Limits to Open Class Performance?

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NASA Vision & Mission

NASA vision is:

- Innovation
- Exploration
- Discovery

The NASA mission is:

- Technology innovation
- Inspiration for the next generation
- And discovery in our universe as only NASA can

Dedicated to the memory of Dr Paul MacCready

It seems that perfection is attained
Not when there is no more to be added,
But when there is nothing more to be deleted.
At the end of its evolution,
The machine effaces itself.

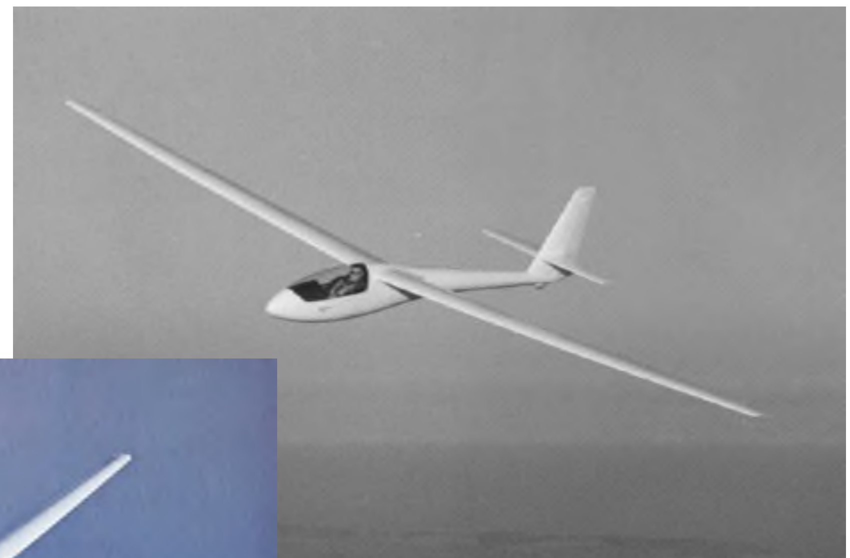
- Antoine de Saint-Exupery

Intro: What are the limits to open class performance?

- Standard Class
- 15m/Racing Class
- Open Class
- Design Solutions
  - assumptions
  - limiting parameters
  - airfoil performance
  - current trends
  - analysis
- Conclusions

Standard Class

- ! Q: What is the size limitation in the Standard Class?
- ! A: 15m span (no flaps)



15m/Racing Class

•! Q: What is the 15m size limitation?

•! A: 15m span
(no restriction on flaps)

Open or Unlimited Class

- Q: What is the size limitation on the Open Class?

Open Class Limitation: MASS!

- 650 kg single-place
- 750 kg two-place
- 850 kg two-place w/ motor

Design Solutions

•! Assumptions:

- no active boundary layer control
- use current technology materials
    - fiberglass
    - carbon fiber
- fits within existing rules
- no variable geometry (camber changing flaps only)
- no active controls (no unstable designs)

Limiting Parameters

- Reynolds number
  - chord limitations: viscous drag
  - max CL
- Mass increases faster than span - modern materials help
- Still need to fly slow, turn and bank
- Still need to dash fast

Limiting Parameters

- Slow climbing flight requires low wing loading
- High cruise speed requires high wing loading
- Minimum sink requires low speed
- Max L/D balances viscous and induced drag
- Low viscous drag is always desirable
- The ‘best” sailplane will always be versatile

- Note: gains in either induced or viscous drag alone will net only half the gain overall!
- Note: other structural problems (yaw inertia & spins, flutter, static loads integrity)

Airfoil Limitations

- Thickness constraints
- Flaps allow thinner (and lower Cdo) airfoils (with limitations)
- Laminar flow drag bucket is roughly in proportion to thickness (NB: Std Class t/c ~17%; 15m/Open Class t/c ~14%)

- Approximately 60% to 75% of total viscous drag of Open Class designs is airfoil profile drag

