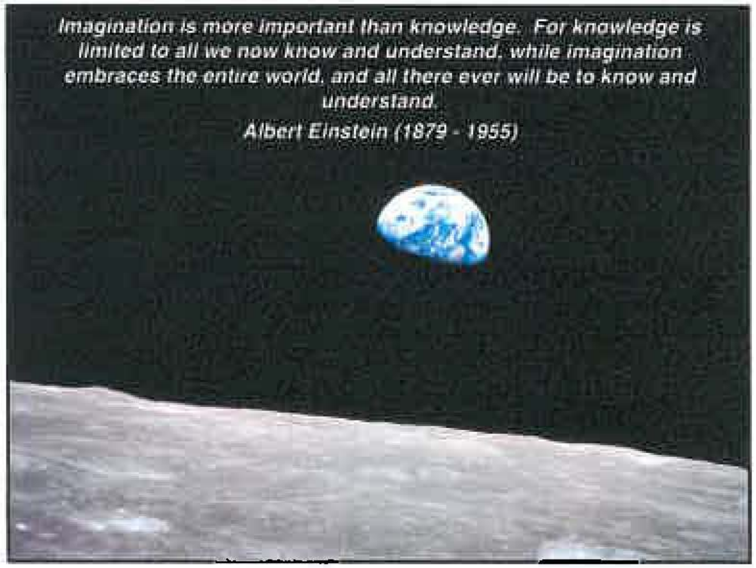


A little bit about me...

- I came from a really small fishing village...
- I didn't speak English at all...
- ...but I really loved airplanes...
- ...and I was good at math & science

My career with NASA

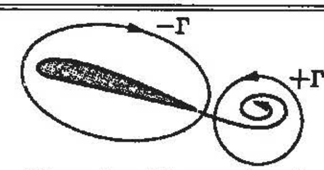
- Intern graduate student (airfoils) 1982
- Hired fulltime as an aerodynamicist 1983
- Aircraft: F-8 Oblique Wing, Deep Stall Schwiezer, hypersonics (M 14.2), F-18 HARV, SR-71A, F-106 Eclipse, X-37, X-38, X-36, X-48, Mars airplanes,...
- Chief of Aerodynamics 2002
- Deputy Director of Research/Engineering 2004
- Washington DC, Special Assistant to the Associate Administrator of Aero 2008
- Project Manager 2009
- Associate Director of Research 2012
- Chief Scientist 2014

On the Minimum Induced Drag of Wings

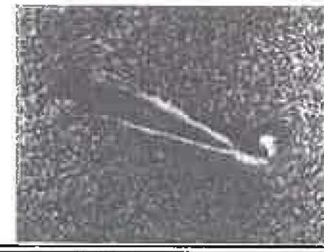
Albion H. Bowers
NASA Armstrong Chief Scientist

NASA Neil A. Armstrong Flight Research Center

Lift



Where does lift come from?
You should wonder about this...



Flying Wings

Flying wings are so elegant and elemental...

Yet they are difficult to fly and handle poorly. Why?

Imagination vs Knowledge

- Requirements and Assumptions
- Concepts and Solutions

Questions vs Answers

- "The important and difficult job is never to find the right answers, it is to find the right question." –Peter Drucker, *Concept of the Corporation* and Management
- "...question the unquestionable." –Ratan Tata, CEO Tata Group
- "They get a kick out of screwing with the status quo. They can't bear it. So they spend a tremendous amount of time thinking about how to change the world. As they brain storm, they like to ask: if we did this, what would happen?" –Meg Whitman, cofounder of ebay, PayPal, and Skype

Personal Air Vehicles

Flying Wings

Flying wings are so elegant and elemental...

Yet they are difficult to fly and handle poorly. Why?

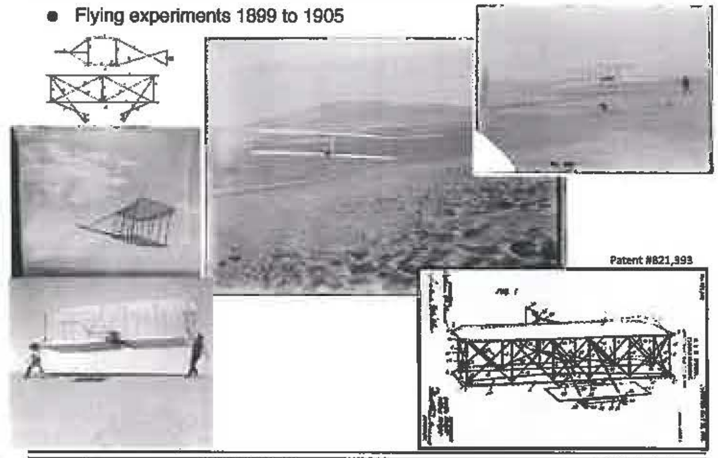
Birds

The Four Ways Birds Differ from Aircraft

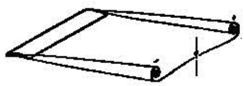
- Birds turn and maneuver without a vertical tail
- Birds have slender tips that carry little load
- Birds gracefully fly formation with overlapped wingtips
- Birds have narrow wingtips without tip stall

Wilbur & Orville Wright

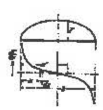
- Flying experiments 1899 to 1905



Prandtl Lifting Line Theory



- Prandtl's "vortex ribbons"



- Elliptical spanload for a given span (1920)
- "the downwash produced by the longitudinal vortices must be uniform at all points on the aerofoils in order that there may be a minimum of drag for a given total lift." y = c

Ludwig Prandtl

This is the accepted theory and the standard for the minimum drag of wings. But what is a wing? Is it only aerodynamic? What about the structure?

Wingtip vortices

Wingtip vortices

Elliptical Spanload

Elliptical Spanload

Elliptical Spanload and Wingtip Vortices

Fundamental Assumptions

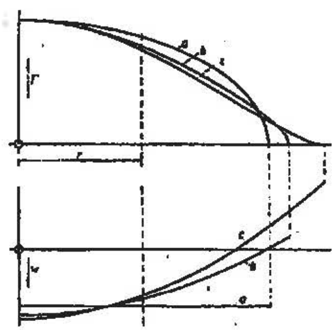
For a long time it was difficult to find suitable functions to express the distribution of lift, from which a plausible distribution of w would be obtained by equation (37). After various attempts it was found that a distribution of lift over the span according to a half ellipse gave the desired solution. According to this, if the origin of coordinates is taken at the center of the wing,

$$\Gamma=\Gamma_0\sqrt{1-\left(\frac{x}{b/2}\right)^2}, \text{ hence } \frac{d\Gamma}{dx}=\frac{-\Gamma_0 x}{\frac{b}{2}\sqrt{\left(\frac{b}{2}\right)^2-x^2}}$$

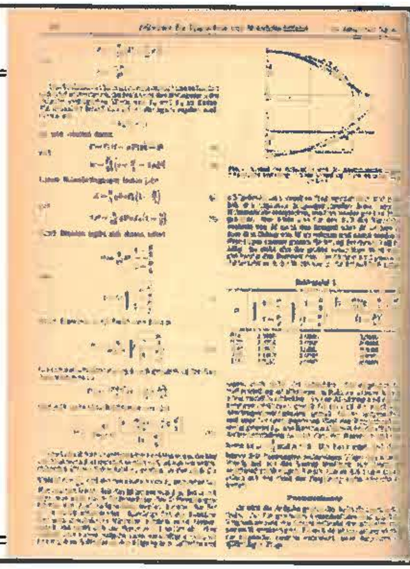
(4) The most important of Betz's theorems, from a practical standpoint, furnishes the complete analogy to Munk's theorem concerning the wing system having the least drag, and, corresponding perfectly to the statements in sections 27 and 28, may be expressed thus: The flow behind a propeller having the least loss in energy is as if the screw surfaces passed over by the propeller blades were solidified into a solid figure and this were displaced backward in the nonviscous fluid with a given small velocity. The potential difference between the front and rear sides of a screw surface at one and the same point furnishes, then, again the circulation Γ of the corresponding point of the propeller blade.

