correct technical answers, the real truths**, the true heart of the matters that the few best pro's know --- and in some cases past what pro's know, because we've dug deeper, **tied more together**, like ***an integrated grasp of plane, engine and propeller logic*** ---- and *explaining better what the professional papers don't come close to making clear*.

In skipping much, assuming much, not digging, not tieing everything together adequately, not making everything clear, the pros can miss a lot too, not understand many important points themselves that get missed, not really grasp it all well enough. Since we've dug through it all, tried to see how to get the real meat and truth over to the pilot who really wants to get it right, it's been ***our objective to write the book with the real truths***. If you have to sweat a bit over $T = \dot{M}\Delta V$, or the coming geometry, it's worth it and I'm betting you can get it. If you can't get it all, hang in, because you can still learn plenty as you go, and in the conclusions. **Our objective is to let you go deep or shallow, as you wish, but always lead you to great insight, clear conclusions** *that everyone can understand, specific, clear!*

This *is* the Advanced Chapter, *that goes for a pro's insight*.

Many pros will gag at the super emphasis, the purposeful repetition, but they're ***not*** the central targeted audience. We're ***trying to help the deserving guy who wants to learn, but needs max. help***. In fact, ***pros waste huge time on the too esoteric papers, and they too can find the real truth here much faster!***

THE WISE OLD BIRD

Rigid Vortex sheet. Constant r tan phi. Constant dT/dQ vs r. Betz Loading. Simple helical pitch of the air inflow, outflow. What's all that stuff? Can I understand it?

A ***necessary*** game in teaching a professional grasp of propeller logic to learners is to *not* drown the new guy with way too much too fast --- and to find "easy enough" ways to teach a subject that has math and interrelationships that took our most brilliant analysts from 1865 to 1934 and 1948, one of the world's most complexly interrelated 3D analytical problems. **Then**, we feel the best way is to **take him right to the heart of the matter**, so he **immediately sees the real core of the logic**. Then, it's the time to go back, take him through each key step of the subject, with enough *chances and time*, super *emphasis* and *help*, that he really has a chance, the time to get it. ***Great incisive conclusions*** insure that *even guys who have to struggle can get real insight*.

> **You can *best help me help you*, —. by figuring out how to best read this book --- *at your level*!!!**

In this chapter there is a **fundamental change**. We're going to be dealing with **heavy loading**, where there is a **helical vortex sheet** ***moving significantly faster in and out of the prop***. The ***whole game is*** --- ***to get the air inflow and rotation correct!*** Betz figured out the proper objective to design an ideal prop in 1919, in the time of Prandtl - Munk, but it took their wing theory for Glauert to *get a good approximation of the air inflow correct*, by 1934. Theodorsen achieved his ~ exact analysis by 1948.

BOOK II --- CHAPTER 3 ***The Graduate Course***

ADVANCED PROPELLER LOGIC

PROPELLERS FOR THE GUY WHO WANTS TO SEE IT ALL
- The Explanation That Has Never Been Offered Before -

Like Babe Ruth pointing to the left field seats, **let's challenge each other**. -- I'll go for the ***most important, incisive, core pages ever written on the never adequately explained subject of propeller logic***. -- **You go for it**. I'll help you **actually get it**

The simple, specific technical objective of ideal prop design, is to configure a prop to have **constant dT/dQ**. That is, simply, **a constant ratio of Thrust vs. TorQue (or HP) at every radius**!! That's a -- **constant efficiency at every radius**, ***every radius as good as any other radius****, max efficiency. It's a huge **Surprise**, **a huge insight**, quite *counter intuitive* if you thought tip loss killed the effectiveness of the tip area, or saw very steep inboard blade angles hardly pull forward, steep airfoil angles appearing to produce more resisting torque, but quite weak forward thrust.

*That assumes the ***simple case*** — ***with no blade drag***, **– but we add low Rn drag*!!!***

Betz saw in 1919 ***that is possible***, and ***how to do it***, a ***"rigid vortex sheet"***, **a constant r tan ϕ_1 at each radius** --- **simply a *perfect helical pitch inflow of the wind*, (a perfect screw surface),** ***in, then out***, ***stretched by the second $\Delta V/2$ to ϕ_2's*** -- by **proper loading!** Phi, ϕ_1 is just the angle(s) *of the wind* vs. *the prop plane* that the prop blade (*at each radius*) sees coming at it. ***Helical ϕ_1's + α•*** sets prop airfoil angle(s) β, vs. the approaching wind. You'll learn it ***combines*** the ***air stream rotation*** with the ***weak ability of the inboard radii to move air axially***. **Easy enough, it sets up the *correct math***

The tricky part: Helical pitch of ϕ is real, makes the math correct. ***But the axial ΔV varies vs. r!!***

Betz Loading is *achieved*, by **setting blade angles and chords** to get **Wind** inflow vectors, **W**, **with simple helical ϕ_1 pitch**, **same pitch at all radii**, adding, **a constant angle of attack**, the simple std. C_L case, -- shaping the blade with the **proper chord at each radius** to actually give "**Betz Loading**" -- **which makes helical airflow!!!** Thus, understanding the geometry of the **air inflow, stretched outflow is extremely fundamental and important**, so it should be, and will be, an early key and fundamental in our explanation.

Helical airflow is just a perfect ϕ_1 screw surface at all radii - ***stretched by a second $\Delta V/2$, ϕ_2's***

Now you can imagine that the 3D math to get that air inflow and outflow precise to < .1 degree, took genius level math that had challenged our greatest analysts for 83 years, from 1865 to 1948. It's far more complex than our incisive explanation. We can skip the wild math, but show you the **marvelous insight** it offers. **Constant Thrust vs. Torque** (or HP) - ***from proper loading, twist, chords, thus shape, helical airflow, is the core objective!***

In the initial Chapters for pilots, we used the Rankine-Froude "Actuator Disk Concept" to teach you Newton's Laws and the *tricky little central logic of props*, "**go fast, get a *Big* natural $\dot{m}$ and final mass flow rate $\dot{M}$ through the prop disk, thus a small required ΔV, thus a low $\Delta V/2V_1$ *axial* loss, thus high efficiency**. The **Actuator Disk Concept teaches the logic, *but* Assumes Constant Axial Velocity vs r**. **It's *not* that simple!!**

Forget $\dot{M}$ ΔV, Actuator Disks, *for awhile*, while we learn 3 D Rotating Wing Analysis.

Now, we're going to **think of doing a rotating wing analysis**. We'll soon **learn to get helical pitched inflow correct**, so we can **get angle of attack correct, *at the prop***. The ***twisting axial velocity* will vary vs. radius** -- but it forms a ***"perfect screw" shaped "Vortex Sheet" that moves back faster than the rest of the stream tube***. So we'll ***only get back to the "whole stream tube" after learning Theodorsen!!!*** Glauert and Theodorsen both recognized that the key to ideal analysis is to ***analyze for Betz's helical pitched airflow sheets, far back*** --- (even if it does ***not*** exist in perfect form far back). **That gets the math correct, all the energy put in at the prop!**

Theodorsen solved it for exact 3 D Flow, feeding the tip vortex, Heavy Loading, Hi Advance.

But, see Tibery and Wrench Kx loading above .5 λ in 1964 vs. T T's Voltage field tests.

Theodorsen finally got it essentially perfect, (if you don't try analyzing it *off its ideal design point*, or consider the fuselage forcing air forward, causing a slowdown). **Separate analysis does those.**

There are some imaginary parts about it, but the math stays correct, you'll see! .

Now the final initial key to your professional level insight ***will be*** to **understand what "Betz Loading" really is**, and to also understand that vs. the big surprise that the thrust vs. radius plot ***will show you the inner radii of the prop can be near useless!!***

A picture plot of Blade Shape and T# vs. r" will show you "Betz Loading", p.147 I.

Confused? Now, in case this explanation, which seems fantastic to me does ***not*** seem great to you ***yet***, don't worry too much. Here, **we're purposely showing you where we're going**. As usual, we'll come back and explain it in more detail, so you'll have more opportunity to catch on. We anticipate that we have to say each item a few times, a tad more and deeper each time to give you time and extra chances to catch on. Hopefully, you'll get it, maybe with some gaps, either new terms, or concepts, and the gaps can go away with more chances to get it. We ***all*** need time and repetition to catch on to new concepts. ***We repeat to help***. If you never do catch on to *some* parts of it all, don't worry, we always lead you inexorably to understandable conclusions -- so everybody can learn plenty, by just hanging in.

Theodorsen, who scares almost everyone because his book is complex and difficult to understand, *even for pros*, is, in fact, much easier to use than is generally understood, simply because he uses "**K(x)** ***circulation blade loading factors*****", vs. radius and Advance simply from his charts, to load the prop to get "Betz loading"**. His **mass coefficient factor Kappa,** κ, relates the actual ***average*** axial velocity of the ***final tube***, to the axial velocity of ***his faster, heavily loaded, higher advance, vortex sheets***). -- His math, which is essentially 1929 Goldstein math, properly considers the stream tube and vortex sheet "far back" - includes a small change in diameter, higher pitch for heavy loading. *Both Goldstein and Theodorsen were very, very smart!!*

(Kappa Shows as Chi, χ in Andy Bauer's Analysis, **Theodorsen Greek Letters easily confused**)

Tibery and Wrench at David Taylor Model Basin, in 1964 got higher Kx Blade Loading, above a .5 λ, than Theodorsen's 1948 Voltage Field Answers, most probably correct.

Glauert ***can*** get "**Betz Loading**" ***only if*** his math is set up to get **constant r tan ϕ, which is just, helical inflow, constant helical pitch of ϕ_1's --- *then stretched helical outflow, stretched ϕ_2's!* He uses *Prandtl's "F" (fraction) Factor* to account for the blade's interaction with the streamtube, *prior passes* at any point on the blade radius (forming the rigid Vortex Sheet)** and **tapering the calculated thrust vs. radius for tip loss!!!** P**roper chords and C_L, thus angle of attack, α°** do it. ***Sketches show the geometry***.

Geometry looks at the prop blade like a wing half. Forget the stream tube for now!!!

Is All The Complex Math Worth it? Yes, Really YES!!!.

High pitch props can calculate to be 90+% efficient. NACA's best postwar tests with small drive housings confirmed 91+%. I was after the truth of the subject, and I'll ***show you the truths!*** I'll show you a stream tube can quickly become a real mess behind a prop, especially on a poorly designed very unsymetrical nose, which makes it look like these guys were dreaming with "a rigid vortex sheet, far back". But they were very smart guys and if **you put all the energy in at the prop, you get the right answer, *if* you've done the math precisely correctly, even if the tube becomes a mess after it leaves!!!!**

The Tip and Root Radial Flow actually breaks into TWO Separate Vortices!!!

There can be big *extra* propulsion efficiency losses, especially on the old, slow, poor plane designs. Gus Raspet tried to teach us that in the 50s, the same truths we're finding with zero thrust glide tests. **But the idealized math works, and teaches us the logic of what's happening**. We're just getting you started on a pro's insight here, just quickly getting you to key central truths of the big picture. Soon we'll go back, ***start teaching you the airflow geometry*** that can give "***constant simple helical pitch of the wind inflow ϕ_1's, then stretched helical ϕ_2's outflow***", thus ***proper blade loading vs. radius*** **---- the best prop for any application** --- with the ideal twist, chords, thus blade shape, a **constant Thrust vs. Torque at all radii**, (not considering blade skin friction drag). **And, we'll teach you a lot of practical insight and great conclusions as we did in the initial chapters**

Betz's *Rigid* Vortex Sheet, Just Pure Helical Airflow Pitch.

You'll soon see the Rigid Vortex Sheet concept is tricky, because the inboard ***axial*** velocities look too weak for the "Rigid Vortex Sheet" to hold together! ***We'll explain soon how it twists into a perfect helix***. But **I'll bet a picture of *what this example of simple helical pitch looks like* will help you better visualize it. It's *simply 2, dual, merged, helical screw surfaces*, from tip to centerline**, ***stretched***, $+\Delta V/2$, ϕ_2's. It's actually ***two merged*** Archimedes' Screws, **one from each blade**. He died in 212 B.C., and they're *still* used in a pipe to pump irrigation water in Egypt. You can actually make one in glorious 3D Technicolor, by simply bolting up a stack of ice cream sticks. It makes quite a nifty piece of modern art, varnished, the natural wood color variation making it look quite nice, a creative 3D art form better than you see in many museums. We have an interesting little art collection and, laughingly, this became part of it. *Few will realize what it is.* **We're simply setting up the math to do this. That's valid, *but* more happens, it also breaks into tip and root vortices, but the objective of the math is simply to set up the air inflow *at the prop* this way, ϕ_1, but next, the stretched ϕ_2's, you'll see. Interestingly, notice how the *dual trail* from *two blades* makes it *look like the pitch is half what it really is – LOOK, realize an RV prop pitch is greater than its diameter!!!* You'll soon see *it really isn't rigid*, the inner rotation faster than at the Tip, at a smaller radius and circumference!!!** √

It's precise SHAPE and *Twist* –
That sets up pure Helical Flow!!!

fig. 1 An RV prop model and its theoretical *Dual* Rigid Vortex Sheets.

Betz's Rigid Vortex Sheets --- An imaginary way to set up the mathematics.

Think of an instantly curing helical plastic sheets with downwash from *each* blade's trailing edge, or **a thin wire of prop diameter size, rotating forward at plane speed --- but *with extra pitch, slipping, feeding the 2 blades a ΔV/2 extra velocity, throwing two* Archimedes' Spirals rearward, *adding the second ΔV/2*!**

Grasp this concept, because it helps you visualize the *two bladed* Archimedes' Screws in the stream tube. That **works mathematically, even for Real World Heavy Loading, where the spirals are moving back behind each blade faster than the rest of the stream tube, a wild proposition you can see!!!**

Later we'll teach you how Theodorsen's *Kappa* gets *an avarage ΔV* from Heavy Loading!!!

I'm ***not*** going to emphasize the "Vortex Sheet term" too much, because it can confuse some, because you'll learn the axial velocity vectors are *not* equal at all radii, so the famous (2) ***rigid?*** vortex sheets don't *seem* to stay together. I'll explain later how the rotation twists it into a helix. Instead, I'm going to emphasize that we want to ***set up simple helical inflow of the airstream, at the prop, in, then out, stretching the helical pitch, the real objective*** --- ***easy enough?***

(We *will* explain *how* the airflow twists into a perfect helical screw!!!)

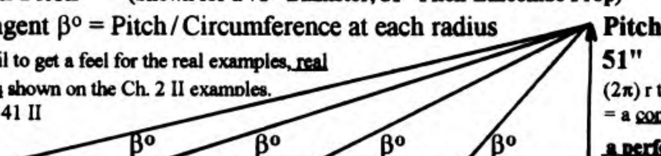
Helical Pitch: Helical pitch is so fundamental, we simply must repeat the easy, basic **helical pitch *blade angle(s)*** layout, β°, that modelers learn to ***advance all radial stations*** of the prop ***equal pitch***, inches or feet, through a soft solid, vs their ***circumference***. Once grasped, ***a calculator with Trig accurately nails angles***. **It's simple: All radii,** (circumferences) **simply go up the proper *ramp angle* to *all* reach the same pitch,** or advance, **in a solid.**

There is "no slip" moving a Blade Helix through a solid.

Helical Pitch **(Shown for a 71" Diameter, 51" Pitch Luscombe Prop)**

Tangent β° = Pitch / Circumference at each radius

Don't fail to get a feel for the real examples, real numbers shown on the Ch. 2 II examples. on page 41 II



(2π) r tan β = P" = a constant Pitch a perfect screw!

71" x π = 223.05" Drawn to scale, divided into equal parts.

fig. 2 **Angles, Circumferences at Several Radii.**

Blade angle, Beta β, Angle of attack, Alpha α, Wind angle, Phi ϕ

Aerodynamicists, logically set up **lift and drag force vectors,** (vectors have an angular ***direction***, and a ***magnitude***, like pounds or speed), **perpendicular and parallel to the airstream**, which naturally is usually considered to be horizontal. But **prop airflow angle** is called **phi, ϕ**. (Look at the following propeller airflow geometry fig. 3.) An airfoil is typically at some **angle of attack alpha, α,** to that airstream, so a **prop blade angle beta, β, is simply the addition of alpha and phi**. $\boxed{\beta = \alpha + \phi}$ That, of course, is **really basic to propellers**, get it, remember it. **Look at the sketch**.

Of course the ϕ and β angles vary at each radius.

You must already recognize that *the basic propeller game* is to get a helical phi, ϕ, a simple helical flow of the airstream, *not* the blade, *not* the blade β°, beta angles. With a small constant angle of attack, **Alpha,** α°, like 1.6°* **for a .55 C_L, or ~ 1.1° for a .5 C_L** on a prop blade, the blade is close to helical, but that different, on a simple case Betz prop, **1.6 degrees steeper pitch at all radii on a Theodorsen RV 6 prop blade, or 1.1°!**

*** Airfoils develope ~.1 C_L per 1° angle of attack, but typically start at ~ - 4 degrees α!**

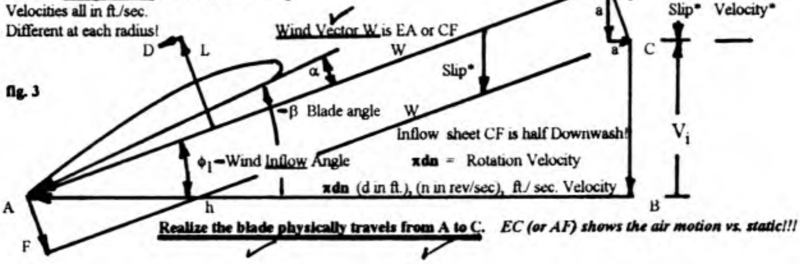
Here Comes The Tricky Part, Understanding The Airflow

In the Basic Chapters the game was to get you to understand, and get past $T = \dot{M}\Delta V$, so you could see through the tricky way basic prop logic worked. Subsequently it got easier, professional insights and conclusions, without more brain strain. Now in this Chapter the game is similar. **Prop Airflow geometry** starts easy with the basic chapter's simple helical pitch layout β°, then a very important **vector diagram** of air movement, **the airflow direction and speed** to grasp what's really happening. *There are some tricky parts*, **that's why we teach it**, so you can really understand As before, *don't get scared away, we'll help*. The challenge will soon pass. You're far better off if you get it, but *if you don't get it all, there is still* ***plenty of great, easier insight*** The whole game in this book is to not be afraid. If you keep trying, we'll be there with help. Everything is easier in hindsight.

If you've never dealt with vector diagrams before don't be afraid. The **Vectors just show the *directions*, angles, of all the separate elements, the *speeds* here represented by the vector lengths, to scale.*** **So it's a picture --- much easier to grasp** than math. We'll explain the tricky insights in words, and how it all works. You'll see it is nifty, tricky, fundamental, great insight.

*** Vectors, usually to scale. a and a' are exaggerated here so you can see them.**

Blade *Inflow* Geometry:



Glauert correctly established the axial and rotation inflow of the **stream tube**, a hugely important step in the developement of Classic propeller logic, using his fundamental ***a and a' factors.*** Think of Glauert as **calculating a rotating wing with a and a'** to **get pitch and angle of attack correct!!!** **He uses Prandtl's F *fraction* Factor to take care of *both*, 1. The interaction with the streamtube and the prior passes of the blade, and 2. Tip loss, tapering the calculated Thrust along the blade to zero at the tip.**

a is a ***ratio*** of **half** Δ**V**, to plane speed, $\mathbf{V_0}$, or V_1 the slowed inflow speed. **a' is a *ratio* of half the rotational** Δ**V to the props rotational V**. Thus, **a** = $\Delta V/2V_1$ --- and **a'** = $\Delta\pi dn/2\pi dn$ **That looks complex but they're just simple little ratios of the axial *inflow only*, a, to the V of the air coming at the prop, before the prop affects that speed, and a' the *inflow only rotational speed ratio* - *to the prop rotation speed*. Note *everything is different at every radius*, and *with heavy loading* a and a' are *both faster* than in the MΔV concept with uniform flow velocities!!!**

Yes, this is complex at first, but noodle it out. It's the key to the Real World of Props.

Grasp how the **inflow ratio a times** $\mathbf{V_1}$, and the **rotation ratio a'** times **πdn**, combine with **the plane's velocity** V, (or the **slowed** V_1), to set up the **relative wind inflow velocity vector W** -- it's **angle** ϕ_1, **vs. the πdn rotating prop plane**. **Setting up** ϕ_1 is **the real key to ideal computerized propeller design**. The

computer ultimately does a Theodorsen solution of ***everything***, Phi, ϕ's at the core of it all **Realize that we're still setting pitch angles here**, and that next we're going to set up **helical pitch for ϕ's**, rather than the blade, but *now* we're **doing it with velocities, *not*** *in." or ft' pitch*. (Recognize a and a' are ***velocity ratios*** to the V_1 and circumferential velocities, but simply multiply out to small velocities.* Grasp: **a** is like ***our*** ***Newton's*** **$\Delta V/2V_1$** ***inflow ratio***, *(**but faster**, **heavily loaded**)*
The hidden secret is, required thrust demands and sets the required inflow, and thus the needed a and a'. ***You'll see that after we add the second $\Delta V/2V_1$ the geometry shows us the downwash angle ϕ_2*** ***Big insight!!***

***Grasp: RV 6 ΔV_{avg} only 5%, *inflow 2 1/2%*. *But, Heavy Loaded a, a' bigger, still small*.**

Downwash, let's **understand it.** Mentally draw in the line from *A to C, the actual prop path*. Notice that establishes a wind line with **no inflow or rotation, no thrust**, *because* it collapses our a and a' triangles to zero, goes right to the top of the **V_1** velocity vector. ***Realize that a symmetrical airfoil set with no incidence in that wind line busily revolves, but at zero thrust!***

Soon we'll show you **zero thrust is ϕ_0, aligned** with AC.

Now look at our wind lines with thrust, which **have *inflow*** and ***rotation*** **increasing the ϕ_1 angle of the two parallel wind lines**. Those set **half the final downwash angle increase to ϕ_2!** The interesting thing to see here is that there is a **real downwash**, and **an angle formed,** ***because*** **there is inflow and rotation**, and the resulting ***wind line W sets half the downwash angle***. ***(Surprise,*** **to the airfoil** now set at an angle of incidence to W, it **looks like it's *flowing up a tad* at the trailing edge!)** Notice that to a cambered airfoil, which can deliver lift or thrust at a small negative angle of attack, that effect could be hard to see.

Now there's one detail that our graduate students, indeed everyone, needs to know to really understand this crucial sketch. Aerodynamicists set everything up perpendicular and parallel to the wind line, so this sketch is done with EC, **the resultant** of the a and a' vectors ***perpendicular to the W wind line***, and you can study the geometry and see that *positions the W vector and ϕ_1*

But actually, EC is a tad off perpendicular, *with drag*, and 3D math, a detail we'll explain later –

We use the term "Tippy Top", Corny, but it helps people "Get it, Remember it", *Important!!*

Slip: Notice how a and a' jack up the wind line W, (it ***is*** EA or CF), to where the ***"tippy top"*** **at D is above E. DC then is the SLIP of the Wind Line W, now *overpitched* to pull wind in at ϕ_1!!!**

We're going to call that **Slip** the **Betz Velocity**. **It's held constant**!

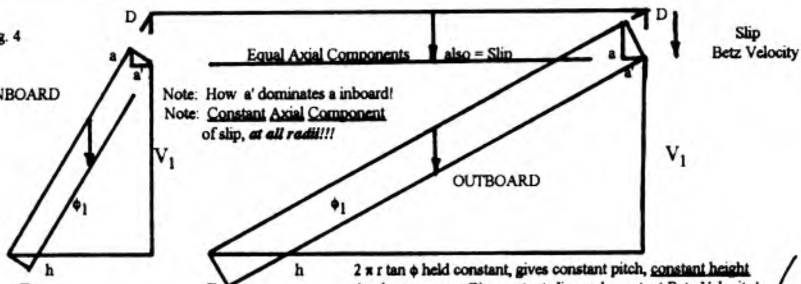
You can better appreciate this geometry sketch when you realize it took 69 years, needed Prandtl-Munk to finish the wing vortex theory, and more. Glauert understood it, applied it to prop logic, finally got inflow and rotation ~correct, an 1865 to 1934 toughie.

Now we're going to move on to a very important sketch that shows how an outer radius and inner radius prop station interrelate, with insights of Extreme Importance, *Really Basic!!!*

I first saw this great sketch in John Roncz's Voyager prop SAE paper.

Constant Helical Pitch of the Wind *Inflow*, ϕ_1 (constant height to D)

fig. 4



2 π r tan ϕ held constant, gives constant pitch, constant height (to the *tippy top*, D), constant slip, and constant Betz Velocity!

The Geometry *that makes* Betz Loading happen - Ideal Props

This is the ***"Rosette Stone Sketch"*** that ***makes the central objective clear***. I've simplified it, leaving all extraneous labels off for clarity, so you can see **the simple key point, the SLIP, Betz Velocity, is constant at every radius**. That results from **constant simple Helical Pitch of ϕ_1**, that is ***set up by a and a'***. **Notice that a is very weak inboard, but a' is very powerful inboard, reversing roles in jacking up Phi, ϕ_1, due to the geometry, to hold helical pitch of the airflow, with enough excess pitch to pull in a and a' the needed amount to get T#!**

Math shorthand holds r tan ϕ constant. That times 2π is constant *actual* pitch of ϕ_1.

This *constant slip*, *constant helical pitch of phi, ϕ_1*, *when made to happen* gives *Betz loading*, an *ideal prop*, *min induced loss!*

It's that simple guys!!! If you load a prop correctly, per Betz, you produce simple helical flow of the air inflow ϕ_1, (***and*** you'll soon see, ***the outflow*** ϕ_2, because all the energy is already into the prop. The slight pressure behind produces the **second** $\Delta V/2$, the final downwash ϕ_2) **All the wild math done by everyone for 140 years is finally aimed at that simple result**, so ***study these basic sketches, grasp them!***

Of course it's hard for you, everyone, at first. — Me too!

THAT SETS THE MATH METHODS UP CORRECTLY.

If you load a prop correctly per Betz you get simple helical pitch of the airflow — and if you actually have that simple helical pitch result, you have loaded the prop correctly.

Constant pitch of ϕ means constant height of the pitch triangles to D — the tippy top.

Realize the huge importance of that insight, because if you know that's the simple objective, you don't have to know the Doctoral level math, you only have to realize that's what they do to get an ideal prop, with minimum induced loss!!! EASY!

For any given Thrust, Aspect Ratio, Diameter case:

Helical airflow is **the result** of a correct Vector Diagram, the **correct angles**, with ***correct chords loading*** to a ***correct C_L***, (meaning a correct angle of attack). The ***simple standard case*** Betz or Theodorsen ideal prop would **use a constant angle of attack, α°, thus a constant C_L**, and the **math then provides the proper chords** to **give the correct Betz loading**, and thus the ***simple helical pitch***, all matching the thrust required, (at the speed, RPM and altitude density applicable to the case). Think it through and you'll see it's ***logical, something you can grasp***. ***Recognize when you've set the chords you've set the blade shape*** (You can use a little **less C_L** matched with a little **more chord**, ***but more drag***, or vice versa), but **let's learn the simple optimum case *first***.

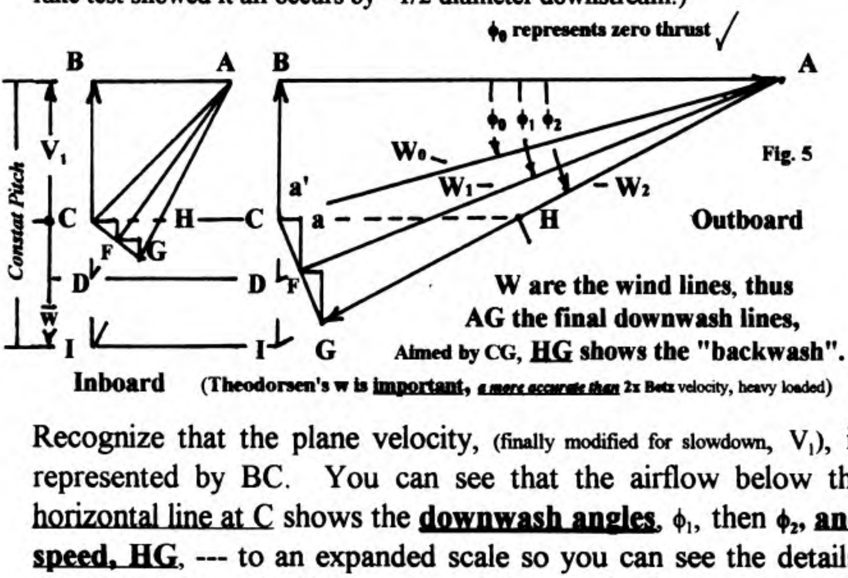
If you have trouble with the concept of chords controlling the load, *help is coming!*

The concept of SLIP can be helpful. *Recognize* that the prop must screw ahead fast enough to **actually go airplane speed,** ***but also*** be **overpitched to pull in air at the needed $\Delta V/2$, and throw it backwards at a second $\Delta V/2$, now *at the full ΔV to make the needed thrust*, and Betz's *rigid* vortex sheet. Once you get it, it's simple enough. Hang in, Learn the Diagrams**.

The Downwash Vector Diagram, ϕ_2 Throwing Air Rearward

IMPORTANT Realize the Prop Blade is Pitched vs. Point D, ϕ_1, LineAF, w/2, + α°.

If the **game here is simply to use a precisely overpitched prop to pull in and throw back air, in a precise helical manner**, it can be very **helpful to turn our vector diagram around** so we can **more easily visualize the air flowing in, at nominally half the downwash angle**, (aerodynamacists say to the quarter chord), ***then speeding up a second ~ equal amount***, going ***out, past the trailing edge***, **finally achieving the full ΔV, the final downwash vector W_2 *and angle* ϕ_2 downstream!** (A wake velocity rake test showed it all occurs by ~1/2 diameter downstream.)



(Theodorsen's w is important, a more accurate than 2x Betz velocity, heavy loaded)

Recognize that the plane velocity, (finally modified for slowdown, V_1), is represented by BC. You can see that the airflow below the horizontal line at C shows the **downwash angles**, ϕ_1, then ϕ_2, **and speed, HG**, --- to an expanded scale so you can see the details. **LOOK at how the "a factor ratio" inboard is far smaller than that outboard!!! Notice that *inboard* the a' becomes much more important than the a in jacking up the phi angles, ϕ_1, ϕ_2, to set up constant helical pitch, as shown before inboard!**

IMPORTANT Realize the Prop Blade is Pitched vs. Point D, ϕ_1, LineAF, w/2, + α° //

The **airflow is *deflected* to establish helical pitch**, by the **combination of a and a'**, as before in our other sketches, but is that helical flow maintained as a ***Rigid*** Vortex Sheet? Look. The **vector direction is correct**, but *the magnitude is just too weak inboard* to make a ***Rigid*** Vortex Sheet real - ***but that's OK***.

Is the Vortex Sheet *Rigid*, Real? Not Without Brain Strain!

The fine print for the brave souls who want to look close, get it all.

I dislike, deemphasize the Rigid Vortex Sheet concept, because it's just too hard for many people to see through. Simply setting up **helical Pitch in, stretched out**, is the **easiest, least confusing way to understand**. Let me explain **what's happening physically to the air particles. Here goes —**

We, of course, normally think of the prop and plane roaring through air, or the air roaring into them, like in a wind tunnel. In fact, **the prop is twisting through *static air***, and **leaves *2 relatively slow screws moving back!*** Look at **vector CG in fig 5, ~ *perpendicular to the wind line, the resultant of the a and a' inflow caused by the prop, with nominally twice that flowing out deflecting* Vector HG, the *downwash, backwash flow*.** CG is exaggerated and thus the *deflected* HG and its angle are exaggerated. CG is rotating more inboard than outboard, but lagging axially inboard, so the outflow wind lines W_2 are all moving axially and also *wrapping up into the two perfect screw surfaces*, finally at a stretched constant pitch as the full ΔV is implemented, constantly being formed, with just the right geometric combination of the a and a' components to stay a perfect screw.

Theodorsen's A_0 shows inflow is not quite equal to outflow. Bigger if Low Pitch ✓

It really isn't a *rigid* sheet, because point G outboard is moving axially back faster *physically* than inboard, but point G inboard is *rotating faster*, and at *a smaller radius and circumference*, than outboard to form the perfect screw surfaces!!! In other words, the axially slower inner radii are continually spinning ahead fast enough to keep up with the earlier outer axial flow so it keeps on perfectly forming so it looks just like the double Archimedes screw photo. Not Rigid It looks Rigid. It can be hard to see without good spatial visualization, so I'd rather go with the sucker stick Archimedes Spiral photo, the concept of a perfect screw surface, constant pitch, formed by the geometry drawings.

It's argued the air *actually does rotate, not move tangentially*, guided by adjacent air!!!

!!! HG is the ***airflow left behind the prop*, flowing backwards and rotating — at *only* a small percentage of prop velocity. HG's are *not* physically moving even close to propeller speed,** because (double) **a and a', and HG** are small percentages of the forward and rotational prop velocities --- **even heavily loaded, and the stream tube average is much less!** **p. 94 II has real data —**

The vortex sheet looks real, looks rigid, but is twisting, stretching to look rigid!!!

Recognize the Pitch to point I stays constant!!! *Forget all the 3D complexity if you wish*, if this gets too deep for you. The Easier way is: Just get the concept of a *perfect screw surface in, stretched, out*!!!

Bringing Everything Together (Forget The Vortex Sheet)

Everything is always more difficult to understand the first time you see it. **Try to get the Geometry**. **It is reasonable enough after you have time to let all the new insights soak in**. The model builder's *helical β prop blade pitch angles* sketch **simply flies a perfect helix screw *through a soft solid*, no slip**, all radii going circumferentially up their perfect ramp angles, to move forward exactly the same pitch distance, **EASY, once you see it**

Only go as deep as you wish, Theodorsen solves it all ---

The **air inflow geometry here simply is *aligned*** at the prop, **to do the same thing**, aimed, to **move Betz's helical phi, ϕ angles of the wind** through **air, *with slip*, *throwing* a second step of steeper pitch as the second half of the ΔV happens** behind the prop blade to arrive at the final pitch, **throwing air rearward, in two steps, HG**. That satisfies Betz's **constant r tan ϕ, phi**, just his math way to say the **pitch triangles** to the ***tippy top, point I*** (corny, but people understand) are ***the same height, the same pitch at all radii***. **It's a very simple concept, once you get it, and that's what sets up the wild math correctly!!!!**

Slipping, throwing helical airflow is only a bit more complex.

We need to do it in **two ΔV/2 steps, *because* Glauert calculates everything at the prop**, at ΔV/2 where the α° **is set**, the **blades being designed for the inflow angles there**, all the **energy going in there**. Theodorsen actually considers his math far back, but that's due to more complex math reasons. ***Note we design for blade, inflow only !***

Grasp that HG's are the backflows, twisting into a helical surface!

Of course the airflow is a step more complex, an airfoil moving air perpendicular to its wind line, drag free, weak a factors inboard, *but rotating more to hold constant pitch*. The math handles all that complexity and more. *Catch on the easiest way at first, even if you're an engineer*. The game is simply ***setting up, getting constant helical pitch of the airflow, a perfect helix, a perfect screw surface***, and you have an ideal prop. ***It's helical going in as inflow, stretches to a steeper helical pitch behind***.

Making Some Minor, But Basic Details Completely Clear

Be sure that you realize that the **final downwash angle** is the **difference between ϕ_2 and ϕ_0**, the downwash ***at* the prop is half that, at $\phi_1 - \phi_0$** feeding the prop as inflow. There's no downwash, of course, at zero thrust, ϕ_0. Don't misunderstand. When we say that downwash nominally doubles, we sure don't mean that ϕ_2 is twice ϕ_1!!!! Just the difference from ϕ_0 doubles.

We show **Actual Downwash Angles** on **Data Page 94 II**

When we showed you the first airflow vector diagram, fig.3, we told you that an *airfoil moved air perpendicular to its wind line W*, so you could grasp the geometry, easily enough. (And Aero's logically set the vectors up perpendicular and parallel to the airstream). ***(But then told you in fine print that it wasn't exactly perpendicular, to be accurate)***. Realize that *drag cocks that vector a small angle*, about 1° and the ~ exact interactive 3D math can alter the exact alignment. Also, in our greatly exaggerated geometry sketch, you can see that CG *cannot* be precisely perpendicular to *both* vector AD and AG, that an insignificant difference in small angles, a *nit*.

Theodorsen uses his **$\overline{w}$ factor, ~ 2 Slip -- for exact heavy loading -- *"Far Back"***

Theodorsen's Ao, precise math shows that the *first increment* of *both velocity and rotary change*, fig. 5, are *not* exactly equal to the outflow, ***a tad more or less.*** **Theodorsen's *heavier loaded $\overline{w}$ is nominally two times the "inflow only" Betz Velocity. The Vortex sheet behind the prop blade moves back faster than the rest of the stream tube, at higher pitch than average!!!*** Trust that Theodore T. did it all precisely correctly, 3D, because he did. Let the computer handle the really nit picking details --- so we don't overly complicate the explanation, but let you know you can trust Theodore Theodorsen's great work. It's proper to bring up nit picking details like ***not*** **perpendicular**, ***once***, or it confuses some guys smart enough to see worrisome details. Trust T.T, he's very, very good! His **K(x) loading charts are listed to *three significant figures***, and his work is precise math. ***If you get thrust, velocity and angle answers equivalent to 1, 1 1/2%, three significant figures, you've broken the bank at Monte Carlo!!!!!***

Realize T. T. did a Votage Field for Kx above a .5 λ, Tibery and Wrench, 1964, got Higher kx

The Concept of Loading by Chord Length

Does the idea of loading a prop by chord length confuse you? You know what **Betz loading** does, it **makes helical airflow** **into then out**, *stretched, just behind the prop blade*. That **makes a constant dT/dQ, max efficiency, constant efficiency,** **If Drag Free!!!** ***Betz loading is set up by chord length,*** ***(as well as C_L, naturally)!*** ***Does that confuse you? Don't let it, -- but there is a Surprise!***

Betz Loading is established by Twist and Shape, meaning α^o and Chords!!!

Think of a wing or a prop **replaced by a wire of zero chord**. Obviously that's not going to make any lift or thrust. But if we start adding an airfoil with chord length, we do start generating lift or thrust, a little bit with a narrow chord, lots more with a wide chord, just like adding wing area. Then, the more C_L, the more lift and downwash. **Do you see that we can generate more lift with *either - more chord, -- or more angle of attack!***

Surprise: Angle of attack, α^o, thus C_L, increases the a and a' pulled in, and thus downwash and lift or thrust created, but more chord, Span, same AR, increases the lift, thrust, *BUT not downwash*! The wing formula: DW angle = C_L / π **AR** Radians, shows the C_L *as well as wing* aspect ratio controls downwash, ***zero DW at infinite AR***, but that ***cannot*** *be reached*! ***A key insight!!!***

At Infinite AR, D.W. goes to Zero. Real Wings can't have Infinite Span, or Zero DW !

That's tricky enough we'd better stop and think a minute. A 747 size elliptical wing, at the same V, AR and angle of attack will have the *same angle of downwash* as a ~Spitfire wing --- but it's affecting a lot more air, gives a lot more lift. Tricky, but it can make sense once you grasp it. Props are wild. That's not my fault, --- but I can sort it out for you.

We'll learn a Betz prop *will NOT have constant DW, Geometry gets involved!!!*

Prandtl's Perfect Wing, Elliptically Shaped and Loaded.

A perfect elliptical wing has ***constant C_L***, split half ***elliptical loading***, loaded by chord length, **lift at any span proportional to chord length α^o and C_L, falling to zero at the tip, zero chord length!!** An ideal wing has **a constant downwash angle, controlled by C_L, and AR, min. induced drag.** ***Variable q props are different.***

Betz Loading --- Peek a prelook at the next few pages ---

Think of a perfect elliptical Spitfire wing. But convert it into a rotating prop, with **twice the rotational velocity at the tip,** vs. the mid span, **four times the q**, (if it wasn't also moving forward.) It's going to become **highly tapered**, even pointy, trying to maintain a perfect lift distribution, with that **big V^2 effect on q**. You'll see next, ***a standard Betz loaded prop***, with a **constant angle of attack and C_L** does have **a highly tapered planform**!

q Ratio - Luscombe 25 : 1, RV ~9 : 1, Reno only 2.275 :1 !!!!

The clearest and easiest way to give you a grasp of **what Betz loading is physically**, is to show you next, a plot of the **thrust vs. radius loading** and the **blade shape** that gives us that Betz thrust loading, and **simple helical flow in and out of the prop**, the **constant dT/dQ**, or HP, the constant thrust to torque ratio, **no inferior radii, max efficiency,** an ideal prop. Peek that look.

Remember constant dT/dQ *only* happens at Zero Profile Drag, (a few % off with it.)

We'll first look at **standard simple case Betz loaded props**, that is, a **constant C_L, a constant angle of attack added** to our **simple helical ϕ airflow**. There are **interesting insights, incisive ways to grasp what Betz is physically, functionally**!

The examples purposely don't use slowdown, to get pure answers.

Betz does ***not***, *cannot*, have a **constant downwash**, $\phi_2 - \phi_0$! It does ***not***, cannot, have a **thrust vs. radius that is constant, or proportional to chord length.** You can see those are not about to happen with a **highly variable rotational Velocity, Prop V = {(Plane Velocity)^2 + ($2\pi r$ n)^2}$^{1/2}$**, (the Sq Root), a **huge variation of q, dynamic pressure, vs. r**, based on **the (Prop Vector Velocity)^2**!!