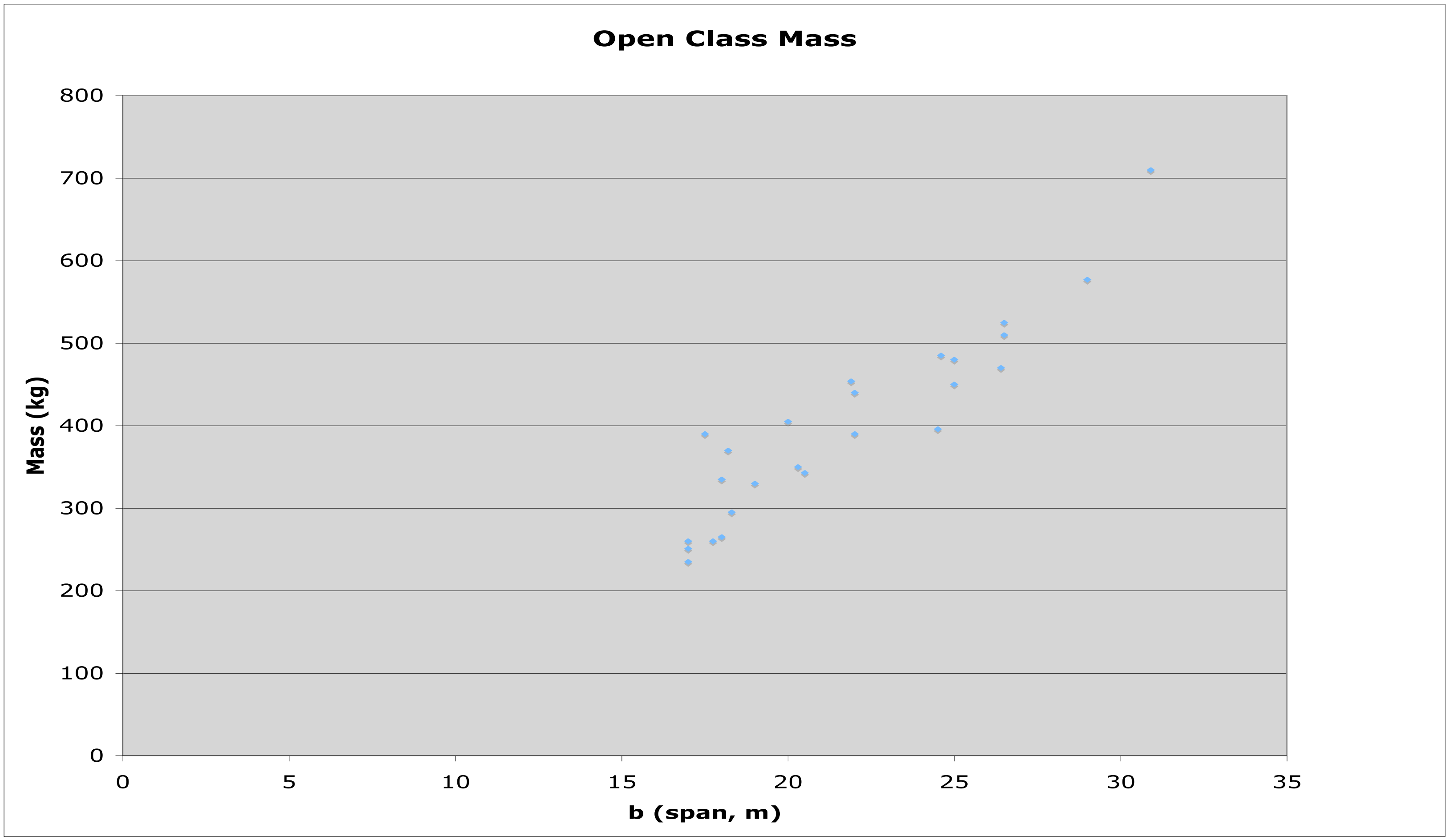
Current Trends

- ! Survey of the Open Class (composites)