Birds

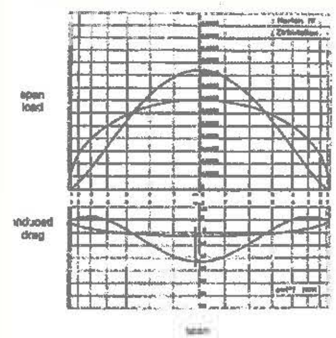
Minimum Induced Drag & Bending Moment

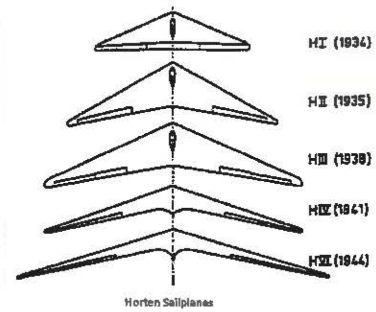


- Prandtl (1933)
  Constrain minimum induced drag
  Constrain integrated wing bending moment
  22% increase in span with 11% decrease in induced drag



Horten Applies a Bell Spanload



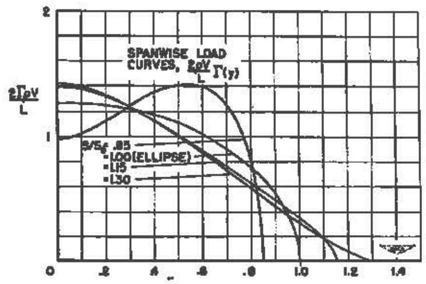


- Horten Spanload (1934-1954)
  use twist to achieve spanload
  induced thrust at tips
  no structural implications

Horten Sailplanes (Germany & Argentina)

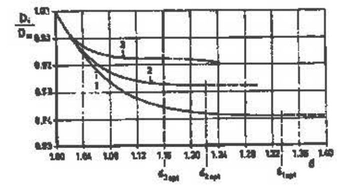
Prandtl & Horten

Jones Spanload



- Minimize induced drag (1950)
  Constrain wing root bending moment
  30% increase in span with 17% decrease in induced drag
- "Hence, for a minimum induced drag with a given total lift and a given bending moment the downwash must show a linear variation along the span." y = bx + c

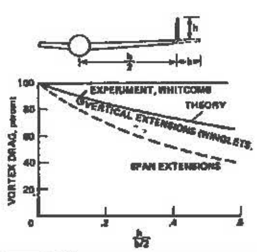
Klein and Viswanathan

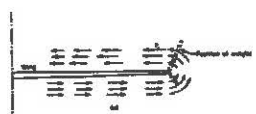


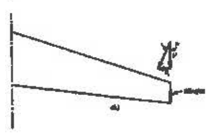
- Minimize induced drag (1975)
  Constrain bending moment
  Constrain shear stress
  16% increase in span with 7% decrease in induced drag
- "Hence the required downwash-distribution is parabolic." $y = ax^2 + bx + c$

Winglets

- Richard Whitcomb's Winglets
  - induced thrust on wingtips
  - induced drag decrease is about half of the span "extension"
  - reduced wing root bending stress







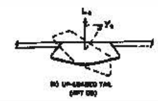
Whitcomb's Winglets

Bird Flight Model

- Minimum Structure
- Flight Mechanics Implications
- Empirical evidence

How do birds turn & maneuver?

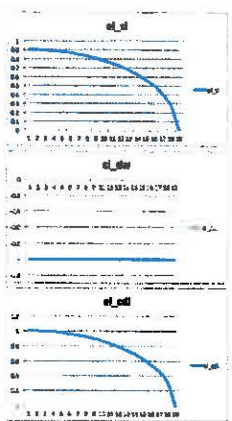
- "First the tail is tilted downward on the side away from the direction of the turn...Perhaps the tail functions as a rudder in starting the turn..." (Koford, 1950)
- Alleviating the load on the tips allows the bird to turn (bank and yaw) correctly (Hoey, 1992)
- "...the tail was loaded upward and the same clockwise tail rotation produced a right force, thus a left turn..." (Hoey, 1992)



Prandtl(1920) vs Prandtl(1933)

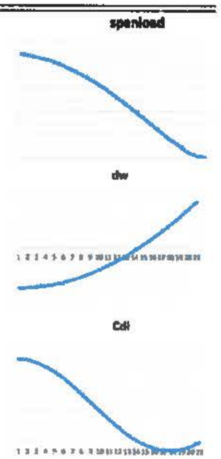
Prandtl 1920

Elliptical Spanload

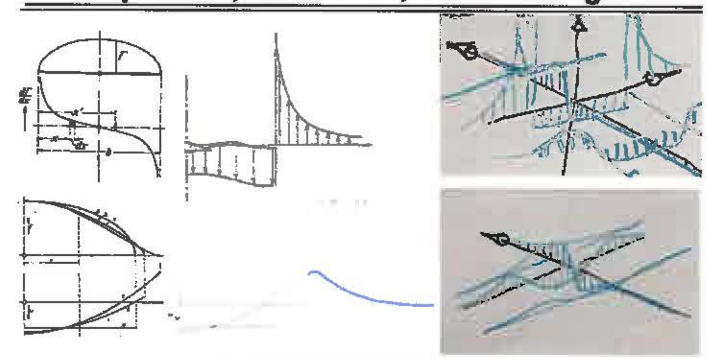


Prandtl 1933

Bell Spanload



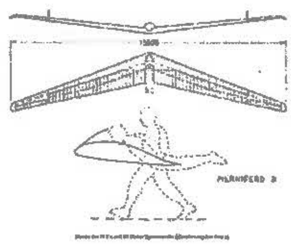
Spanload, Downwash, Induced Drag



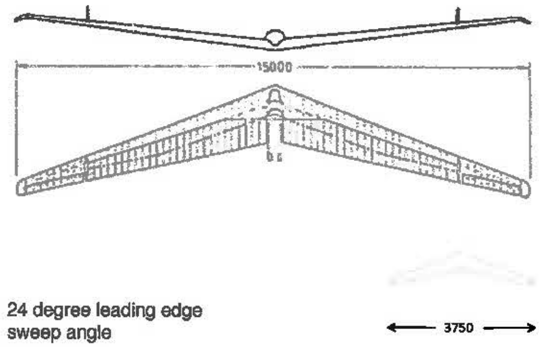
- All wings dictate 3 solutions
- Spanload
- Downwash
- Induced Drag

Horten H Xc Example

- Horten H Xc footlaunched ultralight sailplane 1950
- 24 degree leading edge sweep angle
- Chord:
  root - 63 inches
  tip – 15.75 inches
- Span: 49.2 feet