We have the **blade thrust**, and **shapes vs. radius** you see next. ***NOTICE!!!*** That ***downwash, dT/dQ, blade width, efficiency, maximize ~where ϕ_1 is about 45° on lower pitch props***!! ***See p.146 I*** The ***max chord moves inboard on low pitch, low advance*** props, ***more outboard on high pitch, high advance*** props, **(but pulled back from the tip.)** The ***thrust maximizes at 70 to 80% radius***. The ***a factor is max at the tip, but the chord is narrowed to get the proper Betz T # vs. r. to size that a!*** **The max chord moving inboard on low pitch props, makes them more highly tapered. LOOK!!! Page 146 I helps make this more clear!!!**

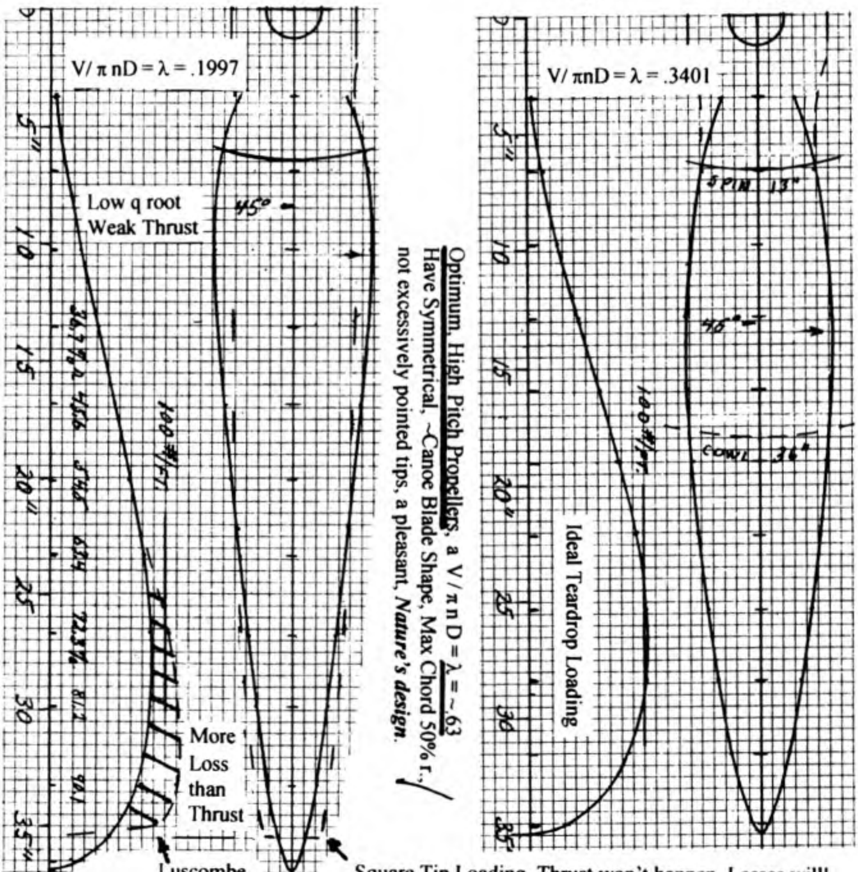
<u>Shapes</u> and <u>Resulting Loading</u> of Constant C_L Betz Props

(These examples are *<u>not</u>* modified for Slowdown)

Luscombe 1400# GW	**RV 6 1600# GW**
73.8" Diamater vs. 71" normally	70 " Diameter, (or 72" is good)
151.5# Thrust (140# T at new η_2 OK)	**164# Thrust,** (156# T at η_2 OK)
.55 C_L 1.612 degrees alpha	**.55 C_L** 1.612 degrees alpha
2280 RPM 48.15 H.P. Alt Cruise	**2400 RPM** 82.9 H.P. Alt. Cruise
100 MPH TAS 85 IAS	**170 MPH TAS** 140 IAS
10,500 ft. Density Altitude	**12,500 ft. Density Altitude**
Ref Analysis 99.36 - 21-23 & 99.75 - 67,68	Ref Analysis 99.36 - 24-26

Realize Betz SHAPE, thus LOADING vs. radius are shown here.

Thrust vs. Radius #/ft.	**Blade Planform** Chords"	**Thrust vs. Radius** #/ft.	**Blade Planform** Chords"



Luscombe Square Tip Loading, Thrust won't happen, Losses will!

High Tip q, but Zero T# result *wants* Outer Chords Narrow for efficiency!!!

Ultimately Realize the Good and Bad of *half* Teardrop Radial Loading --

It's <u>Precise Betz SHAPE</u> and twist that gives <u>Ideal Loading vs. r.</u>, min Induced Drag Loss

We later design for Less Luscombe Thrust, thus a little Less Blade Width, Chord.

 * Remember, for Century 21, we can force Elliptical Loading, do a few percent better!

A Look at Near Equal Prop Thrust, Fast and Slow

The **required 163# thrust RV prop looks rather elegant**, I believe, **like something that ideal math, nature designed**, and noticeably different than the props we use with much wider tips. (Wider tips add profile drag, increase torque, get less RPM, less Thrust!!!)

Later, p.114II, we discuss final, lower Luscombe Design Thrust, not 151.5#, ~137#

It's most interesting that due to poorer η, interference efficiency η_i, and scrubbing drag, that a Luscombe at a slower 100 MPH altitude economy cruise, with a ***gliding drag of 123 #, at a 1400# GW***, requires about 137# thrust, while a ***1600 # RV6 at 170 MPH*** economy altitude cruise, **only needs 163**, (148/.9039η_i). (You'll learn there's **more scrubbing drag, more interference efficiency loss η_i**). *Slow, narrow tapered chords*, the Luscombe Theodorsen prop prefers a little extra diameter, ~ 73.5" vs the normal 71" *to avoid extra blade width*, or high C_L with the highly tapered ideal blade. A wide tip normal McCauley prop, (see outboard dashed outline), with slowdown, not correct loading, highly variable C_L's, loses maybe ~ 10% extra efficiency.

Notice: Thrust does *not* equal Gliding Drag – significently more!!!!

We ***pay attention to blade width to minimize metal prop forging weight, and high AR is most efficient***. The wide chord inboard is a max width of ~ 6.8" wide for Theodorsen blades. My McCauley prop actually quits helical pitch at a 13.3", 37.5% radius, goes to *a constant 29° within the cowl width*. We'd narrow the ~useless, excess width blade inboard of **3/8** r, hardly any thrust loss, you'll see on the thrust plot. *And thrust is ~useless blowing at the cowl* face.

On p.117II the broader tip, mis twisted actual Luscombe prop has irregular C_L's a poor Design!

Hardly Any Thrust Inboard! Look at the dT/dr, ***thrust #/ft*** plot for the **fairly high pitch ideal RV 6 prop**, the accurate result of a comprehensive Theodorsen analysis. It's **another major surprise** on propellers, **very low thrust inboard, even lower at high pitch.** ***Wow!!!*** Many of us might have guessed that a prop's inboard thrust was weak, ***too slow, low q, blades not pulling forward, less circular area***, but I'd bet this weak is a big surprise to almost everyone. The fun of all this for me is ***nailing the real specific facts, all the surprises, after 140 years now!!***

Key Technical Data, Theodorsen RV 6 and Luscombe Props

(But with *no* slowdown, thus Exact Ideal. Done as a study for comparison.)

RV 6 Prop -- 162.543 # Thrust .55 C_L 2400 RPM Cruise Alt. 12,500'

Diameter 70" Pitch 86.617" P/D 1.237 Area 2.0448 A.R 13.479

dT/dQ, drag free = .93341, see below HP = 82.891 Q = 180.717 ft#

J/π Design = .3401368 C_T = .054102 C_P = .065034 AF = 76.186

Eff. eta, η = .88895 (Loss .11105) Zero Drag η = .92601 Thus Drag = .037057

Velocity, V = 170MPH x 22/15 = 249.33 ft/sec ΔV = 9.239 MPH

Theodorsen $\overline{w}$ = .1566 x Kappa, κ, .34704 x V, 249.33 = ΔV = 13.550 ft./sec

A_0 = .078005 $\dot{M}$ = 12.2179 slugs/sec. (Calc. T = $\dot{M}$ ΔV = 165.5578 #)

(with drag)

% r	r"	T#/ft	C"	β°	dT/dQ	η%	DW°	a	a'	ΔHel
x 10 %	3.50"	3.772	3.053	76.383	8710	.8641	2.1212	.00538	.06901	.81673
✓ 18.9	6.615	13.169	4.931	64.384	.8947	.8876	3.3984	.01633	.05887	.32559
27.8	9.730	27.072	5.970	54.492	.9008	.8937	4.0126	.02841	.04769	.07737
36.7	12.845	43.917	**6.342**	**46.637**	**.9022**	**.8950**	**4.1641**	.03897	.03791	**.00535** ✓
45.6	15.960	61.762	6.243	40.464	.9016	.8944	4.0654	.04731	.03019	.03272
54.5	19.075	78.474	5.829	35.591	.9000	.8928	3.8548	.05364	.02432	.10686
63.4	22.190	92.056	5.217	31.699	.8978	.8907	3.6067	.05840	.01991	.19837
72.3	25.305	100.690	4.485	28.545	.8954	.8883	3.3570	.06200	.01658	.29249
81.2	28.420	**101.116**	3.627	25.952	.8927	.8856	**3.1213**	06475	.01403	**.38247**
90.1	31.535	87.367	2.574	23.792	.8898	.8827	2.9054	.06689	.01205	.46561
99.0	34.650	32.456	.799	21.968	.8869	.8798	2.7104	.06857	.01050	.54117

100 % 35" for 70" **diameter** prop Ref. analysis 99.36- 24, 26 1-25-01 Prog. THEODT28

(at .85 η)

Luscombe 8E - 151.47 # T, (140# *final*) .55 C_L 2280 RPM Cruise Alt. 10,500'

Diameter 73.8" Pitch 57.01" P/D .7725 Area 2.1680 A.R. 14.13

dT/dQ, drag free = 1.4601, see below HP = 47.579 Q = 109.206 ft#

J/π Design = .199767 C_T = .042434 C_P = .031367 AF = 63.434

Eff. eta, η = .8490 (Loss .151) Zero drag η = .89693 Thus Drag = .04793

Velocity, V = 100 MPH x 22/15 = 146.66 ft/sec ΔV = 11.658 MPH

Theodorsen, $\overline{w}$ = .21476 x Kappa, .54282 x V, 146.66 = ΔV = 17.098 ft/sec

A_0 = .1100146 $\dot{M}$ = 8.86344 slugs/sec. (Calc. T = $\dot{M}$ ΔV = 151.546 #)

(with drag)

% r	r"	T#/ft	C"	β°	dT/dQ	η%	DW°	a	a'	ΔHel
x 10 %	3.690	3.954	4.725	67.433	1.3941	.8564	4.1960	.01846	.08652	.41211
✓ **18.9**	6.974	13.178	**6.481**	**51.295**	**1.4105**	**.8664**	**5.5007**	.04606	.06176	**.00533** ✓
27.8	10.258	26.076	**6.827**	**40.313**	**1.4103**	**.8663**	**5.4175**	.06701	.0429	**.00545**
36.7	13.542	40.697	6.510	32.865	1.4056	.8635	4.9130	.08040	.03096	.14140
45.6	16.826	55.574	5.947	27.644	1.3993	.8595	4.3629	.08882	.02340	.29860
54.5	20.111	69.176	5.279	23.840	1.3920	.8551	3.8715	.09427	.01852	.44232
63.4	23.395	80.299	4.580	20.969	1.3844	.8504	3.4156	.09793	.01524	.56546
72.3	26.679	87.454	3.864	18.734	1.3765	..8455	3.1082	.10048	.01295	.66912
81.2	29.963	**87.538**	3.082	16.951	1.3684	.8406	**2.8176**	.10232	.01130	**.75629**
90.1	33.247	75.443	2.165	15.497	1.3604	.8356	2.5727	.10368	.01008	.82999
99.0	36.531	27.970	.667	14.291	1.3523	.8307	2.3645	.10471	.00915	**.89280**

100 % 36.900" for 73.80" **diameter** prop Ref. analysis 99.36 -21, 23 1-25-01 Prog. T-DT28

Later we design for19% to 99%, 11, 8 % Segments, and Less Luscombe Thrust.

Real Data -- Let's Look Close, Get Some Great Insight!!!

There are strong parallels and differences between a **Prandtl wing vs. a Betz prop, elliptical loading vs. the T# vs r. shown, (weak root, strong tip loading), elliptical chords vs. tapered tips,** ***each perfectly shaping the loading; cutting to zero at the tip,*** **constant downwash vs. *Betz* geometry controlled variable DW.**

Let's Look

Betz Loading The **T#/ft column** shows the data for the *Thrust vs. Radius Plots* shown --- **the best way to grasp what Betz Loading is and looks like, vs. radius, a bit different for high vs. low pitch. It maximizes between the 70 to 80% radius** on the high to low pitch props, far out, **heavily loaded tips, the 90+% radius still high, zero at the tip!** An excessive tip load would be lost rolling into the tip vortex, a very **good reason to** ***not excessively load with wide tips, with extra drag, and torque, with loss of thrust!!!*** **It is a revelation that a precise Betz loaded prop can maintain constant dT/dQ out there**, (*if* drag free)!!! **The third line of data shows the *ideal* drag free dT/dQ, the sixth column, the dT/dQ at each radius, with drag -- fantastic insight, the decimal loss vs. ideal clear!**

See next, that blade twist and shape are basic to ideal blade loading design.

Betz Constant C_L Chords We purposely teach the simple case **constant C_L, constant α^o, so you can see the more tapered profile *that* ideal design math produces**. If you want a wide blade tip you can unwind the blade twist and C_L, the math will still hold Betz loading, still ***quasi ideal***, **but** it will have more skin friction, profile drag, ***less RPM and Thrust***, no longer ideal!

The columns show **chords**, **dT/dQ**, **efficiency**, and **downwash maximize ~ 45° ϕ_1!!** Note the ***blade shape, high vs. low pitch!***

Math keeps the max chord from moving too outboard on a Reno prop with a near 45° tip!

Blade β Angles, *Not Helical* Column 5 shows the β **angles**, at each radius, **1.612° more than the helical ϕ_1 wind angles** for the .55 C_L RV and Luscombe props. **Compared to a tad higher helical base at 45° ϕ_1**, the ***root and tips twist to a slightly higher angle at each station*** tangent about 45° ϕ_1, *shown in Column 11*

The Blade Angles, β, and Twist, is, of course, the Air Inflow Helix, ϕ, plus 1.6 degrees α.

DW°, The Final Downwash Angles. Clearly the downwash angles are ***not constant***, as ***the Prandtl wing is***. If you study fig.5 you can see that **$\phi_2 - \phi_o$ cannot be constant**, simply because the **geometry controls it,** **(max at ~ 45° ϕ_1)**. Look! At **zero radius $\phi_2 - \phi_o$ falls to zero, as it does at an infinite radius**. Just mentally moving the radius in and out, you can see that the angle between $\phi_2 - \phi_o$ is forced by the geometry to change. Trigonometry controls it. **The thrust required sizes a and a', and the trig sets, and limits, $\phi_2 - \phi_o$!**

See next that blade drag is about 1/3 of the total loss at .55 C_L, a bit more at lower C_L's!!!! ✓

Efficiency **The overall efficiency, vs. the zero drag efficiency on line 5 -- gives easy insight into the percent loss due to drag shown** -- along with the **local eta, η, at every radius in column** 7 --- the max eta moving outboard one plus stations on the high pitch RV prop! Figure the math and see the **.037057** drag loss is **33.36%** of the ***.11105 RV total prop eta loss*** --- the higher **.047935 is 31.74%** of the **.151007 Luscombe loss, a slow, low pitch, high induced drag prop!!!!!!**

Notice Planes fly with more Profile Drag than Induced., Props Opposite, ~2/3 Induced!!! ✓

a and a' Factors Just like in the vector diagram **the a factor maxes at the tip**, but the tip **thrust vs. radius is contoured to that shown by the *highly tapered cords*** working at the ***ever increasing dynamic pressure as radius and velocity increases*****, the inner radius thrust cut by low a, low q, excessively steep β**

Our Theodorsen calcs do not use or generate Glauert's a factors, so we synthetically generate them, ***but with*** Theodorsen's ***heavy loading*** they're a bit stronger than Betz approximate ***factors!!!***

Realize -- With no slowdown these examples have higher pitch than reality! ✓

An Overview of the Fairly Complete Data Supplied Thrust, Diameter, Area, RPM, TAS Velocity, C_L, Altitude Density, AR, Pitch, P/D, Airfoil, etc., etc., are all supplied so the props are well defined, --- as well as quite incisive resulting data, even more on the coming actual Luscombe prop, you'll see. An Aspect Ratio, (based on the outer 90% of blade radius), of about 14:1 is used, since the Luscombe prop is safe for vibration there. For design studies, an NACA 4412, 12% thick airfoil, much like a Clark Y is used, that used on so many early props. Structurally thicker sections at the root, of little consequence, are ignored for studies. A variable thickness RAF 6 is used on the coming *actual* Luscombe prop analysis. C_T, C_P, and AF, taught later are there for reference.

 A Major Look at Thrust, H.P., etc, is in Slowdown Section.

HEAVY LOADING -- understanding w bar, $\overline{w}$, and Kappa, κ

Theodorsen's w (or $\overline{w}$, a ratio of V_1), (Ref. fig. 5). This, w or **$\overline{w}$ is the basis of Theodorsen's calculations** -- it is the **axial velocity of the vortex sheet, to the tip of the vector diagram, point I,** *(It's ~ twice* the *"inflow only"* Slip, or Betz Velocity *of Glauert's similar, geometry), both heavily* loaded, *Theod. more accurate.*) **It indents the stream tube, as explained previously**. Notice that the **$\overline{w}$ is .1566 for the RV6,** ~ 15 2/3 % of V_1, ***bigger***, .21476, ~ **21 1/2 % for the slower Luscombe**. This makes good sense because the **faster planes need relatively less ΔV** than the lower mass flow rate, Ṁ, slow planes. *Get the horse sense of that, easy enough.*

At .55 C_L both blades have similar loading, except q and T are bigger faster--

All props for fast planes have less $\overline{w}$ and ΔV, because they're fast, ***but Theodorsen has about 5% more pitch***, *vs.* ***average loading***, you'll see, ***because they're heavily loaded!*** Theodorsen's ***math accurately has the prop indenting the stream tube a lot***, you'll see, --- where Glauert does pretty well using Prandtl's F Factor, ***(but his pitch is about 1.5 % less, low, for a given Thrust, you'll see)!***

Now here comes an Amazing Insight into Heavy Loading!!!!

The **Small Kappa factor, κ, shocks you into how *very* significant heavy loading really is, because it's a LOW NUMBER!!! Its function is to knock the Vortex Sheet velocity $\overline{w}$ down to the *average* of the Stream Tube,** so **$\overline{w}$ (V or V_1) κ = ΔV**, of an **ṀΔV** calculation. ***A small Kappa, κ, the vortex sheet is a lot faster!***

Note - the $\overline{w}$'s are 15 to 20% ballpark, a lot bigger than the overall ΔV's need to be!!!

LOOK, the **Kappa**, K, is **only .54282 for the slow Luscombe, an even lower .34704 for the fast RV**, which says the **Stream Tube Average is a lot slower than the Vortex Sheet, the heavily loaded Vortex Sheet a lot faster than the average of the Stream Tube!!!!** But Surprise, in both cases the ***heavily loaded pitch is about 5% extra*** *at .55 C_L*. The math's a bit tricky: The pitch is based on ϕ_1 ***thus half $\overline{w}$***. **The trick is to find the Δ pitch difference *between Theodorsen and the average stream tube!!***

RV. **$\overline{w}$/2 = .1566 / 2, = .0783 extra pitch x .34704 = *.02717 avg. vs .0783* = .0511, ~ 5% V_1Δ**

Lus $\overline{w}$/2 = .2147 / 2, = .1074 extra pitch x .54282 = *.05829 avg. vs. .1074* = .0491, ~ 5% V_1Δ

So heavily loaded Pitch is ~ 5 % V_1 more *at .55 C_L* - than average loading!

Glauert --- Using Prandtl's F Factor, vs. Theodorsen

Glauert was the first man in the world to get his *axial and rotation inflow* math basically correct, using the ***geometry taught here*,** and **using his *axial* a, and *rotational* a' factors**. He calculates the prop, *more as a stream tube*, *and* as a **Rotating Wing**, using **his equations** for **Thrust and Torque vs. Radius**, in math terms **dT/dr and dQ/dr**. Of course, they account for **D'**, the **number of blades**, B, **chords**, c, **α^o's**, thus **C_L's**, all at the appropriate **q's, based on V^2, and** ρ, Density, as well as the proper **trig, all oriented in the axial and rotational directions**.

His math was approximate, a necessity before computers, lopping off the minutia ends of long complex basic equations, and approximate trigonometry for small angles where that is often quite sound. His answers, not perfect, are actually quite good, just *not* the perfect ***constant*** **theoretical drag free dT/dQ**, the perfect twist and blade shape of Theodore T.

Glauert's math does *any* prop, does *not* give an *ideal prop* unless constant r tan ϕ is set up!

The ***second key*** is to use ***Prandtl's F (fractional) approximation***, actually a complex *exponential* equation - that gives you a ***(Decimal) Fudge Factor*****, somewhat elliptical, below,** to ***knock down the calculated Thrust at each radius*****, shaping it vs r., zero at the tip.** That makes it ***much more sophisticated*****,** ***close to accounting for real three dimensional heavy loading***, *like Theodorsen*.

Prandtl's F Factor

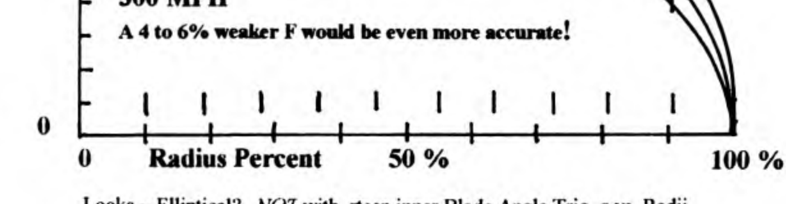


Fig.6

Looks ~ Elliptical? *NOT* with steep inner Blade Angle Trig, q vs. Radii.

F Factor --- **vs. Percent Radius** --- Luscombe, RV, 300 MPH Case

r 10%	18.9	27.8	36.7	45.6	54.5	63.4	72.3	81.2	91.1	99% r
.99267	.98860	.98227	.97243	.95711	.93323	.89591	.83709	.74248	.58074	.19886
.96106	.94864	.93224	.91054	.88177	.84346	.79202	.72190	.62332	.47405	.15783
.90953	.89007	.86631	.83722	.80145	.75716	.70167	.63081	.53704	.40267	.13200

Note, faster, Steep Pitch, gets less Thrust, less ability to move the Streamtube!!!

Glauert, (all the early pro's) started with **(a streamtube)** Multi Blade **Light Loading.** He gets **Heavy Loading** ***using*** **Prandtl's F Factor** *fairly elliptical* **(accounting for ~ 3D flow), shapes the** ***Thrust fall off at the tip***, calculating it somewhat like a **wing, with real inflow and rotation, downwash, backwash** ***(that is the real vortex sheet, if set up ideal, constant pitch of φ).*** Don't tie it to a stream tube yet, *Theod. will!!!*

Weak a factors inboard, and the F factor blends Glauert to ~ Theodorsen's Kx factors

Theodorsen accurately handles everything and finds a huge effect, the **Vortex Sheet ΔV is 2, 3, 8 times faster than the stream tube average ΔV**!!! Kappa, κ, you've seen, cuts that down to an average imaginary stream tube speed for a $T = M\Delta V$ *calc check*. **The prop really is screwing through the air like an English airscrew,** ***blowing the whole stream tube LESS!!!*** The **F factor** ***starting at ~ 90%*** in the 300 MPH case above, shows ***ever less effect on the tube at very high pitch and advance!!!***

Realize the F Factor shapes ~ ideal T # vs radius, and the fall to zero at the tip!!!

Prandtl, who with **Monk,** literally invented wing theory, and the ideal elliptically loaded elliptical wing, created the **F factor as his best shot at a good overall correction factor of the** ***embedded*** **rotating wing in 1919**, an Appendix of Betz's paper. **Theodorsen** accounts for full **3D flow** feeding the tip vortices too, **heavy loading, all radii affecting each other,** ***a wonder of sophisticated analysis, an 1865 to 1948, 83 year challenge!!!***

If F were made even weaker, at high advance, the results could be even closer!!!

Comparing Glauert computer runs to ideal Theodorsen Luscombe and RV prop runs we find they produces 6 and 11# **extra thrust, 4 and 6%, ~1% too much efficiency**. **Untwisting only 1/4 to 1/2 degrees,** (.2842 and .43185°), each about ***1.5% pitch error***, we match the target thrusts, ***a significant error*** if you're trying to analyze ***to .1 degree***, but ***pretty good, really, for 1934***.

Theodorsen -- The Ultimate Ideal Prop Analytical Solution

Theodorsen created essentially ***the ultimate, exact, 3D airflow, ideal prop analytical method, by 1948.*** [With modern *light speed fast* computers, able, with iteration --- (that is, *homing in* trial and error solution capability) --- to do more complex mathematics, attacking actual flow patterns, including vortex formation ---they can simulate more. ***But more*** **analysis won't really be better in any meaningful way**, as far as the prop itself is concerned, because ***an essentially exact method is already available here***, in a form that is pretty reasonable for a pro engineer to use.] (We'll address slowdown and off peak soon.) More fancy analysis is apt to miss some of the wonderful capability already created here by 1948. **Theodorsen**, and his analytical forebear, **Sidney Goldstein**'s work showed they not only had **genius**, but the caliber of genius that only rarely comes along. **Let's make it understandable!!!**

A fancier analysis **that didn't get heavy loading correct would go backwards!!!**

Theodorsen's method is really based on (extending) Goldstein's $K_{(x)}$, circulation, or lift, **blade loading factors** for **heavy loading** and **high advance ratios** -- by simply considering the imaginary vortex sheet ***far back***, thereby correcting for the tube diameter and pressure changes applicable. Significantly, he solved the very complex differential equations ***for complex cases***, before computers, by a ***clever, accurate "voltage field" simulation!!!***

Theodorsen's Charts read to three Significant Figures, accurate to ~.01, 1%. *

The core of the mathematics is based on a **full 3D potential flow solution** of the correct differential equations. What that means is that we have a mathematically accurate simulation of full 3D flow, **axial, rotational, radial flow feeding the tip vortex** with **all radii affecting every other radius**, a wonder of mathematical accuracy, just about **as good as it gets!!!** That is very, very significant, far ahead of earlier approximate methods. He gets the radial flow feeding the tip vortex correct. That plus rotation, the downwash are **the total induced drag loss** -- which is the **largest**, the **most highly variable**, the **most important prop loss**, the basis of our $T=\dot{M}\,\Delta V$ **axial loss logic**, the central key to understanding what is happening physically, logically!

***Tibery and Wrench found Higher Kx above λ of .5, replacing Theodorsem High λ Kx.**

Blade **profile drag is nominally 1/3 of the total loss,** at .55 C_L the **circumferential loss**, unique to propellers, (ie. wings don't have that), at high pitch ~ **20 %** of **induced,** less at low pitch. It's crucial to get the **large, axial,** (and maybe ~equal) **radial tip Vortex** *induced loss correct*. **We know that if we go fast, that induced loss collapses, just like it does for a wing. The max efficiency at optimum J/π is about 91%, depending on how high we get *aspect ratio*, and C_D!**

A coming Design Study Surprise is the somewhat flexible swap of D for C_L.

Here is a capsule insight into how a computerized Theodorsen analysis works in a practical sense. Theodorsen's vortex sheet velocity **w** to the second tippy top of our geometry, (or $\bar{\mathbf{w}}$, w bar, a decimal ***ratio*** of ***that*** air velocity to the second tippy top -- ***to V_0***), represents the ***extra velocity to get to*** **any point I in fig. 5**, p 86 II. **It is the *imaginary* constant pitch *final* Vortex sheet *axial velocity***, defined by the constant axial velocity of that **second tippy top, $\bar{\mathbf{w}}$, caused by ϕ_2 - at *any* radii**. Silly, *tippy top* gets understood!

V_0 is airplane speed in Theodorsen!!! --- We deal with Slowdown, V_1, later! ···

The analyst ***adjusts*** **that $\bar{\mathbf{w}}$** (to the second tippy top), **to get the thrust required**, at the D, RPM, Speed and altitude Density, **rho,** ρ, which, of course, sets up the pure helical flow in and out of the prop, at the prop, ϕ_1, ϕ_2. It's built like ***Glauert's similar geometry, but built from ~ twice Glauert's inflow only a and a'***. (I say similar, because Theodorsen is more accurate.) ***The Heavy Loading Theodorsen (and Glauert) math*** produces ***a taller velocity schematic*** *than the average stream tube*, and that means the comparative *a factors* are roughly 5% bigger, p. 97 II, than average ***a*** factors, *ΔV/2V₁* **for an $\dot{M}$ ΔV** calc. **Look at the $\bar{\mathbf{w}}$'s on page 94 II. They're ~15+% to ~21+%, the Kappa's which converts to the average stream tube velocity, are ~1/3 to 1/2! Remember our schematics of a and a' are exaggerated a lot,** **so you can see them, a few %, *inflow only*, forming a helix ~ to w / 2. They're SMALL!!!**

That ~ 5% extra Heavy Loaded Pitch, or V, is valid at a .55 C_L only, zero at zero C_L. ✓

Behind the scenes the computer is actually referring to a **Chart of K(x) "circulation", or blade loading factors *interpolating*** vs. the proper **advance ratio** and **radius**, properly twisting and shaping the blade chords for the C_L selected at every radius, creating tapered blade tips if a constant C_L is selected, and creating the precise helical screw surface ϕ's for the *imaginary*

Rigid Vortex Sheet -- **in actual fact, simple helical flow, *at the prop* in, then stretched out!!!** Thinking in terms of Glauert's **a** and **a'** factor geometry, the ***weak inboard a factors*** have enough blade width to meet the small inboard axial thrust demand of Betz loading --- simultaneously narrowing outboard chords to ***not*** make excess thrust, again meeting ***Betz loading vs radius***.

Theodorsen's K(x) Factor Chart controls the Thrust vs. Radius Shaping

Theodorsen uses a similar geometry schematic, but everything is based on his w or $\overline{w}$ to the tippy top of the velocity drawing, see fig. 5. He doesn't use Glauert's approximate **a** and **a'**, but , ~ **double their *effect* accurately. *Vector $\overline{w}$,* fig. 5, can be thought of as being in there,** $\overline{w}/2$ **at a ~5 % taller pitch** vs. avarage. The individual air particles are actually moved ~ perpendicular to the phi angles by the airfoils, just like Glauert, *because the schematics have the same objective*, the **pure screw surface flow in and out at the prop**, ***vector HG, backflow***, the result. **Theodorsen simply uses his $\overline{w}$, w bar, to do his math, but remember he's actually working *far back* at *97 - 99% D*, because that math concept is valid for heavy loading and high advance ratios!!**

No axial velocity ever actually moves at the tippy top velocity, the plane and prop moving forward at V, --- the imaginary vortex sheet moving back at w, or $\overline{w}$, formed by the combination of ***twice*** a and a', in our geometry at least in imaginary form, ***ignoring the tip vortex formation***. **The w or $\overline{w}$ is just the best, simple math basis way to do the very complex math**.

When you can follow this banter, you've got it!

To sum up, the beautiful, and key insight that you can come to appreciate and understand is: ***Theodorsen's Kappa, κ, knocks w, or $\overline{w}$ down to the average effective ΔV velocity of the stream tube for a basic $T = \dot{M}\,\Delta V$*** calculation of thrust. *Simple, right in tune with what we taught! Due to heavy loading, a significantly faster Vortex sheet, Theodorsen needs a **higher pitch***, done precisely, Note that the ***w bars, $\overline{w}$, are 2, 3, 8, times the average ΔV, the Kappa's SMALL***, ~ 1/2, 1/3, 1/8, page 94 II, **the Vortex sheet ΔV, is 2, 3, 8 times faster *than stream tube average* ΔV*!***

You wouldn't want to attempt the genius math in Theordorsen's book, but **the picture we give you here is right on track**. For any **engineer** who reads all this, **gets the great level of understanding these four chapters can provide**, you'll find it can **easily save you a year**, if you try going back through Betz, Prandtl, Goldstein, Glauert, and Theodorsen. If you can **start, knowing, understanding, it is hugely easier** to conquer props.

Engineers can attack Theodorsen's math, App. T, much easier grasping all this!!!

The computer concurrently calculates all the many factors of interest for a given thrust case vs. RPM speed and altitude, also with the drags, at first left out as in the basic theory --- Thrust, Torque, Efficiency, $\overline{w}$, Kappa, M. dT/dQ, proven constant drag free, dT/dQ with drag, off ~3% at .1 r., (RV), to 4 to 5% outboard, (Luscombe), where **tip drag increases more**, as shown on 94 II, --- a, a', dT/dr, thrust vs. radius, chords, α^o, C_L, ϕ, β, etc., etc., **a long list** of insightful factors ***overall, where appropriate***, or shown at each of **11** (to 20)**, or more radii, depending on your specific program code**. Modern computers are just wonderful, yielding a **magnificent Xray vision** into what was essentially impossible to see in such detail and accuracy earlier, **a propeller's physical characteristics and physical operation laid open for our understanding!!!** The joke is, our now old computers bought November 1993, terribly slow, only 33 MHz, ***only 33,000,000 operations per second***, gobbles up and displays all the ***answers, almost instantly***, after the design task numbers are typed in.

Two comparable parallel programs ---- modify, retwist the ideal design for *slowdown* --- *or* show results off the ideal design point, slower, for takeoff and climb, where the numbers change hugely, **fantastic insight!** *See Super Magic Graph, p.45-II*

So now let's move on, away from the basic geometry, all its implications - and learn everything else we can about props with minimum brain strain, after this full dose of basics. We only spent so much time on airflow and insight to help!

Is a Triple Ideal Theodorsen Prop actually Better?

On our **Best Test, one Prop had near Twice the loss of the Best, ~81% η, not 90+%..**

We saw tapered props in the old days. A great TV show on **Lindberg** last night, showed his in **1927**, amazingly, ***Ham Standard way ahead***, probably not telling everything they knew, proprietary. The great companies usually have very able engineers.

In WW II, Huge Engines, <u>the focus was on Power Absorption</u>, and Mach, not η.

Why don't we see narrow tips from the manufacturers these days? There are comments in old NACA prop reports that broad tip fixed pitch props are ***<u>better</u>*** for ***<u>static thrust</u>***. **Logically, at runup, slow takeoff speeds, the tips would be "least worst", at more reasonable angles of attack** than steeper, overpitched, middle and inner radii. Are compromise props actually better?

A small diameter, narrow tip Long eze prop, badly stalled inboard - took off poorly!!!

I would not expect the smaller propeller manufacturers to understand, or have a clue of how to design an ideal Theodorsen prop, may not have even heard of him. Our biggest Constant Speed Propeller firm got into Theodorsen in the 70's. Their latest prop, which works best, clearly better than old designs, is almost exactly correct, almost Triple Ideal, still hanging on to a little extra tip area, better than those who got into the math in the 70's, but never understood the Triple Ideal Prop - lots of noisy props.

NOISE is the TELLTALE of UNNECESSARY TIP LOSSES!!! - LISTEN!!!

The 71"D 51"P, Klip Tip, non ideal shape, non ideal twist Luscombe prop can lose 10% more efficiency, 75% not 85% and with interference loss, only 67%, ***<u>at economy Cruise</u>!*** **Bad, we need ideal!**

With Slowdown, the square tip Luscombe Prop has extra losses, loses tip thrust!

Will broader tip fixed pitch props help in climb and takeoff? The computer can look for us! All you have to do is ***<u>not</u>*** use the standard, simple, constant C_L case, we taught for Triple IDEAL. ***You can simply unwind the tip, lower the C_L, swap it for more chord, and still have the same thrust vs. radius.*** But, for an RV prop, dragging more tip surface area, you lose 40 RPM in climb, 2.2 HP, 5# less thrust. ***The hoped for option of an ideal cruise prop that can climb better too, just does not seem to be real. You'll learn Takeoff is the key problem***. <u>We need more good professional testing now, to check the computer.</u>

The Strong Vortex - A Smoke Tunnel Propeller Photograph

This great photograph, with huge insight, was taken in the 50's by F. M. N. Brown at Notre Dame, shown in Eugene Larrabee's excellent Scientific American Article on propellers, July, 1980. It's only a ***very low pitch*** model airplane propeller driven by a spherical gear box, ***not* an ideal prop**, but it still gives great insight. Yes there is ***vortex formation at the root of the blade***, not just at the tip. There are **supposed to be two per blade**. It's ***not*** just turbulence from the gear box, but also a weaker inner vortex. The ***strong tip vortex takes over the real stream tube!!!***

The ***ideal* a factor axial velocities are max at the tip, *but* the ideal thrust profile, "Betz Loading Profile"** is **set up by the narrowing tip chords**. The central issues here is the tip ***vortices engulf the theoretical vortex sheets, but that's OK***, the **energy and math are still correct**. ***Weak axial flow at the low q, steeper angle root is stronger here with a very low pitch model prop*** This broad tip **prop goes for extra thrust at the tip, but you can see it's *swallowed*, killed by the strong tip vortex. Excess tip thrust is a loser! An *ideal*, Betz loaded prop blade is best**.

Fig. 7 **Flow Insight from a Model Propeller**

SLOWDOWN --- The Surprise that Changes Everything!

Now that we've ***taught you how to understand*** and design a theoretically ***ideal, Betz Loaded, Goldstein Theodorsen Prop, with essentially exact math***, we're going to show you that the **subject of slowdown blows everything right out of the tub!!!**

Realize that as a nice, sleek, symmetrical Aerodynamic body moves through the air, the air must speed up as it goes around the fattest cross section, *incidentally dropping the pressure*, per Bernoulli's Law, just like the airflow over a wing airfoil, --- then slowing, restoring pressure as it moves to the tail. We'll skip the *ever thicker*, more stagnant boundary layer, and any separation for now. Most people don't realize that ***a body nose, maybe an ugly engine cowl, signals, pushes a bubble of air ahead***, and if you mount a propeller on its front, the ***prop plane sees a highly varied average slowdown speed vs. radius, perhaps ~17.5% slower at the .367 radius, just inboard of a Luscombe cowl's width***, **~5% at the prop tip, as shown in the accompanying sketch.**

See Luscombe data, p. 117 II

Since that can force, perhaps, a 4.77° angle of attack change at that 3/8 radius, a .61° change at the tip, a .47 and .06 C_L change, respectively, there is **a huge change in calculated thrust**. An ideal Theodorsen prop had to be designed for 106 # thrust at low C_L to hit an early, 151.5# (old) thrust target when dropped into a Luscombe's slowdown, and then, of course, **all the *ideal angles were wrong*, the targeted *C_L now highly variable*, the ideal *chords and Betz thrust vs. radius distribution in disarray*, much more thrust inboard, where the angle of attack, α°'s *increased* the most.** ***Untwisting, with more chord can almost get the ideal thrust vs. r., at a lower q, a small deficit inboard!***

Adding chord can eliminate the small deficit, a tad less AR thus efficiency.

Typically the body nose is highly unsymetrical, and of course, the blades ***can't*** articulate, change their pitch, like a helicopter can, to adapt to that precisely. A pro, using cross sections, *volumes*, models an ***average symmetrical body of revolution***,

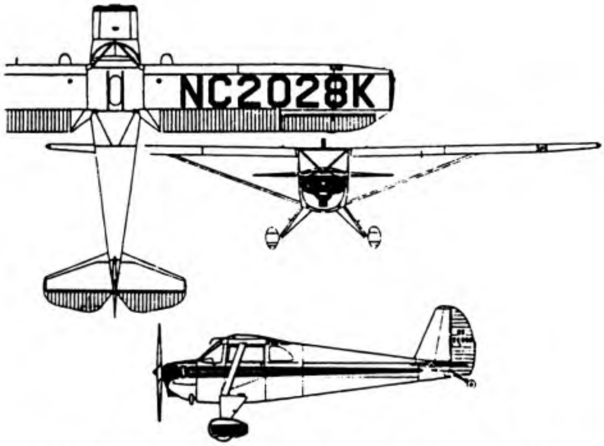


Fig. 1 Three-view drawing of the Classic Luscombe 8E.

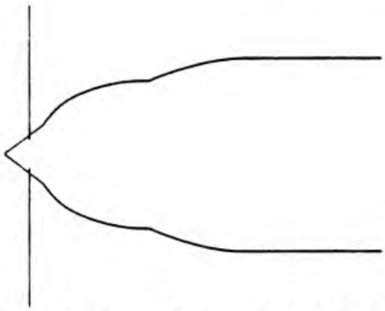


Fig. 2 Propeller plane and the Luscombe 8E fuselage profile.

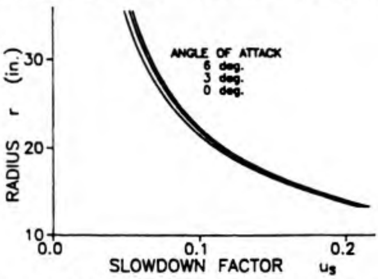


Fig. 3 Luscombe 8E airspeed slowdown factor at the propeller plane.

as we've done here for the Luscombe, he's done **as good an adaptation as is possible**. Using "source, sink analysis", a pro can accurately analyze the ***average* velocity *at each radius***, and we have, ***an orderly basis for a precision reanalysis, retwist,*** but ***not*** one that deals with it better than the ***average at each radius!***

A Source Sink Analysis to Model Nose Flow Velocity

Prandtl and Tiejens, teach the **Source Sink Math Model** method, amazingly credited to **Rankine**, the first Prop Analyst in 1865, who also created the Steam Engine Thermodynamic Cycle, the Rankine Absolute Temperature scale needed in Thermo calcs, and Mach Speed vs. Absolute Temperature, **an early genius!!!**

Briefly, if **an imaginary pinpoint air source** expels a certain **flow rate, cubic inches of air per second** it will force its way into a **100 in./sec. flow stream** and create **a theoretical bullet shaped insert in the stream**, soon converted to a mathematically proper diameter. It turns out that there is **a stagnation point** on the **nose of the bullet** where the flow stream will be stopped dead, faster and faster at bigger radii, finally back to stream velocity far **back at the full D as taught in Appendix SSSS**. Interestingly, the focal point, or source location, will be **1/4 D back** from the bullet nose, and the **90° location** will be the square root of 2, 1.414 times the radius, or **.707 times the diameter**.

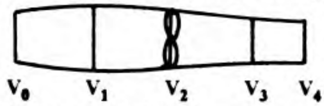
Interestingly, since the *surface area of a sphere is simply 4 times the area of its circle*, *the mathematically effective source velocity* in **in./sec**. at any point, is just the *source flow rate in cubic inches per second* **divided by the surface area of the sphere, $4\pi r^2$**, square inches, thus **in./sec. velocity**, really simple once you see it, catch on. Logically, the source velocity **slows** the stream velocity **forward of the source**, then only pushing outward at 90 degrees, but weaker at ever bigger radii, speeding up behind the 90 degree position, but that **speedup dropping to zero back at infinity**, the air theoretically never mixing, both at 100 in/sec far back, the source now having inserted itself in the stream flow, at D, ***clever!***

See Appendix SSSS for a full explanation of this great Modeling Method

Now, beautifully, by simply using a combination of appropriate flow rate sources and sinks, located appropriately, we can mathematically model any reasonable embedded body, even pull it back in to model a tail cone, (not usually necessary far back), and ***get a decimal, or percent slowdown at any radius, any stream velocity!***

The Stream Tube: Realize V_1 is **at the prop, no prop there**! Then V_2 is added -- With basic axial changes vs. radii, (and slowdown), the tube **acts like a set of concentric shells**.

fig. 1



Grasp this: We use it next for Thrust reqd. **But, with Heavy Loading Betz's Vortex Sheet Speed $\bar{w}$ is Faster than the Stream Tube Avg.** - ***but Theod's Kappa gets the avg!***

V_0 = The free stream Velocity, at atmospheric pressure, P_0

$V_1 = V_0$, ***slowed*** by the body *pushing air ahead*, V_1 **at the prop,** P_0 up to P_1

V_2 = the **V at the prop -- now *also* seeing the inflow to the prop** ($\pm \Delta V/2$)

V_3 = the V due to the prop outflow (thus + the second half of ΔV, $+ \Delta V/2$)

V_4 = the final speedup to drop pressure from **P_1 at V_3 back to P_0**

Mr. **Bernoulli** ***shapes*** the stream tube. When you have a body or nacelle in the stream, it sends a pressure wave ahead, the air slows **a variable amount vs. radius to V_1** as it flows into the prop, and ***expands*** in diameter as the pressure increases to P_1. Then you have the ***natural shrinking*** of the speeded up stream tube as it is sucked into the propeller, thus V_2, **half the ΔV in front** at a reduced pressure, P_2. The pressure jumps back up behind the prop, the tube is thrown back, **half the ΔV behind**. At V_3 all the propeller caused speedup has occurred and the pressure has returned to P_1, but above atmospheric pressure. It now speeds up more to V_4, shrinks more, now back down to P_0. If there were no fuselage, no slowdown, the first and last section does not occur, no V_1, V_4, P_0 existing in front and behind the tube.