company	model	span	L/D	We
Glasflugel	BS-1	18	44	335
	Kestrel 17	17	43	260
	604	22	49	440
Schempp-Hirth	Cirrus	17.74	44	260
	Nimbus II	20.3	49	350
	Ventus 2C	18	46	265
	Nimbus 3	24.5	58	396
	Nimbus 4	26.4	60	470
Schleicher	AS-W12	18.3	47	295
	AS-W 17	20	48.5	405
	AS-W 22	25	60	450
Akaflieg Braunschweig	SB-10	29	53	577
PZL	Jantar 2	20.5	47	343
MBB	Pheobus C	17	42	235
Slingsby	Kestrel 19	19	44	330
	Kestrel 22	22	51.5	390
Glasar Dirks	DG-202	17	45	251
Applebay	Mescalero	21.9	44	454
Grob	G-103 Twin Astir	17.5	38	390
Schempp-Hirth	Janus	18.2	39	370
	Nimbus 3D	24.6	57	485
	Nimbus 4D	26.5	60	525
Schleicher	AS-H 25	25	57	480
	AS-H 30	26.5	61.8	510
Eta	Eta	30.9	70	710

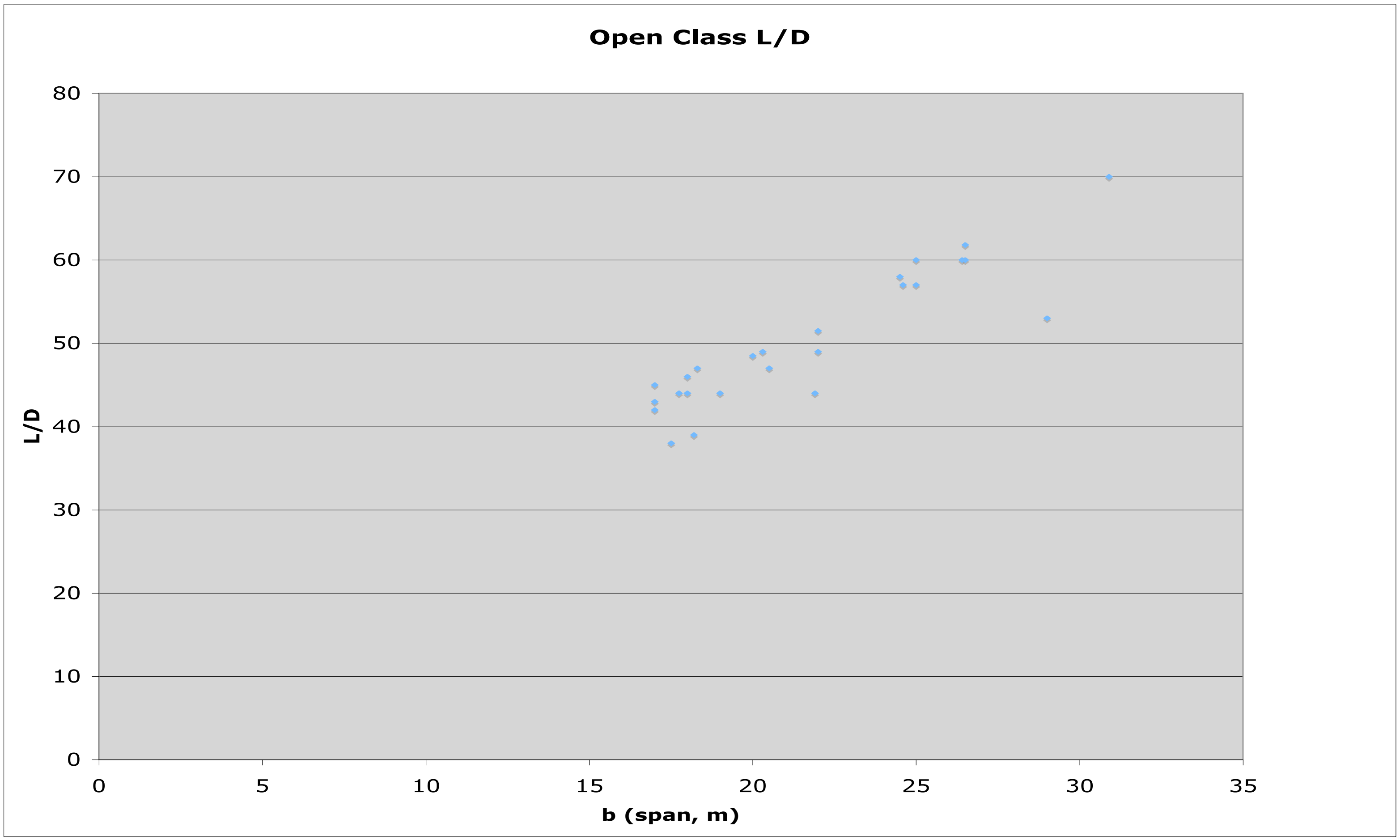
Current Trends (Mass)