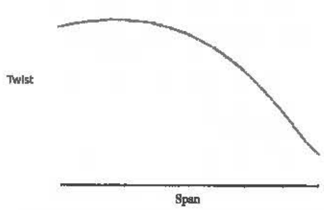
Prandtl Wing



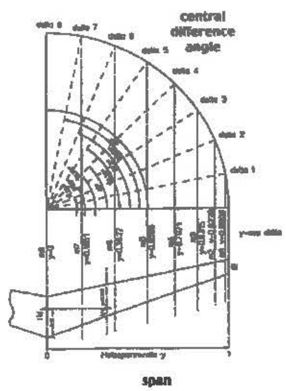
- 24 degree leading edge sweep angle
- Chord:
  root – 15.75 inches
  tip – 3.875 inches
- Span: 147.6 inches

Calculation Method

- Taper
- Twist
- Control Surface Deflections
- Central Difference Angle

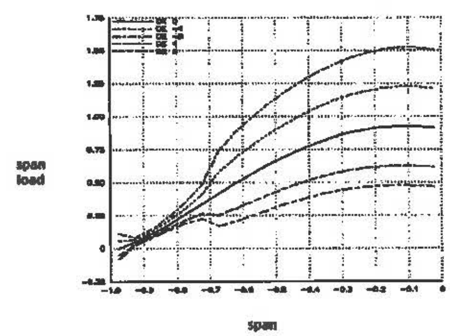


R0	8.3274
R1	8.5524
R2	8.7259
R3	8.8441
R4	8.9030
R5	8.8984
R6	8.8257
R7	8.6801
R8	8.4565
R9	8.1492
R10	7.7522
R11	7.2592
R12	6.6634
R13	5.9579
R14	5.1362
R15	4.1927
R16	3.1259
R17	1.9394
R18	0.6589
R19	-0.6417
R20	-1.6726



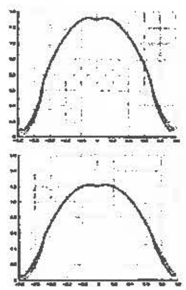
Symmetrical Spanloads

- Elevon Trim
- CG Location

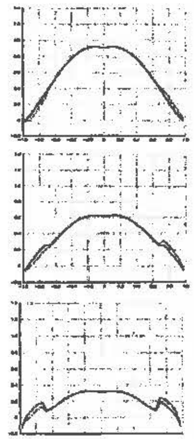


Asymmetrical Spanloads

- Cl∂a (roll due to aileron)
- Cn∂a (yaw due to aileron)
  induced component
  profile component
  change with lift
- Cn∂a/Cl∂a
- CL(Lift Coefficient)
  Increased lift:
   increased Clβ
  increased Cnβ*
  Decreased lift:
   decreased Clβ
  decreased Cnβ*



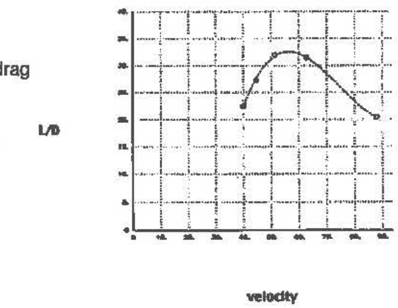
CL	Cl	Cn
.966	.01384	.00055
.774	.01384	.00037
.582	.01345	.00021
.390	.01384	.00003
.198	.01345	-.00015



Performance Comparison

- Max L/D: 31.9
- Min sink: 89.1 fpm
- Does not include pilot drag

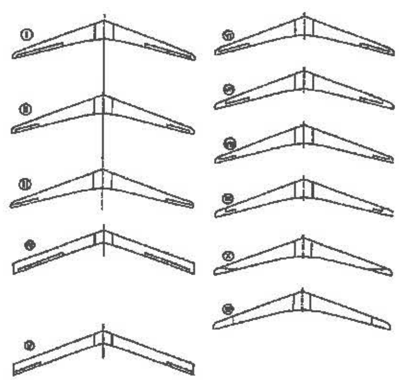
- Prediicted L/D: 30
- Predicted sink: 90 fpm



Dr Edward Uden's Results

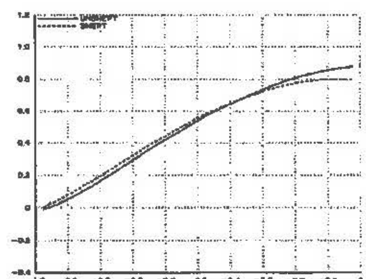
- Spanload and Induced Drag
- Elevon Configurations
- Induced Yawing Moments

Elevon Config	Cn∂a	Spanload
I	-.002070	bell
II	.001556	bell
III	.002788	bell
IV	-.019060	elliptical
V	-.015730	elliptical
VI	.001942	bell
VII	.002823	bell
VIII	.004529	bell
IX	.005408	bell
X	.004132	bell
XI	.005455	bell



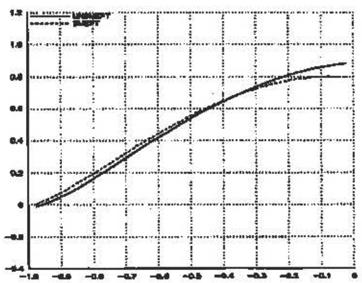
"Mitteleffekt"

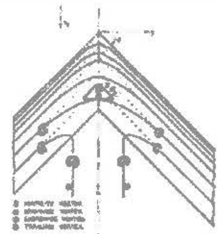
- Artifact of spanload approximations
- Effect on spanloads
  increased load at tips
  decreased load near centerline
- Upwash due to sweep unaccounted for

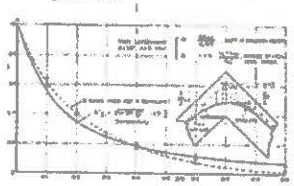


Kucheman

- Effect on spanloads
  increased load at tips
  decreased load near centerline
- Upwash due to sweep unaccounted for
- Residual (Kucheman)

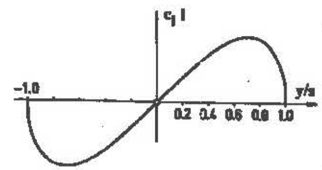


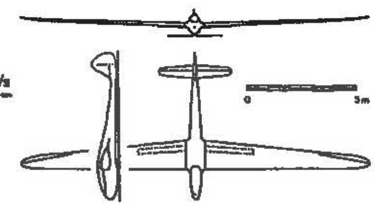




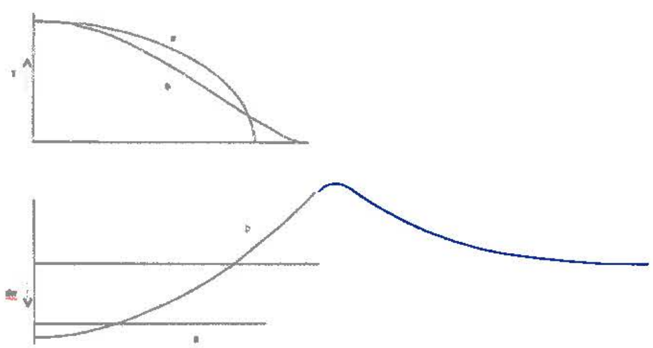
Elliptical Half-Lemniscate

- Minimum induced drag for given control power (roll)
- Dr Richard Eppler: FS-24 Phoenix