In the basic chapter, learning Newton's Laws, $T = \dot{M} \Delta V$, we **assumed constant axial velocity at each radius**. In the advanced concepts here the **axial velocity varies at each radius, as you learned in the airflow geometry, *also* due to slowdown varying vs. radius, *concentric shells***, ***finally with heavy loading, Theodorsen, varies velocity around the circumference, as the prop rotates***, *WOW!!!*

But Theodorsen's Kappa factor relates $\bar{w}$ to the average!!!

With 3D flow, V varying vs. radius, then with Theodorsen's heavy loading, different behind the prop, they had a genius math task. We'll learn the basics, -- then Theodorsen's method handles all that**, gives an ideal prop.** ***Separately***, we'll deal with slowdown, highly variable vs. radius, repitching the blades, for a *symmetrical* body of revolution, since ***the blade can't wiggle*** **β°**.

Gus Raspet Found Terrible Overall Propulsive Efficiency???

In the 1950's **Gus Raspet,** was the **multi facetted**, **creative**, **maverick** head of the Aerophysics Laboratory at Mississippi State, highly valued by his associates and many students. **Bruce Carmichael**, later an expert on Laminar Flow, thought he was great, **Dick Johnson rebuilt his milestone RJ5, 40:1 Sailplane, the real start of Advanced U.S. Soaring. Gus** challenged all -- got students to go try tests, anything that got them into doing real things, getting their hands and brains engaged, challenged to put their education to real use, to go solve real Problems. I've seen the same characteristic at Cal. Poly, San Luis Obispo, that gave us the brilliantly creative (former modeler) **Burt Rutan**, and such great young Engineers as **Brian Hobbs,** of Edwards, my right hand on **Voyager**, intelligently helping resolve complex flight data for writing **Voyager, *the World Flight***, the official flight report, to provide an **incisive X Ray of what was done, how it was done!**

Personal planes, Sailplanes, hands on, brains on, were a real basis of learning

Gus's creativity in the 50's led to **towed propellerless gliding drag tests of key private planes, notably George Lambros's *Bellanca Cruisair*, found 58% overall Propulsive Efficiency** vs. a sealed plane, that was otherwise well regarded. How could it possibly be that bad, ***1/.58 = + 172%, the power required?*** One of our core objectives way back in the 80's was to get better, specific insight into that ***grossly bad result***, not picked up in Aero.

We needed some real Data, FACTS on DRAG!!!

A Windmilling, dragging, power absorbing Propeller, makes it impossible to get an accurate glide, thus drag data, ***never solved!*** So I invented **Zero Thrust Glide Testing**, a simple, insulated, 1/16" inch, stiff, (thus low frequency vibration proof), wire feeler that lit a bulb as the propeller started to transition from thrust to drag in the ~ .016" crankshaft bearing axial slop, ***comically easy, once seen***, the first solution to that conundrum, 86 years after the Wrights.

Necessity is the mother of Invention! I wanted to nail that!!

We got marvelously, reproducible data, gliding in dead air, five miles out to sea at dawn, a little more risky than I preferred, but great results, the L/D vs. Gross Weight converted to ~***Pure Drag***. Dawn, dead calm, E - W, W - E Speed-Power runs over

Camarillo's *former* F 102, 11,100' runway, compared to Gliding Power got us fine **Propulsive Efficiency Data**. Excellent data, all Reproducible, I felt we had numbers as good as we'd ever get.

The surprise was a somewhat jagged plot of the core objective, Propulsive Efficiency, Drag vs. Thrust Required, actually, more specifically, Gliding Power vs. Power required, a slightly wiggly final line. Feeling all smooth, reproducible data was as good as we'd ever get, I felt pretty confident that we were looking at how it really was, that some variable separation, from a pulsing ΔV on the Classic Luscombe, the world's first all sheet metal, small private plane, would be no surprise. See the actual plotted data next. (& Airplane book, p.109.)

It was harder to get good data at the famous, Santa Rosa CAFE Test Organization because we found tight new Lycoming Engines that also swallowed their Axial end play, because of the differential expansion of the Aluminum Crankcases vs. the Steel Cranks, and surprisingly long front bearings on the 4 Cylinder Lycoming Engines. We did feel that we got good Drag Data on an RV 6 and Whitman Tailwind, smooth, it looked just about right. I plan to run matching Speed Power tests as soon as this book is done, but with good overview speed data, we already have good insight.

So how do we explain the terrible overall Propulsive Efficiency, η_P, the multiplication of Interference Efficiency, η_I, and Propeller Efficiency η? The first important insight was to see that the really **bad results** ***preferentially occurred* on the slower light planes*, with propellers that could be seen to be *farthest from ideal Shape***, needing the far more tapered blades required on the slow props, with the **biggest tip vs. root q amplification, (& more ΔV)!**

*** 11 MPH ΔV at 100 MPH, is 11% An RV 9 MPH ΔV at 180 MPH is only 5%!!!**

The next important insight was that a Good test showed a foreign RV 8 Prop could be as bad as 8 to 10% off the BGT optimum Efficiency, quite a lot really, our first solid insight that poor props could be that bad, and that was for an Efficient RV 8 class Prop. A lower η class could be worse!

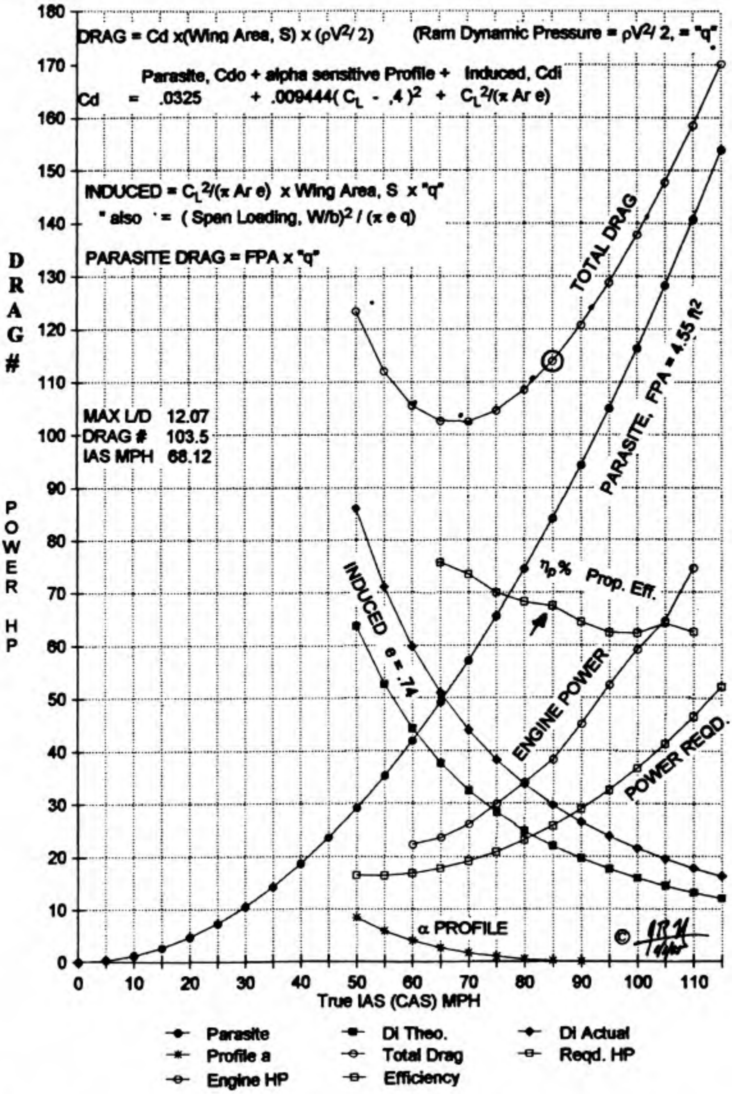
The Luscombe Overall Propulsive Efficiency η_P, was 67% with the cooling ducts open, of course, since it must fly to the ZTGT test. With **cooling drag usually understood to be about 10%,** the sealed ducts **Bellanca and the Luscombe are ~ equivalent**. Undoubtedly, the tightly cowled, and tightly sealed great modern homebuilts, with pressure recovering, slowing, expanding inlets, are doing much better. **Maybe we have a nominal range of ~6 to 10% loss for cooling**, perhaps a wider range for the terrible, to excellent, most diverse examples. (I know of no new hard data there.) We **probably won't have any *actual thrust* cases like the P 51!**

We realized that **with the thrust producing ΔV we would surely get extra scrubbing drag once we turned on the fan.** We had done a lot of looking, calculating, arguing back and forth on how the whole picture might finally fit together. **With the slowdown velocity profile at the nose of an embedded body, the prop is running in slower air, can produce more thrust for a given H.P., - but a *counterbalancing pressure* is created on the nose, which *demands an equivalent Thrust Increase* to get the *original Net Thrust, at the original Power*, a *WASH*, a *surprising trick of Physics, that can look like free Drag!*** There was a lot of arguing about that one, but ***it finally is a wash***, *no cost!*

We have real Airplane Drag vs. Speed, we know there will be some extra Scrubbing Drag, we think we see evidence of Separation. We have what should be a very accurate calculated H.P., η, and Thrust. To get more assurance, we'd need a Wind Tunnel and its accurate Scale. I'd love to do that sometime. We must, for now, trust the Elegant BGT Math. for Efficiency, Thrust, and Power, look at Probable Scrubbing, Separation, **look at how the whole jig saw puzzle** *most correctly*, **fits together!**

If a low pitch Luscombe Prop, a 51"P/71"D, a P/D of only .718, a lot less than the desired 1++, can have **a max η of .85**, but is far from the desired almost triangular shape, twist off too, *perhaps* it is actually **down an extra 10% to only .75 η**, per our best test!

LUSCOMBE 8E
Drag - Power 1250# GW



If that is the case, we only need a .9 interference, η_b, for a .67 η_P! Notice we have an η_P that **degrades with more power**, shows a **jagged line, quite probably variable separation**, happily **an up .67 where we do altitude cruise, 85 IAS, 100 MPH TAS. It is great to *finally* have some real facts, from ZTGT, *to noodle out!***

Hubris is never acceptable in the technical business, *pride precedeth the fall, a good rule in life*, but *within* that admonition, I'd like to take a little personal pride in that all encompassing graph. As far as I've been able to find, that is the first time that complete Aerodynamic Data, ***including accurately measured propulsion efficiency*** has been achieved on a flying propeller driven plane. It took some serious thinking on the subject, the necessary invention, hard work, a little risk, and serious technical care. I did everything I could think of to get spot on, incisive data, and I believe it genuinely is, a little personal challenge nailed. I felt for years that ***Gus Raspet's creativity*** that produced **such insightful data on just how bad propulsive efficiency could be**, **deserved a proper response**, no one else attacking it.

Normally traveling at **1400# G.W**. the drag curve moves up to ~**123#**. At the **49 H.P**. I fly at in Altitude Cruise: At **75%** η, that would produce **137**.81 pounds of thrust, **14.81# above 123**, **to explain.**

(49 H.P. x 550 ft #/sec./H.P. / 146.666 ft sec) x .75 = 137.8125 # T.

123# Drag / 137.81# Thrust = .8925, η_i, OK to justify .9 η_i

A **T=$\dot{M}$ ΔV** calculation shows that $\dot{M}$ & **137.81# T** creates an **11 MPH ΔV**, and that ΔV *can* cause ~**9.5#** of extra scrubbing drag*, thus **5.3#** of variable separation drag, **14.8 + 123 = 137.81** - ***all* worse as more power is applied***, **as we see on the η_P plot,** until we get to full power at sea level, where the degradation, levels out, possibly the faster air somehow conforming better.

***100 MPH TAS + 11 MPH ΔV = $(1.11)^2$ x 41.5# scrubbed profile = 9.5Δ#.**

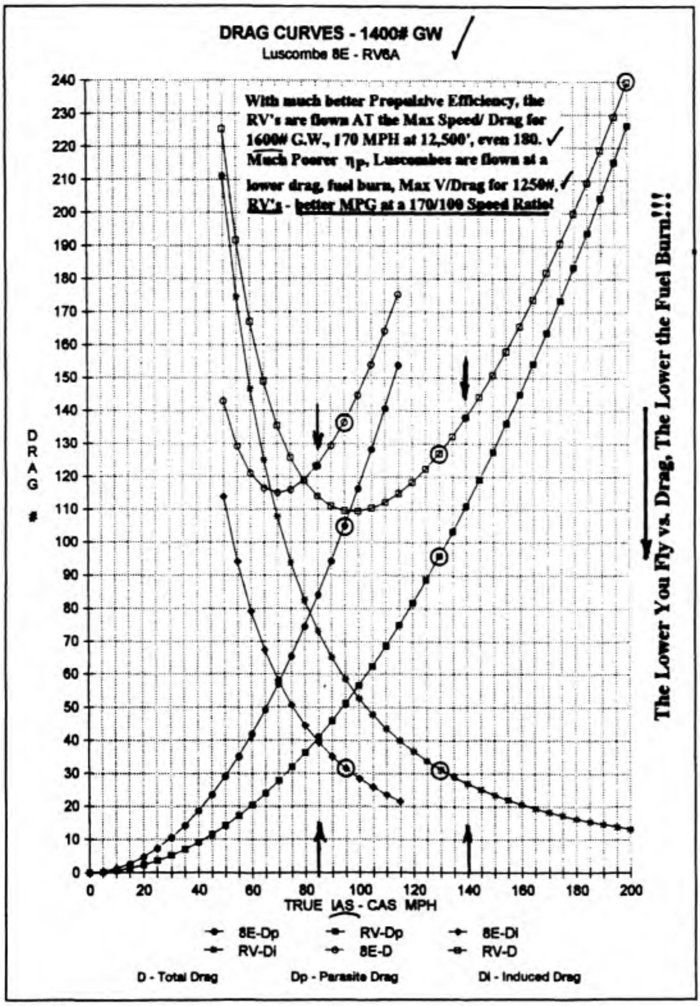
Of the 123# drag at 1400# G.W., 40 is induced, leaving 83# of Profile Drag, perhaps up to half of it, the messy half, body, tails, landing gears, cowling, wing, windshield, body intersection exposed to the slip stream, not sophisticated analysis yet, but perhaps able to produce an extra 9.5# of scrubbing, as above:

11 MPH ΔV at 100 MPH, is 11% An RV 9 MPH ΔV at 180 MPH is 5%!!!

Obviously, that is not a sophisticated Aerodynamic Calculation, but what we're trying to do at this point is rough out how the jig saw puzzle might actually fit together. The clean, fast planes can have very small propulsive efficiency degradation, little separation, and an RV has ~5% ΔV vs. speed - a Luscombe ~ 11%, a big V^2 effect.

Keys, Slow, more misshaped, high q magnification props ***even worse*, more ΔV loss too.**

NOT EXACT, the CALCS ON THIS PAGE, are QUITE CLOSE TO THOSE ON p. 117 II



46 APRIL 1996

In the **Overview on Propulsive (in)efficiency**, it appears to be that **~6, 8, 10% Cooling Drag is to be expected, depending on the caliber of installation, almost none to ~10% due to bad prop design, from ideal, and 3, to ~10% Interference loss,** η_I**!**

We need to run accurate Speed Power data before we can nail RV propulsion efficiency.

The interesting composite drag curve here **confirms Luscombe drag at 1400#**, shows the <u>low A.R. Hershey Bar wing RV has no more Induced loss than a Luscombe</u>, **<u>the RV FAST</u>!** With much better propulsion efficiency, better MPG at a ~180/100 TAS ratio!

An Appraisal of the Luscombe Propeller

Adapting Theodorsen math, for a ~ Perfect Luscombe Prop with slowdown, we then calculated my McCauley 71" D, 51" P prop using exact Luscombe dimensions, actual angles, chords, twist, shape. ***No longer ideal***, the math would lie about efficiency, thrust, power. Our best insight saw η dropping to 75%, not 85%. We made the best rational adjustments, ***checking every way possible!***

GLAUERT CAN GIVE A PRETTY GOOD ALTERNATE CHECK. WE CHECKED EVERY WAY POSSIBLE!

A careful "granite plate" inspection, like the best shop pro's do, taught me that it is easy to get very precise angles, much closer than .1° on an RAF 6 airfoil by simply clamping a 12" steel scale on its flat bottom. It became clear that the prop was in essence a 48" climb prop, retwisted to be ~ 51" pitch at its outer stations, fading a bit right at the tip, and having a constant 29 ° β blade inboard of the 3/8 radius, *a crude accommodation of slowdown.*

NOTICE HOW THE C_L's RISE AS YOU MOVE TIP, TO INBOARD.,shape not right.

The final results on p. 117 II are fascinating! In 1947, not designed for slowdown, the α and C_L are out of control high **above a .55 C_L** target inboard, mid radius to 1/4 r, undesirable, **closer to stall, slow at takeoff** - until the **constant 29 ° takes over killing (the already weak) thrust in front of the cowl**, OK.

Outboard, the **square *Klip Tip* prop forces the math to give a wrong answer, a squarish thrust vs. radius at the tip, which simply can't happen physically, the false thrust rolling off the tip into a bigger vortex loss, *just what Betz wanted to avoid***, with his *teardrop* thrust loading vs. radius. It's a bad tip, more drag out there at max radius, bogging down the engine R.P.M., thus available H.P. spending energy to make thrust, losing the Thrust into an excess tip Vortex, making noise, bum engineering.

REALIZE BELOW, MORE SPEED DEMANDS POWER CUBED. I USE A CONSERVATIVE 2.5 POWER.

Our biggest problem here is that **the Elegant Math *goes for perfect***, so **we have *no comparable way* to calculate how bad the bum ones are**. We saw that on a very good, and fair RV 8 test all props flown on the same plane, the worst prop lost more than 8% η, by going 8.2 MPH slower than the best prop, close to Theodorsen perfect, 90+% for a fast, high efficiency RV 8 prop!

Actual Luscombe Propeller - McCauley 71"D 51"P

V_o = 100 MPH, 146.66 ft./sec. **RPM = 2280** **Thrust = **136.216#** **HP = 49** **Eff.** η = **~.75

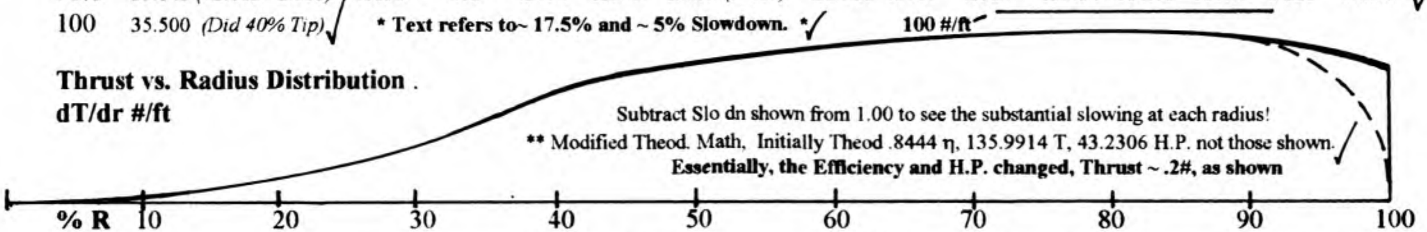
Alt. = 10,500' **P/D** = .7183 **A.R**.= 13.99 Ref. ABB 99.33 - 39.3 and 40.3, 7/13/200 as modified7/9/05

% R	r"	T #/ft	C"	t/c	α^o	C_L	β^o	dt/dq	η%	Pitch	a	a'	V_1	V_3	V_4	T_R	Slo dn
N.A. ~~10.0~~	3.550!	**-1.236**	4.115	.4609	-4.62	-.0607	29°	-6.566	-2.161	**12.364**	.0222	.0476	78.57	82.07	148.57	.5441	**.53575**
18.9	6.709	**7.691**	4.618	.3186	1.52	.5411	29	2.315	.9237	**23.368**	.0394	.0300	95.26	102.76	151.64	.6638	**.64947**
27.8	9.869	**22.594**	4.976	.2181	3.38	.7234	29	2.033	.9397	**34.372**	.0509	.0218	110.37	121.60	155.29	**.7682**	**.75256**
36.7	13.028	**49.270**	5.188	.1589	5.30	.9127	29	**1.737**	.8804	**45.376**	.0577	.0165	121.00	134.96	158.38	**.8391**	**.82499***
45.6	16.188	**65.196**	5.257	.1318	4.04	.7883	25.394	**1.632**	.8736	**48.284**	.0642	.0126	127.78	144.18	161.16	**.8835**	**.87123**
54.5	19.348	**71.951**	5.183	.1116	2.39	.6260	21.786	**1.572**	.8693	**48.589**	.0695	.0098	132.03	150.39	163.38	**.9109**	**.90022**
63.4	22.507	**78.936**	4.966	.0962	1.46	.5351	19.224	**1.518**	.8566	**49.314**	.0730	.0078	134.76	154.43	164.92	**.9281**	**.91884**
72.3	25.666	**84.920**	4.607	.0850	.91	.4809	17.270	**1.466**	.8386	**50.138**	.0751	.0063	136.60	157.11	165.94	**.9396**	**.93136**
81.2	28.826	**87.418**	4.107	.0773	.52	.4428	15.654	**1.414**	.8165	**50.755**	.0762	.0052	137.90	158.93	166.59	**.9476**	**.94025**
90.1	31.985	**83.868**	3.463	.0724	.19	.4105	14.232	**1.359**	.7905	**50.974**	.0767	.0043	138.88	160.17	166.97	**.9535**	**.94689**
99.0	35.145	*(**72.403***	*2.695)*	.0693	-.13	.3794	12.947	**1.300**	*(.7603)*	**50.765**	.0767	.0037	139.64	161.06	167.19	**.9581**	**.95207***
100	35.500	*(Did 40% Tip)*															

*** Text refers to~ 17.5% and ~ 5% Slowdown. ***

Thrust vs. Radius Distribution .

dT/dr #/ft



Subtract Slo dn shown from 1.00 to see the substantial slowing at each radius!

** Modified Theod. Math, Initially Theod .8444 η, 135.9914 T, 43.2306 H.P. not those shown.

Essentially, the Efficiency and H.P. changed, Thrust ~ .2#, as shown

**At Lower Efficiency, Higher H.P., Tip Loading will Actually be Lower, Higher at 3/4 Radius and Inboard, more Teardrop. actually wanting to be more Elliptical. the Core Reason Props Lose More Than Wings, Lower Efficiency, -10% to 25%, not 2, to 3% of a 50:1, or 33:1 L/D Wing!!!

Not the 5% of a 20:1 L/D wing, where 1/20 = 5%

To be accurate and fair here, we must give the devil his dues, **and show what's favorable about this prop, *but see it's still a loser!*** The high C_L, mid radius, and inboard do have the favorable effect of pulling the lift, Thrust inboard, good, doing a favorable thing! Likewise, the low C_L's outboard, also tend to deemphasize the bad, excess blade widths out there, also pulling the loading more inboard from the tip, also good, it could seem, at first.

But there's **a double negative there too, unfortunately**. You just don't win in the overall game, because excess blade width out there, where max q is happening, and **producing much more profile drag proportionaly, and at max radius, max lever arm, the excess, completely unnecessary torque addition, bogging down the engine RPM capability, thus available H.P.!** Not a big thing, some might say? Well, ***there are only two kinds of losses*, profile, and induced**, and **we're hurting this prop's capability, both ways**. **Excess drag, at max lever arm, *creating excess torque load***, bogging down the engine, is hurting, not helping, just not the smart move, **because ease of rotating the prop, for max lift, thrust, is what the game is all about! Outboard thrust is wholly against the proper objective here!**

The gross insult to good sense here, though, is not only excess outer blade width, but **a square tip, massively creating excess induced loss,** trying to create high lift where it just can't be well retained, dumping it out the side door, manufacturing an ***excessively big, and wholly unnecessary tip vortex***, **NOISE**, the worst kind of induced, direct cost, with the ***worst posible payoff!***

And a **slow, low pitch prop with the worst possible q amplification, is the worst, most harmful place to do it**, ***most likely to lose the full extra 10% efficiency loss we've just used!*** **Theodorsen, on his page 33 shows that even with the Betz half teardrop loading done perfectly, *the radial tip vortex loss can be bigger than the axial we must produce to make thrust!!!* Radial flow, Excess Tip Vortes Induced Loss, *Profile there too*, is the CORE, WHY props are less Efficient than Wings!!!**

Are we designing for Sea Level or Altitude - Cruise, or Vmax?

Some Insightful, Bottom Line Conclusions on Prop Design

***First*, You just want to know *the core bottom line* Answers!**

For the SPEED, RPM, POWER AVAILABLE for the given Application :

1. What *SHAPE* should the Prop be?
2. What *TWIST* is correct?
3. What PITCH is correct?
4. What SIZE -- *Diameter and Blade Area* - for available HP?
5. Do I want Big Diameter, Narrow Blades, or stubby Blades?
6. Will a Super Airfoil make a Super Prop?

You'll make CHOICES: C_L, C_D's for low Reynolds Numbers, ASPECT RATIO.

If we **just use Betz Logic, Goldstein-Theodorsen Math, *no tricky changes*,** with an **optimum $\alpha°$ and C_L,** we get a **Classic Triple Optimum, Min. Induced, Profile, Torque, Min. Area Precisely Placed, Ultimate Classic Logic Prop,** ***Norris's 6th. Law!***

IT'S ALL ABOUT CORRECTLY LOADING THE BLADE VS. RADIUS!!!

That fits you right into the B-G-T **Family of Classic Shapes**, vs. Advance Ratio, the **Precisely *Correct Twist***, for ***Constant Pitch***, ***Constant Slip***, of the **Air Inflow, that accounts for the $\alpha°$ and C_L you choose - for heavy loading - where the ΔV at the blades is faster than the stream tube average, and heavy loaded Stretched Outflow — sizes the Diameter, Area - Shape, that are *inter-dependant, can't be separated* -- to use the overall max. Aspect Ratio you chose, and judged sound for vibration.**

WE HAVE THE COMPUTER, AND RARE GENIUS, ELEGANT MATH TO DO THE WORK FOR US!!!

We've learned the **prop EFFICIENCY limit is set by the Plane SPEED,** and **Engine RPM, which sets Pitch, and Advance Ratio, which sets the Max Efficiency Limit, our core goal**!!!

We've learned that we had to **add a drag subroutine** to the **Classic Drag Free Math Program**, and with blades having the speed of Jets, but the small Chords of Model Planes, **C_D's must be higher than normal, for Low Reynolds Numbers, often below 1 Million**, and **thus we'll not get super low drag from exotic Airfoils, especially with bugged or eroded leading edges**.

FINALLY, WE'LL ADAPT THE BASIC DESIGN FOR SLOWDOWN!!!

We'll ***adapt the basic design*** to work in the **Embeded body** nose velocity profile, **shallower angles**, ***especially inboard***, **wider blades**!

REALLY IMPORTANT INSIGHTS & CONCLUSIONS

To get a computerized propeller design really correct it is necessary to recognize and do *three things* that are *not normally understood*, in many cases, even by professionals.

1. To have a **correct Thrust and HP design target** it is necessary to recognize that the required **Thrust** and **HP** can be from **~3%, or more to 10%+, higher than the plane's gliding, or accurately calculated profile and induced drag**, due to the **interference efficiency,** η_i, caused when the extra **ΔV over the embedded body**, creates **extra scrubbing drag**, and possibly **separation drag**. Inefficient, misshapen ***low pitch props*** with more ΔV, typically ***worst***. Separately, cooling drag can be 6% to 10%.

THE Power Loss can be *QUITE LARGE*, especially considering COOLING DRAG!

2. The **truly accurate Theodorsen 3D design mathematical method** accurately accounts for ***heavy loading*,** which can require ***typically 5% higher pitch*** and in addition supplies an **accurate ideal Betz radial loading design**, more accurate, **a little lower thrust and efficiency**, by accurately accounting for 3 Dimensional flow, **axial and radial induced losses, as well as stream tube rotational losses**, - (also ***low Rn blade drag*** when added).

3. ***Significant repitching is required to account for Slowdown***, the body pushing air ahead in the prop plane, perhaps 3 to 4% at the prop tip, ~12% at the half radius, 25%+ at 1/3 r depending on the prop and cowling size, and the prop location. *Prop extension?*

Use Theodorsen's Design Method. It is essentially Exact.

The essentially exact Theodorsen math method, which took 83 years for history's smartest analysts to finally conquer, which comprehensively takes care of ***heavy loading*** and ***high advance ratios***, when **.1 degree design or manufacturing tollerence** is proper, makes it a bad idea, simply unnecessary for amateurs or professionals alike to try their own less comprehensive methods. ***A greenie doesn't have a prayer, and all but the most rare, unique and brilliant modern professional would not either!!!***

C_L Logic --- Selecting a Design C_L vs. Diameter

You know that α^o **and** ***C_L always increase as you slow down***. The key is **the opposite is also true,** α^o **and** ***C_L always decreases as you speed up, even up to and through Vmax level***, then in a shallow dive to and **through zero thrust at Max Rated RPM!!** There is *great significance to that, how everything works out,* not clear until you study everything, see through it.

Here Goes! CL is Powerful --- But **SELECTED** ALT. CRUSE **RPM is a KEY $$$ Decision, Also!!!**

You'll want to **design your prop** for your **optimum altitude cruise condition**, **where your fuel money is spent,** ***at your best overall C_L,*** **(.5 to .55) right up as close to the peak of Andy Bauer's Magic Graph as it will calculate!!!** THEN, **at the max RPM S.L. Vmax condition, you'll move *to even higher*** **efficiency, eta, η, even *more efficient at a lower C_L, ΔV, ever lower induced loss, the key!*** YOU'LL SEE, **both efficiencies can maximize!! Conversely, if you design for Vmax, you're not designing for the condition where you spend the most time, spend the real money!**

Let us now show you a ***Cruise*** **design study *at Altitude*** that I asked Andy to run, that **shows how C_L, Diameter-Area, and Efficiency, all relate, *then* how they perform in *Climb at Sea Level and Altitude - Vmax at sea level,* and *Takeoff at sea level, the problem!!!*** Andy's program is **modeled for actual engine power and torque, *therefore models a real set of tests!***

(Next, 96.8 is max HP available at Altitude, 2400 RPM, *not* all used, Throttled.)

Design Study: 160HP$_{SL}$ RV6 CRUISE, at **12,500'**, **170 TAS**, **140 IAS**, ***163.7# required Thrust*** = (152.24 # drag /.93 *extra* η_i ***conservative***, ~ 82.8% overallη_P)
2400 RPM, **Aspect Ratio 14 : 1** (based on outer.9r) Study Airfoil, NACA 4412
Do a **Study of five moderate C_L's to find the optimum case**. ✓ **Drag %**

C_L	Dia."	Area ft^2	η	HP$_{reqd}$	J/π	Pitch 3/4r	β^o3/4r	C_D 3/4r	% of Loss	ΔV ft/sec
.3	**83.705**	2.815	.88315	84.625	.2844	74.524	20.74	.00900	**62.35**	10.07
.4	**77.308**	2.401	.89290	83.549	.3080	79.443	23.61	.00900	48.86	11.54
.5 ✓	**72.679**	2.122	**.89319**	**83.346**	.3276	84.120	**26.21**	.00917	**38.40**	12.79
.55	**70.788**	2.013	.89111	83.435	.3364	86.434	27.44	.00936	34.32	13.34
.6*	**69.103***	1.919	.88840	83.615	.3446	88.713	*28.64	.00962	31.03	13.86

Note: Pitch here appear larger than normal, since study purposely is *without* slowdown. — ***next***

*** Diameter shrinks, exaggerates β 3/4 r and Pitch 3/4 r increases. Nominal .3 Cl, 3 deg. Beta Increase is ~4 real, shows as 8 Degrees! WHY? There is ΔV and radius change too --**

It is obvious that C_L **changes the diameter grossly!** ***LOOK how small the efficiency change is!!*** But .3 C_L loses the most, and ***requires an excessive diameter***. **.5 C_L is best, but only narrowly. Thus you *could* choose .55 C_L based on weight.** The efficiency change is small, **because blade drag lowers enough with rapid diameter reduction to balance the increased stream tube induced loss!!! Note drag goes to 62% of the total loss at .3 C_L!**

It would be easy to misunderstand that C_L and Diameter-Area are not critical, can float around with little effect. **WRONG!! Once a diameter is selected, the prop *has to be pitched accurately* to *get the design C_L* or you lose your prop-engine-plane-RPM* match, *a Speed vs. RPM change!!***

***Less Pitch, RPM up, More HP, $ Cost, Plane Faster — More Pitch, Less RPM, HP, V, $ Cost.**

Sea Level Climb Performances – ***of props designed at altitude cruise.***

At 1600# max GW, 105 MPH max L/D speed, (above min power, max climb).

With *extra* η_i loss, 130.23# gliding drag/.9412 η_i needs 138.3# thrust *to fly*. ✓

C_L	RPM	η	Thrust	HPAvail	$T\#_{climb}$*	Climb*	J/π	$C_{L3/4r}$	$C_{D3/4r}$	DW°
.3	2019.7	.8276	381.9	129.21	243.66	1407.2	.2088	.680	.0097	4.65
.4	2114.2	.8062	**384.8**	133.67	**246.60**	**1424.2**	.2159	.853	.0115	5.86
.5	2181.9	.7851	383.7	136.83	245.42	1417.3	.2226	1.008	.0144	6.98
.55	2218.2	.7728	382.3	138.51	244.06	1409.4	.2248	1.085	.0165	7.58
.6	**2251.4**	.7614	380.8	**140.04**	242.53	1400.6	.2268	1.159	.0187	8.15

*** This Shows Max G.W. Climb. Light it's ~ Inversely Proportional to G.W., MORE!!!**

Here we see two conflicting logics! The prop design with an overly large diameter, an excessively low .3 C_L, has a new 3/4r C_L ***not*** too big, but with high drag turns less RPM, less HP, but at good efficiency, fair thrust. **The RPM, HP winner is the *small diameter*, *high .6 C_L* prop, that can be dragged through the air well, now at *even higher* C_L, but less thrust, lowest η! Max available thrust for climb, max climb is the .4C_L prop.** The .5C_L prop is close, ***the .55 prop 1% less***, but ***lightest, a tradeoff***. **A narrow tip .5C_L Betz prop has ~ 2.7 inches more D", *vs 70"D often used.***

A Broad Tip Prop Calculates to a Smaller Diameter, 70" for an RV 6, at lower η!!!

Altitude Climb Performances – ***of props designed at altitude cruise.***

At 12,500 ft. Cruise Alt., 1600# max GW, 105 MPH IAS, 127.18 TAS

At same IAS, 130.23# gliding drag/.9412 η_i still needs 138.3# thrust *to fly*

RPM	η	Thrust	HPAvail	$T\#_{climb}$*	Climb*	J/π	$C_{L3/4r}$	$C_{D3/4r}$	DW°
2119.4	.8629	221.6	87.04	83.30	582.42	.2409	.5213	.0099	3.29
2184.0	.8530	223.9	89.00	85.70	599.14	.2531	.6726	.0108	4.25
2235.5	.8397	**224.3**	90.55	**86.06**	**601.68**	.2630	.8144	.0121	5.20
2257.0	.8325	224.0	91.20	85.71	**599.24**	.2674	.8826	.0128	5.67
2276.6	.8254	223.5	**91.78**	85.21	595.72	.2716	.9495	.0137	6.13

Again we find the original .6 C_L prop has the most RPM, the most H.P, but the .5 C_L with **more Diameter and efficiency yields the most Thrust**, the **most Climb**. But the climb rates are so close, you'd never know the difference, and we **could still choose the .55 C_L based on weight**, with **only 2.4 ft / min. less climb rate**. (***Actually***, the program, a tad low on HP vs. RPM at altitude, **.55 climb ~ equals .5 !!!**) **Interestingly**, notice that the **available RPM is higher at Altitude Climb**, because the **127.18 MPH TAS is quite a bit faster** than the **105 IAS-TAS Equal Drag case at S.L.!!**

200 MPH Sea Level Vmax Performance -- *of altitude cruise props.*

247# gliding drag, with high η_i **loss** may need **260#. to 268.8# T at 200 MPH**.

RPM	η	Thrust	HPAvail	J/π	alpha 3/4r	C_L 3/4r	C_D 3/4r	DW°
2743.1	(.8812)	267.4	**161.84**	.2928	-1.3363	.2587	.0090	1.45
2732.0	.8975	271.5	161.37	.3183	- .4201	.3508	.0088	1.94
2717.5	***.9019***	**271.8**	160.75	.3404	.5039	.4414	**.0088**	2.44
2709.0	.9018	271.2	160.39	.3506	.9602	.4861	.0089	2.70
2700.4	.9008	270.3	160.02	.3602	1.4138	.5305	.0090	2.95

Notice how the efficiencies *here* have gained, (not .3 C_L), *both* Cruise and. Vmax optimizing, -- with Vmax climbing closer to the peak of Andy's Magic curve, -- than the cruise case can get, slower, more draggy C_L's, J/π's, than the Vmax cases. It's wonderful to get insight this incisive.

• • • (72.3 % radius data is used for 3/4 r data -- on these extra charts)

Here you can see that with all the angles of attack and C_L's falling due to higher speed, the original 72.7" .5 C_L prop delivers the max thrust, highest efficiency, **but the original .55 C_L, 70.8" prop is still a good compromise, only .6 pound less thrust, with a tad less efficiency.** The RPM's shown are the limits, set by engine torque, the RPM's shown the max attainable, (but some like **Vmax** to **overrev.**)* **All these props can overrev in a dive.**

* An **overrev design** gets you a faster cruise, **but costs cruise fuel** $!!!!.

We've consistently emphasized that **props want to be a very precise device, pitch held to .1 degree** as McCauley does. With everything floating around as it does here, obviously there are choices, but be sure you grasp that ***once a selection is made, if you miss the pitch, your pitch no longer matches the diameter and blade, and you've lost the combination, though it may only change RPM and Speed a little!!!* A 1° error is big!!**

1 degree, .1 Cl, at .5 Cl, is a 20% error, a big change to RPM vs. Speed match!!!

Sea Level Takeoff -- of high Pitch RV props *designed at altitude cruise.*

At 1600# max GW, 50 MPH RV 6 minimum Takeoff speed you want all the Thrust you can get for acceleration, but these Props are STALLED*!

RPM	η	Thrust	HPAvail	R_n .9r	J/π	alpha°	C_L 3/4r	C_D	DW°
1862.2	**.5585**	**509.6**	121.64	963,330	.1078	7.658	1.145	.0180	10.36
2011.9	.4967	479.9	128.84	913,420	.1081	9.639	1.337	.0240	12.11
2147.4	.4407	446.9	135.23	883,530	.1077	11.43	1.491	.0295	13.77
2207.7	.4049	419.1	138.03	871,950	.1075	***12.27***	***1.485***	***.1171***	14.58
2262.5	.3690	388.9	**140.55**	861,230	.1075	***13.08***	***1.159***	***.1379***	15.34

All props are *Stalled* - to the 36.7% radius on the .3 Cl Design Prop. 45.6% at .4 Cl, 63.4% at .5 Cl, 73.2% at .55 Cl, to the 81.2% radius at .6 Cl. This is the Hidden secret on Props for high performance homebuilts. It's particularly crucial on the otherwise great Long Eze which has ***a too small*** ***~65" restricted prop diameter, lacks good slowdown design*** at the rear.

* We'll soon see Slowdown Correction Helps a lot!!!

Realize here, the marvelous Insight available with the modern, speed of light personal computer, with the Elegant, rare genius level math that we have inherited. It's available, the product of 83 years of Historic Technical Work! The *relative* ease of use of **Theodorsen's Math**, the ability to **learn Source Sink Analysis**, makes the use of **BGT logic, and Math**, **for Ideal Prop Design, a task that can be broadly used** to **get Props out of Cut and Try Black Art**. **Andy has the program solved, available!**

Incisive Insight into the Blade at All Radii -- Climb, T.O. Stall
Our Design Study gave great insight into all props, at all key flight conditions, but in a simple format could not show what happens at *all* radii in Altitude Climb, and Stalled at Takeoff

CLIMB at 12,500' - .5 C_L case *ALL* Blade Radii Analysis

105 IAS, 127.12 TAS, 2235.5 RPM, 90.55 H.P., 224 # T, η .8397

% r.	β°	φ	α°	C_L	C_D	Rn_{10^6}	DW°	Eta, η
10.0	75.18	70.88	4.300	.8138	**.0162**	**.2450**	3.159	.8531
18.9	62.78	57.39	5.391	.9220	.0146	.4460	5.783	**.8594**
27.8	**52.70**	**47.12**	**5.574**	**.9401**	.0142	.6345	7.014	.8520
36.7	**44.80**	39.40	5.402	.9231	.0136	.7915	**7.187**	.8466
45.6	38.66	33.54	5.123	.8955	.0130	.9016	6.839	.8431
54.5	33.86	29.03	4.830	.8664	.0125	.9621	6.301	.8405
63.4	30.05	25.49	4.555	.8391	.0122	**.9728**	5.733	.8382
72.3	**26.98**	**22.67**	**4.306**	**.8144**	**.0121**	**.9345**	**5.198**	**.8357**
81.2	24.46	20.38	4.084	.7923	.0121	.8365	4.719	.8327
90.1	22.37	18.48	3.886	.7729	.0124	.6518	4.298	.8286
99.0	20.61	16.90	3.711	.7557	.0165	**.2205**	3.931	.8106

Notice Here: The angle of attacks, **C_L's** and **C_D's** are reasonable, the 127 MPH TAS better than S. L. Climb IAS, but the **C_D's** are up somewhat, **above .01**, (at 12,500'), the **Reynolds numbers below 1,000,000**, down in the 200,000's at Slow Root and Narrow Tip. We've Highlighted the ~3/4 radius data, 72.3 % r, used in the Study. **45° φ, - half the Total drag angle**, (Profile *and* Induced), is normally the **best radius at the design point**, max. efficiency, ***but*** off the design point here things get distorted a bit, as you can see. For insight, the .55 C_L prop has higher angles, ~ 1 degree, more ΔV too.