- Open Class mass (kg)



Current Trends (L/D)

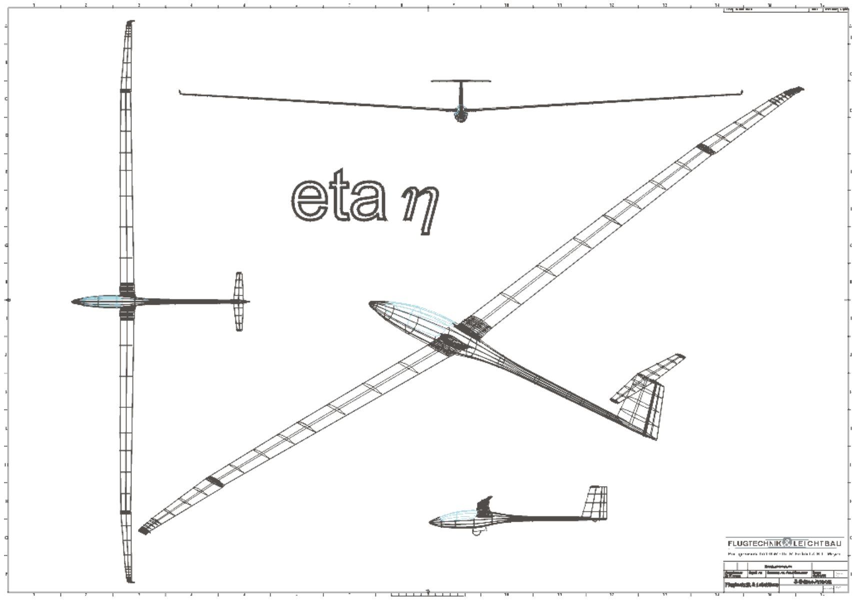
- Open Class (L/D)



Analysis

- Eta is the current performance benchmark
- Near elliptical span load
- 30.9m span
- 710 kg empty
- 70:1 L/D
- Yaw inertia