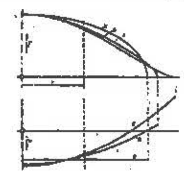
Prandtl's Bell Spanload



Prandtl's Spanload

$$sl = (1 - x^2)^{3/2}$$

$$w = 3/2\,(x^2 - ½)$$

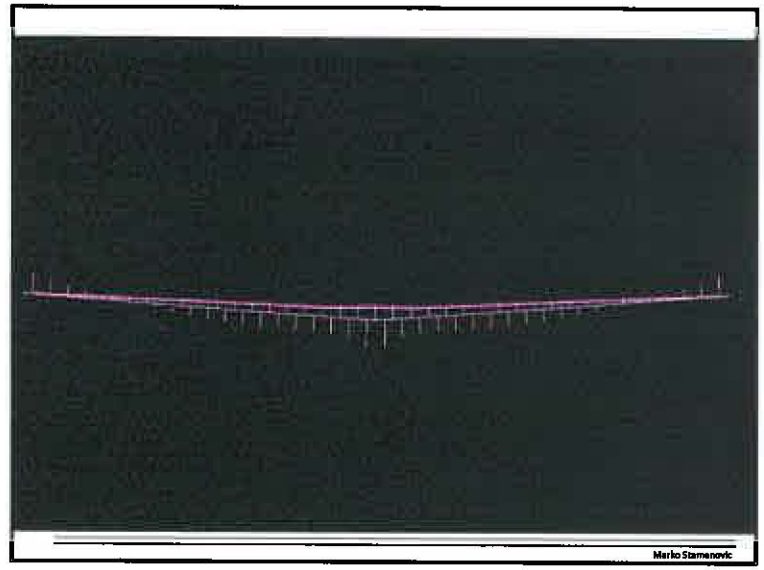


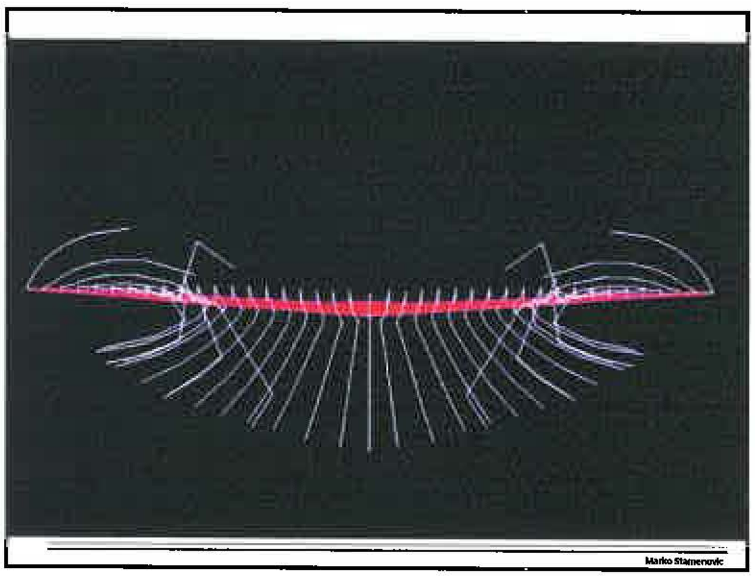
$$\lim_{x:\,0 \to b/2} L(x) = 0 \qquad (1)$$

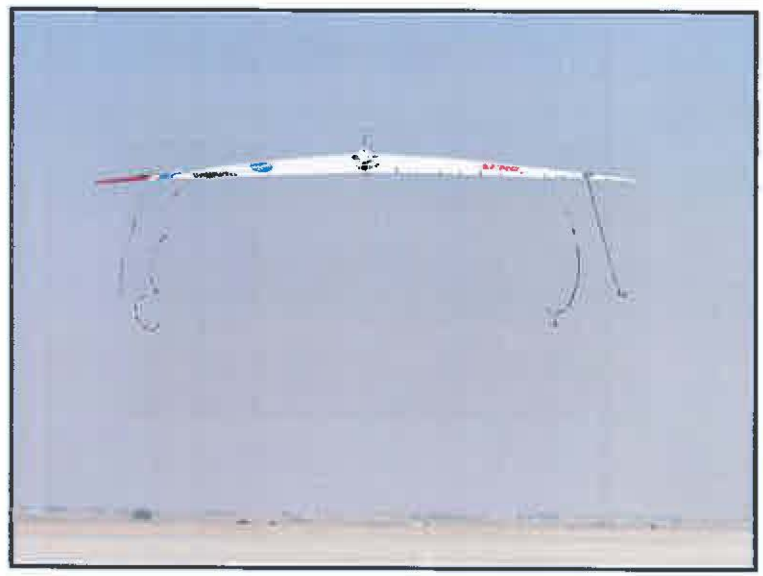
$$\lim_{x:\,0 \to b/2} \frac{dL(x)}{dx} = 0 \qquad (2)$$

$$\lim_{x:0 \to b/2} \frac{d\,DW(x)}{dx} = \lim_{x:\infty \to b/2} \frac{d\,DW(x)}{dx} \qquad (3)$$


Mike Allen


Marko Stamenovic

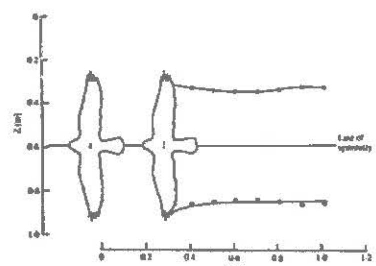

Marko Stamenovic



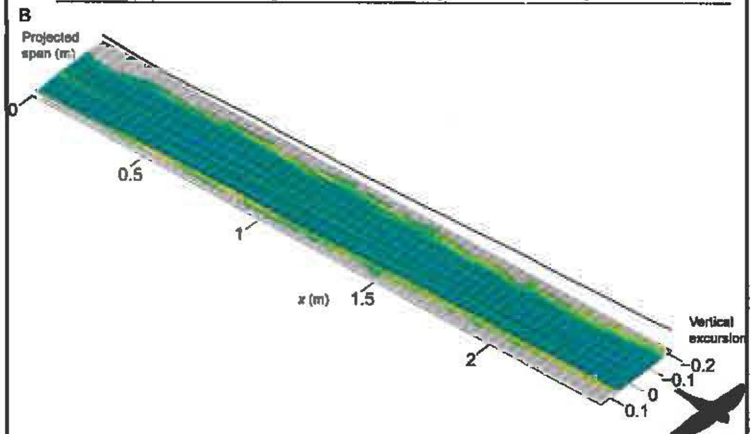
Spanload

Spedding's Gliding Falcon

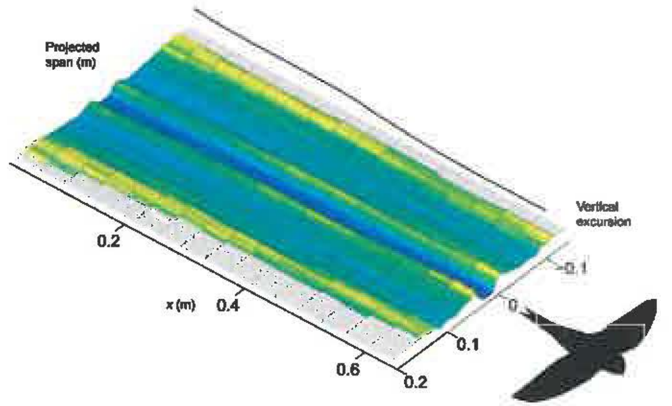
- Spedding photograpgh's a gliding falcon's wake with He bubbles
- Vortex cores are 0.76 b apart
- Elliptical spanload is assumed, so the vortex cores are assumed to come from the wingtips