S. L. TAKEOFF -- .5 C_L case *ALL* Blade Radii Analysis

50 MPH IAS/TAS, 2147.4 RPM, 135.2 S.L.H.P., 224 # T, η .4407 !!!

% r.	β°	α°	C_L	C_D	Rn10⁶	DW°	Eta, η	S.D°	α°
~~10.0~~	75.18	*21.98*	*1.045*	*.4267*	**.1792**	11.31	.2797	*new°*	*new°*
18.9	62.78	*22.32*	*1.040*	*.4329*	.4149	20.40	.2879	- 17.6°	4.72°
27.8	**52.70**	*19.65*	*1.095*	*.3757*	.6825	**22.73**	.3009	- 11.4	8.25
36.7	**44.80**	*17.17*	*1.232*	*.2715*	.9278	21.74	.3472	- 6.9	10.27
45.6	38.66	*15.20*	*1.340*	*.2013*	1.1143	19.69	.3763	- 4.0	11.20
54.5	33.86	*13.66*	*1.421*	*.1540*	1.2302	17.51	.3970	- 2.5	11.16
63.4	30.05	*12.43*	*1.479*	*.1211*	1.2726	15.51	.4131	- 1.6	10.83
72.3	**26.98**	**11.43**	**1.491**	**.0295**	**1.2419**	**13.77**	**.4960**	**- 1.0**	**10.43**
81.2	24.46	10.60	*1.425*	.0274	1.1244	12.29	.4953	- .72	9.88
90.1	22.37	9.89	1.492	.0259	.8835	11.04	.4983	- .49	9.33
99.0	20.61	9.29	1.200	.0268	**.3008**	9.97	.4863	- .19	9.09

wow!

Look at all those wild ***stalled*** α°'s, C_L's, C_D's in *Italics* **It's worse slower, and at .55 C_L** + ~1° stalled one station farther out. Notice how high the C_D*'s* go, post stall, leaving **a big separated wake**. **But LOOK: The Slowdown Correction, eliminates the excess, on the edge of stall, but all radii unstalling just as Takeoff starts, even with this Fast, High Pitch Prop, even at a slow 50 MPH takeoff speed, for such a fast plane. A Slowdown Corrected prop is *fundamentally fixed*, unstalled for Takeoff. Of course it's a mess at Runup, and rolling to T.O.** !

Looking at some Key Insights Visible in the Study.

Variable Pitch Constant Speed Props: We're purposely studying fixed pitch Props. They're the ones to learn on, so you understand the tough parts, everything. A variable pitch prop is the easy way out on a stalled root problem, on the otherwise hi efficiency, high pitch props, and clearly the way to go if you have a fast plane that justifies the expense, weight, complexity, especially if your plane has a T.O. problem!

The Cost of Missing your Pitch: We've been saying that Pitch must be precise, within .1 degree, either as **a manufacturing tolerance or a proper precision needed for a computer design** calculation. The easy way to understand is that there is only **.95° difference** at the 3/4 radius between a relatively free turning 48" P, 71" D Luscombe climb prop vs. a relatively lugging 51" P Cruise Prop -- which ***limits the altitude cruise RPM to about 2300 RPM***, (more economical than a climb prop that would turn about 150 RPM faster), **slower like you'd use a Constant Speed Prop in economical cruise at a lower RPM!**

To yield a consistent manufacturing product McCauley properly uses a +/- .1 degree blade tolerance. **Remember the blade has to screw ahead at plane speed, but then be accurately overpitched *only* enough to account for and pull in *only* a small ΔV/2, *only* a few percent of V, plus a degree or so angle of attack**. **Δ1º error is:** 16.9 º(3/4r) vs. 15.9 º is **1.06289**, a 6.29% ballpark speed loss, ~ **6 MPH at 100**. or **2444.6 RPM vs. 2300** an increase to get back to the same speed, on **a simple ratio basis**, **purposely skipping the precise computer to keep it a simple calculation. You can easily think and see through that yourself --- no computer!!!**

DEAD SIMPLE, the Ratio Method is only a bit off the exact calc!!!

Cruise Design RPM: **A Key Cost vs. Speed Decision** Excess pitch, (or too big a prop), lugs the engine, less RPM, less H.P. less Speed, it probably can't reach rated RPM and H.P. But too little pitch, extra RPM, H.P. and Speed, **overreving, at Vmax what the go fast guys do on purpose** --- but you see **that costs you economy every hour you fly**. **The economy game is to lope along, wide open, leaned, the engine perfectly matched to the plane, High, getting free TAS, (but not excessively high where your engine loses too much efficiency)**. **You're not going slow, you're going Vmax at altitude**, , but you're **using the Prop and its design as though it was a costly Constant Speed Prop**. **Realize, fixed pitch, *you never get or use Rated RPM*, and H.P. unless you're doing a buzz job, on the deck, and how often do you do that --- and who cares, *or can judge your exact speed, V?*** **Going nonstop, you beat the go fast guys!!!**

Selecting Cruise RPM is one of the most important choices in designing a prop. Make it low enough and you have a good economical cruise prop, wide open, a best chance at good mixture distribution, but can't go as fast. *Higher RPM, you have the go fast option too,* ***but throttled may have uneven mixture***.

Digressing to the Merits of Electronic Fuel Injection.

We've been to the Moon, but we're flying with 1930's technology. Electronic ignition, Leaning, ***Fuel Injection covered in the Engine Chapter can bring exact Science to economical flight***. A carburetor can be an amazingly subtle, sophisticated device created by masters, in the best cases, but it's also potentially a crude device, and **a canted throttle plate** can be a busy **liquid droplet separator**, ***assuring you won't get an even mixture*** distribution, unless you get both Smart, and get Lucky.

If we can inject ***even***, ***lean*** fuel shots, with **knock proof variable advance electronic ignition**, we can fly with modern Science. Till then try to get ***even fuel distribution, wide open***, ***lean***.

Because we can fly at altitude we can do what autos can't, ***reduce our power, without throttling***, avoiding the pumping loss sucking air in from a duct throttled *below atmospheric pressure*.

Weight: A really interesting insight is that if a **constant Aspect Ratio** is held, the Diameter, Chords and Thickness go up in proportion, **a cube of the ratio!** Look at the study .3 C_L vs. .55.
83.705" D. / 70.788" = **1.18247)^3, = 1.6553**, a **65% weight penalty!**
.5 C_L vs. .55, it's 72.679 / 70.788 = **1.0267)^3 = 1.0823, 8.2% penalty!**
Clearly weight is a proper consideration, .55 C_L a possible alternative, shown purposely, but do consider stall, of course.

RPM, HP, Thrust *Slow* -- Big Dia., Low C_L vs. Small D. Hi C_L
For years I've wondered whether it was best to have a Big Diameter, Low C_L, prop ***Slow*** -- or vice versa -- from an RPM - HP - Thrust standpoint?? Well there's the answers, sitting right there in front of us, just begging to be understood. With all the complexity and interdependence, there is no way any of us mere mortals will see through that one cold. **Fantastic Insight: In slow climb, the High C_L Small Diameter wins the RPM and HP race, *but not* the thrust race!!! LOOK!!** But, ***conversely the BIG D prop has max RPM and HP, at Vmax, but*** **the middle .5 compromise is best!!** ***Insight you just can't find!!!***

Really Understanding the Aspect Ratio Subject

Aspect Ratio High AR props are more efficient than *low* AR props, ***1 to 2% better***, going up from ***12 to 14 : 1***, ***low to high J****, **λ.** A friend, whose bright comments I value, cautioned me about pushing that concept, arguing that it was really the diameter increase that caused the improvement. Smart people will regularly show you it's really lowering Span Loading on wings, by increasing Span, that knocks down wing induced drag.

*LOOK AT THE ADVANCE RATIO GRAPH, p. 48 II, TO SEE THE GOOD EFFECT OF ASPECT RATIO.

Smart guys know even more good fundamental reasons why a big D, should be the driver here, a big D, a bigger Disk Area increases $\dot{M}$, mass flow rate, lowers the demanded ΔV stream tube Speed Increase, a lower $\Delta V/2V_1$, less induced loss, more efficient. Additionally, pros know the Thrust coefficient is a D^4 function, a D^5 for the Power Coefficient, the modeling tools a pro uses to scale props, small test props to big, at NACA, for example. So to a pro ***D the driver*** seems a pretty pat conclusion. **All the smart guys know D is an 800# Gorilla, in Prop logic**.

But look what the Study just taught us: D vs C_L can swap, cancel each other, **relatively little efficiency or other change at *constant AR*. More Diameter got you more blade area, drag went way up**. Thinking back to the Advance Ratio Graph, calculated with all up math **Aspect Ratio is *itself* a key driver** at constant C_L, constant Advance ratio! ***What's going on here?***

You only need so much prop *Size*, (Dia. Area, Shape) to meet your **Thrust requirement**, at Spec. conditions. As AR goes up, yes D goes up, but **now narrower tips keep Drag loss in check** and **we get the efficiency gain** we didn't get swapping D vs, C_L. Yes, ***D is important, like we learned***, but ***AR is also a true basic***

How all this works out, the fundamentals and subtleties, the true interactions that you can learn from this study, is one of the most important Insight Opportunities you will ever find on Props --- because it is as close as you will ever get to a grasp that is all encompassing!!! ***Think it through, Soak it up!***

A Bottom Line Insight -- Ideal Betz Props vs. Black Art Props

We've been teaching Ideal Theodorsen-Goldstein-Betz Props for 3 Powerful Reasons:

1. **There is a Precise Design Math** developed by Rare **Genius** Historic figures that allows us to get creditable ~ **exact design point answers, only adding Profile Drag, for next level insight**.

2. **Betz Logic** provides the **magnificently orderly, logical insight** basis we find **in Nature, Science**, that **makes one of the most complex, convoluted problems in Engineering, explainable, understandable**, all from **simple helical flow**, and a **constant dT/dQ**, **every radius equally valuable, efficient**, that **cuts through the gross complexity like a Magic Knife**.

3. The concept of **Ideal Minimum Induced Drag Design**, with **Practical, Helpful, *Easy Enough* Math**, offers the hope of finally **getting propeller understanding and design out of the Black Art Category** it's been **stuck in for 135 years** at the Millennium --- **Getting Propellers Properly Efficient!!!** --- even win **proper recognition** for the 7 **Intellectual Heros** who over 83 years **won us an Essentially Exact Analytical Solution**!!!!

Rankine, Froude, Betz, Prandtl, Goldstein, Glauert, Theodorsen!!!

It's always proper to recognize the Giants, rare Genius Work!!!

If you are maybe beginning to **realize the initial Mental Jungle** that **Propeller Logics were, before they were rendered orderly** using our 7 heros, you'll know how indebeted we are to their past genius!

So Now, **What is the GIANT BOTTOM LINE to all this?**

If a normal **Clean Wings** can have a **20 : 1, to 25.:1 L/D**, that's only a **4% to 5% loss**, a **95% to 96% efficiency**. Now, if a perfect BGT prop normally falls into an 85% to 90% efficiency band, 10 to 15% loss, ***or worse, if Black Art Props***, 2 to 3 times worse, it's time we **understand WHY**, ***get everyone aware***, ***get them right***, a full half Century late, look to how we can **get more of an Elliptical Thrust Distribution** for Century 21, maybe get 92% to 93% η. TIP LOADED WINGS ARE BAD, DUMB, **Do Better**!

It makes absolutely **no good sense** to **expose excess tip area to the high q, high profile drag acting at the longest possible radius arm against engine torque --- when the productive thrust you hope for is just going to DISPROPORTIONATELY roll off the tip, lost, but its cost paid**. It's **just not possible to maintain a high thrust at the tip**, **it just rolls off** and at the high q cost, **proportional to the high tip (velocity)^2**. **(Go look at Prandtl's F factor plotted on page 98 - II to grasp how strongly a calculated thrust is knocked down at a tip. It's riveting, thinking of a square tip)**

Once you see the **modest inboard Thrust vs. Radius Loading of Betz plotted,** like p.92 - II, **realizing that tries to stall slow, (OK with S.D correction??) that area might be narrowed to cut weight!!**

WANT TO ENLARGE THRUST -- OUTSIDE THE COWL TO ~75% RADIUS IS THE PLACE TO GO!!

So **the world makes broader chord outer radii props, going for a better combination climb-cruise-takeoff prop???** No sweat, we mistakenly thought at first, we can **just unwind the blade angle to a lower α^o and C_L**, add chord, shrewdly **maintain Betz's ideal Thrust vs. radius loading**. **unwind it ideally**. **WRONG!** We promptly got the excess drag you could predict, **lost 40 RPM and 5 # Thrust** for Altitude Climb!!

Cutting diameter, we restored RPM, got Thrust, but started getting **more induced drag** naturally, **lost efficiency, required more HP**, could at least play with it, **not lose too badly, but ALWAYS LOST**. It's positively **amazing how smart Betz's insight proves to be, a 1919 wonder. (What we did gain was the ability to help the gross inner blade stall problem** we just demonstrated in the study, **on otherwise efficient high pitch props. Slowdown makes very big angle corrections inboard, especially in front of the cowling, and as shown in the angle corrections in the last column on p. 125 II, there's lots of help**.)

The point is IT ALWAYS COST US!! We learned how to fix a problem intelligently, neatly, go backwards the least!!! The basic point that dawned on us pretty quickly is that **not only is a Betz prop best, a constant C_L with the min. area drag wins!**

An Important Grasp of the Overview, The Final Results ---

We've been teaching you the Logic of Propellers using the **Betz** Minimum Induced Drag concept, and the **Theodorsen-Goldstein** Math, specifically because Betz has a great ***understandable, explainable, learnable logic***, and Theodorsen Math gives us a credible, ***essentially exact solution***, a proper base for learning. **That is reason enough for using the method --- learnable!!!**

Now the obvious questions is **are these props actually better, should I be trying to use one on my plane?** When I originally wrote this in 2001, I had full faith, but said we needed to test them to prove them. No real technical Pro would answer differently.

With a lifetime of technical experience, and my products all over the world, a pro is always cautious, **makes all products prove themselves**. There is nothing in this business quite as good as actually making products prove themselves, *shake out the unforseen*. Jim Rust, WhirlWind Propellers, El Cajon, San Diego jumped at the opportunity to prove our 10 year's work. His new 200 RV Two Blade, and 151, Three Blade beat all his prior Products.

On a valid RV 8 test the WhirlWind 200RV beat all other props, except Hartzel's excellent latest, the only other basically Betz Theodorsen Prop, with all of Hartzell's best tricks, airfoils, a little extra tip area, **208.9 MPH**, 2500 RPM cruise, vs. the 200 RV **208** BUT, I'd expact **the *.9 MPH Δ is just what I'd expect forever*.** **A metal prop should always beat a composite prop by a tad, *finer edges*, but the Composite prop was a BIG 17# lighter, no vibration vulnarabilities, a BIG Plus!!!** ***BGT beat all here!!!!***

A HUGE test proof to me here, the worst prop was Europe's best, 200.7 MPH. 200.7/208.9 =.960746 $)^{2.5}$ = **.9047**, inverted = **1.10529, 91/2 % Δ.** **A Speed increase is normally said to take power cubed. I conservatively used 2.5.** That was a three bladed prop, which normally **costs 1/2%** η. So lets say that this high pitch prop that was expensive and looked great, **cost 9%**, say 81% η, not the 90% a BGT RV 8 prop target. *How much can non BGT Props miss by?* ***This data* 8 to 10, 9%.**

Just How Bad can a Non BGT Prop Really Be -- and WHY?

All of the Prop Math that everyone has worked on for 140 years, now, has been on how to design a prop Right, Correctly, doing a **poor, to good job,** (BGT), **of recognizing the *real* size of the losses**, and as we come to the goal line here, wrapping up our long project, to me that is clearly **the area of weakest insight!!!**

Flip way back to page I 18, and I 19 of the introduction, to me, among the most important pages in the book --- because they expose the core, insightful fact, that **a propeller is really, in effect, two outer wing halves, at best, ~no center wing, even with BGT loaded too far out, a big mass of excess radial flow, greatly excess tip vortex induced loss**, ***mathematically nailed on p. 32, and 33 of Theodorsen***, as **BIGGER than the AXIAL induced loss that we must have to make thrust**. To me that is the **fundamental reason an 85% to 90% prop efficiency is so much worse than a 20 to 25 L/D, 5%, to 4% loss wing!!!!!!!!!**

Most prop design, unaware, has no understanding at all that is the core problem, fully able to klutz it up, make it worse!!!! To me, that makes the 1 legitimate data point in Van's RV 8 test above hugely valuable, a good honest test that shows a good looking professional prop can rationally, conservatively calculate to 9%, or more, worse than a BGT prop, almost twice the loss, ~81% overall, vs. ~90% overall. (An old pro, I'm not about to lose my head over data of 1 point, but **that is hugely more important than none**!!!)

NASA, cutting funding on aircraft, Langley is now deemphasized, (Lewis actually did the last turboprop work), but we need some serious testing to get specific answers on real prop losses, specifically how bad wrong props can be. Bureaucracies do become useless. **NACA should have nailed Raspet's interference loss, got us real data, this level of explanation --- a half Century ago!!!**

If I could see we had no prop explanation as a kid, waited a half Century, finally had to do it with Andy Bauer, where was the Research Establishment? **I've never heard one word that propellers are fundamentally flawed, try to tip load, two outer wing halves, no center, BAD - - a HUGE hole!!!**

With ***five*** **C_L vs. Diameter Design Cases** laid open, then **explored for Sea Level Climb, Altitude Climb, Vmax**, and **Takeoff**, you are never again apt to get an opportunity with such all encompassing specific insight. Don't miss your opportunity to see and grasp the inner workings and interactions of all the real outcomes of propeller logic. **The insight is marvelous, and quite different than you might expect!!!**

C_L vs. Diameter -- Induced Loss vs. Profile Drag Loss ***(Two Pairs).*** The **interaction** ***within*** **each pair**, then **the interaction** ***of*** **each pair** with the others **is extraordinary** --- seeing that large variation in the powerful basics of props produces ***only small differences in efficiency, and each performance characteristic***.

Diameter ***is*** *a powerful 800# Gorilla* in Props, but **see how C_L, another 800# Gorilla makes such large changes in Diameter**! Likewise, **see how induced loss** and **Profile Drag** loss **interplay**, obviously as **diameter goes way up induced** loss **drops**, but **profile expands startlingly to counterbalance induced** loss, **becomes 62% of the loss**, but **only relatively small changes in efficiency, thrust, H.P. amazing insight.**

Vmax, $\dot{M}$ up, ΔV, C_L fall, efficiency improves, logical after you think it through, as explained in the text, **both altitude cruise and Vmax efficiency as good as they can be,** ***winning 2 ways!***

Takeoff tries to be the problem case. Those props with a **P/D**, Pitch / Diameter Ratio **above 1**, ***the only ones that can be truly efficient are the ones that have a substantial Stall Problem*** at Takeoff. But, see on **p. 125 II how** ***Slowdown really helps stall!***

Notice the Study fine print offers Extra Insight!

Climb, ETC. Look at **how altitude affects H.P**., **how Speed effects RPM, thus H.P., thus Climb**, more RPM at Altitude due to a higher TAS. **Marvelous! A treasure trove of Insight!**
Look for yourself. See what else you can see, EXPLAIN???
Marvelous! Am I too enthusiastic? You can't buy this $$.

Learn from your Friends. With different backgrounds. and interests, your friends, and associates, over a lifetime, are apt to know all the things you don't. Listening, learning, growing can be the secret to maybe even getting wise. And ***friends insights, queries, taught me many things I needed to clarify in this book***

An ace Engine man ***quizzically*** said, **"Propellers seem to be pretty forgiving"**, a casual, but **very perceptive truth at several levels**, but exposing hidden lies. I instantly knew I had to **show how and why there was both truth, and lies there too.**

1. We learned early that it was **the Speed that determined the Mass flow rate, the RPM that divided the Speed into a High or Low Pitch, or Advance Ratio, thus the steepness of the corkscrew path of the prop Tip, that sets the cap on efficiency!**

The final steps to Max Efficiency hide in the final BGT details!

2. We've all seen **highly variable shapes, and they all seem to work OK** -- but the Truth is Hidden. The **Hidden Secret is that a Speed Increase requires Power^3, cubed,** (or at least a 2.5 power). **A Careful Test is Required! Airplane Math hides Poor Props.**

5% more efficiency only gets you ~2% more Speed! (1.05 HP)$^{.4}$ = 1.0197-- 10% only 3.9%!

3. We just showed you in our comprehensive study that TWO 800# Gorillas of Prop Logic, **Diameter and C_L simply swapped with each other, facilitated gross changes in Diameter with amazingly small effect on efficiency, all the key performance specifics. Profile drag, normally a lesser ~ 1/3 loss, jumped to 62% --- as induced dropped --- as Diameter got quite big, (but too heavy)** - ***startling***, and ***vice, versa, a small D, a balancing wash!*** It starts looking like nothing matters, but of course, that's a lie.

You can match Torque, get your RPM, but configure a poor Prop!

4. Another friend, **nailed a *Correct* objective, but caution here. The first job of a fixed pitch propeller is to load the engine correctly, get the correct RPM, get available HP**. ***Simply one must get torque vs. RPM matched*** That's absolutely true, basic, ***but*** economy argues we really do ***not*** want to design for an excess cruise RPM, or you'll be burning a lot of fuel, and not going much faster. **You want to be able to do economical**

cruise, with the engine as efficient as possible, more subtly, matching the plane where it's efficient, *"max speed vs. drag, at Cruise RPM"*. My Luscombe *with only* 67% overall propulsive efficiency, BAD, can fly 800 Miles, at 100 TAS, LA to McCall Idaho on its 30 gallons, only 33/4 GPH, 26.66 MPG, at 2280 RPM. Its Cruise Prop ***can't reach 2575 rated RPM***, **only 2535 Vmax on the deck**. **A big shortcoming? I couldn't care less**, a bit less climb. ***I'm cruising just like I had* a constant speed prop!**

You set Economy, Range, Vmzx, climb, when you set Wide Open Power vs. Cruise RPM

5. We've learned another key insight that looks fairly close to another wash, but isn't. **Because of Item 1. there are only small efficiency differences, a few percent, with some undesirable moves, and that's a trap. It turns out efficiency is not the whole story, you have to look at performance specifics to see if you lost there.** If, for example you hang extra tip area out there at less α^o to try to counteract a stalled root, you drop RPM, also you don't want thrust at the tip where we just took it away, get less, lose more profile and induced. Just use Betz Goldstein, Theodorsen as the logic intends to maximize efficiency, results.

6. Here's the Bottom Line, a FACT, a TRUTH. In 1990 at a **CAFE 400 Comparative Aircraft Flight Efficiency contest, Dick Van Grunsven, of RV Design Fame ran a test of all the supposedly best props for an RV 6** --- and **there were significant performance differences, design does count**! Many designers had substantially **missed the RPM** target, **missed on SIZE, Diameter, Area, Shape,** or **PITCH**, **RPM simply too high or too low**. But there were **several designs** that got that correct, but then **went on to work better or worse, so you'd buy one, not the others**! ***There were winners, losers - off target.***

7. Design Does Count, Betz has True Merit: That narrow chord tip gets you More Thrust for Less Drag, *BGT* Optimum. Slowdown correction makes the excessive inner Beta Angles of efficient high pitch props much lower for slow speeds, a big help. *Want to do even better, try an Elliptical distribution!*

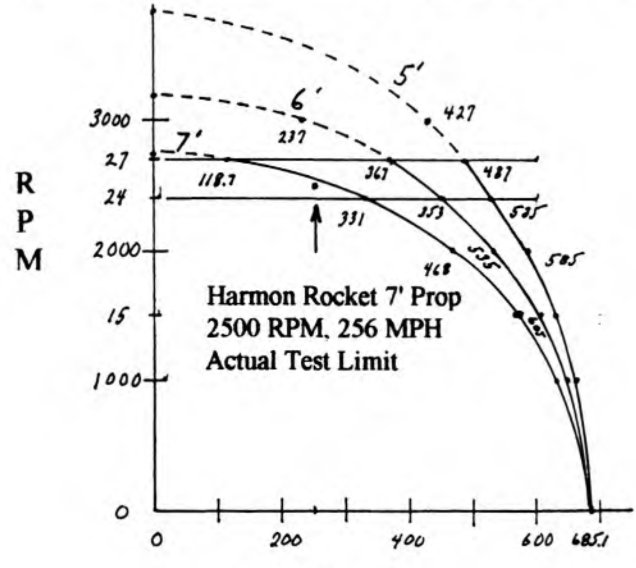
The Speed of Sound, Mach Number Effect -- Mach Limit

As a body moves through the air it sends a pressure signal wave ahead **at the speed of the molecular motion speed of the gas**, and thus related to its temperature vs. **Absolute Zero, - 459.7 F° where all molecular motion stops**. The Speed of Sound is quite logically the speed at which that pressure wave propagates. If that speed is exceeded, the air can't signal ahead, piles up in a pressure wave, and wave drag is created that acts very much like the bow wave of a ship. **The relationship is proportional to the square root of the Absolute Temperature** in **degrees Rankine, R°, 459.7° + the degrees above Zero° Fahrenheit**. It is **a function of temperature only**, surprising to some, at first, is **completely unaffected by pressure**. On a prop, logically, it's **the combined vector velocity of the forward and rotational velocity**. **(Remember school, the hypotenuse of a rectangle is the square root of the sum of the squares of the sides.)**

Sonic Limits Mach 1 on a standard 59° F day, (518.7° R) is 1116.46 ft/sec, 761.243 MPH, and **decreases at altitude proportional to the square root of the absolute temperature**, ***unaffected by pressure***, to 968.09 ft/sec, 660.06 MPH at -69.7° F. at 36,089', the beginning of the, **(in theory)**, constant temperature stratosphere. Even relatively thin airfoils may have a 30% speed up, which can cause standing shock waves, like you can see on a jet wing surface on an East or West trip when the light is correct, but those are *weak shocks*. **On Prop tests the drag rise really starts at ~ .9 Mach, 1004.84 ft/sec, 685.119 MPH at sea level, 871.28 ft/sec, at Stratosphere** temperature, and ***the vector*** of forward and circumferential V ***must be kept below that .9 limit. A 6' prop at 2700RPM, 250 MPH, is at a 924.1 ft/sec vector V***.

Now, that was the party line at NACA long ago, but John Harmon in his Rocket ran careful tests and went no faster above 2500 RPM, at 2550, with a 7 foot, 84" prop at 256 MPH, at a standard **~59 F°**. That's ~Mach .88, so we give you a graph, with John's ~.88 test point. **I'd thus be a bit conservative on .9**.

Understanding the .9 Mach Graph It shows allowable V vs. RPM



Realize it's better on a hot day, worse on a cold day, as explained vs. 518.7 R°, a standard 59 F° day, in Rankine temperature!

You can see that a **6 foot prop stays out of trouble even at 2700 RPM and 300 MPH**. John Harmon's **7 foot prop gets into trouble above 2500 RPM at 256 MPH**. An **8 foot prop gets into trouble above 250 MPH, even at 2200 RPM, starts needing to be geared down if it's on a really fast plane.** The Furias and Dreadnought at Reno have a very low 3/8, 3 to 8 gearbox from a Boeing C 97 Tanker, only 1125 RPM vs. a 3000 RPM P&W 4360 engine -- would you believe **advancing 37.5 ft. per revolution at 480 MPH --- 4 1/4 Tons of air per Second!!!**

At 480 MPH, the **13.5 foot prop** turning that 1125 RPM, **18.75 rev./sec**. has a tip speed of **1062** ft./sec. / **1116.46** ft./sec. is **Mach .951279!** But on a 100° F day, (559.7 / **518.7**)$^{.5}$, the Speed of Sound goes up a factor of 1.03877, so dividing the tip Mach goes down to Mach .915775, probably the reason that the Dreadnought goes about 480 MPH top. Can you see that OK?

Activity Factor vs. Aspect Ratio Activity factor is a Calculus based characteristic based on the following formula that ***pro's use to understand the "Power Absorbing" characteristics of a prop blade's shape*** --- where wide chords outboard are big power absorbers. Calculus Integration ***"Integrates, sums up" the effect of the blade chords, shape***. To understand, notice $(r/R)^3$ gives very heavy weighting to outboard radii chords, ie. $(.8)^3$, a much bigger radius ratio, gives a lot more weighting to outboard chords, because it's a bigger number, than $(.3)^3$, an inner radius ratio, a small number, gives to inboard chords. Do you get it? an r/R of .8 is out at the 80% radius, and that number cubed is much bigger than .3 radius cubed. (weights outer chords more)

$$\text{Activity Factor} = 100{,}000/16 \int_{.2\,R}^{1.0\,R} b/D \cdot (r/R)^3 \cdot \text{derivative}(r/R)$$

We don't want to teach you calculus so just see the "Integral sign" just sums up all the chords from the 20% radius to the 100% radius and the $(r/R)^3$ gives more weight to outer radii. The factor 100,000/16 just jiggles the numbers to make the answer come out to be from roughly 60 to 110, **100 nominal** for a wide blade at the outer radii, which absorbs a lot of power. It's all just a way to tell pros if you have a wide tip, a power absorber, or a narrow tip. ***Betz Props*** with ***narrow chords*** come out ***about 70***. ***Fast, Hi H.P. Mach Limited Planes use Hi A. F., but that hurts efficiency*** (I sure didn't want to get you into Calculus, but you should know about A.F.)

Thrust, Torque, Power Coefficients. NACA used to run small Test Props and Scale Data up or down using Thrust, Torque, and Power coefficients, and they are used in Theodorsen's Math.

$T\# = T_c\, \rho\, n^2 D^4$ $\quad Q\ \text{ft.}\# = Q_c\, \rho\, n^2 D^5$. $\quad P\ \text{ft.}\#/\text{sec.} = P_c\, \rho\, n^3 D^5$

These are quite useful and with the exponents show how powerful n revs/sec. and Diameter ft. are and how to scale data up or down **for geometrically similar, propellers, and similar test conditions**. For Thrust, one D^2 may be thought to come from *Disk Area,* a second D^2 from the V^2 *q effect* of radius, thus D^4. For ***torque*** we need a lever arm effect for the drag, thus D^5. Power = $2\pi Qn$ so a bigger **D** ***and, or*** **n** increase **Torque, or RPS** so Power is equal to $P_c\, \rho\, n^3 D^5$ --- vs. the Thrust Formula form.

We have No Bias, Not Selling Betz. <u>We're After the Truth</u>!

This Technical Business Works, because we are able to stand on our Predecessors Shoulders, and in fact, we did just that, and we expect those who follow to improve and refine our work.

With modern computers, we might have charged off on our own, confident that with modern tools, we could do better than any old fashion worker. Two lifetimes of experience taught us to respect that we had 83 years of **genius level work here**, and that we would be **better advised to first learn what those who came before us had learned**. As is so often the case in this business, **we found that brilliant analytical work has been done, long before its time**, that was **just too poorly understood, recognized and used**, and that **the task that needed to be done was to fully understand, evaluate, check, appreciate, explain and <u>use it</u>** --- to get propellers out of the too long Black Art status.

We've tried to do good professional work here, to add as much significant contribution as we could, so that we could offer more to those who follow, who can check and refine, and carry forward what we have tried to contribute. **We've tried to add to the body of knowledge and understanding, and subject to the review of those who follow, we believe we have, *<u>real insight</u>*.**

In inventing **Zero Thrust Glide Testing**, <u>we got the first **valid glide tests of drag** on *flying fixed pitch propeller* planes</u>. We were able to do **<u>repeated glide tests in dead air out over the ocean at dawn, and got excellent repeatable drag data</u>**, which, when **compared to the higher powers required, confirmed <u>Gus Raspet's incisive 1950 discoveries of very poor overall propulsive efficiency</u>, using propellerless glide tests**. We've carried that forward to find **significant interference efficiency loss** <u>compounding propeller efficiency loss a lot</u>, **<u>potentially explaining the phenomena</u>, <u>a combination of scrubbing drag, and a rear fuselage variable separation drag loss</u>, <u>caused by the higher ΔV imposed by the prop.</u>** <u>all worse on slow planes</u>.

In *explaining the logic of propellers*, and of the **Betz, Goldstein, Theodorsen analytical work**, and **the conclusions to be drawn**, we believe we have contributed significantly to potentially **broader appreciation and understanding** of their benchmark, historic analytical work, by the flying public, as well as **engineers, who can gain a far quicker understanding of this complex subject**, in **easier preparation for any work they may wish to pursue**. ***If you already understand, it's easier***.

In view of the substantial depth and breadth of the explanation here, based on Theordorsen-Goldstein-Betz math, and the enlightening insights presented, we hope that we have met our original objective -- which was **the first propeller logic explanation in words, not math, that is both understandable to a broader audience, and technically comprehensive, based on an exhaustive review of what this historic body of work -- really implies and means**.

That's what we tried to do. If you are a Pilot just looking for a basic insight, this may well have been far more than you'd ever want. But **remember, several times, we admonished everyone to only go as far as their interest carried them**. With 650,000 pilots in this country, we have the full spectrum audience. **For those who want the whole explanation of propellers, it's all here, and for all those in between, as you wish.**

I've purposely written this book in a more conversational tone, if in bold, with a lot of Emphasis, because there's more real technical meat here than most of the audience would normally see in a lifetime. I want to both help the new guy, and not only not be "put-offish" but **have it as conversational as possible**. ***If*** I think an insight is ***marvelous***, ***I say so***, even if some may see that as less professional. **I've been looking for some of these insights for a lifetime**, and it's ***great*** **to finally nail the *Truths***.

We'll cover several additional subjects that need to be covered, but **then** do **a whole Chapter of Summation and Conclusions.**

Additional Basic Classic Subjects ---- **If You Want It All**

There are so many things to teach you about props that we don't want to extend the matter, but there are **a few more classic subjects** that need coverage for a really complete job, and a few **last items that shout for clarification** --- so we're offering them.

Angle of Attack, α^o --- **Trickier than you may think!!!** .

Modern Airfoil data, α^o vs. C_L vs. C_D is taken in a Wind Tunnel with α^o, **quite naturally measured from the horizontal**, the **direction of the airflow**. The tricky part, not clear to a Novice, is that the **wing section runs from side wall to side wall**. That makes it act like an **Infinite Span, Infinite Aspect Ratio** - which has **no downwash theoretically and actually**, **otherwise impossible!!!**

In a **limited span wing or propeller there *is* an inflow**, $\Delta V/2$, **Theodorsen's w/2, Glauert's a factor, from the front of the propeller, --- and the top of the wing**, which is never mentioned on the wing, **half the final downwash angle**. There is an ***effective* angle of attack *decrease*** --- **that Pro's correct, on a wing** The formula gives the angle in Radians, **so we multiply by 180/π, to give it to you in degrees.**

Effective Change to wing $\alpha^o = 57.29578^o\ C_L / \pi$ Aspect Ratio.

Since the **air is flowing in from the top** the α^o **is LESS** that you thought, *a decrease to the effective α^o measured from horizontal*.

Now to really muck up the subject, if you've seen a smoke tunnel flow into an **airfoil it starts below the airfoil, and heads *up* too it**, simply because it's attracted to the lower pressure field above the airfoil. In the same vein the **whole mass of air *above* the airfoil is also attracted to the low pressure** surface, and the **net effect**, vs. the infinite span wind tunnel data is a ***decrease* in the effective angle of attack**, just as we've explained -- **honest injun!!!**

Now it is very important that we make this clear for the sharp guys looking close, because **our propeller geometry drawings account for the inflow and rotation**, ***no correction needed!!!*** **Glauert's a and a' factors**, or Theod's w/2, **account for the inflow** -- so we **correctly define the *actual and effective*** α^o **vs,** ϕ_1, the wind **inflow line W**, see fig.3, p. 94-II --- **No Correction Needed!!!**

__**The Nitty Gritty of Propeller Aspect Ratio**__. **Also inflow ---**

Props like to be High Aspect Ratio, as high as is sound vs. vibration, as **long and narrow** as the case allows, generally higher than the AR of the wing of the plane. The problem is that it acts as ***__two separate__*** **rotating wing blades**, __**affecting air 180° apart in the stream tube**__, even has **a tip vortex at both the root and the tip, the one at the root weaker, of course.**

However, the hub is structural, hardly a wing, and it makes no sense to include it in the wing calculation. We had to make a command decision on how to present it all. Andy chose to use **the outer 90 % of each blade**++. Thus **when we design a 14 : 1 AR prop it's really 14 :1 vs 90 % of the diameter, and it __really is two separate 7 : 1 blades__**. It seemed misleading, maybe confusing to novices, to call a long skinny prop 7: 1.

To help your insight -- if we used the α° change formula above for a prop we'd **use a 7 : 1 Aspect Ratio, that of __one separate blade__**. Thus for a .55 C_L ***__if__* the prop blade were a wing**, **which it is *__not__***, the correction would be:

$$\alpha^\circ \textbf{ correction} = 57.29578^\circ \times .55 / \pi \times 7 = \mathbf{1.4329^\circ}.$$

The **final downwash** would be **nominally twice that**, **2.8659°**

***You can see __Actual, Variable *Bigger* PROP Downwash__ vs. radius on p. 106-II**

BUT Surprise: Theodorsen's $\bar{\bar{w}}$, is __Big__, __cut down__ by his kappa factor, to maybe ~1/2, 1/3 or 1/8 __to find the average ΔV__, half that for inflow, ΔV/2. __Props have more inflow__, *__because they don't move the whole stream tube__*, and also vary vs. radius.* BUT now realize, __the correct inflow is already built into our geometry__ – *__No correction is used__*, this just to teach you all the nitty gritty at work here! __Only wings are corrected__.

I'd sure prefer to not have to teach you so many things, but all this is why props never did get __comprehensively__ explained before and **this *__is__* the advanced chapter intended for those who want to go all the way**. A lot of things are clarified and pinned down here that you would have a hard time finding any other place. If you're ***making a game out of this you're right on***.

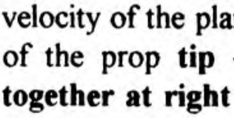
++An RV having an 18% Spinner, we later used only 81% of the diameter for Aspect Ratio calculations, our 8% stations at 19% to 99%. Thus a 14 : 1 Aspect Ration is equivalent to 12.6 A.R..

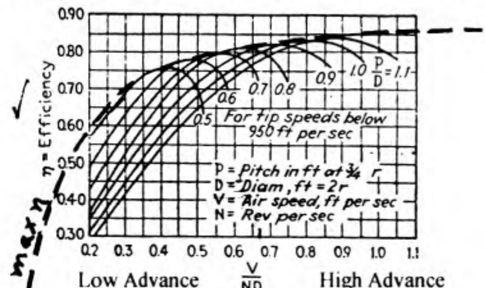
A Final Look at Advance Ratio, Efficiency, and P/D Ratio

Advance Ratio, J = V/nD, mystifies people because they can't grasp what it means physically. As you've learned, if you simply **divide both sides** of the equation **by π** you get **J/π = V/πnD** which is **still valid mathematically**, both sides now **just smaller**, **still equal**, and it's easy to see it's **just the corkscrew AAA**, **actual advance angle of the prop tip, or AAR, actual advance Ratio of the prop tip**, because it's easy to see **V** is the forward velocity of the plane and **πnD**, is just the circumferential velocity of the prop **tip** --- and when you **put those two velocities together at right angles** you get the **AAA, or AAR, or J/π** in the simple little sketch below. Now those are **velocities**, but obviously they have a **close relationship to Pitch, Pitch Angles, P/D Ratio** in inches, feet or even angles, because the **prop blade has to be at a little steeper angle to account for inflow and angle of attack α°**. **A prop appears to slip, accounting for inflow** + α°.

V/nD = J **Advance Ratio**
n = revs/sec. D = Diameter
V/nπD = J/π, λ
AAR

AAA°





Efficiency of a Series of Two-blade Propellers.

P/D Ratio I hope you caught that the **Advance Ratio Graph** p 48 is made up of the **max. efficiency points** of a **jillion Ideal props**. Now, this old graph in an early McGraw Hill, Marks, Mechanical Engineers' Handbook, does a great job of tieing together the **individual efficiency curves vs V/nD, *Advance*** of a varied **P/D** range of props and **how they form the Advance Ratio Curve!!!**

Very old, the efficiency is low, not accurate, vs the real J Graph, p 48 II. All left ends must go through 0,0 on the horiz. V/nD, and vert. efficiency axis, but nails how they all fit together. Grasp how all props start at 0,0, but the high P/D props, a huge speed range --- the inboard stalls slow*!!

Blade Element Analysis - vs. Actuator Disk - vs. Theodorsen

A few pages back we went through the drill of showing you that **wings need an angle of attack correction**, but that **props do *not***, *because* the **inflow is already accounted for in prop geometry and math**. ***Then*** for very good reason we showed you that if you try the wing α^o correction on a prop it doesn't work right, **and some insights on why not**, the **real prop inflow and final downwash are bigger!!!** That could seem confusing, but we're ***helping you grasp inflow, outflow is faster, higher angles***.

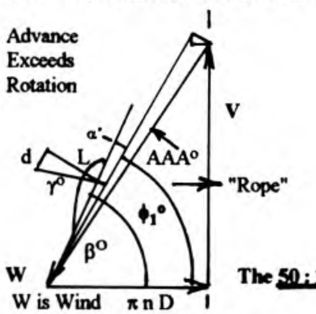
The Newton Actuator Disk --- gave us very important major **insight into the tricky basic logic of props**, ie. Go Fast, Get a high mass flow rate $\dot{M}$, thus a **low ΔV** for any required thrust --- only a **small $\Delta V/2V_1$**, a **small axial energy loss**, thus **High Efficiency -- only a High Pitch, High Advance Ratio prop can be efficient** -- Low pitch has high induced losses, too long a path to the destination, thus high profile drag energy losses also!!! We **tend to Lose Efficiency if we Increase Required Thrust, Go Slower, Reduce Prop Diameter, or Raise RPM, (a longer path). Great -- but it didn't deal with the prop geometry needed, was quite unrealistic in assuming constant axial airflow, useless for actual design**.

Blade Element Analysis --- Is the kind of analysis engineers love and some very smart guys spent decades trying it, but **never got really correct answers!!!** It considers a radial sliver of the prop chord and calculates its thrust --- and HP absorbing torque --- at the proper RPM, radius, thus velocity, thus q, dynamic pressure, all at the correct angles, correct trigonometry, desired C_L, then sums it all up with calculus. Thousands of Aero's were taught that way. **We'll use it next to get some interesting insight**. The flaw is that it ***assumes*** an α^o, C_L, **doesn't calculate, solve the accurate complex actual air inflow -- or ideal shape and twist**.

Theodorsen, **of course**, is our technical hero who got the complex, **heavily loaded**, 3D flow correct, accurate, finds a higher velocity helix moving back through its stream tube, the **only way you get real accurate inflow calculations real usable calcs**. **More Soon!**

Do Wildly Steep Blade Angles Really Work ??? Key Insight!