Eta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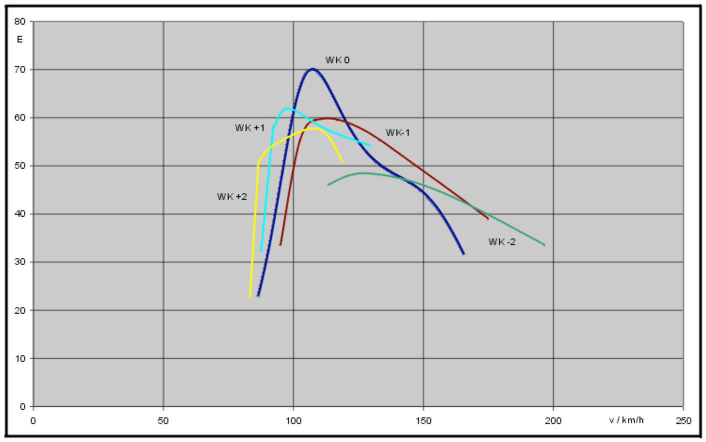
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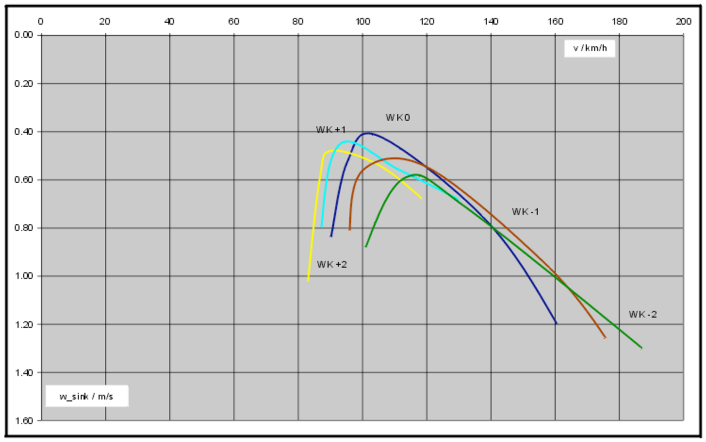
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WK -2
w_sink / m/s

Spanload Development

- Ludwig Prandtl
  Development of the boundary layer concept (1903)
  Developed the “lifting line” theory
  Developed the concept of induced drag
  Calculated the spanload for minimum induced drag (1908?)
  Published in open literature (1920)

- Albert Betz
  Published calculation of induced drag
  Published optimum spanload for minimum induced drag (1914)
  Credited all to Prandtl (circa 1908)

Spanload Development (continued)

- Max Munk
  General solution to multiple airfoils
  Referred to as the “stagger biplane theorem” (1920)
  Munk worked for NACA Langley from 1920 through 1926

- Prandtl (again!)
  “The Minimum Induced Drag of Wings” (1932)
  Introduction of new constraint to spanload
  Considers the bending moment as well as the lift and induced drag

Practical Spanload Developments

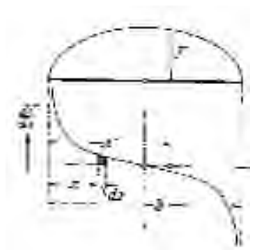
- Reimar Horten (1945)
  Use of Prandtl's latest spanload work in sailplanes & aircraft
  Discovery of induced thrust at wingtips
  Discovery of flight mechanics implications
  Use of the term "bell shaped" spanload

- Robert T Jones
  Spanload for minimum induced drag and wing root bending moment
  Application of wing root bending moment is less general than Prandtl's
  No prior knowledge of Prandtl's work, entirely independent (1950)

- Armin Klein & Sathy Viswanathan
  Minimum induced drag for given structural weight (1975)
  Includes bending moment
  Includes shear