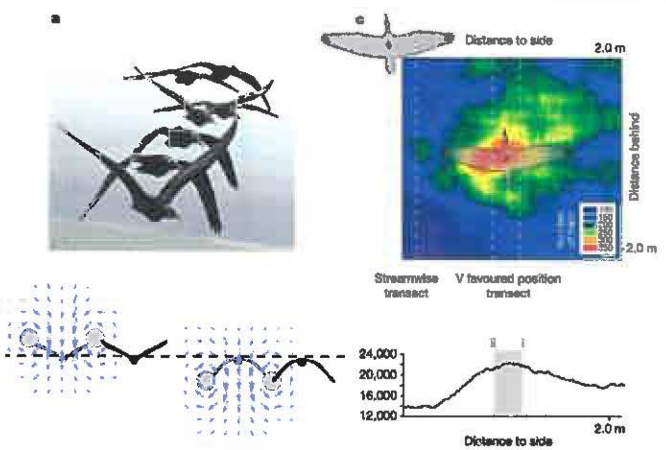
Henningsson 2014 (PLOS One)



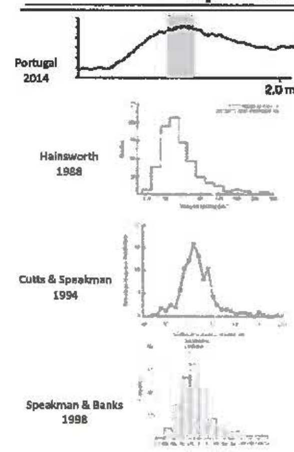
Henningsson 2014 (PLOS One)

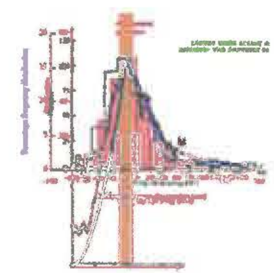


Portugal, et al 2014 (Nature)



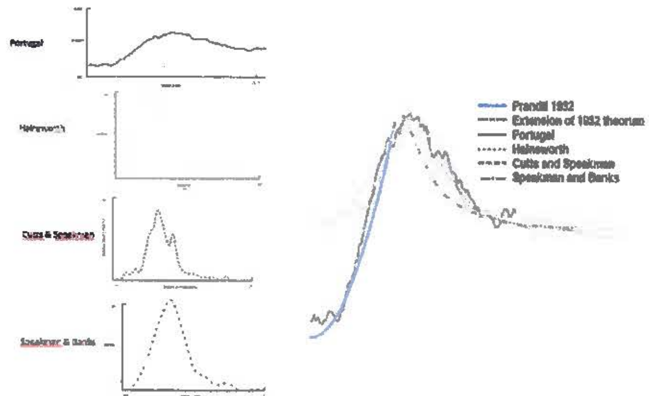
Upwash and Wing Beats





Brian Ellinger

Upwash and Wing Beats

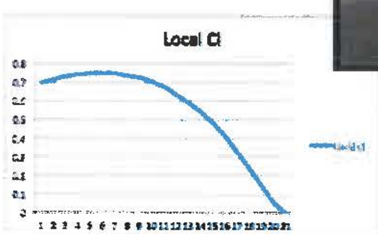


Brian Eslinger

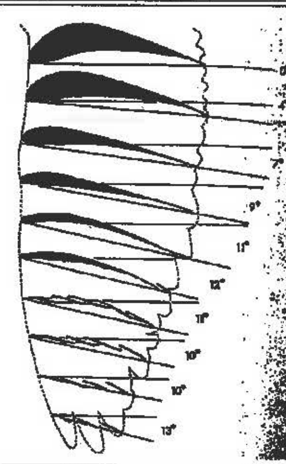
CFD

Paul Yoo

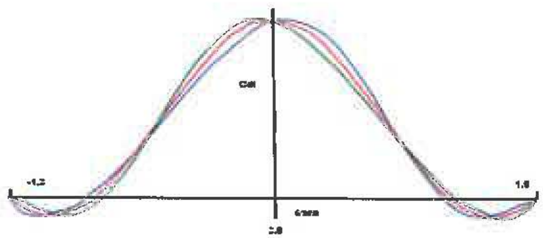
Pointy Wings and Wing Stall



Nachtigall 1966 (J of Exp Bio)



Effect of Sideslip



- Wing twist
- Sideslip is imposed
- Distorts the bell spanload and the induced drag/thrust profile

PRANDTL-D Proverse Yaw?

What would Proverse Yaw look like?

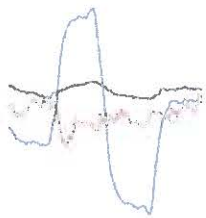
Flight Data

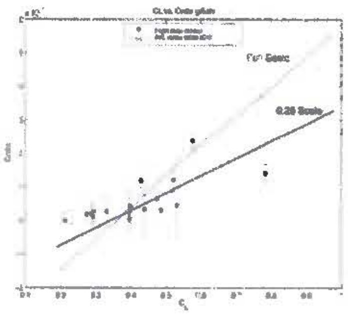
- Measurement of proverse yaw would be the final hurdle to achieve
- Icing on the cake: measure Cnda (yawing moment due to aileron deflection)

- NOT ONE SECOND OF FLIGHT DATA EXISTS TO PROVE ANY OF THIS IS TRUE

Proverse Yaw

- ...until June 26th, 2013
- Roll and Yaw are the same sign
- From Uden: Cnda is +ve
- uncertainty