Think of a prop sliding ***up*** a steep, ***greased*** **60° Wind line, W** incline, pulled by a *horizontal rope*. **With low *Profile friction* drag**, *only* - a 50:1 prop airfoil, **"moves farther forward than the *rotation* rope moves"!! Though it isn't pulling forward well, actually pulling against engine torque, it's moving forward more than the engine rope that's turning it is moving, so it's *using energy efficiently*. Realize, *drag free*, we get constant dT/dQ!** ✓
Per this Sketch: Bottom Line - A Prop *IS an Airscrew: **That works OK!*** ✓



Vector diagram of a blade element

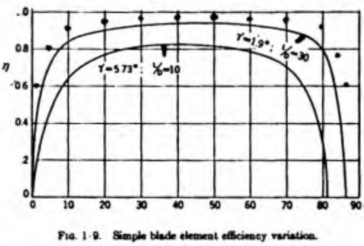


FIG. 1·9. Simple blade element efficiency variation.

The 50 : 1 L/D Graph ••• is for Profile Drag, SKIN FRICTION ONLY ✓
Graph is of Actual inflow ϕ_1°, not Blade, β, not AAA)
Blade element efficiency vs. inflow angle ϕ_1°

(fig. 3, p.94-II, shows how stream tube inflow sets the angles ϕ and α° to get β) Also see ~ p. .60 II

Blade Element Analysis, using Algebra and Trig., with all the forces and angles **(even if it can't calculate air inflow correctly)**, calculation, can easily enough look at the **efficiency** of **a screw at any angle**, and yield the plots above, and for various blade airfoil L/D ratios.

The key Graph insight is that a phi$_1$, **ϕ_1 inflow angle of (45° - γ/2) is the most efficient** -- the blade angle at α° steeper. (γ is the drag angle, like L/D, Lift vs..Drag in angle form). Per the graph it shows the **efficiency of any and all inflow angles at all reasonable blade airfoil L/D's**.

Now, the great insight gained here is that **efficiency drops moderately as you vary from a ϕ_1 inflow angle of (45° - γ/2), but is hurt most at very shallow or very steep angles. Now that is some quite instructive, practical overview insight** --- ✓

For Insight, *If a Prop were a Wing!* For a low N_R, **profile drag C_D of ~.01** -- and a C_{Di} for Induced drag* for a .5, or .55 C_L and a blade Aspect Ratio of 7 we'd get a C_{DI}, **of about .015, .025 total. and vs. a .5 C_L that's an L/D of maybe 20+ : 1, a ~ 5% loss!!!!** ✓

*(Remember, a Wing $C_{Di} = C_L^2 / \pi ARe$ -- where e is Oswald efficiency, ~ .8)

Now that becomes a hugely incisive insight on the subject of propellers!!! We know that a pretty high pitch, efficient RV prop can be 89 to 90% efficient, 10 to **11% loss** -- using an airfoil that on a wing would have a ~ 20+:1 L/D, **5% or less loss**. **WOW!!! Use an airfoil on a propeller and you get *at least* Twice the Loss, at a comparable C_L and Aspect Ratio**!!! Even with BGT half teardrop Loading we get excess tip loss, can do even worse with poor design. **Props, *better than Ducted Fans*, are the best, most efficient Propulsive unit, but *at least* 2 to 3x loss**!!!

A Low Pitch Luscombe Prop, at 85% η has 3x loss, 5x if at 75%, if bad Design!

Furthermore, only Theodorsen Math copes correctly with the **heavily loaded faster inflow**, faster movement of the pure helical inflow, stretched outflow, gets the complex 3D flow correct, **so you can get what your calculations show**, and it **gives Betz's Ideal Minimum Induced Drag Twist and Shape**.

Blade element Analysis, like a Newton Actuator Disk, can teach us a bunch about basic logic, but designing a prop with anything but the real math is just not correct, just kidding yourself, because you only have it right when you accurately calculate airfoil inflow. That's a pretty simple Key Insight!!!

But there's more!!!. We learned from Gus Raspet that there can be a big interference loss, maybe another 10% loss on slow planes with a bigger ΔV, less on fast sleek planes with less relative ΔV vs. V. Zero Thrust Glide Testing, a Classic like the Luscombe, we found 67% overall η_P, with a ~75% prop η, a ~ .9 η_I interference efficiency. We don't have final overall numbers yet on RV's because we must do Power tests, but they can be quite good maybe 85% overall with an 89% Prop. That's key Insight --- never available before!!!

The Real Induced Drag Loss. We've purposely been treating Induced Drag like it consists of **Downwash** and **Tip**, **and Root Vortex loss**, like it is on a wing, to not confuse learners, **Rotation Loss separate**. But **Think**, obviously **Stream Tube Rotation loss is just another type of Induced loss**, part of the reason **props have ~ twice the loss of a wing, or much more**!!!!

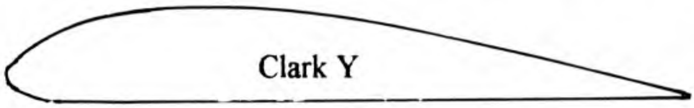
Get a Professional Grasp of Theodorsen's w factor. It's BIG

Go back and look at Theodorsen's **W, w bar on p. 94-II. the Total Extra Velocity Speedup Ratio** of Betz's Helical Vortex Sheet. **See that it's .1566**, a ***BIG ratio of plane speed V_l*. At 170 cruise, on an RV, it's 26.622 MPH, much bigger than the average 9.239 MPH ΔV we've been talking about!!! Why?** Hopefully, you already know. Theodorsen's **Kappa Factor, κ which knocks the $\overline{w}$ down to the average ΔV is .34704** for the RV on p. 94-II, so the **effective ΔV is 9.239 MPH**. But you see the prop has to be **pitched for nominally half the full w, 13.311 MPH** above 170, .0783, 7.83% faster, .0511, 5.11% faster than the .02717, 2.7% that would fit if the whole stream tube moved at the average ΔV!!! **That confirms the ~5% extra pitch rule we told you about earlier that seems to work at ~.55C_L**!!!!!!

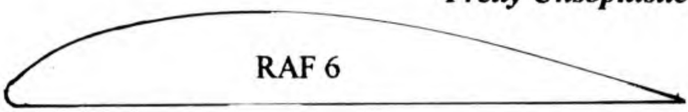
Theodorsen's A Zero Inflow Factor, A, Actually, Theodorsen's **A, Inflow Factor**, (.078005), accounts for whether the inflow is a little more, or a little less than half the $\overline{w}$. This guy is Amazing in his thoroughness and mathematical insight, a true genius. Of course when we're setting pitch we have to **account for angle of attack, alpha, best if its simply a constant α° added to the helical phi's of the air inflow – because that's what sets up a constant C_L** for a minimum Ideal Profile Drag, as well as Ideal Minimum Betz Induced Drag. **Now we're ending with this little drill here so you both understand the extra pitch that Heavy loading demands and conclude that Theodorsen is the only sensible way to go about designing a Propeller**, because **he deals with all the complexity and gets it right**, all else an amateur drill, not worth wasting your time on.

Theodorsen's Epsilon Factors ε Theodorsen actually divides his 3 axis losses into 3 axis Epsilon Factors and makes it possible to take the losses apart, shows that **the radial flow loss is very big, bigger than the axial loss, the big loss, never understood! In Appendix T we concisely deal with Theodorsen's math methods and equations, so you can see his methods.**

Airfoils Profile Friction Drag For Decades props simply used a basic, old **Clark Y** airfoil or an **RAF 6**, a special prop airfoil that actually had its **bottom cut away**, which gave it an **easy to measure**, **absolutely flat bottom**, not all bad if we must **measure to .1 degree Beta,** β^o. Tests showed the **RAF** was better for **Takeoff**, the **Clark Y best for Cruise, a lower C_D**,.



Pretty Unsophisticated!



Yes, we want **low *PROFILE DRAG***, but with **eroded**, **bugged**, and buggered leading edges and **low Reynolds Numbers**, betting on **low C_D's is not realistic**. Conservative is appropriate. The game in laminar flow is to **Hold Laminar at Reynolds Numbers of several million, hold a ballpark C_D ~.00 5**, not let it jump up to the **significantly higher Drag of turbulent flow, ~.008.** The problem is that as you drop to **R_N**'s of a **million and below, even laminar C_D's raise to .01 *and above***. At a .5 C_L, 1 million **R_N** an **.01 laminar C_D ballpark is a proper conservative nominal**.

On the other hand an ideal airfoil with really good leading edges can't hurt. John Roncz designed special optimum airfoil sections for each station on the special **Hartzell around the world Voyager propellers**, and they worked great, **compliments to John Roncz**. **Compliments to Hartzell too**, because those props **they contributed saved the Voyager Program** when a **controllable pitch wood prop failed**, a blade pulling out of the hub!!! The really nifty 1986 trick was John designing the special props on his computer, loading them on **a floppy disk**, Hartzell creating an NC Machine tape directly, the Numerically Controlled machine milling the blades out of a forging, untouched by human hands in minimum machine time - **ready for final hand finishing**.

Low Reynolds Number Drag.

Below is a standard Graph for Profile Drag at a Wide Range of Reynolds Numbers, both for a lower range below 1,000,000, down to ~200,000, then above, to 2, or 3,000,000, common ranges. Low Reynolds Number Drag Data is pretty limited with rather inconsistent answers. Basically, see that there are large changes below a 1,000,000 Rn, from below .01 to well above at 200,000 Rn. For our Low Reynolds Number calculations we conservatively assumed turbulent flow, used .01, rising above that down to 200,000, and also rising with greater angle of attack. Actually if one uses a conservative overall C_D of ~.00937 overall results can be comparable, so we used our private chart only where we were looking for significant effects, because Reynolds Numbers easily get down to 200,000 at slow inner radius chords, and also fast, but narrow outer tip chords.

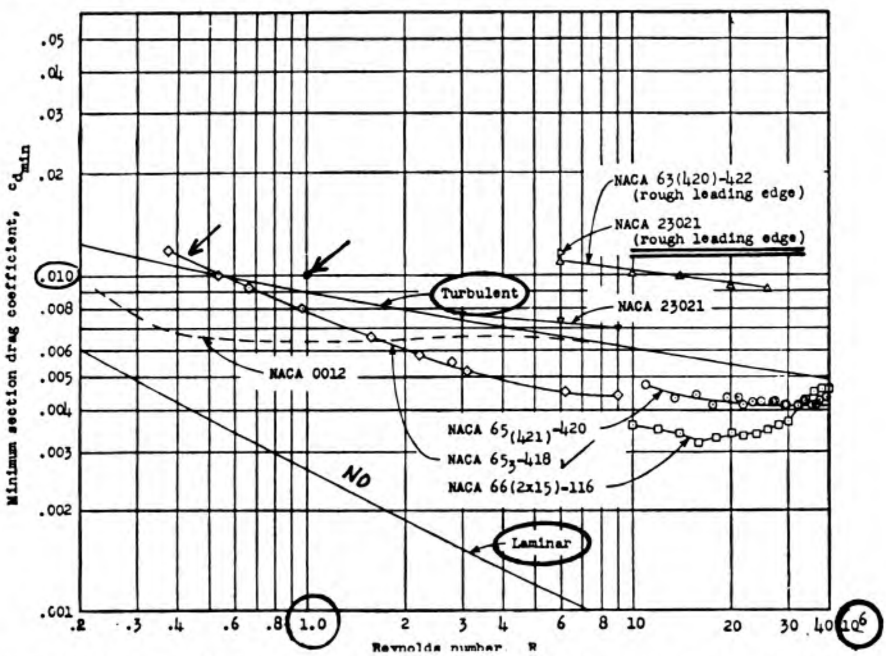


FIG. 66. Variation of minimum drag coefficient with Reynolds number for several airfoils, together with laminar and turbulent skin-friction coefficients for a flat plate.

A Goal Line Personal Comment, and Evaluation of all This

Understand that I'm a very Senior Aerospace Technical and Top Management Consultant, long ago financially retired, *exactly* how Airplanes work, ***a lifelong serious challenge hobby***. I've been watching, waiting for the serious Propeller explanation, for 60 years, since I was looking for it as a kid, winning the National Model Championships two of the three years I was there to compete in 1946, 48, 107 of my Moon Program Spacecraft Small Rocket Maneuvering Controls in the Milestones of Flight Gallery, the Central Hall of the Smithsonian, National Air and Space Museum, July 4, 1976, the day it opened --- about as qualified as one can get to finally, Technically, practically explain Propellers.

For decades, I've thought it was ridiculous, unacceptable that we never got the Professional Level, but Incisive, Understandable Explanation of Propellers, especially since Theodore Theodorsen, maybe the top technical professional at NACA, nailed the genius level Mathematics almost 60 years ago in his 1948 book.

Understand, that I'm neither the technically flaky top management guy, or the narrow vision technical guy, who lacks the no fault allowed Top Practical Grasp. I spent a lifetime in key, core flying products that had to be on the Technical Leading Edge, but absolutely could not be allowed to fail, or we had a National, Front page disaster: First, big, tri-axially Stressed Landing Gears, the Absolutely must never fail for *ANY* reason, Primary Jet Flight Controls, that your, and a few hundred other lives depend on, the Spacecraft controls that had to, did live through the Apollo 13 explosion, brought it home safely, maybe man's greatest adventure!

The core point that I'd like to make is that Theodorsen's work, was ***not*** the flaky, too far out theotrician's analysis, but the ***Tough Minded*** all up ***Final Professional Work***, that accurately accounted for **all the 3D losses** after 83 years, the smartest rare geniuses the industry had produced, giving the final most conservative, most correct technical work. **I work at the, *it must be correct level!!!***

The 7 Historic, Genius Pros - The final really correct Answers

Propellers are, and should always remain, our most efficient method of rotary propulsion, especially important as inexpensive fuel disappears, but almost laughable, the dumb things are **trying to work inside out, trying to make max Thrust, and Drag at the Tip, where Thrust *must* fall to Zero**, Dumb as a Stump. That was **the first thing we taught you**, by far the ***easiest, most fundamentally important basic grasp in the book***.

The **Ultimate Technical Swamp**, the reason Andy and I chose it as **a Life's *Give Back*, Goal Line Intellectual Challenge**, they were such an unexplained morass, that no one saw through the **Aero 101 insight**, that they were trying to operate inside out, and that was **the main thing we had to recognize and fix -- Theodorsen's magnificent technical method**, as a **SIMPLE BLADE LOADING CHART**, sitting there, ***waiting an Extra Half Century*** for us to get Computers, Wake up, and put a great example of an ultimate Technical Answer to Work. I hope old Theodore is up in Heaven having a big laugh --- **we finally got it!**

It's hugely Proper, that we clearly honor Rankine, Froude, Betz, Prandtl, Goldstein, Glauert, Theodorsen, already Technically Historic figures - or their Rare Genius work in our behalf, clearly deserving Historic Recognition and Status - providing us with a ready to go, and use, sophisticated solution to probably the most complex fundamental problems in Aerodynamics — a practical, understandable, accurate analysis of Propellers - *amazingly, a simple Blade Loading Chart*

Doctor Andy Bauer, my lifelong friend and Collaborator in all this **clearly deserves to be Historic person # 9**. It was he, with a lifetime of top Technical Experience, who wasn't snowed, put off by all the Partial Differential Equations in Goldsrein, ***smart enough to see the final answers were in easy chart form***, seeing that **with his final 19 page program we could nail everything. Andy earned, deserves a proper place in Propeller History**

Gus Raspet, that marvelous Creative Mississippi State Maverick, **clearly deserves to be # 8** for showing us all in the 50's **how really terrible overall propulsion efficiencies could be**, a good looking, Classic Bellanca Cruisair, **a terrible overall 58%**, ditto Cubs and old Cessnas - the marvelous insight that got my attention, got me interested and started on the whole project, essentially got me qualified to be Technical Director of Voyager Mission Control, by its 1986 date, all sharpened up ready to go with a Steel grip on all Flight Fundamentals.

I absolutely want to name **Paul Lipps of Arroyo Grande CA**, as **pro # 11 in Nailing Props**, because ***thinking outside the box***, a highly intelligent RCA Radar Technical Pro from Vendenberg AFB, his mind not cluttered with Party Line Gross Aero Technical Detail, but very bright, creative, he was **brilliant enough to recognize that perhaps a prop should go right back to Prandtl's ideal Elliptically Loaded Wing, as a rotating Wing, a genuinely top level technical perception** that Betz, or Prandtl themselves might have seen a Century ago - saving us a Century of gross, noisy tip overload losses, if we mortals were perfect. His Elliptically Loaded props, that look wild and crazy, seem to perfectly correctly do the next better step compared to the Betz, Goldstein, Theodorsen Half Teardrop loading, vastly better, quieter than the ridiculous tip overloading of too many of todays products after 140 years. ***Good Work Paul!***

I'll leave room for myself as #10. Hell, at age 79, I earned it the old fashioned way, in addition, a lifetime of creative products, that absolutely had to work, soundly, reliably, lots more than you heard here, creative, simple, technically astute Nuclear Plant Seismic Protection, good stuff all over the world, ***great satisfaction***. To me, it was totally unacceptable that something as fundamental to flight as propellers, went unexplained for 140 years, answers I was looking for as a kid of 18, 19, 20! I wasn't ready to quit at the answers that Andy and I had years ago. **I wanted technically sophisticated answers - simple, clear!**

The Wise Old Bird

This Crazy Guy decided,
as a challenge, he was going to
do **the real propeller explanation**
that **never did get written** before,
- making the ultimate morass
Understandable ---

The secret insight is: **All of nature, no matter how complex, is always orderly, logical** --- and that is the way our brains work, in order and logic, and thus if someone can figure out the logic, we can understand anything in nature! **That's what Science is**, the first guys **figuring out the order, the logic**, so it can be **universally understood and put to work for the good of man**.

For those of you who know of Stephen Hawking, who have seen him on TV, or read him, you may realize that he points out that if we can finally understand, we ***amateurs*** can know the mind of God.

Computers are **a specialized tool** that we can put to work for us because they can **process numbers** at essentially the **speed of light,** even do it in accordance with complex mathematical programs we can set up, **without stopping to think**, giving us almost instant evaluations, numerical answers, often even put out in non mathematical form like this text, or movie special effects. **Our minds can't work *fast* in math, so we put computers to work!**

So you see, **it's imperative that we decode the order, the logic of propellers** and ***teach it to you that way***, **because that's the way you can understand it**, have it make sense to you, all interrelate, **make it possible to remember it, *because* it does make sense!**

Our minds work in layers of logic, remembered if something does make sense, relate in logical ways to other things that make sense to us. **So the *Summary* you're about to read is the first, comprehensive, orderly, logical explanation of propellers.**

BOOK 2 --- CHAPTER 4

PROPELLER SUMMARY

THE CHAPTER with the **GREAT HINDSIGHT SUMMARY**
JUST ENOUGH DETAIL to help an ACCURATE GRASP

With Fan Duct Losses, and potential 21st Century gains in Propeller Efficiency, the Propeller is, and most likely will remain our most efficient method of creating Thrust from a Rotating Engine. It is Amazing that it has taken until now, 2006, to get a Comprehensive, Understandable, Explanation of the Fundamental Engineering Logic --- recognizing that Rankine, Froude, Betz, Prandtl, Goldstein, Glauert, and Theodore Theodorsen, all Genius, Technical Historic figures, labored 83 Years, from 1865, to 1948, but in that time had created Betz's Classic Propeller Theory-Logic, and Goldstein, Theodorsen, essentially exact Math Solution of Betz Logic! It is Amazing that such a Fundamental Aerodynamic Device has been allowed to remain an unexplained, technical Swamp this extra HALF CENTURY. WHERE WERE the PROS? I saw this gaping hole as a young model builder in 1946, 1948!

The most fundamental insight that I want you to realize is that all this time, all too unattended, the Propeller has remained, essentially *not* understood, a rotating wing, *not* with the easy 4, to 5% loss of a basic, clean, nominal Aspect Ratio wing, but rather the much larger nominal 10, to 15% loss, *or a lot worse*, of a device with excess radial flow tip vortex induced loss, losing paid for thrust, and all too often, excess profile wide tip losses, at max lever arm, bogging down the available engine torque, losing H.P., losing 4 ways!

It is particularly Amazing, that this excess loss situation was never adequately grasped, since Theodorsen was such a respected figure in the Aeronautical Engineering Community. He showed on his page 33 that the radial tip Induced, Vortex loss could be *Larger* than the Axial Induced Loss Necessary to Produce the Basic Thrust!* We normally fly a wing, at more like a 25% ballpark induced loss*. *Induced flys ~TWICE Profile* on Props.* What a BIG FAT HINT!! Clearly, everyone in the Research Community, running off to Jets, abandoning this Most Fundamental Aerodynamic Device, no one was looking!

***REALIZE TIP VORTEX IS JUST A ~25% *part of* INDUCED LOSS ON A WING!!**

The basic Betz-Goldstein-Theodorsen Propeller, in it's pure form, the Family of Ideal BGT, Triple Ideal, Minimum Induced, Min. Profile, Min Torque Propellers, MINIMUM AREA, PRECISELY PLACED, Norris's 6th Law, should have been the basic design Standard in the Industry for the greater part of the Last Half Century. The Research Community has been, unfortunately, Missing in Action!!!

The first appropriate step is to get some approximation of everyone involved to understand, that Propellers can be "easily enough understood", just get the radial loading correct per BGT, by a move, no more difficult than getting the **SHAPE, and *Twist*, correct**, ***of course*** Pitch, and all other Size, Area, Diameter, and all other optimum, ideal characteristics. **That's easy to Grasp!** BGT math has been available for over a half Century, since Theodore Theodorsen's 1948 book. **We have the Computer Programs running, checked, can teach those manufacturers who don't have the knowledge and resources -- learn how to use them.**

Understand Prop Engineers, Good Guys, Deserved Help Here*

We have to be smart enough to know, as customers, that we won't get them, unless we are smart enough to go after them, because old manufacturers have a half Century of old design props, all approved, and will only slowly get modern, unless we get smart. *Research gave prop engineers no help since 48! In these days of ever more costly energy, we need our props as good, efficient, Quiet as they should be! It's time!!

The Areo 101 of Propellers - Fantastic Summary *x-ray* Insight

We've learned that a 7:1 Aspect Ratio Wing can nominally, have a 20:1 L/D, thus a 1/20 total loss, 5%, 95% efficiency. But even an optimum BGT private plane prop can only be 85% to ~90% ballpark, nominally, and poorly designed, may lose another 10%, **2, 3, 4, 5 times as much loss** - ***Clearly***, **a big wasteful loss here!**

Theodorsen shows us the basic problem on page 32, and 33 of his book. Even for an efficient high Pitch, .5 Lambda, λ, prop, the radial loss, the **Tip Vortex Induced Loss, is even a bit Bigger than the Axial Induced loss, fundamentally needed to make the Thrust.** Rather than a nominal 25% extra Induced, common on a wing, **the extra, auxiliary loss** you'd hope was only a fractional loss, **is Bigger than the Needed Loss to make the Thrust! With poor design, trying to get thrust at the tip,** where the Smart Game is to Get both Profile and Induced Away From the Tip, **it's possible to kill another10%, create a 4x loss on a 90% case, 5x at low pitch, at 75%, not the basic 3x loss!**

It's our job to understand, know how to Professionally Counteract Excess Prop Tip Loss!

You just don't tip load *any* wing, exactly what the fast, very high q prop tip is trying to do to itself -- where the Aero 101 of a wing shows us the lift, thrust must fall to zero, pretty much elliptically, into a ~ 25% extra Tip Vortex Induced Loss, with a .8 Oswald efficiency factor representing a nominal tip Vortex loss, over and above the needed theoretical loss to make lift. Of course, the prop has rotational *induced* loss too, *but the Tip is worst!*

Now knowing that Betz-Goldstein-Theodorsen always pulls the radial blade loading back into their "**Half Teardrop Loading**" we see ***that high loading is still unfavorably close to the tip,*** the reason radial tip loss is as big as the axial. **YOU DO NOT TIP LOAD ANY WING, EVER - BAD, WRONG, COSTLY! The core ball game in prop design is being smart at the tip!!!**

With essentially exact Theodorsen Math, and Source-Sink nose profile correction, we have *the* accurate, pro way to go, to design. With Heavy Loading, BGT Pitch is nominally ~5% higher, a significant error, if you use less accurate methods.

1. The new *Century 21*, Lipps, Elliptically Loaded Outer Prop

Betz and Prandtl, *or a host of others*, **anyone calculating**, *might* have seen that BGT fundamentally pulls the blade loading back away from the tip, into **a half teardrop radial loading**, to prevent unnecessarily excess tip radial flow tip Vortex, induced loss, and unnecessary tip Profile Drag, at Max lever arm, bogging down the available Engine Torque, increasing cost, reducing available H.P., **but I've never seen it before this text**.

Paul Lipps a very smart Radar pro, and hobby plane improver, saw, **without knowing of BGT classic Theory and Math**, that ***we could, should move the loading back even more inboard to Prandtl's Minimum Induced Loss Elliptical Radial Loading***. It makes a pretty crazy looking, concave outer blade shape prop, but it ***simply does what BGT does, just a little more inboard***, to ***an elliptical tip loading***, from the BGT half teardrop. As such it ***does have the potential to do even better than the BGT loading!***

Winning Races at Reno, more testing, refined math, and slowdown design, Truth soon!

The two pages, way back in the Introduction, though quite brief, do a good job of showing Lipps basics in easy picture form. so I suggest that you go back and read it again, ***see the core logic of it***

See pages I - 28, and 29 - II

Now, if you ***reread*** the Introduction on Lipps Props, or if not, you should be able to easily enough, by now, see that the very **fundamental flaw of the basic prop**, and unfortunately still the Lipps prop, is that **all rotary props effectively have No Center Wing**, effectively have **two separate outer halves**, **almost only two separate outer wings**, **connected to the engine by two ineffective, low q inner halves. That's fundamentally Poor!**

ONLY **TWO OUTER WING HALVES, IS MOST UNFORTUNATE!!!**

If you think about it, the spectacular 60 : 1 glide ratio modern sailplane, **1.666% Whole Plane loss, 98.33 percent efficiency**, can do that because it has a **huge Center Wing, far removed from tip loss**, all very high Aspect Ratio, long narrow tips, themselves far removed from the tip, ***cutting the entire induced loss to near an absolute practical minimum!*** That cuts the induced from the basic lift, and 60: 1 **slashes down tip loss too!**

So, with the Lipps Elliptically loaded *outer half* Prop, what we're potentially doing is *practically* opening up the *possibility* of getting Propellers to their Ultimate Possible Efficiency!!!

CAUTION: FIXED, HIGH PITCH, IT MAY TAKEOFF MORE POORLY!!!

If a fast, 200 H.P. RV 8 has just over 90% η BGT potential, let's just say 90% max for the best of the non all out speed merchants, time, more testing, refined math, may get us **a bit above that with a Lipps** prop, ***never as good as a 95% wing!*** Trying is ***a legitimate piece of normal Engineering Progress*, a proper objective for this 2nd Century of Flight!!!** We'll certainly make more, prove conclusively if they really can be better, try to get math equivalent to BGT, if possible. **GO!**

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2. Thrust Required The **first thing** to **understand** about props is that **Thrust does *not* equal Gliding Drag!** There is an eta$_i$, η_I **interference efficiency loss** once you turn on the prop throwing back a downwash, backwash ΔV wind to make the thrust. That causes **extra $(1 + \Delta V/2V_1)^2$ scrubbing drag***, and ***possibly***, some separation. **In Slowdown, a pressure force on the imbedded body does *not* cause a new loss, a wash actually, the prop now running in** slower air, at less H.P. But there is a need there, to generate a bigger Gross Thrust, for the same old Net Thrust to balance the pressure, a wash, at the original H.P.!

***On a Clean, Fast, low ΔV Plane, the extra loss can be a Small Percentage, RVs Good!**

As taught in the Advanced Chapter, 3, if you know the ***accurate gliding, or calculated drag***, and the ***interference efficiency***, η_I, you can get the **necessary design thrust** by **dividing glide drag by η_I**. If you don't know those, but know the actual H.P. and speed, V, since Horse Power is T # x V ft/sec / 550 ft #/sec per H.P. you can easily find the **Available Thrust** for 100% Propeller Efficiency, and then decrease that by the proper (high) prop efficiency, to get the proper (high) thrust available - Somewhat above glide drag, (as related through the interference efficiency, η_I, eta$_i$). **Ideal** (high) prop efficiency can be found from Advance Ratio.

That is taught in the Advanced Chapter 3, because it is one.of the final sophisticated caps on propeller knowledge and one that has not been understood, only clarified herein where we have **actual gliding drag** and **interference efficiency test data, η_I**.

3. <u>**Newton's Laws, The Actuator Disk**</u> Everyone can see that a prop is ***kind of*** **a rotating wing**, but very much of the basic <u>logic can best be grasped</u> by understanding that it can also be seen as <u>**pulling in and throwing back a surprisingly heavy mass flow rate of air**</u>, **$\dot{M}$**, (M dot), <u>**mostly from plane Speed**</u> only **a surprisingly low ΔV**, (delta V) speeded up wind required, **to make any <u>Required Thrust</u>, maybe only 9 to 11 MPH *<u>average</u>*.**

$\dot{m}$, $\dot{M}$, is called M Dot, just like it looks.

<u>**Newton's 3d Law**</u>**, is the familiar "equal and opposite force reaction" to <u>throwing a mass, or flowing fluid mass flow rate</u>.** <u>**Newton's 2d law**</u>**, $T\# = \dot{M}\,\Delta V$ calculates the actual Thrust, Force. The concept is called the Rankine - Froude Actuator Disk**, because it <u>**assumes a constant axial flow rate**</u>, which is a great oversimplification, the 3D flow being quite complex, but it <u>**teaches and decodes**</u> **the following <u>Tricky Basic Logic of Props</u>**:

<u>**Speed, V**</u> **is <u>the Fundamental Controller of Prop Efficiency</u>**, because it produces a ***high <u>natural</u> Mass Flow Rate***, **$\dot{m}$** through the prop Disk, (only increased a little to **$\dot{M}$** <u>by the factor</u> **$\Delta V/2V_1$**), thus <u>**only a small required ΔV wind speedup**</u> *<u>for</u>* **Required T#.** That is efficient because ***<u>the axial efficiency loss</u>*** is ***<u>also</u>*** **$\Delta V/2V_1$**

<u>**Only High Pitch Props can be Efficient**</u> because they go with a **High Speed,** big $\dot{M}$, a <u>**small ΔV**</u> **- a big V,** *<u>a twice small</u>* **$\Delta V/2V_1$ and that *<u>small axial loss</u>*, foretells *<u>a small total induced loss</u>*.**

<u>**Only**</u> sufficiently <u>**Low RPM Props**</u> **can be <u>efficient</u>**, because **RPM vs. Speed**, V, controls whether you have High Pitch, a **low $\Delta V/2V_1$** thus **low Induced Loss, High Efficiency**. But also:

High Pitch equates to ***<u>a steep corkscrew path</u>*** to the destination which equates to **less profile drag energy loss - <u>a shorter path</u>**.

The poor Prop is *<u>not</u>* even in control of its own Efficiency!!!

Thus <u>**High Speed**</u> and <u>**Low RPM**</u> equate to **Hi Pitch,** ***<u>both</u>*** <u>**Low Induced Drag Loss**</u>, and <u>**Low Profile Drag Loss**</u>. Thus <u>**HIGH SPEED**</u> and <u>**LOW RPM**</u> become the <u>**fundamentals**</u> of <u>**HIGH Efficiency**</u>, the <u>**simple key**</u> to the <u>**Tricky Basic Logic of Props**</u>!

BUT: Slow, Hi RPM Props can be geared down for Big D, Lo RPM, Hi Pitch, Hi η!

4. **An Orderly, Logical Way** --- **to Look At** --- **ANY PROP**

We give you an Orderly, **Logical way to look** at **any prop** --- for a given **Required Thrust**, **3 Spec Items**, **3 Decision items**, **3 Design steps** -- **9 Orderly Logical steps**, **easy to remember.**

Design Thrust, Greater Than Gliding Drag — can be thought of as # 10

3 Spec. Items: SPEED, RPM are the two **basic controlling** items in propeller **efficiency**, **Altitude DENSITY, rho,** ρ, is the basic that defines the media the prop works with, ***fundamentals***.

3 Choice Items: Coefficient of Lift, C_L which basically **controls Diameter**, **Aspect Ratio, which affects efficiency**, and controls the **proportion of Area vs. Diameter**, **(shape preordained, *if* an ideal prop)** and **Coefficient of Drag, C_D** is set in the computer, as graphs of multiple curves, dependent on Reynolds numbers, Rn, and α°. **From our Design Study we select best choices for each!!!**

3 Design Steps: **(Realize Shape, Twist, is Preordained if it's to be an Ideal Prop)**

- **Sizing: Area, Diameter, Shape are interdependent**, can't be separated*, but with **Aspect Ratio** selected, that **sets the proportion**, for any given shape selected -- and the prop simply **scales up or down vs. the C_L selected and Thrust Required**.
- **Pitch:** Speed vs. RPM control Pitch + Inflow, and α° required
  With 1 degree error, .1 C_L representing a 20% error on a .5 C_L prop, +/- .1° **tolerance is required to hold a +/- 2 %** manufacturing tolerance, or design Analysis Target tolerance.
- **Twist vs. Shape: Controls** *whether or not* **a constant C_L** and an **Ideal, Minimum Induced Drag Betz Loaded Prop results**.

There are other minor, only secondary variables covered at the end of Ch. 3

With this **relatively simple outline**, for a very complex subject, it is possible to come to understand the Physical Parameters of propellers in an Orderly, Logical grasp. Most Significantly, as a result, one comes to realize the valuable **insight** that it is **simply Twist vs. Shape that determines if a Prop is Ideal --- or *not!***

4. ***Highly Variable Dynamic Pressure q** The highly variable **Vector Speed** of **rotation and forward V** causes **a very big V^2**, ***q difference, root to tip***, **makes ideal props very different than wings** in ***how they are loaded and understood!***

5. **Betz, 1919, defined the Minimum Induced Loss, Ideal Prop**.

There is the Classic *Betz Logic* that we hang the whole prop explanation on, a wonderful, fundamental Ideal Prop Logic.

- **It is First Done with Zero Profile Drag, drag added *later!***
- **It yields an Ideal Minimum Induced Loss Prop by**
- **Creating the exactly ideal Thrust vs. Radius Loading by**
- **Holding a perfect helical air inflow, stretched outflow by**
- **Setting the Inflow Geometry for Constant Pitch, thus Slip!**
- **That yields a Constant dT/dQ, Thrust / Torque, or H.P. Ratio**

Constant Airflow Pitch, Slip, acts like Constant Inflow, when Axial Inflow is Not Constant!

This concise, incisive outline makes this subject much more **clear, much easier to grasp**, than you will find any other place, but it is the **marvelous technical work of our forbears** that allows this **Orderly, Logical insight and grasp**, and the **equally, or more marvelous following math solution**, possible.

Crucial to our explanation for Pilots, or professionals, is the fact that the **ideal simple, pure helical screw surface Air Inflow, and Stretched, still perfect helical Outflow can be visualized as a Simple Picture**, (p.79-II), not the wildly complex rare genius level math that it took to solve the total problem.

Blade SHAPE, & *Twist*, counteracting q (: V^2), Controls Radial Blade Loading

Furthermore, the **Ideal Blade Loading, Root to Tip**, and **Ideal Blade Shape**, *Twist*, the **characteristic variation in loading and shape - vs. Pitch**, or Advance Ratio, **can be seen as pictures** **p.147 I**. **Thus,** either a technically inexperienced Pilot, or Pro Engineer can **quickly, easily grasp the heart of the subject**, **Pure Gold!**

Furthermore, the **constant dT/dQ**, simply **a constant Ratio of Thrust to Torque -- at every radius -- every radius equally efficient,** (if first considered drag free)**, not only makes the concept simple, it proves to be THE MAGIC BULLET** that ***cuts through the impossibly wild complexity*:** heavily loaded, 3D, 3 Dimensional Airflow, --- compounded by all the trigonometry of the twisted blades and forces, the drop off in the shape of the thrust loading from max, to zero at the tip, + tip vortices, **Pure Gold!**

6. <u>Instant, Easy Computer Answers, Theodorsen's</u> *Solved* <u>Math</u>

Goldstein, in **1929**, solved the Partial Differential Equations for the Betz *Rigid Vortex Sheet* concept, but he believed only for the Multi Blade, Lightly Loaded, Low Advance Ratio Case, where the helical downwash outflow from the prop moved back uniformly in the stream tube, at the Same Speed as the Tube.

Early workers called that Multiple Blade Light Loading, not a final solution

Theodorsen, 1948, published his book, brilliantly recognized that **Goldstein's solutions were valid for full heavily loaded, 3D, high Advance Ratio flow, if one simply considered the 3D flow, and a reduced effective diameter existed far back!!** Interestingly, the **reduction is slight, ~ 99% Diameter**, except for **very** low pitch, **low Advance Ratio Props**, maybe ~ **97 %**.

Theodorsen used Goldstein's simple **Charts of Kx circulation Blade Loading Factors**, **vs. Advance Ratio and Radius**, which the computer can easily and accurately **interpolate to 3 Significant Figures, for answers of ~ 1%, error!!!**

The Kx factors are what control the Ideal, Min. Induced Drag Blade Loading, Root to Tip!!!

Theodorsen's work was no less brilliant, because he **accurately saw through the whole problem**, produced **other factors related to 3 D flow,** most notably the **Kappa Factor**, "κ" that related the rearward speed of the "Rigid Vortex Sheet" helical backwash, **w**, **(or w, a ratio of Plane Speed)**, that showed that with normal heavy loading the imaginary helical backflow moves back nominally **2, 3, 8 times faster than the whole stream tube average**, ***a very important, incisive, X-Ray insight***.

Andy Bauer used Chi, χ, pronounced Ki, in his Program, odd Type in T T's Book

Furthermore, Theodorsen provides a **full set of Engineering Equations** that make it **easy enough** for an Engineering Pro to program and use his method, **especially recognizing that the Kx Charts** are **easy to set up** for the computer to **use**. Additionally, he **solved advanced, complex, multi blades, counterrotation, before computers using a voltage field simulation**, as an analog.

Later, 1964 Tibery, and Wrench work got bigger Kx loading above .5λ.

The **Hugely Important Point** is ***with the math solved*** we ***don't have to learn it***, but can **use the computer for X-Ray Insight!**

7. X-Ray Insight into an Impossibly Complex 3D Problem

Realize Constant dT/dQ is Betz's Simple Outcome to this Technical Swamp

Let us make clear just how prohibitively complex the 3 D flow problem is, compounded by the twisted blade and force math, a swamp so complex no one could possibly see through it - evaluate.

Air is Pulled in and thrown back to create Thrust. Since the Blades are **at an angle the air is also rotated**, progressively **more at the steeper angle root radii**. With **higher pressure behind the blade, lower pressure in front, radial flow and tip vortices are generated** with **opposite flow directions on the front vs. the blade rear**. Interestingly, there are **root vortices and radial flow there also**. With **Heavy Loading**, the **Helical** Backwash is *moving back through the Streamtube* ***2, 3, 8 times faster than the average*** rearward motion of the streamtube. The Disk Diameter shrinks from Bernoulli pressure reduction too.

And Remember, Theodorsen Considers a Reduced Effective Diameter - Far Back

At the same time, the **ever more twisted blades inboard** not only **don't pull straight forward**, they seem to **lift more sideways, seem to pull more and more against the available Engine Torque**, **lugging down potential RPM, H. P. and Thrust. Actually it works perfectly as a pure Helical Screw!**

Thinking of the ~ elliptical lift distribution on a wing vs. span we **recognize that it is *not* possible to have calculated high thrust loadings near a tip, the thrust just rolls off the tip into a tip vortex, Thrust vs. Radius Loading another complexity!**

Now Recognize that the **Theodorsen - Goldstein 3D Potential Flow Solution**, (meaning every air particle affects and is affected by every other particle in a complex 3 D flow field), **handles all this, in addition to all the trigonometry and force computation,** but done initially drag free, **drag then added in, easily compared.**

Betz's CONSTANT dT / dQ is the SIMPLE OUTCOME — of this Quagmire, See Appendix dT/dQ

With this wildly complex **3D flow** and force geometry you could wonder if the basically **2D flow geometry** we teach you (p. 94 to 98-II) is valid. The 2D picture is easier to grasp, the 3d D radial flow is just perpendicular to the page, ***Theodorsen's math handles it all, 3D***.

8. Understanding the Pure Helical Air Inflow, *Stretched* Outflow

To Start: First, we teach simple **Pure Helical *Propeller* Pitch**, (p. 51-II) like a competition model builder might learn as a young teenager, because it can teach a Pilot exactly what propeller pitch is, quickly, pretty easily, all radii going up their proper circumferential ramp angle to arrive at the same pitch, inches or feet, *with* **zero slip, moving like a perfect screw through a solid**.

That's Prop Pitch, p. 51-II, *NOT* the AIRFLOW, Phi, ϕ

One must be careful though, because if we purposely **varied C_L**, it would **no longer be a perfect screw**. Also, if a prop designer properly accounts for ***slowdown***, **much slower inboard** the actual prop **moves further from a pure helix**, ***a less twisted blade***. Thus, **pitch is usually defined as that at the *benchmark* 3/4 radius**.

Figure 3, p. 82-II shows Glauert's ***a factor***, ***axial inflow***, a small **ratio** of the air velocity at the prop **V_1, at each radius, (V_1 as if no prop were there**), and his **a' factor** showing the ***inflow rotation***, a small **ratio** of the prop rotational velocity ***at each radius***. Studying that sketch teaches **how inflow works**, how **it jacks up** the **air inflow angle, phi$_1$**, ϕ_1, to account for **inflow to the airfoils**. **Adding angle of attack, $\alpha°$, sets Blade Angle, $\beta°$, Beta**.

Helical Airflow Photo on p. 71 II

Figure 4, p. 96-II is the Rosetta Stone Sketch, that teaches that **if you simply set up Constant Helical Pitch** of the **Air Inflow**, **constant Slip, at each r.**, you create pure, simple Helical Pitch Airflow, **create Betz's ideal, minimum Induced Loss Prop**.

Figure 5, p. 98-II, *turns the flow diagrams around backwards*, adds the second $\Delta V/2$, thus shows the **downwash, backwash, still helical, now stretched,** "**Betz's Rigid Vortex Sheet**", (just our perfect Helical Screw, Stretched Outflow) **Helical Airflow Photo is on p. 71 II**

It's important to realize the **Prop Design is Pitched for the $\Delta V/2$ inflow only**. ***Everything Happens At The Prop!!! All the Energy is Put in There, the stretched helical 2d $\Delta V/2$ backwash*** **is already set up, maybe happens 1/2 diameter behind, from a slightly higher pressure**. Theodorsen's marvelous math even **defines if the inflow or outflow is a bit bigger, his A_o factor!!!**

9. Tip Vortex Swallowing the *Imaginary* Pure Helical Flow
The **Smoke Tunnel photograph** on p. 105-II makes it abundantly clear that the ***tip and root Vortex swallow the theoretical pure helical outflow*** from the propeller, make Theodorsen's **Analysis *Far Back*** seem ludicrous, but if the **math is done scrupulously**, as it is, it is **perfectly valid, all the energy put in at the prop!!** √

10. Computational Accuracy The **Goldstein-Theodorsen Kx Blade Loading Factors,** .xxx, created before computers, are basically accurate to **2+ Significant Figures**. One in 100 is 1%, but one in 999 is .1%, far better! *Thus, the basic method is held to be good to 1% or better*, the calculation at that twice as good as the +/- 2% that manufacturing a prop to +/- .1 degree tolerance gives you, the good work that McCauley's shop offers. √

Ribner-Foster do correct, improve some of Theodorsen's secondary numbers, and Hi λ..