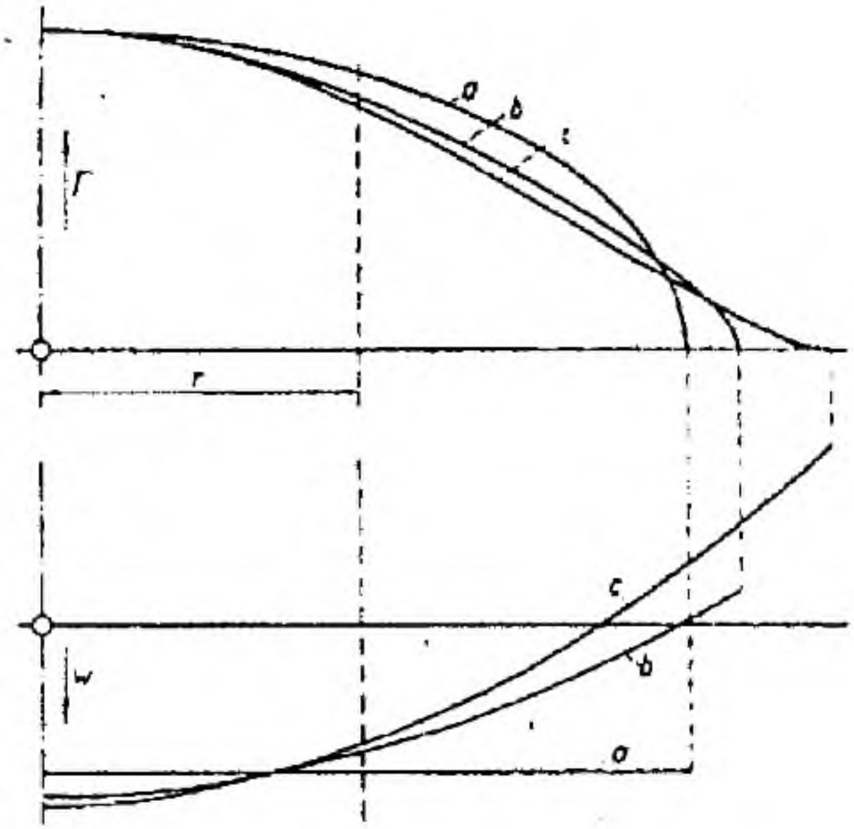
Prandtl Lifting Line Theory

- Prandtl's "vortex ribbons"



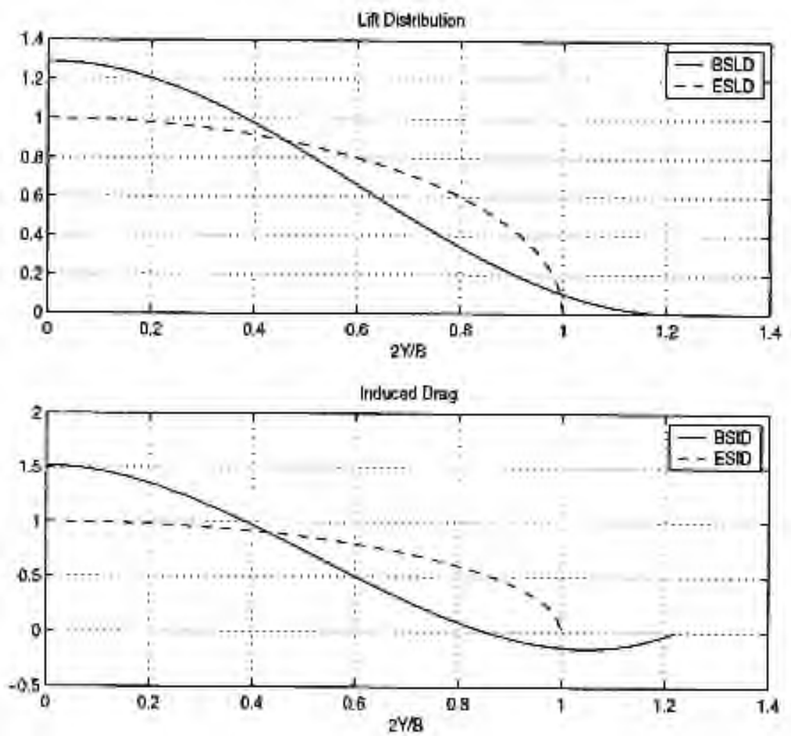
- Elliptical spanload (1914)
- "the downwash produced by the longitudinal vortices must be uniform at all points on the aerofoils in order that there may be a minimum of drag for a given total lift." y = c