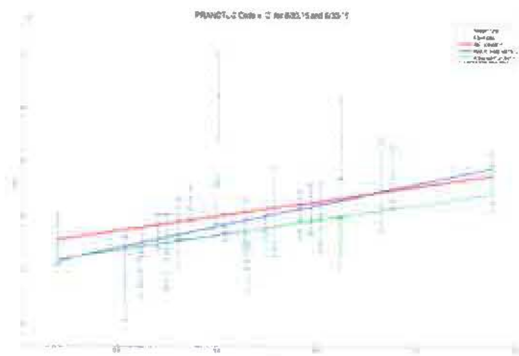




Inertias; configuration changes, turbulence, and slope of Cnda

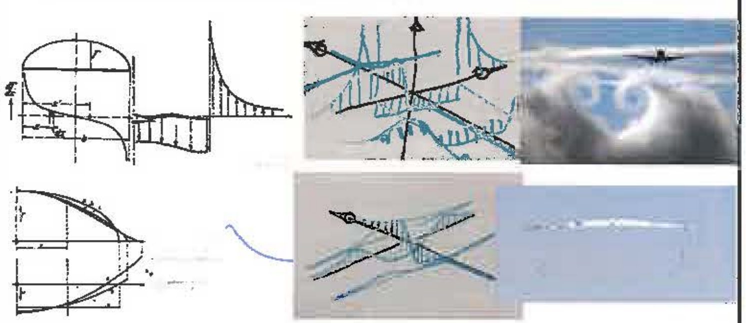
Kristyn Kadala

Revalidated Proverse Yaw



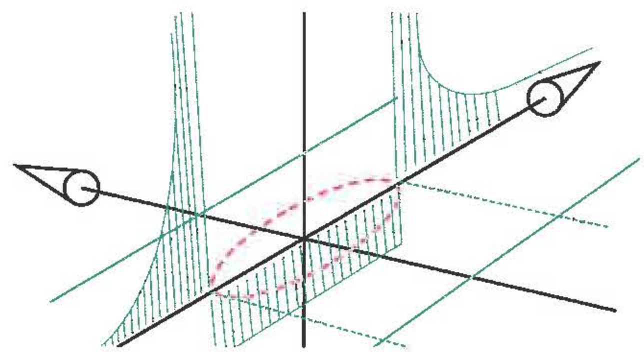
Loren Newton & Keenan Albee

Spanload, Downwash, Induced Drag

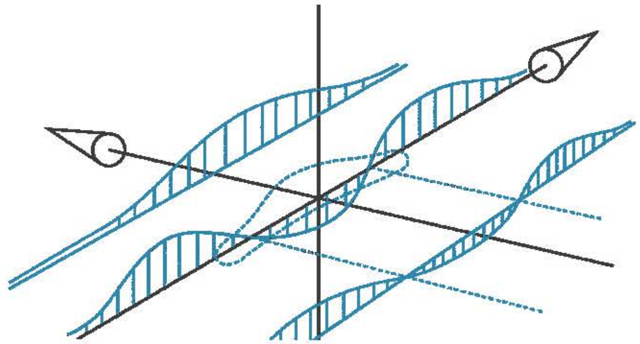


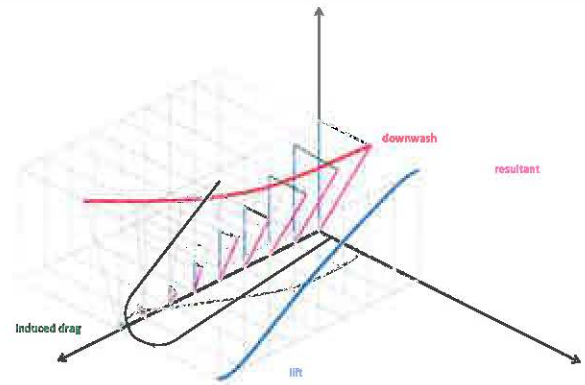
- All wings dictate 3 solutions
- Spanload
- Downwash
- Induced Drag

Elliptical Spanload Flow



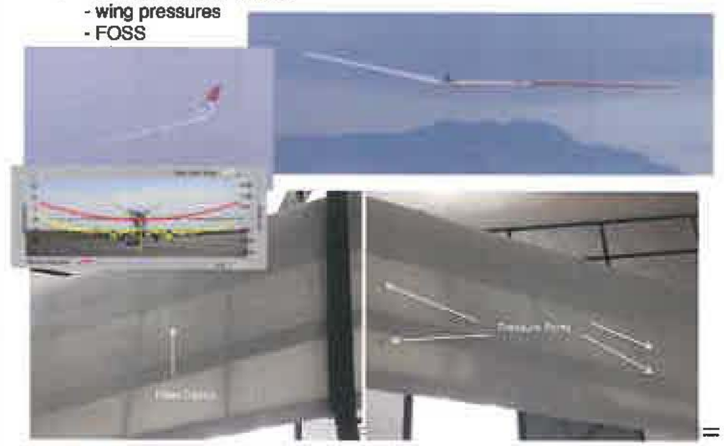
Bell Spanload Flow





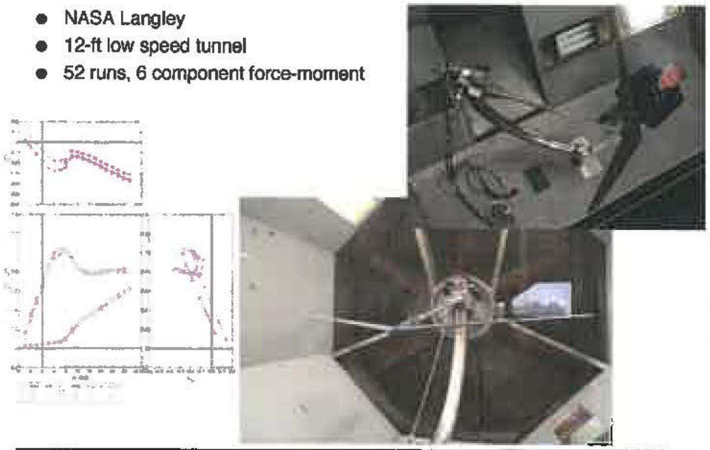
Prandtl 3

- The aerodynamic testbed
  - wing pressures
  - FOSS

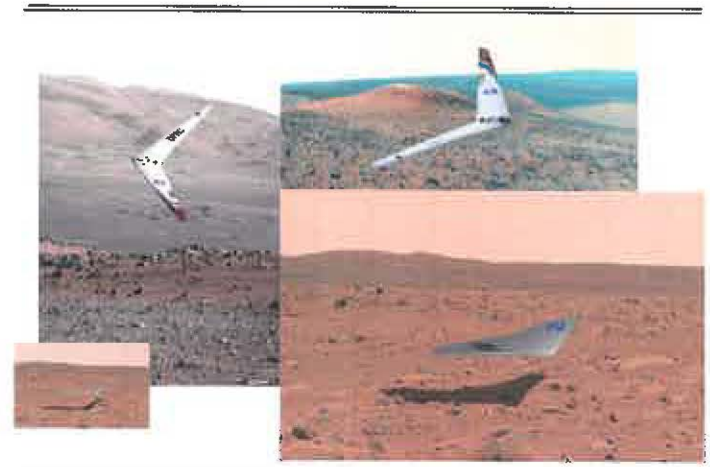


Wind Tunnel Test

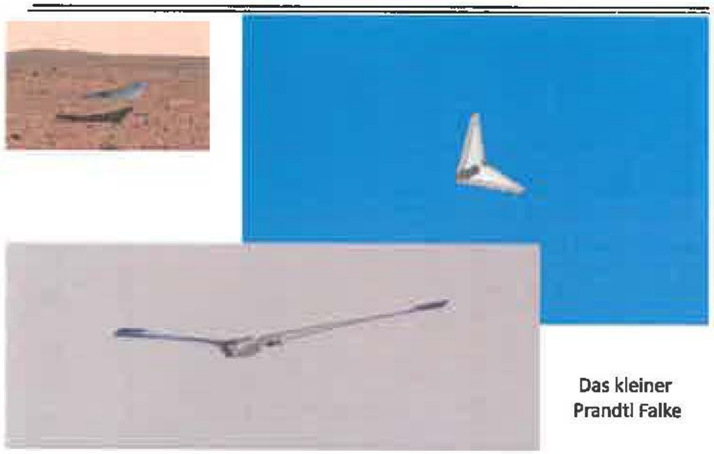
- NASA Langley
- 12-ft low speed tunnel
- 52 runs, 6 component force-moment



The Future: Prandtl-M on Mars?



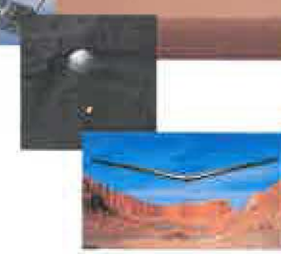
The Future: Prandtl-M on Mars?