Ribner and Foster of the University of Toronto, working in the 90's **confirmed Theodorsen's math using modern computers**, a valuable confirmation so no one misunderstands that this final math of propellers that took the smartest professionals 83 years to create is in any way inferior. A review of their work shows **at worst a 1/2% difference**, in the Kx loading factors, locally. Solving math as complex as propeller math to 1/2%, < .1°, is as good as "breaking the bank at Monte Carlo", winning the lottery.

Tibery and Wrench, 1964 increased Theodorsen's Kx Blade Loading factors above .5λ. Do!

11. Advance Ratio J = V/nD Advance Ratio is the Classic Graph that teaches how Propeller Efficiency works. **(p. 48-II)** If both sides of that formula are divided by π, **J/π = V/πnD** **becomes far more meaningful**, because **V is just the plane's Speed** in ft./sec., and **πnD** is just the **circumferential velocity of the tip of the prop** in ft./sec. **(n being revs/sec, D, Diameter in ft. π being π).** Those two speeds become the **AAA, Actual Advance Angle of the Prop Tip, shown on the Graph for easy insight**, the **Advance Ratio/π, J/π.** √

The Graph clearly shows **Low Pitch**, **low Advance**, **low angle of advance** props are **poor in efficiency**, but swoop up to high efficiency, leveling off at ~91%, also depending on Aspect Ratio -- Allowing for **Slip**, **ΔV/2,** and **α°**, *of course sets Pitch and Blade Angle*. √

12. **P/D, Pitch/Diameter Ratio** Once you grasp what J, or J/π is, it becomes obvious that you can **tell the max efficiency possible** of a propeller **by just looking at *blade angles***, or ***more easily and specifically at the very simple P/D Ratio*** which piggy backs right along, tied to J or J/π, **simply slipping to account for prop inflow, ΔV/2, and angle of attack** α°.

It becomes even easier when you realize that a **P/D somewhat above 1 are the highly efficient props**, and those somewhat **below 1 are the low efficiency props**. It's easy to calibrate your judgment. A **51"P, 71"D** Luscombe prop, **P/D = .718 is limited to 85 % max efficiency**, whereas a **79" P, 70" D** RV 6 prop, P/D = 1.128 is ~89% efficient, getting close to the 91% max you might find on a P/D of 2, **depending on Aspect Ratio**, as seen drawn on the ***Advance Ratio curve*** ***done with all up Math***, ***drag***.

A P/D of 1 is ~88%, a 200HP RV8, 1.27, 90.2% η - Aspect Ratio able to raise or Lower η.

13. **Andy Bauer's Magic Graph** **(p. 50-II)** If you **plot Efficiency vs. Speed** -- for various Advance Ratio or P/D Ratio Props, they spread out across a wide spectrum of Speed. *However*, if you ***Plot all P/D ratio props vs. 100 % of their Zero Thrust Speed***, (where the props simply **run out of Pitch**, thus Thrust, in a shallow dive at max allowable RPM), **all props plot on the same horizontal scale for comparison** and we have Andy's Bauer's Magic Graph, which offers much more insight than you might expect.

Below a P/D of 1 all props have roughly the **same characteristic shaped hump, obviously low P/D inefficient, high P/D efficient** But notice that the operating point at low P/D is even lower, far from the peek at low pitch, **high P/D near the Peek winning twice,** *both cruise and Vmax plotted* **vs. the max η line!**

On the Magic Graph, you see that **all props start at Zero Efficiency at Zero Speed,** *runup*, blasting a **Hurricane in Fan Mode, going nowhere, using fuel**. All props swoop up to their max efficiency as Speed increases, finally running out of Pitch and Thrust, **Zero Efficiency again at Zero Thrust, (in a shallow dive) using Fuel, but making no Thrust, *not* helping**.

14. Super Stall Above a P/D of 1, the good efficient props, **you get into *more and more stall, slow*, which is going to *hurt takeoff!!!*** Jumping to the **very high 2.75 P/D Ratio**, perhaps like the 400 MPH **1930's Schneider Cup Seaplanes**, or maybe the first **Spitfires** that actually had fixed pitch wood props, we find **Deep Stalls SLOW** at **very high blade angles,** ***Poor Takeoff!!!***

This is where you absolutely need a Constant Speed, Variable Pitch Prop

Extreme High Pitch, a very interesting situation, shown by the big stalled S Curve. Props or wings still make substantial lift or thrust stalled, but the **thrust drops significantly** and the **drag goes way up**, especially in a deep stall dragging a **big separated wake**. But what happens is a **Big Surprise!** Before Stall, the very steep blade is lifting sideways, **pulling very opposite to engine torque** and **lugs the engine RPM way down**. Starting Takeoff, **Deep Stall**, but **pulling weakly against engine torque the RPM runs up significantly**, but then lugs down as the prop finally unstalls, limits RPM power and thrust and the prop jumps up to a surprisingly high efficiency, the low prop RPM, low thrust more matching speed, a strange case. As you can see vs. the big stalled S curve, extreme high pitch props exhibit more and more of this characteristic at high P/D ratios!!!

Slowdown Correction, Lower Inner Blade Angles, Helps All Props, Slow

15. Super Magic Graph (p. 45-II) Andy Bauer's Super Magic Graph is also marvelously insightful in that it **shows what happens to all the major variables vs. percent of Zero Thrust Speed.**

Angle of Attack, α^o at the benchmark 3/4 radius **falls as speed increases**, even steeper after max allowable RPM is reached. **Coefficient of lift C_L 3/4 r follows in parallel to α^o, but Stalls Slow.** **$\dot{M}$, Mass flow Rate** naturally **increases with speed**, a bit less drop at slow speeds, higher $\Delta V/2$ slow, tweaking $\dot{M}$ up a bit more there. **ΔV starts very high, slow**, the Prop in Fan mode trying to create a Hurricane, falls, **curves down as Speed Increases, dives, in a dive, the prop now RPM limited, less and less able to make a ΔV.** **Thrust**, blade stalled slow, shows **falloff starts as the root stalls, worse as the 3/4 r stalls, slower.** The 79/70, 1.128 P/D RV prop **efficiency *humps, like the Magic Graph.***

Far off the design case, expect the non BGT math will be less accurate --

16. THE FIVE 800# GIANT GORILLAS of PROP LOGIC

You come to realize there are FIVE -- 800 Pound Gorillas -- that are **the strongest factors in propeller logic**. Of course the real basic is to **understand how induced** and **profile drag** ***interact***. The **Chapter 3 Design Study** holds some ***Real Surprises for us!***

1. Dynamic Pressure, q, proportional to V^2. The fact that the prop tip is going so much faster than the root, *especially on slow, high RPM planes,* and that **q** is : V^2, is the fundamental that makes props, their theoretical constant C_L shape, p.147-I and ***ideal lift-thrust distribution vs. radius, basically different than wings***

The Plot on p.147 Book I, is essentially the Bottom Line on 138 years of Prop Insight!

2. Diameter, is obviously hugely important, because it controls the **size of the stream tube** and the **mass flow rate, $\dot{M}$**, (also considering speed), the **lever arm of the blade drag**, especially when you learn it's D^4 in the Thrust coefficient, D^5 in the Power coefficient, but surprisingly C_L, the next gorilla, can trump it.

3. Lift Coefficient, C_L Surprisingly, a **.6** C_L shrinks a needed RV 6 diameter to **69.1"**, a **.3** C_L balloons the needed diameter to **83.7"** proving to be **an even more powerful basic than D*!** A real surprise is that the **profile drag** on a proper .55 C_L prop changes from a nominal **1/3** of the total loss to **62% at .3C_L!!!**

***Narrow Tip Chord Betz Props Like a little Bigger Diameter --**

4. Speed is hugely important because it **directly raises the $\dot{M}$, mass flow rate,** *thus* **reduces the ΔV** required to make any given thrust required, *thus* **reduces induced loss, raises the Pitch** and **Advance Ratio**, thus reduces the corkscrew path length, **less drag** energy **loss, all raising efficiency**, and the cap on eta, η. **Speed** also **acts to reduce the optimum diameter required!!**

5. RPM is vastly more important than realized, because with speed, it directly **controls Pitch, Advance Ratio**, thus directly **controls** the **Cap on Efficiency**, (with Speed), and of course the **induced drag** and **profile drag corkscrew path**. Engines want high RPM for max HP vs. weight, **a direct conflict** with **props that want** low RPM, **high pitch for efficiency**!!! **FIVE Gorillas!!** √

17. The Chapter 3 Design Study -- All Key Flight Conditions

If I told you the **Broad and Deep insight available, p. 121-II** etc., is **Marvelous**, you see, I would ***Not*** be **Bragging!** Separate from my day job as a serious Pro, my lifelong Hobby has been Flight, and understanding it better and better. Finding, as a kid, flying competition models, that **the real specific factual insights and help on ideal Diameter, Pitch, Shape, Twist was ~ Zero,** I have to tell you that today is one of those Lifetime Benchmark Smile Days, nailing a personal challenge ***we set our cap to nail!***

Andy Bauer has been a marvelous collaborator, friend, partner.

• The Altitude Cruise Design Case shows specifically how **Lift Coefficient**, C_L and **Diameter** simply **Swap**, as **Induced Drag** and **Profile Drag** Swap in Lockstep, amazingly **small efficiency** and **performance** changes --- ***if*** the ***Pitch matches the case*** to **hit design RPM, intended Power and Speed**, Diameter and C_L counterbalancing over **pretty broad ranges**. Amazingly **drag rises to 62% of the loss on the Big .3C_L Prop** What we have here is specific insight on **exactly how and why props can be pretty forgiving, flexible *if*, --- *if* engine load is maintained,** maybe **only a bit of Pitch change,** ***to tweak it correct***. **See p. 121-II**

The practical insight to grasp here is that **a prop has to be pitched to screw ahead at plane speed -- then to be precisely overpitched just a little bit to account for *only* a small ΔV/2 and an angle of attack of *only* a degree, or so!!!** A **1 degree** miss, **.1 C_L** is a **BIG 20% error** on a .5 C_L prop so we'd be **shaving a wood prop, <1 degree, or tweak twisting a metal prop** to **hit the balance!!! I learned that as a kid. It only took a half Century to nail the hard facts!!! Voila!!!**

For years I've heard how ***Diameter*** is the real basic on props, and as you can see that's ***WRONG!*** **Diameter, Lift Coefficient, C_L, Induced and Profile Drag swap in Lockstep**, (but remember, we're comparing ideal props). **Ideal, that takes some Smarts!!! But you see the whole message of our prop Chapters is that's EASY: Betz defined Ideal, Theodorsen solved the Math!!!!**

• **Sea Level Climb** The .5 C_L had been best at Altitude Cruise, the lighter .55 C_L prop quite close, **but here the bigger, heavier .4 C_L Prop climbs best even at significantly lower RPM**. p.122-II Notice the **Drag Coefficients have risen well above .01 C_D, low Reynolds Numbers --- worse at higher C_L's, smaller Diameters**. **Weight**, a cube function, the **.4 C_L** is **1.30 times heavier** than the **light .55 C_L prop**, (77.308" D / 70.788" D) = **1.0921)^3 = 1.3025**.

• **Altitude Climb**, 12,500' Still p. 122-II. Most interestingly here the **best climb rate returns to the .5 C_L Prop**. Additionally, notice that the **RPM is significantly higher than it was at S.L. due to the higher 127 MPH TAS** at the same drag 105 MPH IAS at Sea Level. The **extra RPM**, of course **helps** the available **H.P., helps keep a respectable altitude climb rate**, though the available H.P. is much lower. Interestingly, **notice that the C_D's fell**, but **only at the higher RPM smaller diameter props**, indicating more **favorable Reynolds numbers** at higher RPM and TAS despite a considerable reduction in air density thus viscosity. There are so many things going on in Propeller logic it **can be quite an education**, going through a study like this, the **math and computer giving us X-Ray insight**, a unique gift.

• **200 MPH Sea Level Vmax** p.123-II As well described in the Text, **α, C_L and ΔV drop, efficiency gets even better at Vmax**. Look close, ***see how everything varies***. ***Can you figure out why?***

Nest, Realize Slowdown correction helps a lot, lower blade angles, especially inboard!

• **Sea Level Takeoff** p. 123-II The Study lies, an **otherwise desirable High Pitch, High Efficiency Prop** ***seems to*** **go Bad**, slow! **The higher the β° and C_L, the more tendency to stall,** ***slow***, the higher the speed it occurs at, extending outboard. It seems a misfortune that **above a P/D of 1**, just where fixed pitch props are starting to get good, quite efficient, they start running into stall at slow speeds, **worse slower than 50 MPH**. But fortunately ***Sowdown correction helps a lot, especially inboard!***

An **RV 6 seemingly stalls inboard,** if you tried climbing at **a min. power speed of 80 MPH**, but S.D. correction makes it OK.

18. Slowdown The Ch. 3 Study was purposely done without Slowdown to give ***pure answers***, But once we teach you how to understand a Betz, Ideal Minimum Induced Drag Prop, we must **show you how it must be modified to account for Slowdown, so it can stay ~Ideal, the same Radial Blade Loading and Drag**.

Realize the STATIC Air is pushed Forward, and Outward, by the Embedded Body!

A Source Sink analysis of the prop plane, at a Luscombe's nose, shows that locally, at the 37.6% radius, the air is slowed nominally 17.5%, but only 5% at the tip. Any body pushes a pressure wave ahead, the phenomena that breaks down at the Speed of Sound. The air has to speed up as it goes around a typical body, but in a Prop Plane, at the nose, you'll find a **highly variable slower velocity profile vs. radius -- p.106-II, App. SSSS.**

Obviously it's **a major correction**, first **untwisting the blade** a precise angular amount, more inboard, but now, **at a lower q**, Dynamic Pressure, **we need a slightly wider blade also**. The **precise T# vs. radius loading can be maintained**, and you ***do not*** *suffer a drag penalty,* because the **q goes down as much as the chord has to go up**. It can be ~ **4.77** degrees at .367 r, **.61°** at the tip, **HUGE corrections if we're trying to hold .1 degrees**.

19. Vibration A **WW II Rolls Royce Merlin**, which sounds so incredibly Smooth is **actually a jungle of many strengths and frequencies of vibration** --- trying to drive a low damping metal prop, which itself has multiple modes and natural frequencies of ***response***. And engine Forcing Frequences change as RPM changes, ***a mess***. **If the Engine frequencies find a propeller mode to excite, it can be a life or death matter!!! Don't try modifying a prop. You might kill yourself -- big complexity!**

See Appendix V, for Basic Insight on Propeller Response Frequencies

20. Off Design Point Performance Analysis To actually do prop analysis you need **Three Separate Computer Programs**.

Also — an Addition to Theodorsen Adds Profile Drag

- **A Basic (Ideal) Design Program** Theodorsen's Legacy
- **A Source Sink based program to correct for Slowdown**
- **A Program to account for any combination of Speed, RPM and ρ changes. All of these take serious Professional work --**

Off Design Point, The Farther we get from BGT Math, the greater the Error!!!

21. SUPER PROPS -- There are no Super Props and there never will be! The Max Objective is to get it Right, IDEAL!!!

A Partially Elliptically Loaded Lipps Prop, has the potential to add a few % η.

If you're just reading this as an introduction to prop logic it's OK to wonder if you can gin up a little computer program, or buy one and design a Super Prop for your Homebuilt. If you read and learn what's herein you'll pretty quickly learn propeller design is a good approximation for **one of the most challenging Engineering problems in history**, and that **it took the 7 smartest guys who came along in the industry 83 years to get Theodorsen's really correct math design solution, (Drag Free).**

What that permits a pro to do is to easily enough, after a lot of long, smart, hard work - to **design an Ideal Prop, Drag Free**. It takes a pro's capability to do that, go on correctly, and only if he goes after ***low Reynolds Number drag***, because Propellers have ***Jet Speed* - *but Model Airplane Chords***. That causes the blade to have ***higher than normal drag***, and to ***Stall earlier*** at ***lower C_L's***. Then -- what is the drag for the excessive STALL angles found??

To complete an Analysis one has to **create the next two programs above**, and learn all that is taught herein so you don't take years to figure it all out and get it right. ***That's the bad news***.

The Good News is that we've been through everything with Gun and Camera and **Andy Bauer has the Program that's been worked out over a long time and cross checked every way possible, including some good flight test data that agrees**.

We hope to offer Andy Bauer's Computer Program to Propeller Companies and Propeller designers. After years of development, cross checking, and refinement it would be a huge waste to not have it productively used. It will also **get the fantastic work of Betz, Goldstein and Theodorsen more broadly appreciated, *used!!!*** It's not a Windows Program, but a more Pliable, GW Basic Program where you simply plug in the numbers for the variables you wish right in the Program Lines. It's possible that we may have, and offer. a Windows Program.

22. Ideal Theory and Good Sense Blade Shape We know that whether or not you end up with an **Ideal Prop** depends on whether or not you design in the proper **Blade Shape vs. Twist**, to create a **Pure Helical Pitch downwash, backwash outflow**. **It is most Ideal, has the minimum surface area, min. drag if a constant, optimum C_L** is used, ***a pretty simple final concept!!***

Look at the **Thrust vs. radius loading**, and the **blade shape** that produces that loading on page 147-I. **Betz**'s result is a concept that is **Ideal in Theory** and makes Very **Good Old Fashioned Engineering Horse Sense**. The **weak inner loading is practical** with the **weak, lower q, lower potential to make thrust inboard** -- and since it is the **steeper angles inboard that go to *excess angles slow***, it is **highly desirable** that it ***not start highly loaded***.

Next, a prop with **high q tips** is going to ***try to load itself highly outboard*** and it's ***wasteful to try to load it heavier*** than the ideal that ***is already loaded heavily at the 90 % radius***, but ***must drop to zero at the tip!!!*** **Narrow chord tips load props correctly!!! To try to manufacture even more thrust out there, at high drag, at a max lever arm --- when the thrust must drop to zero out there --- paid for but lost, is like manufacturing loss.**

Betz has it right, Ideal by the math, and good sense too. It would make no good sense at all to overload it out there ---- Square Tips just don't make any good sense --------

23. Modifying Blade Shape ***for better*** **Climb, Takeoff, Cruise?** Years ago NACA tests showed broad tip Props gave **better Static Thrust**, and ever since then we find Broader Tip Props. So we tried unwinding the blade outboard with broader chords to maintain ideal thrust vs. radius, every combination we could think of. Guess what? **We lost every time, just like horse sense says we should, more drag, more tip loss. Ideal is Ideal**.

We could help a badly inboard stalled prop at takeoff with a broad tip, but that **costs in cruise and climb, less RPM, H.P., less thrust!** The Computer says **Performance loses**, every time!

Any Arbitrary Blade Width Increase would be best, ~ 1/2 to 3/4 Radius

Clarifying an Important Unexpected Result

24. Does Wrong Design lose Efficiency or Performance???? Interestingly, as we just saw in the last case, if we hang on **extra, non-ideal blade area**, analysis shows **extra drag causes a drop to lower RPM, less H.P.** is available, and we **get less thrust**, not more. ***But the lower thrust ~ matches the lower H.P.*, so we can see a performance decrease as the telling insight,** ***rather than a BIG efficiency decrease*!!!*** That's a **tricky unexpected result**, but **Props Work that Way!!!** Props are **Chock full of unexpected outcomes like that**. **Remember how that can work!!** ***It's tricky***. Theodorsen Math is ~exact, but leave the ideal loading and the the final, *simple, non 3D math*, **can be fooled, a bit** This subject was a real bear to tame!!!

Interestingly, a key insight is that efficiency really is limited by Speed and RPM. When you monkey up the blade you can lose performance, not efficiency. **Where** we see **we do lose Efficiency is with a Square Tip like the Luscombe Prop**. It has extra Drag, and the computer tries to calculate a "square thrust load" at the tip which can't happen. It appears to ***lose ~ 3 pounds of thrust getting 151 pounds not 154, a 2% loss,*** paid for but lost. With other flaws, early we took the Luscombe Prop to be 82.5% efficient, not the Ideal 85%. It's worse, ~ 75%!!!

25. Mach Limits - A function of Absolute Temperature, R° The Game is to **keep prop Tips below .9 Mach** number, **maybe .88**. We handled Sonic limited Props in Chapter 3 with all the ***key numbers*** and **a graph on p.137-II** that shows **allowable RPM vs Speed** -- **for typical Diameters, at Sea Level**, so we'll just suggest that you refer to that graph and adjoining numbers.

Wildly, Prandtl, the Father of Wing Theory, Teaches Rankines Source Sink, (Slowdown)!

It's interesting, in passing, that Rankine, the famous 19th Century Scottish Scientist-Engineer won fame for the basic Steam Engine Thermodynamic Cycle, and is credited as the ***first*** water Propeller Analyst in 1865. The Absolute Temperature Scale (needed for Thermo, and the Speed of Sound) is named for him, **R°**, **Rankine degrees**, Fahrenheit degrees plus **459.7°** above Absolute Zero. He managed to be **first and last**, the Speed of Sound being the last barrier!!! A Standard NASA 59 F° day is 459.7 + 59 = 518.7 R°

Have Pity, Understanding for the Poor Struggling Author

I usually Don't Write in this Style

As a Professional, I had in mind a first class, computer generated, clean, artistically attractive page, professionally written book, incisive, right to the heart of all subjects, all the answers you couldn't normally find. I intended it only for planes, certainly not the gross complexities of the never explained propeller, certainly not all super emphasized, a professional little book to be proud of.

I almost didn't publish it. The pilot, normally an adventurer, not a techie at all, usually avoiding anything that looked like Science, Math, even a graph, which after all is the picture of how things work. With often zero practice on anything technical since High School, I quickly saw I had to give the reader every help I could, and **before I knew it I had backed into super emphasis, repeating, expanding, summing up, everything different than the concise, say it once, depend on the reader for a lifetime of prior knowledge writing style of a pro!**

Knowing full well that propellers automatically had 12 times the gross content and complexity they'd like to see in the friendly, dumbed down, artistic cartooned book, I knew everyone, who would also want it to be written at his specific level, would soon be ***shooting the messenger***, wanting to tell me what I did wrong.

The interesting thing I found, however is that a pilot artist friend could read it and actually get it, which, of course, was the objective: **Put it out there for the guy who wanted to learn how things really work, in flight, his passion, with all the help possible. Damm the Torpedoes --- Put it out there!!!!**

What happened: a guy with no background, who had never heard many of the terms, fairly soon, **if he cared enough**, **to hang in, take it on as a Challenge, a Game, could grasp what we pros never did!** There's 10 years insight here, plus a lifetime, **in a day**, or so, **the keys highlighted**, not for speedreading! People who care enough can get it, the real insights and inner workings of propellers, all the surprises. **Hopefully, trying, easy enough!**

I'm not the guy who made props complex, they're a bear. I tried for EASY ENOUGH!!

Is The Book Perfect? No Mistakes?

Well, as a Pro I sure tried! Unfortunately, I was out there all by myself, much more than one might normally be. My Lifelong Friend and collaborator was getting old, really no longer wanting the job of pouring through a book for Pilots, technical novices, looking for obscure technical traps, as well as things that the "new guy" reader could fail to understand, miss, or read wrong.

Of course the Book is also for Lifetime Pros too, a Very Demanding Audience!

Milly, the love of my life was a huge help, as always, could see the missing, or wrong punctuation, spell check mix ups, that do occur. No matter how hard I tried, I would soon be mostly reading for content, obscure technical missteps, logic accuracy, that pros might see, not on the same thought train as I.

Invariably, pros will find some items they object to, it would be no other way. And then there will be progress, better future insight. We always stand on the shoulders of our predeceases, and many will invariably stand on mine, on the new insight here.

The hardest task of all is to make the most complex Problems Simple, Easy Enough!

If I have indeed brought the Black Art of Propellers down to Understandable Logic, even the Horse Sense of What is Happening Physically, I'll settle for that as a good contribution to our ability to understand flight, my lifelong Hobby, Avocation. It's a worthy addition to my Spacecraft and Jet Primary Controls. Both are Products that can never be allowed to fail, that must work reliably, no excuses, whether, or not the requirement is in the Design Spec. Lives, and on Manned Spaceflight, our National Reputation were at risk. A long string of products, fun!

As a Kid Modeler, it was great fun to see my Spacecraft Controls go into the Smithsonian!

The Big Funny here, I was really bugged as a kid modeler, a high performance model designer, little F 16's, with more thrust than Weight, that had to fly themselves, without crashing! I eliminated the Spiral Dive by age 19, but there was not one intelligent understandable word in the books on how to get props right, in 1946, 48 when I won the Senior National Model Championships twice. The Big Funny, Theodorsen's 1948 Genius waited a half Century for Andy Bauer and I to sort it out for you!

APPENDIX

Betz	B
Constant Ratio, Thrust to Torque	dT/dQ
History	H
Newton	N
Slowdown	SSSS
Theodorsen	T
Thruat Ratio	TR

Appendix **B**

BETZ - Classic Ideal Propeller Logic.

An Incisive Review of Ideal Blade Flow Geometry

Betz, Gottingen Germany, 1919, saw the central requirement, and fundamental definition of the **ideally configured propeller, comparable to, but fundamentally different than Prandtl's Ideal Wing**. Prandtl's classic wing definition is simply the elliptical lift distribution, elliptical planform, which yields an ideal 1. constant downwash, 2. minimum induced drag, which results in minimum downwash, min. tip vortex loss, the two sources of **wing induced loss**, the energy cost of holding up the aircraft.

Prandtl, The Father of Wing Theory, defined Circulation, and the Vortex System!

Concisely, Betz foresaw the **ideal propeller** as one forming his now famous **Rigid Vortex Sheet***, and mathematically defined that as **holding r tan ϕ constant**, which we'll soon see sets **a simple rule** for **setting up the *geometry* of all the *air flow velocity vectors***, which means that it firmly sets up the ***direction and speeds of all the airflow at all radii of the prop***, a really very neat trick, controlling a very complex flowfield with, as you'll see, **a very simple math expression**, with a very simple **understandable objective, constant airflow Pitch, constant Slip,** great consequences, subtle and hidden. **Making all that clear will be the central objective here in this Appendix!**

***The Simple, Pure Helical Archimedes Screw Flow shown on the Book Cover**

But first we must clarify the famous defining term, the Rigid Vortex Sheet*, because as you'll see that is **a name**, easily misunderstood, by the public, really not a vortex as understood by the public, the whirlpool like tornado, like a sink drain, which can cause a lot of initial confusion*. It is not really rigid, since it stretches as the second $\Delta V/2$ happens behind the prop, and another Surprise, the math of propellers says that it does not rotate, but its air does, rotating as the helix moves straight rearward. Let's get a clearer picture, easy enough to grasp, **a simple screw surface!**

The Rigid Vortex Sheet, Better Defined

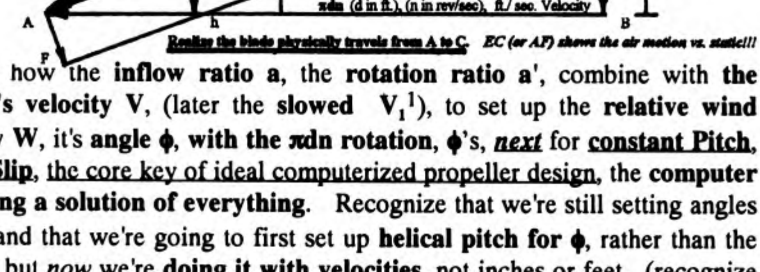
THE SIMPLE PURE HELICAL ARCHIMEDES SCREW ON THE COVER, SHOWS THE correct PICTURE

Think of an **instantly curing plastic sheet** coming off of each prop blade trailing edge, **precisely aligned with the W wind sheet,** forming **two helically twisted ribbons, 180° apart.** They're helical because back in our advanced chapter sketch, and in the sketch below, the wind lines are all set up to describe simple helical pitch, just as shown in Chapter 9 --- except here we refer to the incoming W wind lines at helical ϕ angles, (here set up by velocity vectors, whereas in our Chapter 9 example, we set blade angles by inches or feet of pitch and diameter).

Remember, the Vortex Sheets stretch behind the Prop, a pressure, the second ΔV/2

Look again at the cover photo of these helical ribbons coming off at the W wind angles, the ϕ's at each radii. We purposely repeated this here, because it is at once a simple concept, but visually challenging especially at first, and we want this as easy as possible for you, comfortable as you proceed. Visualize, but ignore that the prop tips will have strong tip vortices swirling around them, recognize they're there, we can't get rid of them, but they need not complicate the axial flow we're nailing here.

*** Vectors, usually to scale. a and a' are exaggerated here so you can see them.**

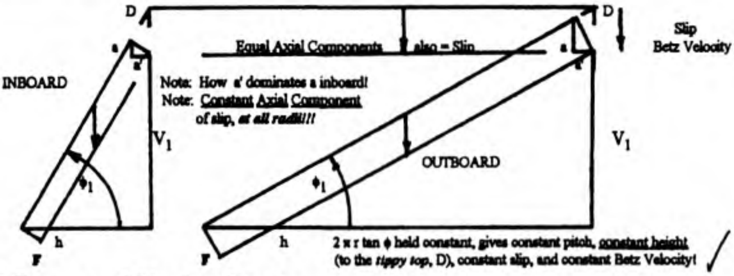


Realize the blade physically travels from A to C. *EC (or AF) shows the air motion vs. static!!!*

Grasp how the **inflow ratio a**, the **rotation ratio a'**, combine with **the plane's velocity V**, (later the **slowed** V_1[1]), to set up the **relative wind inflow W**, it's **angle ϕ, with the πdn rotation, ϕ's**, *next* for constant Pitch, thus Slip, the core key of ideal computerized propeller design, the **computer creating a solution of everything**. Recognize that we're still setting angles here, and that we're going to first set up **helical pitch for ϕ**, rather than the blade, but *now* we're **doing it with velocities**, not inches or feet. (recognize a and a' are ***velocity ratios*** to the axial and circumferential velocities, but can also be understood as small velocities, but remember **a** is simply $\Delta V/2V_1$, the inflow ratio.) ***The hidden secret is, required downwash sets a and a', and thus the vortex sheet that comes off the prop, thus thrust -- real insight!***

[1]Later the Slowdown Design loses this perfection, but after we've designed the Basic Prop.

Constant Helical Pitch of the Wind *Inflow*, ϕ_1 (constant height to D)



Ideal Props and Vortex Sheets

This is the ***"Rosetta Stone Sketch"*** that ***makes the central objective clear.*** I've simplified it, leaving all extraneous labels off for clarity, so you can see **the simple key point, the axial component** of the Downwash Sheets, the Vortex Sheets coming off the prop blades are **equal velocity at all radii**, a theoretically **constant axial velocity stream tube**, no unbalance to create extra radial flow, optimum. The downwash sheet, the Vortex sheet comes off the trailing edge of the prop at the required velocity to give the needed a and a' and ΔV and thrust, all tied together. It might help you to think of a set of "concentric glass barber poles", all with **equal (*height*)**, **(Slip)** red stripes, all moving up at equal velocities. For all the guys who like math, and grasp it, (Theodorsen has expanded height), but all methods hold **r tan ϕ constant**, which simply makes each velocity triangle the same height, **constant slip**, makes the ϕ at each prop station **simple helical pitch, easy once you see it!!!**

There is more on Betz in the book, this a concise core summary---

A Complete Outline of *Classic* Betz *Min Induced* Prop Logic

Betz Core Objective: Getting Ideal Minimum Induced Loss!

(Basically Achieved by Pure Helical Inflow, *stretched* helical Outflow)

- **It's purposely First Done on a Drag Free basis, the simple case first ---**
- **Drag can then be easily added, Min Induced, *then* Profile Drag** *(separated)*.
- **It's an Archimedes Screw into, out of each Prop blade** (see Cover Photo).
- **Achieved by designing for Constant Slip, *holding constant Pitch Inflow*.**
- **Slip is the difference between inflow speed and Airplane Speed**, *constant*.
- **(Mathematically that is done by holding r tan ϕ constant. (ϕ inflow angle).**
- **The Geometry teaches how *highly variable* inflow and rotation combine.**
- **Amazingly, a Constant dT/dQ results, a constant ratio of Thrust vs. Torque.**
- **That means a constant efficiency at every radius, *steep root angles too!***
- ***But remember, it's first done Drag Free, then Drag Added,*** separated.
- **Bottom Line: that results in "Ideal Betz Loading", Thrust vs. Radius.**
- **Betz Loading is like a half tear Drop**, weak root, stronger, hi q outboard.
- **A Family of Ideal Blade Shapes *and* Matching Twist** *results, if constant α^o, C_L*
- *Most Significantly*, **Tapered Tips** *vs. Advance Ratio*, **Pulls Back Excess Tip Loading.**
- *Not Allowing* **Greatly Excess Tip Induced and Profile Drag at hi q Tips.**

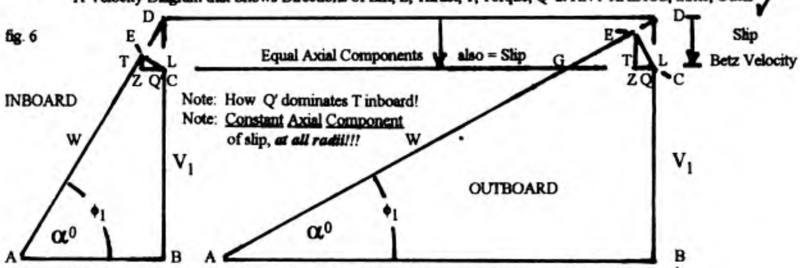
That final Hidden Imperative is the SECRET, Never Adequately Seen!.

(If the Fine Print is Unreadable -- it is Larger on the Appendix Last Page)

Constant Helical Pitch of the Wind ***Inflow***, ϕ_1 (constant height to D)

A Velocity Diagram that Shows Directions of Lift, L, Thrust, T, Torque, Q at ANY RADIUS, Inner, Outer ✓

fig. 6



2 πn r tan ϕ held constant, gives constant pitch, constant height (to the *tippy top*, D), constant slip, and constant Betz Velocity! ✓

The Geometry *that makes* Betz Loading happen - Ideal Props

Also The Basic Geometry to Prove a Constant Thrust / Torque Ratio, dT/dQ ✓

4 Triangles - ABD -- CED -- EZC -- GCD -- All Similar ✓

Notice: The Four Triangles on each side, (Right and Left,) 4, are Similar, ~ Triangles, *to each other*, that is, exactly the same angles, and all sides proportional in length, just bigger to smaller size -- but that the **triangles family on the left**, for *much steeper Blade Angles*, (2nd 4), have a much smaller Thrust component T, a much bigger Torque component Q, in proportion. (This is the same Rosette Stone Sketch as on p. 84 II, with more labeling, for explanation –because we want to work with **each item**)

Now the trick will be to prove that the steep family on the *left*, with weaker thrust, Stronger Torque *Force*, but smaller radius, has the same Thrust to Torque ratio, dT/dQ as that on the right!!! ??? In other words the **smaller radius must exactly counteract the bigger Torque force.** ✓

Slip x cos α° = EC, Blade Lift, L, perpendicular to Wind Line, W, = Slip x cos α° ✓

$$\frac{T\#}{Q \text{ in } \#} = \frac{\cancel{\text{Slip cos }\alpha}\cos\alpha}{\cancel{\text{Slip cos }\alpha}\sin\alpha \; \mathbf{r}} \quad \text{Canceling where we can} \quad = \frac{\cancel{\text{Slip cos }\alpha}\cos\alpha}{\cancel{\text{Slip cos }\alpha}\sin\alpha \; \mathbf{r}}$$

But, $\mathbf{r} = (\text{Slip} + V_1) / \tan\alpha$ or also, $\mathbf{r} = (\text{Slip} + V_1)\cos\alpha / \sin\alpha$ ✓

So, when $(\text{Slip} + V_1)\cos\alpha / \sin\alpha$ is substituted for **r.** ✓

$$\frac{T\#}{Q \text{ in } \#} = \frac{\cancel{\text{Slip cos }\alpha}\,\cancel{\cos\alpha}}{\cancel{\text{Slip cos }\alpha\,\sin\alpha}\,(\text{Slip} + V_1)\,\frac{\cancel{\cos\alpha}}{\cancel{\sin\alpha}}} \quad \text{Canceling where we can} \quad = \frac{\cancel{\text{Slip cos }\alpha}\,\cancel{\cos\alpha}}{\cancel{\text{Slip cos }\alpha\,\sin\alpha}\,(\text{Slip} + V_1)\,\frac{\cancel{\cos\alpha}}{\cancel{\sin\alpha}}}$$

Everything Cancels out, ***except*** **T# / Q in#**, = $\mathbf{dT/dQ = 1/(Slip + V_1)}$ ✓✓

And that shows dT / dQ is a constant, the Same at every Radius. ✓✓

Appendix dT/dQ

Betz Geometry, Constant dT/dQ ✓

Rankine, Froude, ***Betz***, Prandtl, ***Goldstein***, Glauert, ***Theodorsen***

The **Most Important Basic of Betz Logic** is that he sets up a **Constant Slip**, **Constant Pitch**, **Perfect Helical Screw Air Inflow**, and **Stretched, Perfect Helical Screw Backwash, Outflow,** first considered **Frictionless, Zero Drag.** ✓

It turns out that the Geometry of a **Frictionless, Perfect Screw** does have a **Constant Thrust vs. Torque Ratio at Every Radius**, specifically, because it is **working as a perfect screw**, Advancing, Friction Free, up a Perfect Pitch Screw at every r.

In the derivation page opposite, we want to keep the Math brief, but it's probably too concise for anyone not practiced in Geometry, and Trigonometry, so we'll explain that a bit more.

In geometry, we learn that all triangles have 180 degrees of angles, and with one right angle like our Lift Line EC perpendicular to the Wind Line, W, the other two angles must total 180 degrees. Now look close at how the four, 4 separate triangles on each side nest together. Each may be rotated 90, or 180 degrees from another one, but you should be able to see **all four are Similar Triangles, same angles the same place, sides** bigger, or smaller, but **all in proportion to their like triangles!**

Now in Trig, one learns the **three basic angle vs. side relationship** for **sine, cosine, tangent**, as follows:
sin = opposite side / hypotenuse **cos** = adjacent side / hypotenuse
tan = opposite / adjacent

All we do in the derivation on the opposite page is juggle those Geometry, and Trig relationships. **Silda Smith** my **11th. grade high School Math** teacher would be pleased to see I got it!

And that shows dT / dQ is a constant, the Same at every Radius.

As a boy, competing, and consistently winning nationally with my model designs, I had a very good grasp of basic Flight, Aerodynamics, really good designs, that worked for the right, well thought out reasons, but with Zero Help from professional's insight on the intricacies of Propellers, frustrated, the reason this book happened a half Century later. A key, core that I had enough insight to see, was that the Inner Blades, at a Steep Angle, **seemed to be Hardly Pulling Forward**, but **seemed to be Lifting, Pulling against available Engine Torque**, more and more as the Blade Angle Steepened! **Smart, but Dead Wrong**, exactly why I was looking to see what the Pros had to say, after maybe the better part of a million Props in WWII, **I found a Barren Desert, Zero Help!**

My lack of Incisive Insight, was to fail to look past the Prop as a Rotating Wing, and see that, acting as a perfect, frictionless screw, those steep inner radii were working in perfect unison with all other radii, all doing exactly the same thing, perfectly, a perfect SCREW!!! I know today that friction hurts **a bit** more at low, and steep angles, but that's not a major loss, the size of the loss easily seen when we run the prop, first without drag, then with drag, all shown in the computer printout if we run it in two steps, the normal one step run showing the efficiency, with, and without drag.

The screw concept is the perfect, necessary insight on why those steep inner blade angles don't hurt, and that teaches us to get past thinking of a prop, only as a rotating wing!

When I first set off to **find out how Betz's Logic had a constant dT / dQ**, I was wondering if I faced fearsome Math. Was I shocked to find that I could prove it in an hour, simply **grasping that it really was a perfect screw**, and that I could derive it, **prove it with High School Geometry and Trig.**

I had this marvelous old Math Teacher, who liked boys, wouldn't let any of us be "Laggards"!!! Thanks Silda ------

And that shows dT / dQ is a constant, the Same at every Radius.

There is one other important detail here that has both technical and human significance. To be creative in the technical fields, one must, of course, be quite intelligent, have your subject well in hand mentally, so that you can see opportunities others do not. But then, in addition, it is quite desirable to have a brain configured in a way that you can think freely, creatively, break the bounds of overly disciplined, constrained thought patterns.

But, in contrast to that, in engineering there is great need to be a very careful, disciplined thinker, because in so many cases the core need is to create a product that will never fail, under any circumstances, whether in the formal requirements, or not. This takes a very detailed, disciplined orientation. The very best Engineers somehow learn to be both, freely think creatively, and then, almost change personalty, able to dig deep, nail the details.

Usually individuals are ***not*** capable of switch hitting, doing both, and if the boss is smart he may realize that he must have a creative team, and a team of disciplined thinker, checkers. If he's fortunate to have a switch hitter he can appreciate it, use him.

There is a case in point here. We used **a velocity diagram** here for a derivation proof, cutting incisively to a compact finale to make it possible to maybe grasp it simply, in concise form. But there is an illegal operation there, because we talk of Thrust **Force Pounds,** and **Torque Pounds, soon Ft. Pounds, ft #,** creating the sin of **mixing apples, oranges, and bananas!**

In a more disciplined way, we can develop Thrust and Torque Velocity into force, by using air density, ρ. rho, Area, and V^2. Now, what Betz, Goldstein, Theodorsen do is create precisely the correct SHAPE, Area, with proper twist, rho being equal at all radii, canceling out, In a complex way the Torque radius accurately factors down the extra strong Torque Force, inboard, with the trig involved, then the V^2 effect cancels because we have the same dT/dQ ratio at all radii. The derivation is finally legitimate, but formally, with many more steps than shown.

This Assures the Derivation Page Fine Print is Readable

Fine Print on the derivation page was necessary to permit a compact derivation organization that was comprehensible -- and place everything in the correct relationship to each other, ✓

However on the " book page masters", that were clear enough, it was seen that if the printing, or paper degraded, in publishing, you would hate me, So here is a solution, that can help.