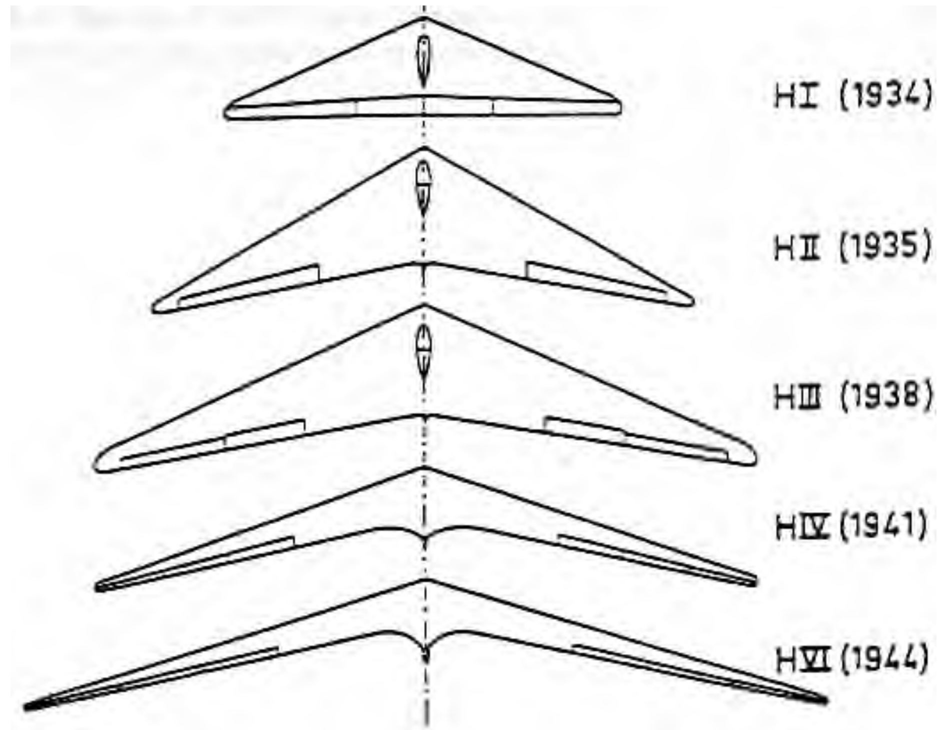
Minimum Induced Drag & Bending Moment



- Prandtl (1932)
  Constrain minimum induced drag
  Constrain bending moment
  22% increase in span with 11% decrease in induced drag