Das kleiner
Prandtl Falke

The Mars Mission

- Deploy cubesat from large Mars rover
- Use Exobrake parachute for Mars atmosphere entry
- Deploy Prandtl-m (2 lbm, 2 ft span) from cubesat at 15,000 ft agl
- Glide 5 mins, 22 miles, Mach 0.6
- Crash land on Mars
- Transmit images & data back



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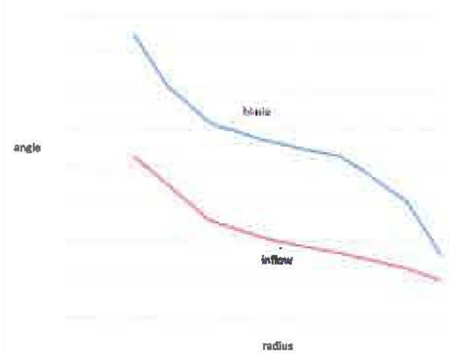
Prandtl Propulsion

- Propulsion systems currently use "minimum induced loss"
- What if we switched to minimum torque for a given thrust? +15.4%



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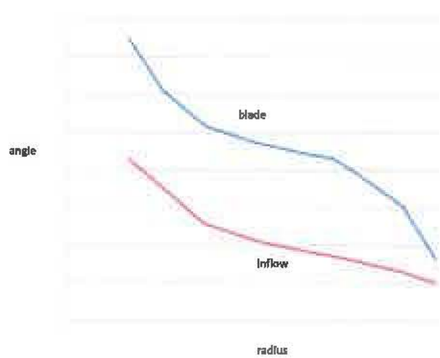
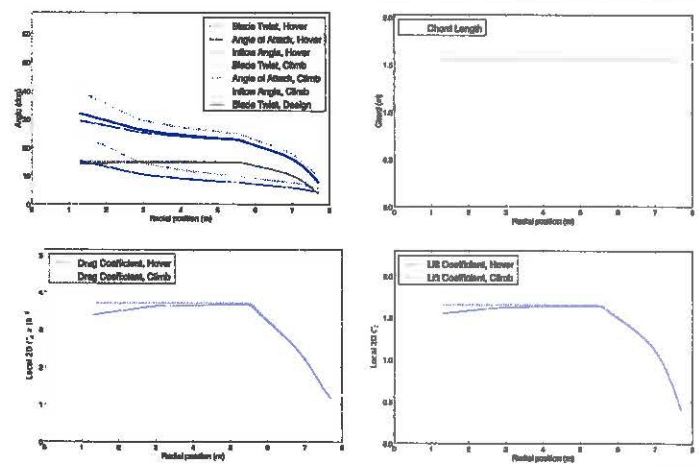
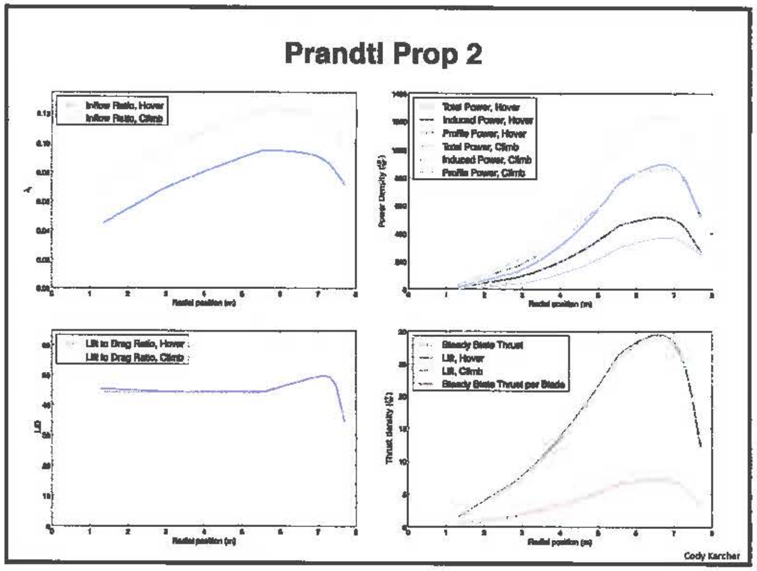


Prandtl Prop 1

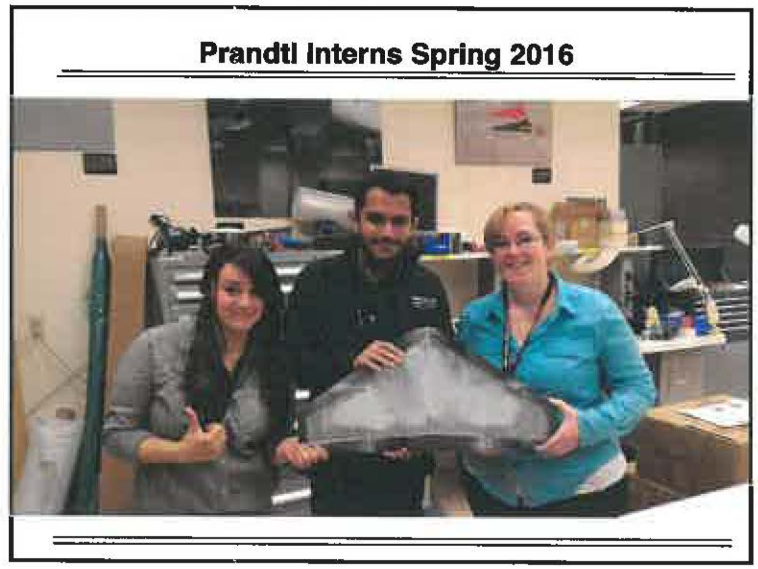


Cody Karcher


Prandtl Prop 2
Inflow Ratio, Hover
Inflow Ratio, Climb
Radial position (m)
Total Power, Hover
Induced Power, Hover
Profile Power, Hover
Total Power, Climb
Induced Power, Climb
Profile Power, Climb
Radial position (m)
Lift to Drag Ratio, Hover
Lift to Drag Ratio, Climb
L/D
Radial position (m)
Steady State Thrust
Lift, Hover
Lift, Climb
Steady State Thrust per Blade
Radial position (m)
Cody Karcher


NASA Aero Academy 2015


Prandtl 3 Team


Prandtl Interns Spring 2016

2016 Interns & MARTI

PRANDTL-D

- Videos

  - TEDxNASA 2011
  http://www.youtube.com/watch?v=223OmaQ9uLY

  - NASA Aero Academy 2013
  http://www.youtube.com/watch?v=Hr0I6wBFGpY

Red Jensen: pilot, engineer

Red Jensen, Justin Hall, & Derek Abramson

PRANDTL-D Aircraft

Control of Yaw

- You Have Three Choices:
- 1/ drag a vertical tail around with you all the time to create a yawing moment
- 2/ manipulate drag at the wing tips to control yaw

} Current Design Options

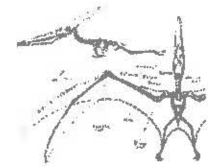
-OR-

- 3/ manipulate **THRUST** at the wing tips to control yaw

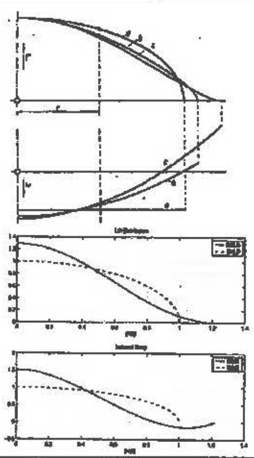
- Biological vs Mechanical Flight

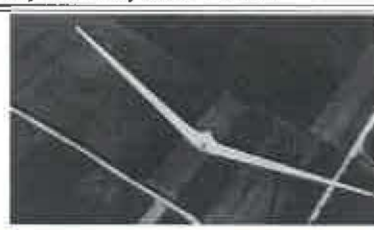
Biological Flight

- Mechanical Flight (110 yrs)
- Vertabrate Flight (128 My)