Sorry for the inconvenience caused by the 6" x 9" page format

All Print here is raised to 10 Point Type

A Velocity Diagram that Shows Directions of Lift, L, Thrust, T, Torque, Q at ANY RADIUS, Inner, Outer

Equal Axial Components also = Slip (The Key to Betz Logic!) ✓

Note: How Q' dominates T inboard!
Note: Constant Axial Component of slip, ***at all radii!!!***

2 πn r tan ϕ held constant, gives constant pitch, constant height (to the *tippy top*, D), constant slip, and constant Betz Velocity! ✓

T# = ~~Slip cos α~~ cos α.
Canceling where we can ✓
Q in # = ~~Slip cos α~~ sin α (Slip + V_1) $\frac{\cos\alpha}{\sin\alpha}$ =

Appendix H_p

HISTORY --- of Propeller Analysis

A Brief History of Propeller Analysis, Who, What, When

Axial Momentum Theory: is simply based on "***pulling in and throwing back air***", adding a ΔV speedup, increasing the *natural stream tube mass flow rate* $\dot{m}$ to $\dot{M}$, adding a +ΔV *velocity* passing through the propeller disk, causing *"a rate of change of axial momentum"* to yield thrust. Don't be confused by that. The thrust is simply the ***reaction force from the mass of the air thrown rearward*** --- just like *you* would be pushed throwing a heavy mass! It was initiated by **Rankine** in **1865** [1] for marine propellers, and was further developed by **R. E. Froude**, publishing his "**Actuator Disk**" concept in 1889 [2]. **Both show the maximum efficiency limit possible, since all losses are *not* included -- *only the primary axial loss*.**

Though historically called *Momentum Theory*, it is more accurately, and easily understood specifically as a Newton's Second Law concept where **Thrust = $\dot{M}$ ΔV**, *the fluid flow version* of Newton's more familiar F = Ma formula for throwing *solids*. $\dot{M}$ is the final *mass flow rate* ***in slugs/sec***, [just like pounds/sec. divided by g, (32.174 ft./sec. per sec)*, simply a smaller number of the **bigger units of mass**]. The basic formula is very simple, just multiply $\dot{M}$ by **ΔV**, the total speedup in **ft./sec.** = **Thrust#.**

The problem with momentum theory is that it tells you nothing about how to design the propeller, *only covers the thrust created and the primary loss, not how the prop needs to be configured!* ***Most important, it teaches that air must be pulled in and thrown back to make thrust, and ΔV is easily seen as a loss --- wasted, settling back to zero, calm***. **It thus shows that it costs to create thrust --- that efficiency can never be**

100%, even with zero blade drag. *Also*, **hugely important**, a **fast plane with a big $\dot{M}$ needs less ΔV, or a Smaller Prop!!!**

Looking closer, it also teaches the tricky hidden point that although *the full ΔV is used to calculate thrust*, **only half ΔV**, the average **ΔV, ΔV/2** vs. the speed V_1, feeding the prop, before any speedup, **$\Delta V/2V_1$** counts as an energy and **efficiency loss ratio**. The reason for this is hidden in the basic energy equation, $E = MV^2/2$, which involves one *average velocity* in calculating the distance over which the energy is added! *Also*, ***only*** the $\Delta V/2V_1$ ratio increases the natural mass flow rate $\dot{m}$ through the prop disk to $\dot{M}$, *because* the calculation is made *at the propeller disk* where the speed has only increased to half the ultimate. The **air is pulled from a larger Diameter, thus $\dot{M}$, not $\dot{m}$!!!** Subsequently, the V goes up, the second ΔV/2, p drops, the **D. shrinks, Bernoulli, no more increase in $\dot{M}$!** The key to grasp is that ***making thrust requires a*** **ΔV** ***speedup --- and making a ΔV causes a loss!***

Huge insight from a simple formula, tricky details exposed too!

The basic concept is very simple, just $\dot{M}$ times ΔV -- ***the trickier details give great insight for those who grasp the full explanation.***

Blade Element Theory: divides the propeller blade into "several radial airfoil segments" with the necessarily *different twist and rotational speed at each station* for individual analysis and averaging -- for the *constant forward but highly variable rotational velocities*, ***as well as the extra axial and rotational inflows induced***. **W. Froude** [3] made a first try at Blade Element Theory in his 1878 paper, but **S. Drzewiecki** [4] did the major initial development covered in his book, Theorie generale de l'helice, Paris, 1920. All the early work did ***not satisfactorily understand inflow***, ***and rotation*** which caused wrong airfoil lift and drag answers. Also, ignoring Aspect Ratio didn't work, because stream tube **ΔV losses are, in fact, the induced loss**, which must ***not*** also be charged again in the airfoil drag. Several analysts attempted a proper concept and N.E. Joukowski got close by 1918. Betz, the Germans, started using Momentum Theory to determine inflow, seemingly logical, but only half of the full ΔV happens by the prop disk, and it's actually ***not constant*** **vs. radius**. ***Getting inflow and rotation correct was the big hurdle, and that needed Prandtl's work.***

Betz [5] in **1919** looked at *the vortex system of the slipstream*, assuming a frictionless, ***lightly loaded*** airscrew consisting of many blades, (equal advance *at all blade radii, constant pitch*). Betz first used momentum calculations for inflow, no rotation. Importantly, finally, he determined **ideal load distribution** along the blade for the *minimum loss of energy*, analogous to the elliptical loading of wing theory was --- "**The Rigid Vortex Sheet concept**". That is sometimes described as a **rigid helical ribbon** of flow emanating from each propeller trailing edge, which *conceptually* stay intact far behind the propeller. The hidden secret is that holding **simple helical pitch for ϕ**, phi, the wind inflow angle, with proper math and geometry yields a *uniform vortex pitch* as the excess pressure behind the propeller yields the second $\Delta V/2$, staying as ***slightly stretched rigid vortex sheets, just Archimedes Screws!!!*** An ***equal ratio of thrust vs. torque and HP at every radius***, results before drag is added. (Realistic heavy loading, as ultimately used and proven by Theodorsen, shows the heavier loaded vortex sheets *move faster than the unloaded areas* of the stream tube). Betz is *historically recognized*, for ***the optimum rigid vortex sheet concept*** as the fundamental **Classic Prop Theory, a milestone!**

Goldstein, 1929 [6], in his paper "On the Vortex Theory of Screw Propellers", using the rigid vortex sheet concept, **solved the 3D Potential Flow Math for a lightly loaded, single rotation propeller, low advance ratio, devising his Kx circulation factor**, (**shown to .5λ**). That was used by Theodorsen, **for heavy loading**, extended for higher Pitch, Advance*, 1948. He credits Goldstein's analysis as **the greatest single step in propeller theory** and uses it, bypassing Glauert's 1934 approximate method. ✓

*But by 1964 Tibery and Wrench got **higher**, **High Advance Kx**, **above .5λ.** ✓

Prandtl, in an appendix to Betz, gave an approximate correction to the thrust distribution for few blades, the first try at real loading. But, it was the ***Prandtl-Munk wing theory*, 1918 to 31** [7], that finally allowed ***rational calculation of the induced inflow, and rotation***, the remaining speedup farther downstream, nominally half at the prop disk. Prandtl conceived the ***Vortex Theory of wing lift*** that tied the Kutta-Joukowsky circulation around a curving baseball or a rotating cylinder to the ultimate horseshoe vortex system of wing circulation and trailing vortices. Prandtl taught the **Ideal Elliptically Shaped, and loaded Wing**, ***circulation***, ***trailing vortices***, ***constant downwash, minimum induced loss***. **His wing theory allowed *Blade Element Theory*, and prop analysis to get on to a rational basis**. Before you know the *induced inflow, and its rotation*, you cannot do a correct analysis of the airfoils as a "rotating wing". That is the major milestone that solved that major inflow hurdle, absolutely fundamental to getting it right!

Glauert [8] in **1934**, writing **the propeller section, Division L, of Durand's multivolume classic tome, Aerodynamics**, is generally credited with writing the best exposition of "modern" propeller theory and logic. He makes clear that nobody could get correct inflow answers until Prandtl [7] did his Airfoil theory work, which made it possible to get correct "**induced flow**", the ***inflow***, ***rotation, and downstream stream tube speedup***. Thus Glauert finally got prop logic essentially correct, except for heavy loading. He still assumed light loading, multiblades, ***not indented*** for heavy loading, and advised that all analysis done in that (pre computer) era is of necessity done on light loading. ***Also, Inflow is not equal at all radii, we learn!!!*** Also, reading Glauert shows that, in deference to his computerless era, he makes several math simplifications so that his math could be used and solved at the time. The full unsimplified equations would require iteration, trial and error solutions, essentially impossible by hand. That offers an obvious opportunity for the modern PC which iterates at a speed beyond the comprehension of engineers in the 30's, which obviously offers the opportunity to account for the lesser terms Glauert left out. **But next, T.T.:**

Thedore Theodorsen, a true genius, NACA's Chief Physicist during W.W.II went all the way in his **1948** book [9], including **heavy loading, high Advance Ratio, a 3 D flow example, a**

radial flow feed to the tip vortex, (p 32, 33), **that exceeds the axial flow**, **AMAZING**, (the source of excess prop loss), and the pressure and velocities far back in the wake. He makes the point that the actuator disk concept does *not* represent the true limiting efficiency case, because (in addition to circumferential and huge radial tip vortex feeding velocities) there are heavy loading axial pressure and velocity differences far back. **Significantly, the wake far back, not the prop, is the key to correct analysis**.

Before computers, he used ingenious electrical field simulation, not the complex differential equations, for the potential flow problems, extended the K(x) circulation function, for λ above .5 to 1, See Below*. He points out that the Betz Theorem, the Rigid Vortex Sheet is a key to heavy loading analysis, along with Goldstein's mathematical analysis, **as long as the final result of the vortex sheets far back in the wake is targeted**. He offers a mass coefficient, κ, kappa, that ratios average ΔV, far back to ΔV at the Prop. A simple Kx blade loading chart allows accurate analysis by all who make the effort to understand his insight and math. H. S. Ribner and S. P. Foster of the University of Toronto carried the work forward in a interesting 1990 paper[10] for frictionless propellers. It includes computer analysis by Kramer, and it compares the losses with the basic actuator disk momentum theory, simulating perfection, for two bladed props through multiblades, quite insightful. *(Tibery and Wrench work[14], 1964, nominally confirms Goldstein Kx Factors up to Lambda of .5, but not Theodorsen's Kx Factors above a Lambda of .5 - if proven correct, the final needed step!

Theodorsen says much more of course, more than we can or should cover here. He was generous in his credit for Betz and Goldstein, who laid the groundwork so long ago, now. Practical, realistic, he hastens to point out that the wake will be unstable, not in the form analyzed far back. (That's true, but OK. since he basically analyzes it theoretically, correctly!)

Thus, though *purposely avoiding all the complex math* in the book text, (it **is in App. T**) - targeted for a civilian, pilot audience, but **aimed at getting the correct sophisticated**

conclusions across without drowning everyone in math, **this book *is* based on all the long history of propeller math**, and theory. We very purposely show the most basic math, like the $T = \dot{M}\,\Delta V$ *where it is simple enough, and shows great insight* for Pilots who want to stretch and get it, and even more detail in fine print for those who want the deeper grasp. Clearly here, prop analysis has been brought to essentially final fruition over more than 100 years, after benchmark analysts in 1865, 1889, 1919, 1929, 1934, 1948, 1964, 1990, and here. Theodorsen's splendid work, the milestone, Tibery and Wrench[10], the necessary final Kx. Professor Eugene Larrabee [12, 13], MIT, and Adkins and Lebeck[14] advanced, updated and refined the classic Glauert analysis, which can give good results, and is more adaptable to off design point analysis, important. (Larabee designed the optimum propeller for the Gossamer Albatross which made the 1979, 22.26 mile man powered English Channel crossing possible, after the original prop proved unable.) Quentin Wald found the ***Tibery and Wrench Kx work missed by Aeros***, a fine overview, a simplified look at Theodorsen like math.

Work continues with *much needed on the efficiency loss of props and afterbodies.*

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7. Prandtl-Tietjens, Hydro und Aeromechanik, Berlin 1931.
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13. Design of Min. Ind. Loss Props. SAE T. Paper 790585, 1979.
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15. The aerodynamics of propellers, Quentin R, Wald, Science Digest, 2006

Appendix **N**

Mr. Newton - and Engineering Units.

Engineers always work in **a consistent system** of **physical "units"**, **"foot, pounds, seconds"** in the U.S., until the more recent trend to the less friendly and familiar international units. The reason is simple and the advantages great, among them that you can **get the correct answer**, *as opposed to wrong*! Just as you can't add apples and oranges, to get a correct answer to a calculation each item in a potentially long complex calc ***must*** all be in consistent units. Thus you'll find engineers don't do basic calcs in MPH, but rather in ft./sec., or they multiply by 22/15 to put MPH into ft./sec, since 60 MPH is exactly 88 ft./sec.

A **huge side benefit** is that you can do "**dimensional analysis**", that is, put the dimensions, or *units* in a long string calculation and see "if the units cancel out to" the "***units*** answer" you want, *or* if you made a mistake. A simple example: The weight of a 100 foot cube of air: $(100\ ft)^3 \times .076475\ \#/ft^3 = 76{,}475\#$. **Wow**, you just learned **two** important insights! 1. If you want a thrust or lift answer you better be sure your calc does in fact come out in pounds, and you'll see shortly how easy it is to be wrong on that one. 2. Yes air has serious weight, and it has to if "throwing it down" is going to hold up a 920,000# 747!

If the feet, pounds, and seconds do *not* cancel out to give the "correct units for the answer you want" in a long calculation where you'd get lost, you *know* you have to chase through and see where your mistake is. It's a very simple check on a basic that could prevent someone's death. I started this way, because **Mass and Dynamics**, basic to Aero, ***is where you need a check***

It's a very simple concept, that gives you a simple check on calculations that can get wildly obscure and complex, a method and insight that will keep you straight, save your life or someone else's, literally, when you're confused, in need of help. Bridges that *don't* fall down come from Engineers **who check**.

Our modern life started *literally* when Sir Isaac Newton and his contemporaries in the 1600's started ***precisely*** nailing how the physical world works, **the specific laws**, so that precise calculations could be done, to produce a Space vehicle, or just a connecting rod on an old "Iron Horse". His **three laws** that nailed "*exactly* what that falling apple was doing", started the field of "Dynamics", that makes it possible to calculate a wing's lift, a prop's thrust, or propulsive efficiency, a long list of basics.

Newton found the concept of ***Mass***, related to weight, but fundamentally different than weight, **weight #, divided by the "acceleration of gravity, 32.17405 ft./sec^2**. That makes the **units of mass** pretty weird, **# sec^2/ft**. **Rho,** ρ, the **mass density** of air, that is "mass per cubic foot", thus is **# sec^2/ft^4**, even more weird, weird even to non Aero engineers, who sit down and pencil it out to get themselves straight every time they hit it. M dot, $\dot{M}$, the symbol for Mass flow rate, in propeller analysis, "mass per second", mass/**sec**, thus becomes **# sec^2/ft sec** = **#sec/ft**.

Now don't let all that weirdness blow you away, because the whole purpose of this Appendix is to explain it all to you, show you how to handle it without getting all confused and defeated by it. It can really screw you up, or you can defeat it and be the master. I think what we have here is pretty good, if you just dive in, do what I say, learn just --- **that one magic paragraph**.

First, **just** look at, think through, and **understand that one paragraph**, just get it. In all of Aero, grasping "those three terms", plus the little we'll do with Momentum are the three keys to **clairvoyance**.

Second, recognize that those weird units, while tending to complicate the eminently simple subject of dimensional analysis, can be easily tamed by that simple analysis -- because you can **easily see if you have it correct or not**. If you want a thrust answer in pounds, like you do on **p. 136**, you can easily check that you are in fact correct**, as we do there!** Look there, check.

Incidentally, let's be sure we didn't confuse the new guys back in the key paragraph. "Acceleration is a speed up in velocity", vs time, foot per second, (ft/sec), per second or **ft./sec²**. We don't want anyone lost or snowed by what is a very friendly system of writing units, once you get it. Everything seems hard for everyone when you're learning. Later it's easy, so our objective is to help. **Get that one paragraph, follow it through, word by word, with your finger if you have to**, and you'll see that it's *weird but* not *hard*, and you will have conquered a basic that causes no end of grief to people who never nail it.

Now so that we have a rock solid basis for this book and our insight into Aero Engineering let's go back and learn what Sir Isaac said **about linear motion**, carry it through to new insights.

- **Newton's First law**: Objects at rest tend to stay at rest, and objects in motion, tend to continue in a straight line (at the same Velocity), unless acted on by a force (that changes either).

- **Newton's Second law**: An unbalanced force acting on a body causes the body to ***accelerate*** in the direction of the force, directly **proportional to the magnitude** of the **force**, and **inversely** proportional to the **mass** of the body**.** a : F/M. From this we get the famous equation **F = Ma**, that we'll tie to gravity in *a gravity based system* where *force* and *weight* are *in pounds*.

- **Newton's Third law**: Every action has an equal and opposite reaction. (In other words, if we throw back air we'll get thrust!).

Sir Isaac, through Galileo in the "leaning tower" knew that the apple didn't just drop, it accelerated. Later pros finally ended up at **g = 32.17405 ft./sec²,** which means that the apple at sea level, at 45° latitude, speeds up that much each second, in a vacuum where there is no drag. That's a most important insight, but it also tells us **mass** is ***not*** in **pounds**, as we'll now see.

If it takes 1 pound of force to hold up 1 pound of weight, and if we drop it, it accelerates 32.17-- ft./sec², the following is true.

F # = **Wt** # = **M** ?· **a** ft./sec² --- then the **units of Mass** must be **# sec²/ft** (do you see how it works?), and we know that a = g, the acceleration of gravity, 32.17 ft./sec². If *one* "***Slug***" of Mass, M = W/g, it's a ***BIG*** unit, **more than 32 pounds**, but with **very different units**. That will take some getting used to, but it's really not difficult, and with this **one paragraph** of explanation, you can go back and justify the units of ρ**, mass density**, **# sec²/ft⁴**, and M dot, $\dot{M}$, **mass flow rate, mass / sec**, # sec²/ft sec, in the magic paragraph above, which can be simplified to # **sec/ft,** if you wish. That nails the ***three key terms*** in all of Aerodynamics. Yes, that's some new thinking to do, but if you want to, I'll bet you can cope, ***because*** **that's *all* the meat**.

Mass is simply W/g, numerically, and dimensionally, ***not*** a brain buster. All the mass units that spring from it fit in *one* paragraph and grasping that *one* paragraph will let us go on and do all the basic calculations in Aero. *Learn the units of those three terms*!

M = W/g **M = # sec²/ft** **Rho, mass density**, ρ = M/ft³ = # **sec²/ft⁴**

$\dot{M}$ = M/sec. $\dot{M}$ = # sec²/ft sec. **or** $\dot{M}$ **= # sec/ft.**

Weird as those may first seem, nail them and you'll succeed.

Finally: **Recognize** F = Wa/g implies Force # = Mass x accel.

Recognize "G" load = a/g - If you accelerate 3 times 32.17 ft/sec² you have a 3 G load!

Recognize Load # = W· a/g a simple proportion really!!!!

PROPELLERS ---- For everyone, and in particular those interested in propellers, it is very worthwhile to press on and understand the special and basic relationship between Newton's Second law, F = Ma = Wa/g, and ***momentum***. Propellers are often said to work on Momentum, and there are indeed some momentum concepts that are important and basic to propellers, but the idea that props work on Momentum, is fundamentally ***wrong*** and can be ***seriously misleading***, and we can best clear all that up in the next few paragraphs!

Understanding F = Ma is one of the most fundamental things in Physics, (and it turns out that there is a special nifty version of it that works with flowing fluids, like the prop stream tube that gives us our thrust). First we'll look at it the regular way. ---

If you throw a heavy 15# medicine ball, M, backwards, *hard*, you'll feel the big reaction force. You didn't just throw it back at some speed, or velocity, *you had to accelerate it*, speed it up, let's say to 10 ft/sec, in .1 second, which is an acceleration of 100 ft per second, per second, and that is 100 ft/sec^2. Got it? Now, we can calculate the actual force with our formula, F = Ma, put it in weight form, F # = W # a ft/sec^2/g ft/sec^2 = #
That's 15# · 100 ft/sec^2 / 32.17 ft/sec^2 = 46.627# (That's 3.108 G's).

Now here's the nifty trick with a fluid like water or air. The problem is we don't have a solid medicine ball to throw, but a flowing fluid! What do we do about that one with our F = M a? Well a = ΔV/t, so we can convert our formula to F = M·ΔV/t. Now math is flexible and it does not care if the t divides the ΔV, or the M, it's all the same from a math standpoint. But now you see M/t is mass/sec, mass per second, and that's ***mass flow rate***, which we call $\dot{M}$. Now engineers would do this as follows:

Remember that *acceleration is rate of change of velocity*, ΔV/t.

$$\textbf{Thrust \#} = Ma = M\,\Delta V/t = (M\,V_2 - M\,V_1)/t = (M/t)\Delta V = \dot{M}\Delta V\ \#$$

So now, hopefully, you can see how we tweak the F = Ma, #, formula, which works for solid masses, around to **T = $\dot{M}\Delta$V, #,** which gives us **Thrust** from our flowing fluid *prop stream tube*.

Now momentum is **MV**, Mass times Velocity, which you're now smart enough to figure out has the units of **#sec**, --- Mass, **# sec²/ft**, times Velocity, **ft/sec** = # sec, specifically not # -- but if you *divide by sec*, consider a "*rate of change of Momentum*", we have what we need, *pounds thrust*. The big picture thing to grasp is that **props** from which you want **pounds thrust** work on **F = Ma**, which is equivalent to **T = $\dot{M}\Delta$V, #,** per Sir Isaac, or ΔMV/sec, #, rate of change of Momentum, an equivalent but not very helpful concept, **but specifically *not* MV, momentum.**

Now there is a good simplified example that helps to explain how propeller thrust works that we use on page 135 and page E 18, but it also exposes a subtle, initially confusing little point that we'll expose here.

Imagine a hypothetical plane flying along at say 200 MPH, momentarily, magically, with the prop at zero thrust! There will be a 200 MPH **stream tube passing through the propeller disk diameter at some "mass flow rate"**, ***mass/sec***, **$\dot{m}$** rate.

Propellers work by "throwing back air", per Newtons Third Law. When they do that they **increase the mass flow rate** *to* **$\dot{M}$**, and "**provide a ΔV velocity increase**". Amazingly that **ΔV may be only 20MPH, or so, *not* a big number**!!! **But notice** that **ΔV *both* increases the mass flow rate a relatively small percentage, and then turns around and multiplies $\dot{M}$ to produce a Thrust in pounds** as we've learned above.

The explanations on pages 135 and App E 18 are fundamental and important, so we didn't want to complicate them with going **from $\dot{m}$ to $\dot{M}$**, and that **ΔV acts twice**, so we're doing that here.

Appendix **SSSS**

SLOWDOWN - Source Sink Simulation

Potential Flow, Slowdown, and the Source Sink Method

When a body is moving through the air, it tends to shove the air **forward** and **outward,** or **slow** an airstream coming at it, and move the stream **outward**. This **creates a slowdown and a radial flow in the plane of the prop**. We can somewhat ignore the radial flow, but we need to **accurately know the axial slowdown** vs. radius, to **correct the angles and chords of the ~perfect helical inflow ideal prop,** for any particular airplane. Since we want inflow angles into the prop airfoils to **.1 degree accuracy**, and these corrections can be several degrees inboard, more than 17 degrees next to the spinner, maybe .3+ degrees at the tip, 3+ times our accuracy objective, even at the tip, this is a hugely important correction at design speed. (Incidentally, notice the correction would be zero at zero speed, greater the faster we go, ultimately important in making **a properly corrected fast prop better at slow takeoff speeds**, and **climb**.)

Now, since a prop can't change blade angles as it rotates, we'll convert our body nose cross section area, vs. axial length, into an **equivalent *average*** *symmetrical* area body of revolution, around the crankshaft axis, like a special shaped bullet - that causes the *correct **average** effect at each radius* of the prop, in the plane of the prop, ahead of the nose. That makes it an easier two dimensional flow problem, not a much more complex three dimensional problem. We're simply after the average slowed factor at each radius, maybe .497, at 19% r, next to the 18% spinner, .645, at 27%, .757, at 35%, inboard, ... .968, at 91%, .973 at 99% out near the tip, **real RV 8 numbers**.

Aerodynamacists use the **Potential flow concept** to be able to deal with 3 dimensional flow, or the mathematically easier 2D flow. The **Potential function**, a capital phi, Φ, with a little calculus, a derivative vs. a location gives **a flow velocity at that location.** just the **capability to produce that velocity**, at that place, like a *strength, more easily handled,* if we have to deal with, or divide up flow into more complex 3D, or 2D flow. Goldstein and Theodorsen work with a genius level of this method to accurately understand the complex 3D flow of our basic propeller solution, and resolve it into a chart of **optimum blade loading vs. radius**, vs. **any *Advance Ratio*, low or high**. (J/π, our Lambda, λ, the AAA, Actual Advance Angle of the Prop Tip.)

Rather than talk about *Potential*, or do any Calculus, we're simply going to **First: create** a chosen axial lineup of pinpoint **Source+, and negative Sink Strengths** along the prop shaft axis, to **mathematically simulate our actual *average* body nose**. (Here comes Rankine, a genius on yet another subject.)

Prandtl, Tiejens teaches us Rankine's **Source, Sink concept** to create a way to **mathematically create the synthetic equivalent of an embedded body**. First, think of a **simple imaginary bullet shape** with one air source of just the right air flow volume rate, at just the right axial position, (it turns out, ¼ D back from the bullet nose, to mathematically model a bullet shape). A certain cubic inches per second flow rate, CIS, from a point source, has an infinite potential and flow velocity right at the point source, ***but*** its Strength, **velocity quickly drops off, divided by the surface area of an *ever bigger* Sphere**, (literally the CIS divided by the surface area of a Sphere, $4\pi R^2$, simply 4 times the area of a circle, to get **a simple velocity in in/sec**, in. per sec, **at any radial distance from the source**, **$in.^3/sec.$ *divided by* $in.^2$ = in./sec**).*

THINK, *get it*, that's easy enough, once you catch on!!!

Now, if we have **a uniform flow field moving from left to right**, and our perfect point source flowing out in all directions from the longitudinal axis, it's easy enough to see there will be **a stagnation point on the nose of the imaginary bullet**, where the right to left potential of the source exactly equals the left to right potential of the flow field --- and the flow field is stopped, **a stagnation point**, caused by the **one radial** of the source going exactly straight forward in opposition to the stream potential, the source strength, ***its velocity*** stops the flow V! As above, it's at 1/4 D, the diameter of the bullet. **Of course, the bigger the source, the bigger the bullet.**

***Realize we might use inch, or foot dimensions, but we must be consistent!**

There is some advanced math here, graduate level math based on a partial differential equation solution, but it all comes out easy enough to grasp, **insight that we can understand** OK. We **do get a bullet shape**, with **all the source air staying inside the bullet boundary**, like you see in **figure 1**. a **nice definite mathematically definable boundary, all the flowfield air kept outside that defined boundary**. Now, I'm sure you can see where we're going with this. **With multiple sources and sinks we can bump that bullet into any shape we wish** to **essentially exactly match our actual body of revolution** - and the computer will quickly do the math work for us.

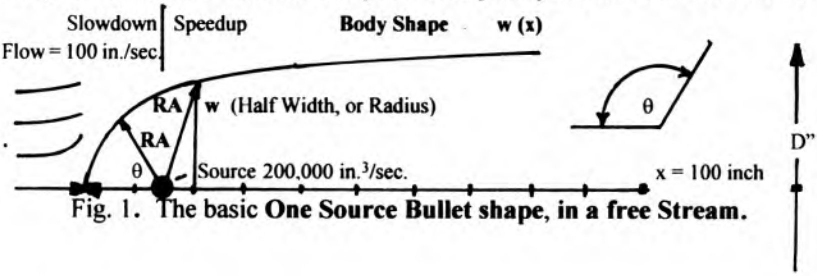


Fig. 1. The basic **One Source Bullet shape, in a free Stream.**

Now, realize that at all x axis locations **to the left of the source**, the **source is slowing down the flowfield** --- but **to the right of the source**, it is **speeding up the flow**, though the flow inside and outside the bullet doesn't mix! Don't worry about maintaining **continuity**, the constant flow rate outside the body, the **outward flow** at the nose ***keeps the flow rate constant***. Now, realize that **in the plane of the prop**, the **axial flow is slowed at *any* radius, a lot inboard, much less as we move out in radius**, past the body.

For the Engineers in the audience who want to understand ***all*** the math, we recommend the book **"Fluid Dynamics" by Victor L. Streeter, McGraw Hill Book Company, 1948**, which does a more complete job of explaining the math than the classic Prandtl - Tiejens, text. Streeter gives the following **two formulas, first for the bullet half width w**, or radius of our **one source** synthetic body of revolution, **at any axial location, vs the θ Angle**:

$$w^2 = \frac{m}{2\pi U}(1-\cos\theta)$$

m = source strength in.^{3}/ sec.
w = body half width, or radius, in"
U = uniform stream velocity in./sec.

The important key to understanding that: the cosine moves from 1 at 0°, to zero at 90°, to minus a minus 1 at 180°, a +1, thus the (1- cos θ) term goes from 0 to 1 at 90°, to 2 at 180° way back at infinite length, the half width, w, forming the bullet shape full $\sqrt{\ }$ **D"** far back, gradually as an asymptote.

Mathematically, m/2πU is a constant, the bracket goes from 0 to 2 as θ goes from 0° to 180°. But we need the square root of those to get any half width **w**, so we have the **square root of a constant, times the sq. root of 0 to 2, Physically**. The source stops the stream at the stagnation point, weakens as the area of a sphere as the radii increase with θ, slowing the flow less, no longer directly opposing it, shoving it outboard, **but weaker and weaker**, as RA grows

This next tricky equation plots the Bullet boundary shape at any axial location, including far back based on **r, the diagonal length, source to point.**

$$r = \frac{1}{2}\sqrt{\frac{m}{\pi U}}\ \text{secant}\ \frac{\theta}{2}$$

r is labeled **RA** on the sketch.

Now, notice that both formulas have **m/U**, the **source flow rate** in **in.^{3}/sec.**, divided by the airstream velocity, **U**, **in./sec.**, which gives us a distance^2, **a distance after the square root is taken**, the units we need, want, plus the nondimensional trig. functions that the complex differential equation math decrees. **Two tricky secant insights there -- hide right before you. A secant of θ, the hypotenuse of its triangle / adjacent side, goes from 1 at 0° to infinity at 90°. Now, with θ/2 controlling the action, the diagonal length, r, reaches way back at θ = 180°, goes to the infinity of 90°, reaching way back, so the bullet shape approaches a perfect cylindrical diameter as an asymptote far back at infinity, just like the last formula. That diameter will be 4 times the nose radius at the stagnation nose, that radius 1/4 D.**

Andy Bauer's Computer Program to do Slowdown, Three Major Steps

1. First: We must measure the cross section area of the cowl - nose at several logical axial locations --- and **create an equal area vs. length symmetrical body of revolution to use as a master to compare, match** vs. the radii, or **w half widths of the math model** we create. **Do realize** that with most noses quite unsymmetrical, **the prop angles of attack will be cycling from above to below our design α^0 and C_L, but if not extreme, the linear C_L - α^0** relationship will **keep our math and average result OK,** ***no better possible!***

2. Second: By **trial and error**, we must **find that combination of Sources and Sinks, at x axis locations, that model our actual equivalent body of revolution in 1. above**. The computer will **do the math for us, reading out w, half widths, so we can home in on matching our nose body of revolution half widths, or radii, and contour in 1! More below ---**

Andy's Program prints out all selected widths, w, vs. x's for each source-sink guess.

3. In the **last major step** we will be finding the **slowdown at the various prop radii**. To do this we divide the source strengths **Q*, in.^{3}/sec.**, by the expanding sphere surface area, **in.^{2}, $4\pi R^2$**, where R is each diagonal distance, or radius, from the source to the desired prop radius --- for multiple sources and sinks, to **get a velocity, in./sec**. The **horizontal component** of those **slow the flow field, easy, once you catch on. Notice how dimensional analysis keeps the units correct, helps us to understand what we're doing!!! in^3/sec. / in^2 = in/sec.**

***Andy's Program uses Q for flow rate rather than Streeter's m.**

Now, Andy Bauer's program uses an iteration program that calculates the effect of a long axial string of needed sources and sinks, for **First: matching our synthetic body half widths, or radii, to the symmetrical body of revolution that equates to the actual body nose shape. Second: once we've mathematically matched the real body axial cross sections --- the program uses that assemblage of source-sinks to find the slowdown at each prop radius -- as above, by summing the effect of all source-sinks.**

Realize it's the horizontal component of all those that is the slowdown at each radius.

Andy's program, as it comes to you, has the **actual sources and sinks** that **solve the Triple Ideal RV 8 prop slowdown problem**, so you have an example to learn from and mimic. ***Finding the source-sink array that solves any problem, is trial and error***, easy enough with the ***computer to find the matching*** **w's** for you. Just play with source flow rates, locations to solve it.

Notice the RV 8 model on the next page. The RV 8 has a big source up front, then a sink, pretty typical. That produces a **more blunt nose**, the next sink then **pulls in the bullet shape**, then selected sources and sinks to **bump out and pull in the math model to match your body of revolution model.** Andy's instructions shows the line numbers to plug in your numbers

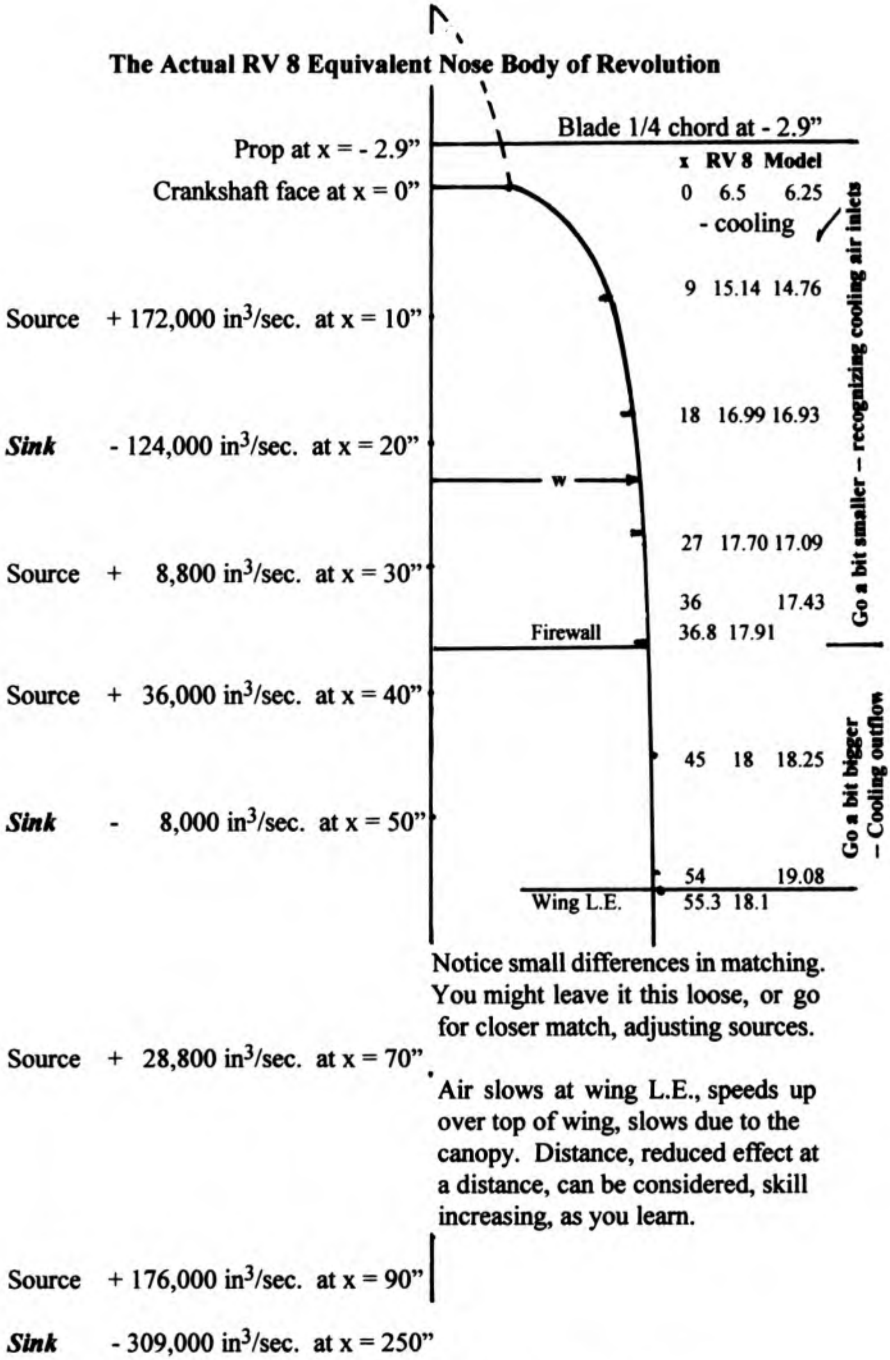


Fig. 2. **RV 8 Nose Equivalent Body of Revolution**

To reasonably account for a tapered rear fuselage: You put a sink at the tail, so that you haven't created, or lost any air, for arithmetic zero. Now, you could duplicate the whole body this way, but if you just model the nose, maybe a little back behind the cowl, including the windshield *if it's close and big*, you'll do just fine. We've done it to also model the circulation about a wing, a slowdown from under a high wing, a speedup tendency from above a low wing, but that's usually not done, a small effect. With the rapid Spherical drop off, distant sources have small effects, soon insignificant. But the big final sink for algebraic zero is big enough, it does change the RV 8 enough to not ignore it. We really don't care about the speedup behind each source, just want the ***composite*** slowdown at the prop.

There is not a more simple way to say where the body boundary is, than Streeter's formulas show, simple enough for how it really works, those final formulas much more simple than their math. More said a few pages forward.

Notice it's simply m/u at the core of both formulas, easy as it could be!!!

Now, I must tell you that Andy's iterative program to handle multiple sources and sinks, spaced out along the prop axis centerline **works a little differently than Streeter**, equivalent math developed more than a decade before we found Streeter's simplified, easier to see single source formulas.

As θ increases past 90 degrees, down to 180 degrees far back, **the cos θ is negative past 90 degrees**, all correct with Andy's math. Naturally we used Streeter's single source formula to check Andy's Math and Program, and they both plot identically, a nice double check that there are no nasty little math or program errors, the scourge of computer math and programming.

I did a lengthy, but simple, rock solid 10 digit hand calculator check of the RV 8 prop slowdown at the 75% radius, and an inner radius, and matched Andy's computer **slowdown calculation** through the 4th decimal place, so we have a solid check that both Andy's Math and Program are correct, also with the identical plot of Andy's body contour plot vs. Streeter's method!!!

For Prop Radii Slowdown use the Diagonal r, each source to each radii!
Slowdown: Sum the Horizontal Components of all the Vr(s) !

My rock solid check method was simply to decrease each sources velocity at the 75% prop radius by **dividing** each source strength **in.^{3}/sec.** by the **$4\pi r^2$ surface** area of its Sphere, for the **correct r**, to get a **slowing in./sec. velocity summation** from all the sources, **the fundamental principle here**. Their **horizontal velocity component checked the program, essentially exactly**.

Andy uses all inches, not feet, in./sec., but of course, all feet, and ft./sec. can be used.
Andy uses 100 in./sec. flowstream velocity, so the slowdown at each radius can be read like a percentage of any velocity, fast or slow, *smart!*

How and Why Rankine, Streeter and Bauer's Math Works Correctly

In all the explanations in this book it was necessary to **go way past the math** to **understand why and how** the math was working correctly, ***what logic is implied***, why it is correct, to explain the logic of it all, the engineering sense.

Here, we're creating a math simulation of an embedded body in an airstream which slows the approaching flow and shoves it outward. As often happens in a math derivation of a complex situation, a fairly simple algebraic formula falls out, often different, and more simple than one might expect.

When we plot the results of Streeter's math, we find a bullet shape is generated, that the source **slows** the airstream in front of the source, that the flow is **right back to stream speed at 90° above the source**, that the airflow is **speeded up from 90° to 120° behind the source**, that the stream slows ***back down to its initial velocity far back at infinity***, as the diameter slowly approaches its ultimate diameter at 180° at infinity, as an asymptote at max D

1. The Bullet Shape-Size: Streeter's first formula is $\mathbf{w^2 = (m / 2\pi u)\ (1 - \cos\theta)}$
The angle effect parenthesis multiplier goes from 0 to 1 to 2 at 0°, 90°, 180°, as the cos goes from 1 at 0° to 0 at 90°, minus a -1 at 180°, 1 + 1 = 2, at 180°. That *facilitates* the final correct bullet Shape as cos θ goes from 1 to 0 to -1, the parenthesis from 0 to 1 to 2, all smoothly as the cos θ function over 180°.

That's nifty, tricky, Streeter's math making what's happening clearer.

The **size** is controlled by **(m / 2πu)** which divides out to be **a constant**, the source strength **m**, in^3/sec. , divided by the stream speed, **u**, in/sec, thus in^2, but we must take the square root of the whole, (or each parenthesis of the formula), which sizes the half width at each axial station. The π is in there, because we use polar coordinates for the angle in deriving the equation, the 2 is there, because that's what the derivation decrees. (***not*** the spherical area **4π**)*.
Streeter's second formula works in a similar manner, except it uses the diagonal, or radial to shape the bullet, which plots exactly the same. The **math magic here is that simply m/u is the core *simple ratio* controlling the bullet size, the complex boundary between the internal and external flow, the exact synthetic simulation of the bullet and the flow around it.**

* ***Interchanging u and*** $\boldsymbol{w^2}$, **shows u is twice the radial velocity at 90° θ**, tan 1/2, 26.56° flow.

2. Speed, and Slowdown: The source strength, and speed drop off as the source strength **m**, divided by the area of a sphere, of **r** radius, $\mathbf{m/4\pi r^2}$, in./sec., where **r is the radius, or diagonal distance from the source** to the **bullet shape boundary**. But *that* **speed is multiplied by the cos of θ to get the axial, horizontal slowdown effect *at the body* ahead of the source, or speedup behind the source!!! --- *But*,** finding the **prop slowdown** is a **two step process** where you must **first define all the sources, get the diagonal, r to each prop radius - calculate the sum of all the axial V components!!!**

Using, Understanding Andy Bauer's Source-Sink-Slowdown Program

For those who buy and use Andy Bauer's Ideal **Propeller Design Program**, and his **separate, but included Source-Sink-Slowdown Program** to do the very necessary, very big correction of an Ideal Propeller Design, for any given airplane nose, you need a little additional explanation over and above the basic explanation possible with **Streeter's specific** **<u>one Source bullet</u>**.