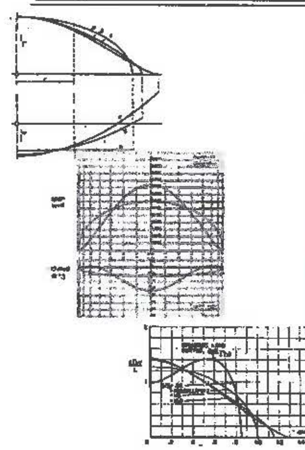


Prandtl, Horten, Jones, and Birds





Prandtl, Horten, Jones, and Birds



Efficiency

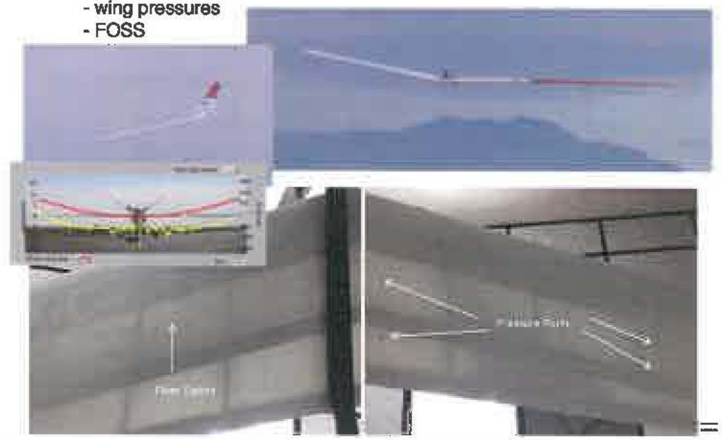
- Efficiency: 12.5% increase in wing efficiency
- 20-30% increase in efficiency by eliminating the tail
- 15.4% increase in propulsive efficiency
- TOTAL EFFICIENCY INCREASE: 69%

- CY2011: world jet fuel consumption $134B
- $55B in jet fuel saved

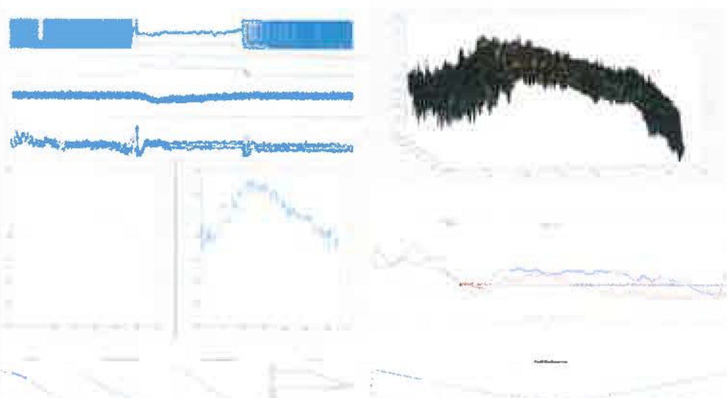
- CY2011 World GDP: $69.7T
- World power production: $12.0T
- $1.85T savings in world power production

Prandtl 3 & 3c

- The aerodynamic testbed
  - wing pressures
  - FOSS



Prandtl 3c cFOSS



Deborah Jackson

Noah Edwards, Abbey Waddell, Deborah Jackson & Tori Hawkins

Concluding Remarks

- Birds as as the first model for flight
- Applied approach gave immediate solutions, departure from bird flight
- Eventual meeting of theory and applications (applied theory)
- Spanload evolution (Prandtl/Horten/Jones/Klein/Viswanathan/Whitcomb/Bowers)
- Solve performance, structure and control with ONE spanload solution!
- 12.5% increase in L/D, ~2% increase in prop efficiency, 20-30% decrease in drag eliminating the tail, ~43-62% reduction in total aero efficiency
- Assumptions and Solutions
- The Wrights disintegrated the flight of birds, and Prandtl/Horten/Jones reintegrated the flight of birds…
- Thanks: Red Jensen, Brian Eslinger, Dr Christian Gelzer, Dr Oscar Murillo, Hayley Foster & Steve Craft, Dr Bob Liebeck, Nalin Ratnayake, Mike Allen, Walter Horten, Georgy Dez-Falvy, Rudi Opitz, Bruce Carmichael, R.T. Jones, Russ Lee, Bob Hoey, Phil Barnes, Dan & Jan Armstrong, Dr Phil Burgers, Ed Lockhart, Andy Kesckes, Dr Paul MacCready, Reinhold Stadler, Dr Edward Uden, & Dr Karl Nickel

NASA Aero Academies & Others

- 2014 NASA Aero Academy
  - Brian Plank, Joe Lorenzetti, Kathleen Glasheen, Bryce Doerr, Cynthia Farr, Nancy Pinon, Heather Laffoon, Jack Toth, Leo Banuelos
- 2013 NASA Aero Academy
  - Eric Gutierrez, Louis Edelman, Kristyn Kadala, Nancy Pinon, Cody Karcher, Andy Putch, Hovig Yaralian, Jacob Hall
- 2012 NASA Aero Academy
  - Steffi Valkov, Juliana Plumb (Ulrich), Luis Andrade, Stephanie Reynolds, Joey Wagster, Kimmy Callan, Javier Rocha, Sanel Horozovic, Ronalynn Ramos, Nancy Pinon
- Mike Allen, Alex Stuber, Matt Moholt, Dave Voracek, Jaiwon Shin, Ross Hathaway, Brian Eslinger, Oscar Murillo, Lesli Monforton, Red Jensen, Aamod Samuel, Brad Neal, Brad Flick, Chris Acuff, Rick Howard (NPS), Marko Stamenovic, Jim Murray, Nalin Ratnayake, Eric Nisbet, Jeromy Robbins, Nelson Brown, Curtis Stump, Andrew Burrell, Anthony MacPherson, Brian Taylor, Chris Miller, Victor Loera, Cameron Law, Koen vander Kerckhove, Bob Hoey, Russ Lee, Reinhold Stadler, Edward Uden, Paul MacCready, Karl Nickel, Walter Horten, Diego Roldan Knollinger, Michael Cox, Jeff Jennings, Phil Barnes

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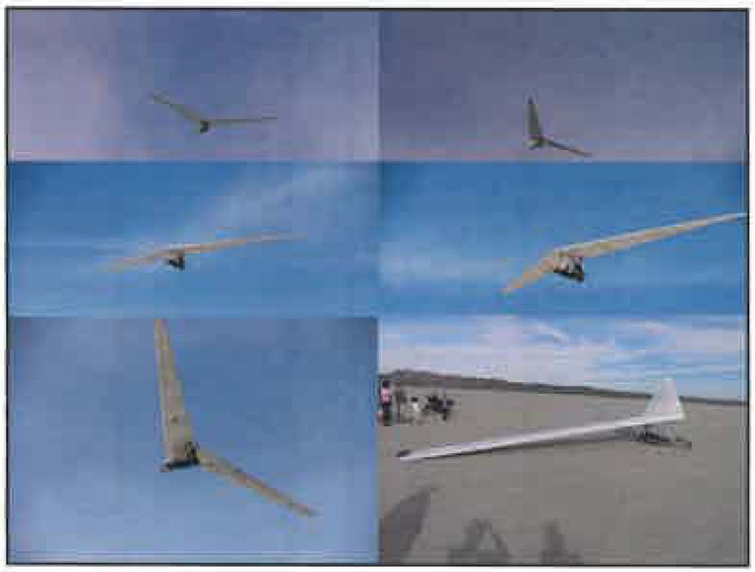
Full-Scale Wing

Erich Chase & Steve Davey

Full-Scale Wing



If you want to build a ship, don't drum up people to collect wood and don't assign them tasks and work, but rather teach them to long for the endless immensity of the sea...

- *Antoine de Saint-Exupery*

Questions?

The End

Questions?

www.nasa.gov