Andy's program works different than Streeter's math but accomplishes the same thing. You could have a tough time understanding just how it works. Andy's program must integrate, or totalize the effect of any multiple combination of sources and sinks **so we can synthesize any required non bullet shaped nose**. To do this Andy plugs in a **20 inch w**, half width, or symmetrical body radius, bigger than the actual, and a **10 inch w**, smaller than the actual, and lets the computer loop, or iterate to find the ***<u>resulting body shape from all the sources and sinks</u>***, and provide the **w's at all the desired check points**. To do a different problem than the RV 8 case, you ***adjust the source or sink strengths, location***s, as necessary, to **home in on matching your body model**. The program works, does all that correctly.

The program will find answers above the 20", and below the 10" limits.

Andy uses **Q**, rather than Streeter's **m** for source strength, thus the formula core **$Q/2\pi u$** In program line 1410 and 1420 math similar to Streeter is there, but you'd have trouble identifying it exactly, because it works with the rest of the program math. You won't find ($1 - \cos\theta$). Andy uses $\cos\theta$, not ($1 - \cos\theta$), because he **goes after the slowing effect of all the sources, iterates triangles to solve it,** <u>adds a U, the stream speed</u>, in $(U + VxT)^2$ for Vr in the next, second equation in program line 1420. That confuses this explanation, a little, makes the iterating program harder to follow, but gives you the necessary clue that **Andy programs the math a little differently <u>for the same result</u>**. That clue can save a user from a lot of confusion and wasted time, if he digs to see how Andy's program works, having learned Streeter's more simple one source bullet case to learn the logic. <u>Streeter is easier, as presented, but Andy's program handles multiple sources and sinks</u>. //

Andy provides **a user instruction with the program**. That shows you the line numbers where you must plug in your trial source-sink flow rate sizes, and their location axial dimensions, to match your body of revolution nose model. You'll see Andy uses a series of subroutines to loop, or iterate, find the size and shape of your synthetic math model to match your average nose dimensions, w's, (and diagonal radii the program uses for its **Spherical area calculations**). **You don't have to dig into the nitty gritty of the program, and I suggest you don't. Just use it, it works just fine. Just get your nose model and source-sinks correct. Spend your time learning that!**

Now, let me make a **hopefully clear final summary** of how this all works, so that I can be as sure as possible that you can understand correctly.

Andy's program, like Streeter's first formula, puts out **radial widths**, **w**'s, at **all axial stations set up**, so you can fiddle with **Source-Sink size** and **locations**, so you can home in on a synthetic math model that matches your body of rotation model of your actual nose. Now, when that is resolved, you have, in essence **plotted your math model body shape**.

Now, you might plot your math model body shape using the equivalent of Streeter's second formula which defines the body as the diagonal distance and angle from each source to the body boundary. But we **don't do that**, don't waste that effort. **The body is already defined.**

WE'RE GOING TO USE THE DIAGONAL FROM SOURCES TO PROP RADII!!!

What we must do, is find the slowdown at each desired prop radius, which is progressively farther out and farther ahead of the body shape as we move out in prop radius. So, **Andy's program does three steps**:

1. It finds the **diagonal** ***distance*****, RA, from each source to each prop radius**.

2. It finds the related **diagonal velocity**, **in./sec**., by dividing each source strength, **Q**, **in.**^{3}**/sec.** by the area of the Sphere of that diagonal radius, **Q/4**π**r**^{2}, or **RA**^{2} --- **in**^{2}. But to **get the** ***axial*** **slowdown** at the targeted prop radius, Andy's program ***multiplies each diagonal velocity found, by the cos*** θ. and **sums up the axial effect of all sources and negative sinks**. **Source sizes are set to match the bodies - But we calc** ***axial*** **effect AT the PROP**!

3. Finally, ***YOU*** **Must subtract each summed axial slowing Velocity**, from the **standard 100 in/sec flowfield velocity, u**. That **gives you a decimal, or percent slowed velocity**, like maybe .497 next to the spinner, maybe .968 at the 91% radius, like the RV 8. The computer prints out its answers as Vxt. **You put YOUR slower inflows in line 203 of the Prop Design Program**!!!

Now, aren't you glad **you don't have to do all that math drill,** just let the computer do the drill for you. Learn how to use Andy's program, and you can make **essentially perfect corrections to essentially perfect props**, at **any design point you choose**. You'll find the corrections are big enough that to not do it well is to unnecessarily fall right back to amateur status.

But, see below --- We actually design a whole new prop for the slow condition!!!

Finally, I should repeat the heads up that Andy's program works more with the simple sides of the right triangle, **w**, Δ**x**, with **RA as the hypotenuse**, using squares and square roots, rather than trig functions, in case you want to confuse yourself and start digging through the program.

A surprise is that there is a pressure interaction, prop to body, slow -- so:

The text explains that we design a whole new prop for the slowed condition for a ***higher gross thrust*** **-** ***same net thrust and HP*** **- in slowed air**

Seeing Through the Real Nitty Gritty of Andy's Math Solution Here!!!

The **most fundamental principle in Source-Sink work** here is that of the **Source Velocity V_r dropping as the Source Strength divided by the ever increasing surface Area of a Sphere, $Q / 4\pi r^2$, (equals V_r), (as r increases).**

This is the most fundamental and important principle in Source-Sink work!

Now, a **very important insight** is to realize that Streeter's formula that deals with the half width of our model body, *(not the diagonal radius),* divides by **2π**, ***not*** **4π**, the **very simple**, but **key difference** resulting from a more complex partial differential equation solution!!!! The result of combining the algebra in line 1410 and 1420 in Andy Bauer's program for the w, half widths of the model body, does divide by **2π**, ***not*** **4π**, ***correct!***

The basic formula is always valid -- But This Finds the Boundry *vs. w and x.*

Andy then simply correctly deals with the distance and velocity vector triangles operating within that, (also recognizing the math manipulation in the next paragraph that legally interchanges w and u, etc. to better see through the math). Dealing with multiple sources and sinks, he makes two wild guesses for high and low w's of 20" and 10", and **lets the program, loop, or iterate** to **home in on final correct values for each axial w location chosen**, as affected by all the sources and sinks. Taking the horizontal, axial component, the cos effect of each source-sink he accurately gets the ***slowing*** effect of the sources on the flowfield, the speedup of the sinks, on the body nose --- or all the desired radii of the prop plane..

Looking at Streeter's first formula for **w**, we have $w^2 = (m / 2\pi u) \times (1 - \cos\theta)$, the square root of all that, or the product of the square root of each part. Now, Algebra allows us to solve that formula for u in terms of w, by simply interchanging them, so, $u = (m / 2\pi w^2) \times (1 - \cos\theta)$. Now, at $\theta = 90^o$ where cos = 0, the parenthesis falls to 1, and we just have $\mathbf{u = (m / 2\pi w^2)}$ --- which looks just like our basic formula --- *except* we have flowfield horizontal speed u, not the radial velocity of the source, though w is the correct radial distance at 90°. Now, since we're dividing by 2, not 4, we get the **great insight that at 90°**, where there is no $(1 - \cos\theta)$ effect, other than 1, and **u is back to its initial value**, the ***u is twice the radial flow speed*** -- **because we're dividing by 2, not 4!!!!** (As in the text, after 90°, the flowfield is speeded up by the source, maximizing at 120°, then gradually falling back to u at infinity, the source now so far forward that it has no ΔV effect.)

Very Simply, m / u gives Bullet Area, thus D, far back, all at u Speed, Insightful!!!

Separately, if $(1 - \cos\theta)$ goes from 0 to 1 to 2, at 0°, 90°, and 180° and the basic formula solves for w^2, the half width is 0 at the nose, 1 at 90°, and the square root of 2 at 180°, far back at infinity --- or playing with all the math --- **with a nose radius of 1**, the **w is 1.414**, the square root of 2 at **90°**, and **2 far back**, the ***nose radius 1/4 the final diameter, for our basic bullet!!!***

Source-Sink-Slowdown A Terrible Subject, at first, to Teach or Learn!

I expect you'll have a terrible time trying to understand this subject the first time you read it. I assure you it's an equal problem to try to write understandably. It doesn't get easier if written longer or shorter.

Like many involved technical subjects it's easy enough once you start catching on, but can seem difficult the first time you dive in. Let me suggest that you just try to grasp a few key basics, don't try to grasp it all at first, **learn how to grasp the few basic steps to run Andy's program, trusting him and me, and you can work your way into grasping it all!!**

Steps For Running the Propeller Design Program with Slowdown

1. Run the basic Propeller Design Program without slowdown, using desired RPM, Speed, etc. This requires that AAAA be set at 0 (zero) in Line 205.
2. Lines 201 to 204 contain slowdown data for blade stations 1 through 11 for several aircraft. Turn on one of these lines by deleting the ' on the data line that best represents slowdown on your calculation, (or create your own).
3. Adjust AAAA, (ratioing factor), on line 205 to better match slowdown magnitude for your case. AAAA=1.0000, unchanged, may be a good choice.
4. Run the program again and type GOSUB 257 and push the Enter key. A list of eleven negative numbers will appear on the screen. They represent the changed blade angles needed to account for the slowdown effects. Put these negative numbers into Line 1048, replacing the eleven numbers there. Also, remove the apostrophe at the start of Line 1048, to activate it.
5. Run the program.
6. Go to Subroutine 4600 to find the new eleven lift coefficients brought by the blade angle changes.
7. The above is generally not enough to bring the lift coefficients to the desired values.
8. Repeat steps 4 through 7 several times. Generally, about three times will bring all 11 lift coefficients to the design value, normally .5, the value for the no slowdown case. The program will have the new blade angle results in Subroutines 4400 and 4500. You are changing the blade angles to obtain the desired lift coefficients. But, the Thrust and H.P. will fall in the slowed air!
9. Now, rerun the basic program several times adjusting the $\bar{w}$, w bar, up to get back to the desired H.P. and/or Thrust. When achieved, you will have a full 2 pages of complete design data. Significantly, realize you will also have the final correct Blade Chords, and, of course, the final Blade Angles, β^o.
10. Print out, record your final results, your final slowdown corrected Prop!

Appendix T

Theodorsen Calculations (Heavy Loading)

An Overview of Theodorsen Calculation Methods

To make it as easy as possible to use his calculation methods, **Theodore Theodorsen**, the **WW II, NACA Chief Physicist**, intended that we use a basic **Blade Element Analysis**. taught to, or understandable by Aeronautical Engineers, together with his, *simple enough*, **special factors** that **accurately account** for **Heavy Loading**, the quite reasonable, **logical fact that what is happening "right at the propeller blade", is greater than what occurs, *on average*, across the whole stream tube!**

When you think about it, **in the real world, that would be no surprise**, and all Theodorsen is doing**, is simply getting the calculations really correct, especially for such core related issues as *inflow*, *needed pitch*, *advance***. When we see, quickly below, the **quite significant magnitude** of the $\overline{\overline{w}}$, vs. average **ΔV differences**, you can quickly see that going off to create your own, less accurate, technically less sophisticated method, is pretty ill advised, since the 7 smartest, special geniuses of the industry worked 83 years, from Rankine's 1865 start, finally Theodorsen's 1948 book ~exactly accurate result. **Theodorsen precisely, finalized Betz, Goldstein, for Heavy Loading!!!**

Betz, of course, **created** the recognized, **Pure Helical Inflow, Stretched, Pure Helical Outflow**, Classic Minimum Induced Loss Propeller **Theory - Logic in 1919,** with all its insightful ancillary characteristics, **constant dT/dQ**, ***a constant ratio of Thrust vs. Required Torque at every radius***, thus **constant efficiency** at every radius, **constant Slip**, a **Math Basis - all if first considered profile drag free,** ***purposely, the simple, basic case***, **without drag. Drag is readily added in a separate, *segregating* step, better, since each loss can be separated, each effect readily seen. Realize Betz Logic** is **created by proper Blade Loading vs. Radius, and Advance, controlled by blade SHAPE, with proper matching *Twist* --- changing vs. Advance!**

Be sure you fully understand the ***Flow Geometry in Chapter 3***, p. 82 II through 86 II, **particularly 84 II, which shows how *air Inflow Pitch is the Same at All Radii*, the core of everything!!** The constant pitch of the air inflow, gives **Constant Slip, vs. Plane Speed, which acts like the inflow is constant at every radii --- when the axial inflow can be seen in the sketch to vary a lot!!! It's the Magic Geometric Combination of Axial inflow, and Air Rotation, greatly bigger inboard, that makes all the Magic Math work out, makes all the nifty, hidden ancillary characteristics happen.**

Mathematically, Hold r tan ϕ constant, to hold Inflow constant.

Be sure you grasp that in the sketch, the **"a" inflow factor**, a ratio to the V Plane Speed, **times ~2 is the** ΔV the prop is throwing back. **If you think of that as the Average for the whole stream tube, ~ the same, that's ~"Light Loading". Theodorsen simply substitutes his w, or $\overline{w}$ for the full ΔV. But locally, *at the prop, that's much greater than the average ΔV*. Simply, that creates the way he handles Heavy Loading!!!**

Kappa, κ, the "Mass Coefficient" Ratios the Difference.

Of course, you know by now, that **Goldstein precisely solved the 3D Potential Flow**, Partial Differential equation Math, **for Light, Low Loading of the Stream Tube, in 1929. Then, Theodorsen precisely finished the 83 year *Rare Genius Level Challenge* in 1948, for real world Heavy Loading, quite different, a fantastic, readily P.C. usable, Gift to us all!**

Extraordinarily simple, ***after*** **Goldstein's** rare genius level math, realize **Theodorsen just uses Goldstein's Basic Math Solution, *shown as* Goldstein's Simple Chart of** K(x) **blade *Average* Circulation, or Lifting, Loading, at each radius, for the various Lambda's, λ. But T.T. targets *Heavily Loaded*, constant Air Inflow Pitch, or Advance, at each radius, for low to high Pitch, or Advance, by using his own Lambda, λ! It's IMPORTANT to realize, that to implement his method, T.T. uses a different, special definition of Lambda**, that **includes his w, or w bar, $\overline{w}$, factor, to get Inflow, Pitch,**

Advance, really correct. Lambda, is <u>usually</u> defined as the Actual Advance Angle of the Prop Tip, the Plane's Air Inflow Velocity, V_1, divided by the Tip rotational, πnD velocity, simply, $\lambda = V/\pi nD$. (A minute's thought, if you don't already understand, realize that's quite simply, the Actual Tip Advance Angle.) **!!! Notice below that T.T.'s λ *<u>has w, or $\overline{w}$, added, the key, core step</u>* to get the heavily loaded inflow, outflow, really correct**, using his method, <u>realizing that he simply uses</u> **<u>Goldstein's K(x) Blade Loading Chart</u> --- <u>unchanged</u>!**

It's, of course best if you can find a copy of Theodorsen's 1948 book to read and understand, see his text, K(x) Chart, and Equations, but this Appendix T, teaches T.T.'s equations and method Overview. OK if you're a pro who understands. (Also, telling you here exactly how to grasp it, use it, is a huge time saving over figuring it out for yourself in the book.) In addition to considering a λ steepened to account for the full w, or $\overline{w}$ velocity, as just described, he treats his Math as occurring "far back", where there is also a reduced diameter, D_o, simply from the Bernoulli shrinking of the now <u>$\overline{w}$ faster helical sheet</u>. For a high pitch prop, at cruise, that diameter shrinkage may only be 1%, but for a low pitch prop it may be more like 3%, a ***97% D_o***.

What Theodorsen is doing, in **solving his math far back**, is **getting it really correct, (also at the ~ half way point, <u>at the prop</u>, where all the energy is put in, *<u>an "also result"</u>* , <u>all the action happening there</u>.** Using his "Heavy Loading", not our own method, or someone else's less sophisticated concoction, is the <u>difference in getting your design really correct</u>, ***<u>or not</u>!!!***

I know Engineers, an extra dose of Hubris, who feel that with their modern computer, no one from the past could possibly be smarter, do better than they can with their self created program, not a clue, that the rare genius line of Historic figures, were more aware, much smarter in 1919, 29, 48, than they are today!

Frankly, with experience in interviews, and armed with a Psychological screening test, I was avoiding hiring guys like that 40 years ago. Hubris is not a good thing in Engineering or Science. **Checking, knowing what got accomplished before you came along, is always correct, because there is so often, a brilliant man who preceded you, gave you a much smarter starting point.** Checking, then creating, then a lot of double checking, is the proper game. It was often, the rare genius, who accomplished the next significant step in complex propellers, for example, the math here far beyond the capability of the mere, mortal engineer. ***Never skip past rare genius work.***

K(x) Blade Loading Chart - vs. Radius and (Theodorsen's) **Advance, λ.**
Realize x is Radius Ratio, r to Tip Radius, R, simply r/R, (~defines itself).
As above, realize Theodorsen uses his own special definition of λ, for Heavy Loading.

Goldstein and Theodorsen K(x) Blade Loading Chart
vs. Radius and Lambda, Theodorsen's Lambda for **his Math**.

Theodorsen's *Heavy Loading Lambda* $\lambda = V(1+\overline{w}) / \pi n D_0$.
n, rev/sec. D_o is reduced Diameter, far Back w bar, $\overline{w} = w/V_1$.

Values Interpolated for Even Fractions

x \ λ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.1	0.517	0.291	0.184	0.127	0.092	0.070	0.055	0.043	0.035	0.027
0.2	0.773	0.513	0.338	0.237	0.1735	0.133	0.105	0.085	0.068	0.055
0.3	0.876	0.645	0.456	0.3225	0.2445	0.195	0.158	0.128	0.102	0.079
0.4	0.927	0.732	0.538	0.393	0.299	0.240	0.196	0.160	0.1275	0.098
0.5	0.9475	0.769	0.5825	0.433	0.3325	0.2675	0.220	0.181	0.147	0.115
0.6	0.955	0.782	0.593	0.444	0.3435	0.279	0.232	0.192	0.157	0.124
0.7	0.942	0.750	0.569	0.430	0.337	0.275	0.228	0.190	0.157	0.124
0.8	0.890	0.673	0.504	0.3795	0.300	0.248	0.209	0.175	0.145	0.118
0.9	0.739	0.523	0.385	0.297	0.235	0.193	0.1625	0.136	0.113	0.092
0.95	0.565	0.382	0.284	0.217	0.169	0.1375	0.114	0.0955	0.0805	0.067

Values of Goldstein - Theodorsen K(x) vs. Radius and Lambda, λ.

This chart with even Decimal Values is generally the easiest form to understand. Goldstein's comment was that these values are accurate to 2 to 3 in the 3rd decimal place. That sets the accuracy ~1%, in usual ranges, *as you can see.* Do look.

Realize: In designing a Propeller with Theodorsen's Math, we select a w bar, $\overline{w}$, essentially his greater ΔV at the prop, adjust it to give the required Thrust, or often, the H.P. available, *if* Thrust # is not known!

Quite naturally, we also **select a C_L** and **proper C_D for Reynolds numbers.**

Note Later Tibery and Wrench Loading Data referenced at the end of this Appendix

Theodorsen's Equations All units *in* ft. #, second, *Angles in Degrees.*

Solidity Factor, $\sigma = P c / 2 \pi r$ P = number of blades (2) C = Chord

Simply, the **decimal of solidity, at each radius,** of blade **chords** vs. *full* circumference. Found just above T.T.'s equation 4, in text. **σ Is Sigma.** It is used in **line 1055** in Dr. Andy Bauer's Propeller Design Program --- ABB Prog. **line 1055**

Beta, Blade Angle $\beta^o = \alpha^o + \phi^o$ **Beta = Alpha + Phi**

Simply, **Blade Angle = Angle of Attack + Air Inflow Angle.**

This is the **standard Angle basis *for* Propellers,** unsaid in the text.

Using Sigma $\cdot$ C_L to find the Chords - With Sigma Formula above.

$$\sigma C_L = \frac{(1+\overline{w}) \cdot (2\,\overline{w}\,K(x))(\sin^2\phi / \cos\phi)}{(1+\overline{w}/2)\,[1 + (\overline{w}/2 \cos^2\phi)]}$$

Theod. **Eq. 4, p. 47**
ABB Prog. **line 1040**

x = r/R r/R is simply the radius Ratio, actual r / tip Radius, *used a lot*

Important: realize K(x) in loading chart, is just Loading at that r/R

Theodorsen points out that this equation is not exact - has 2 (very close) approximations, Insignificant. Inflow is *not* exactly equal to outflow, Blade lift Vector is *not* exactly perpendicular to Wind Inflow Vector and Phi, ϕ. Both could be made more exact, but it's not worth the considerable complication for very little improvement in accuracy.

Finding Wind Inflow Angle ϕ, from tan ϕ Theod. **Eq. 8, p. 48**
ABB Prog. line 1015

$$\tan\phi = (\lambda/x)\,[(1+\overline{w}/2) / (1+\overline{w})]\,[1 / (1+2\overline{w}Y)]$$

x here, is just r/R, the Radius Ratio, as above, better used that way to avoid confusion.

There is a small contraction in the wake from the propeller Diameter to Do.
It is the convention to show that contraction as a Radius Ratio: Eq 6, p 48.
$\Delta r_o / R = (c_s$ /kappa, $\kappa) Y = \sim 2\overline{w} Y$ So, to solve for **Y**, we need **c_s**, and κ.

Thrust Coefficient ABB term, DRO means Delta Radius Δr_o..

$c_s = 2\kappa\overline{w}\,[1 + \overline{w}\,(.5 + \varepsilon / \kappa)]$ So: Now **we need both ε and κ** ABB Line 153.

And these are found on **Theodorsen p. 37,** his **Graph,** Fig. 10, **for 2 blades.**

DRO = Y R C_s / Kappa, κ T.T. Eq. 6 p. 48 DRO & DO on ABB Prog. **Line 160.**

The Propeller Wake Final Diameter is: DO = D - 2DRO ~.99, .97 D.

Again, be reminded that **Kappa, κ** was inadvertently called Chi, Xi, in ABB Program, due to unusual type setting symbols for Greek Letters, in Theodorsen's Book.

Including Blade Drag in Theodorsen Calculations

If no drag is included, the **efficiency** is simply the **Thrust Coefficient C_s**, previously defined, **divided by the Power coefficient C_p**.

Efficiency $\eta = C_s / C_p$ where **$C_p = 2\kappa\bar{w}(1+\bar{w})[1+(\varepsilon/\kappa)\bar{w}]$**

with **Epsilon, ε, and Kappa, κ,** available on **Theodorsen fig. 10 below:**

If Drag is involved we must *add the tangential and axial factors*, t_t and t_a.

Theod. **Eq 18, p. 54** ABB Subroutine 8000, to 8070.

Efficiency $\eta = C_s - t_a / C_p + t_t$ where:

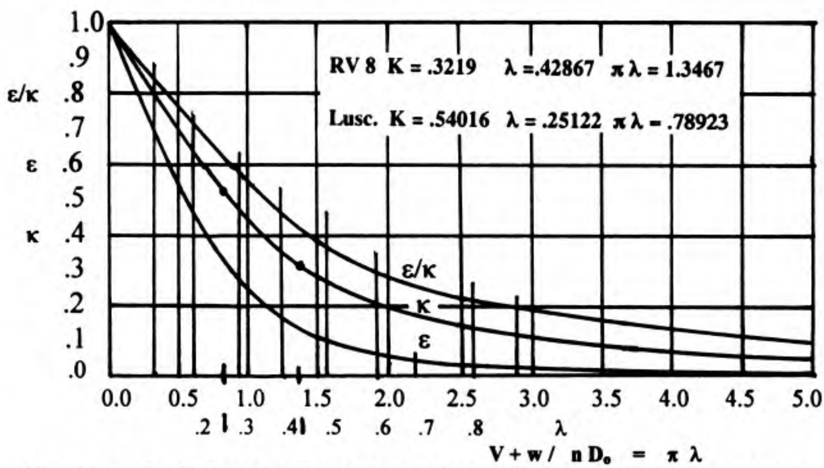
Theod, Eq. 26 p. 55 — Eq. 27 p. 55

$$t_t = (2/\lambda^2) \int_0^1 (\sigma C_D / \sin\phi)\, x^3\, dx \qquad t_a = 2 \int_0^1 (\sigma C_D / \sin\phi)\, x\, dx$$

Or Theod. Eq. 14 and 15 p. 49 – ***started*** in ABB lines 8020 and 8030.

$$t_t = 2/\lambda^3 \int_0^1 \sigma C_D (\lambda^2 + x^2)^{1/2}\, x^3\, dx \qquad t_a = 2/\lambda \int_0^1 \sigma C_D (\lambda^2 + x^2)^{1/2}\, x\, dx$$

Theodorsen's Graph of Kappa, κ, Epsilon, ε, the axial Part of κ, and ε/κ.



Theodorsen Fig 10 Tentative Values of ε, and ε/κ for 2 Bladed, *Single Rotation* Prop.

The Huge Significance of Theodorsen's Kappa, κ, Factor.

Notice that Kappa, in the Graph here, might be ~.5+ for Luscombes, .3+ for an RV, .12+ for a Reno Racer. The Huge Significance of that is that when inverted, a Luscombe w is ~2x the average stream tube ΔV behind the Prop, ~3x on an RV, ~8x on a Reno Racer, greatly more than the Average ΔV. What is happening **Physically,** is that as **a High Pitch Prop** screws through its Stream Tube, it **has less and less effect on the Stream Tube, uses its mass less well the higher the pitch,** the **huge insight that only T.T.'s Heavy Loading gets Pitch, Inflow, Advance really correct!!!**

The Milestone Capability, that got us to This Time and Place

Only a sufficiently accomplished, experienced Aerodynamacist, and Programmer should attempt to write his own Program for Propeller Design, a thicket of pitfalls, realizing the core complexity of Propellers. It was only because of Dr. Andy Bauer's lifetime of Knowledge, and Experience, that he was able to correctly sort through that thicket, and **make it possible to find the hugely simplified final insights you see in this book**. The final Program, in Basic Language, is 19 pages long, and was made ever more complete, sophisticated, and correct, for the multiple capabilities finally appropriate, over many years. A very accomplished, experienced, proven engineer, I would not have ever attempted it, without the specifics of Andy's lifetime of knowledge and experience in Aerodynamics, needed to ultimately find his way through Betz, Goldstein, Glauert, Theodorsen, and the total Swamp that propeller math can be when you first wade into it all.

Our mutual collaboration in ultimately getting far past where others had been, in being able to ultimately see through all the myriad of complexities, and **find the core simplicities, for incisive explanation**, took our two lifetimes of experience, but **was only possible, *after* Andy cut through all the best, past Historic work in the Mathematics of Propellers, with an incisive, Theodorsen computer program for broad and specific analysis, World Class Work, that went far beyond where any had been!**

Without any question, Dr. Andrew B. Bauer deserves to be recognized as the 9th Historic figure in the long, now 140 year conquest of Propellers, following those famous Historic technical figures, Rankine, Froude, Betz, Prandtl, Glauert, and the Ultimate Genius, Theodore Theodorsen, who finally got the math precisely correct, after the initial 83 year period, from 1865, to 1948. But, then the job never got finished through a Comprehensive, Incisive, Understandable Explanation, because the core job was just too hard, too time consuming, too daunting. Everyone, even Senior Professionals shied away for an extra half Century, ridiculous, never an explanation.

Not to be missed, if we properly include Gus Raspet, of Mississippi State, with his innate curiosity and creativity, with students, and coworkers at his Old Miss Aerophysics Laboratory, as milestone figure # 8, Andy would be # 9, in that long, and distinguished, Historic List. Gus showed us how really bad overall Propulsive Efficiency could be, only 58% overall on a Bellanca Cruisair, inverted, 178% more power required than that in Gliding Flight, a huge insight, another unanswered challenge by Industry, since his milestone 1950's test work.

The collaboration between Andy Bauer and I began in the last half of the 80's, after the work I did before and during my 1986 work as Technical Director, Mission Control, on the **Voyager world flight**, and started to write **The Logic of Flight**, *The Thinking Man's Way to Fly*. Andy did an Adkins LeBeck analysis of the Luscombe Propeller, and I invented, **Zero Thrust Glide Testing**, and carried out, what was ultimately the **first full Aerodynamic testing of a propeller airplane, including full speed range, Accurate Propulsive Efficiency,** in full flight configuration. It showed degrading, overall efficiency as more power was applied, and a non smooth, accurate curve implying, we believed, some variable separation, which interestingly, seemed to level out, not as bad at the higher speeds. We gave an AIAA presentation and paper at Reno, January 1990, and a final paper, Journal of Aircraft Vol. 30, No. 4, July August 1993. The **final Graph** of **Full Luscombe 8E Aerodynamic Data, EAA, Sport Aviation, Mar. 95**, is used today at NASA Langley as their best reference on Propulsive Efficiency.

A Blade Element Analysis to Create an ideal Propeller Design

To do a Blade Element Analysis of a Propeller, one divides the blade into even radial Elements. We ended up using 10, 8% radial sections from 19 to 99%, 11 boundaries, considering the 18% D. RV Spinner, and the desire to have the last boundary be on the prop blade at 99%, with a real chord, not air, at the tip. The Blade Angles and Chords, are found with the equations above. The whole blade Lift is calculated, Blade Shape curve smoothed, integrated, and resolved into forward Thrust, and Resisting Torque. That can work accurately, if you use **real Theodorsen Heavily Loaded Flow**.

Among all the historic complexities of Propellers, let me show you some **relative simplicities here**. If you can get the genuinely accurate **Chords,** and **Blade Angles,** β, from the above equations, you have Blade **SHAPE,** and **ANGLES**. You have **chosen a target D, Diameter**, or **Aspact Ratio,** and quite simply, **can see** from the chords, **if your objectives there have been met**. Of course you've juggled $\overline{w}$ to get the **Thrust** and **H.P.** you seek. Of course, you chose an Altitude and density to start. Of course, you also **chose a C_L**, and **C_D**, the **C_L** probably **.5**, or **.55**, if you're seeking a smaller, lighter propeller, almost as good. In your program you should have set up **a subroutine** to give **proper C_D**'s vs. the Reynolds numbers at each radius, based on a set of curves you selected **vs. angle of attack, and Reynolds number**. With experience, you can guess, and arbitrarily set an overall, higher **C_D** that, though not as locally accurate, gives comparable overall results, satisfactory for a less precise analysis, for example, a quick, more simplified look at overall possibilities, though with modern computer speeds, and capacities, there's no real time difference.

If you accomplished a creditable, sufficiently professional printout of overall results, listed for each radius, **you can have X-ray insight into all local characteristics of the prop at each radius**. Naturally, that depends on whether you are really competent to do the overall job, or not, and how much time you invest. **Our work was done over years**, as Andy created an ever more capable program, that confirmed that a constant dT/dQ actually happened at each radius, what it was after Profile Drag was added, showed **dT/dr, Thrust loading at each radius**, **before and after slowdown** correction at each radius, **dTT/dr**, the Net of Gross Thrust considering the pressure interaction with the body in Slowdown, **listed Reynolds numbers, Wind velocity, C_L, C_D, Efficiency, η, the LONG LIST of things you really want to know at each radius, finally, a 2 to 3 page data printout**.

We Engineers tend to want to do everything ourselves, start from square one to feel correct, complete, sure we got it all, but where major work was done, that can be less than wise. Only one, far more capable than normal mortal Engineers, is even qualified to repeat Goldstein, Theodorsen. Knowing how much work, how long it took to develop Andy's Basic Language Program, **I'd recommend you simply buy Andy's Program, save your time, more profitably spend your time learning all the capability in that program, and all the insight on real bottom line results that are available, at modern, essentially instant computer speeds, and capacities**. Using the simple (originally IBM) Basic Language, the programming is easier to learn than more sophisticated, later code. The now old GW Basic does have some disadvantages, newer computers don't like to print it out, and you must use some easy enough tricks to print, after the early Windows 3.1, where we started in 1992. We do have a later Windows Program developed by Jim Rust, Whirlwind Propellers, quite slick, but less total capability, flexibility, We hope to have a program available, as time allows, after book publication

A few extra details need to be covered:

A_z A_o Azero. On his **page 31, Theodoreson** gives an **equation (42)** that shows the **exact inflow, *not* exactly half the total w, or $\overline{w}$** delta V at the prop, but quite close, often part of a percent, or so, less, not a biggie. It is of interest in developing the theory, and seeing that precisely analyzed. **The inflow vs. outflow are *not* exactly equal, *not* each half the displacement velocity w, or $\overline{w}$. Andy has it in his program**, printed out where he looks at several specific T.T. data characteristics, but we'll not cover more here.

There are actually 3 Epsilons, Axial, Tangential Rotational, and Radial feeding the Tip Vortex, 3D losses = κ. T.T. p. 33, fig. 8 plots 3D losses at .5 λ, shows radial, the tip Vortex loss exceeds the axial at .5 λ, WOW!!!

<u>One Last Time</u> --- <u>Don't think that you can easily do better math *now!*</u>

Betz logic is Elegant, in its ancillary detailed insight, Goldstein's 3D Potential Flow Solution is far beyond the math capability of all but the most exceptional modern Engineer, Theodorsen's insight and work, equally brilliant, a rare, exceptionally tough team to challenge. <u>Ribner and Foster did check the work by modern computer in 1991</u>, generally concurred within approximately 1%, a few less central items a bit more. The chief practical problem there, doing even more on multi-blades, etc. they <u>*plotted*</u> most of the results, inadequate for us to do a digital check.

Of course progress won't stop. We won't close the patent office, though the Administration is severely cutting Langley funding, the surest way to get bypassed. **The clearest path to progress, potentially greater propeller efficiency, a few more percent, is <u>going for elliptical blade loading</u>, cutting tip losses even more than Classic Theory**, loading the blade more inward, **impossible inboard of R/2, without gross chords, far lower q inboard.** Logic, and Math work comparable to BGT, will demand very smart new work.

Appreciate the wildly complex Math that Goldstein, Theodorsen solved.

We're pulling in and throwing back air, not unevenly, but with <u>accurately held constant Pitch of the Air Inflow at each Radius</u>, perfect Screw Surfaces, Classic Archimedes Screws, stretched pitch finally in the outflow, uneven rotation and axial inflow, optimally, brilliantly, but easily geometrically combined to produce that perfect Math Model, far weaker axial inflow inboard, but precisely assisted with much greater rotation inboard, at the steeper blade angles there --- Tip Vortices not seen in the Model, but accurately accounted for in Goldstein's 3D, Potential Flow Math - radial too.

The Radial flow is, of course, outward on the bottom of the outer Blade, inward on the top, but with a two bladed prop acting as two separate, but not independent flows, 180 degrees apart in the stream tube, there are two opposite radial flows on the inner blades, weaker root vortices too at low q.

Theodorsen's brilliant insight that <u>Goldstein's Math Solution, and Blade Loading Chart IS Valid for Heavy Loading, if you just consider the resulting flow Far Back</u>, <u>at a significantly higher Pitch</u>, perhaps 14 or 15% local ΔV vs. V, much less on average across the stream tube, as in the text above, and at a **smaller D_0 diameter**, shrinking essentially as Bernoulli would teach, but with the overall incisive, yet relatively simple math offered by Theodorsen, as used in this Appendix. **I submit that's <u>as Elegant an overall solution as you are ever apt to find and use in all of Engineering</u>.**

Including Blade Drag in Theodorsen Calculations

Our Program <u>does</u> include Profile Drag, and Low Rn when implemented

If no drag is included, the **efficiency** is simply the **Thrust Coefficient C_t**, previously defined, **dived by the Power coefficient C_p**.

Efficiency $\eta = C_s / C_p$ where **$C_p = 2\kappa w\,(1 + w)\,[\,1 + (\varepsilon/\kappa)\,w]$**

with **ε and κ** available on **Theodorsen fig. 10 following**

If Drag is involved we must *add the tangential and axial factors*, t_t and t_a.

Efficiency $\eta = C_s - t_a / C_p + t_t$ where

$t_t = 2\,(1/\lambda^2)\ \int_0^1 (\,\sigma\,C_D\ /\sin\phi)\,x^3\,dx$ **$t_a = 2\ \int_0^1\ (\,\sigma\,C_D\ /\sin\phi)\,x\,dx$**

Remember that **analysis** is more **correct *<u>if</u>*** the program uses **low Rn C_D's.**

<u>Updated Information</u> Tibery, Wrench - David Taylor Model Basin, 1964

Tibery, C. L. and Wrench, J. W., at the David Taylor Model Basin, Report 1534, Applied Mathematics Laboratory (of the Naval Research Laboratory), did an extensive update of the Goldstein Factor in this 1964 report It is reported for Propellers from 2 to 12 Blades, and **most valuable, is reported in numbers,** not graphically, as Ribner and Foster did in their 1990 work.

Note that the Goldstein Factor is reported for 1/λ, thus requires manipulation

While this work was done much earlier than Ribner and Foster, and before the modern proliferation of computers, we can believe that NRL data of that time deserves to be trusted, and as such, *if correct* can be a very valuable addition, extension of the Goldstein - Theodorsen Tables. Most significantly, where it tends to confirm the original tables up to a (basic) λ of nominally .5, (~ 1%+), at the higher Lambdas it shows that the Kx factors for the higher Lambdas should be progressively bigger, at higher Lambdas, (~ 6% effective, at λ .8), favoring even higher Pitch, and Blade Widths

Thus, at those errors, <u>the implied factor updates, and changes **would not significantly affect normal props**</u>, but **only those of quite high, to very high pitch**. Since we became aware of this work only as we were bringing this book together for publication, we have <u>not</u> changed the book, other than this heads up, or our computer design program. We'll leave the appropriate checking for a next step of work. However if I were faced with a very high pitch prop design, I'd be inclined to use the Tibery and Wrench data, and get busy checking, because David Taylor work is probably correct.

Ref.. The Aerodynamics of Propellers, Quentin R. Wald, Science Direct, Progress in Aerospace Sciences 42 (**2006**) p.85-128 www.sciencedirect.com

A final Overview, and Summation of BGT Calculations

Just Finding the Wald Paper, and thus Tibery, and Wrench expansion of the Goldstein Kx Blade Loading Chart Data, as we were bringing this book together, we did not want to publish without a proper review of Wald's work, and the Tibery and Wrench Tables, did not want to stop our completion of our long project, but most of all did not want to take any chance of publishing wrong, or incomplete information. A few telephone calls to Quentin Wald proved most satisfactory.

1. Even though Tibery and Wrench did their work in the 60's, before the modern availability of powerful Personal Computers, we agreed that working at David Taylor they would undoubtedly have the best of equipment available then, and we should be able to expect that there work had every chance of being correct. It was Wald's view that they had a good math solution of the crucial loading factors.

2. Presuming that the Tibbery and Wrench tables were simply the inverse of Goldstein's Lambda, 1/λ, I had checked their results vs. the original Goldstene Table reported only to a Lambda of .5, and the Theodorsen table to Lambda of 1.0 that we had used as a base, and reported in this Appendix. Simply, T & B seemed to confirm that the Goldstein Math solution was essentially accurate, nominally ~1%, to a Lambda of .5, but that the Theodorsen Kx Loading, obtained only by Voltage Field Tests were not high enough! Since all the props we designed were at less than .5 Lambda, our work, and conclusions should be correct, simply realizing that very high Advance props need higher loading!!! (Thus our blade Shapes, and Loading on p.147 would change to a proper degree, the mathematically ideal Canoe Shaped Prop would occur at a lower speed.)

3. Wald Advised that although he had done new math to clarify Theodorsen, make him easier to understand he did not disagree with T.T's result.

A Bottom Line Overview

1. Betz Classic Prop Theory, 1919 remains Valid – unless we go for Elliptical Loading, to try to achieve a bit more efficiency.

2. Goldstein's Light Loading, Low Advance Ratio Classic basic Solution, and Kx Chart remains valid, subject to a final, exhaustive check vs. T & B

3. Theodorsen's adaptation of Goldstein for Heavy Loading, and his math method, the work that could have won us essentially perfect props a half Century ago remains valid.

4. Presuming a careful review confirms the validity of the Tibery and Wrench Loading Charts, we can convert to that loading, .5 λ, or 0 to 1.0 λ.

Appendix TR

Thrust Ratio - Net Thrust, There's a Loss

Why you need More Thrust Than Drag

Gus Raspet, a somewhat legendary Aero Teacher at Mississippi State was always challenging students to **try the unusual**, **Dig Deep**, **find the Truth**, **understand things better**, the kind of **creative, unique personality that students remember for life**. **He ran a series of gliding tests** towing up popular light planes with the **propeller removed**, sometimes with the cooling ducts taped shut --- **risky enough, few professors would be so bold**.

He did all this in the 50's --- a Half Century ago!!!

To me, he earned the right to be honored as the eighth man in our string of 7 historic figures who accomplished the Benchmark Steps in the Conquest of Propellers!!! He found **correct drags**, but when those drags were compared with the **actual *high* H.P. required** it **implied absolutely terrible overall propulsion efficiency.** And there was **no way his drag data was wrong**, too low. A plane just won't stay up longer than its drag allows. ***Glide drag errors go high***. A pro, he would have his weight, speed and sink rate right, and he always got the same end result of bad overall propulsive efficiency. A Cub, a Cessna, --- a Bellanca Cruisair had **a terrible 58%**, when he compared **the min. drag taped ducts test with real required Power!!!**

That's hugely different than people have understood!!!

This guy nailed one of the most important fundamentals in Aerodynamics, *a huge missing insight*. The problem, the great injustice was that everyone was off working on jets, the new craze in the 50's, and **nobody seems to have caught on to the fact that this was breakthrough fundamental insight, facts!!**

It was Gus's great work that motivated Andy and I to get into this whole subject, invent **Zero Thrust Glide Testing, see if we would duplicate his results, figure out what causes it all. I want to see Gus get Credit for great Creative Aero Work!!!**

Picking up where he left off, it was clear that the **overall efficiency** was far worse than any propeller (in)efficiency could be, and that **there is a significant interference (in)efficiency**, η_I.

We found a **.67 overall propulsion efficiency,** η_P, a **.8933** η_I **interference efficiency** = **.67 / .75 prop efficiency, eta,** η, at **85 IAS** at sea level, ***or*** 85 IAS, **100 TAS** altitude cruise at **10,500'**. That **.8933**, you'll see, ***explains Gus Raspet's big mystery loss***!

It takes 49 H.P. at altitude, just what's available, lean, ~ 2280 RPM.

In the big picture, the **interference efficiency** logically seems to show up **on the high drag, slow classic light planes**, where the larger ΔV added to the Stream tube, is a much bigger ratio to the slower plane speed. Thus, it's sometimes quite small on **modern, fast homebuilts. Fast is twice better** with a more efficient prop ***and also*** better interference efficiency too, the **slow, high drag planes losing twice** --- all much **better when flown at very low power, even worse when flown at high power, Vmax.** ***It's quite Variable but logical, Understandable!***

The best thing we can do, as usual, is to **show you all the basic numbers, right up front**, so you can immediately ***see where it's all going***, so it makes easier sense as you learn all the details. We're ***purposely*** going to use too many decimal places so we can flip around from any number to any other and hit it ~exactly.

Books are printed in 64 page signatures. This book, already longer than intended, this longer Appendix, just would not fit.

If you are interested, and would like a copy, simply send a STAMPED, SELF ADDRESSED ENVELOPE, WITH $ 1 TO COVER COPY COSTS, and we'll forward a copy. Include your phone number, so we can solve any problem!

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