Horten Applies Prandtl’s Theory

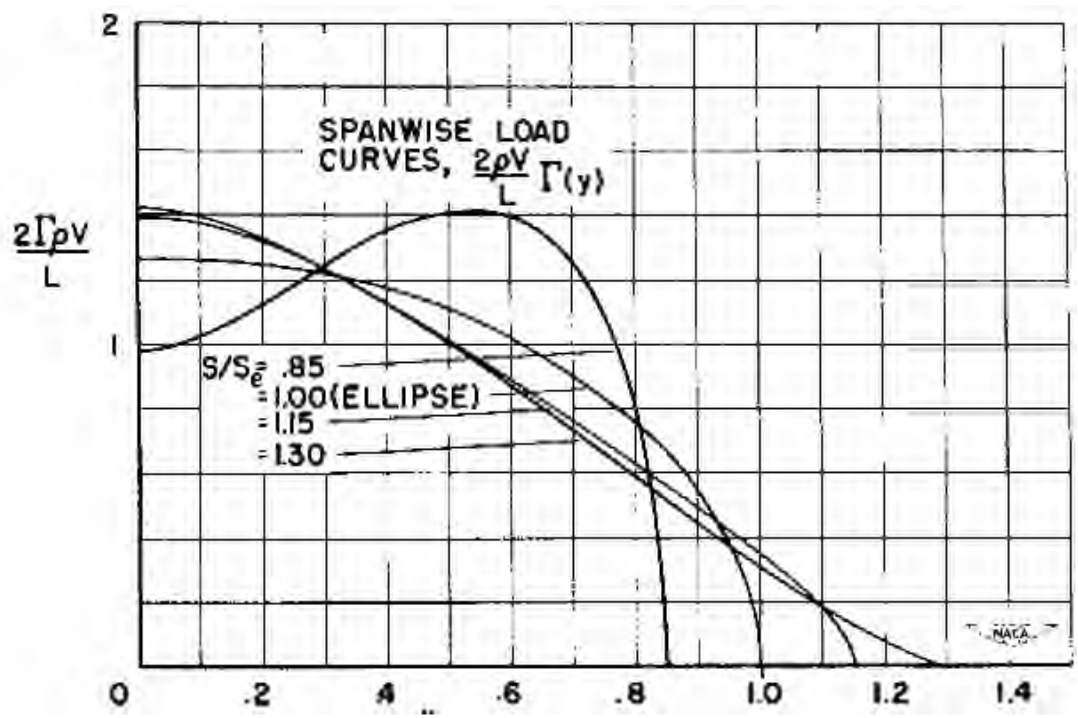




Horten Sailplanes

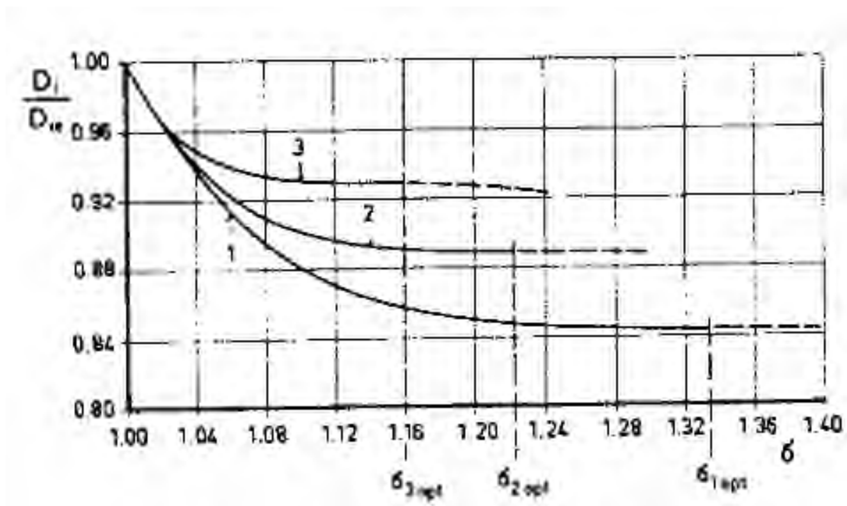
- Horten Spanload (1940-1955)
  induced thrust at tips
  wing root bending moment

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

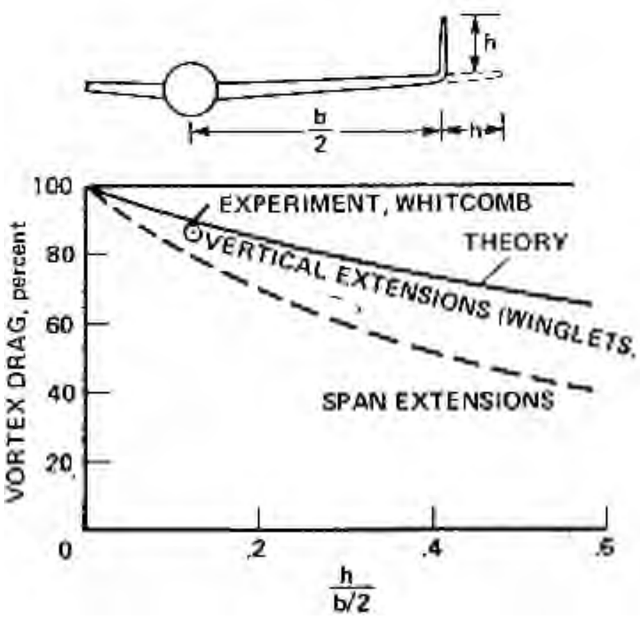
Klein and Viswanathan

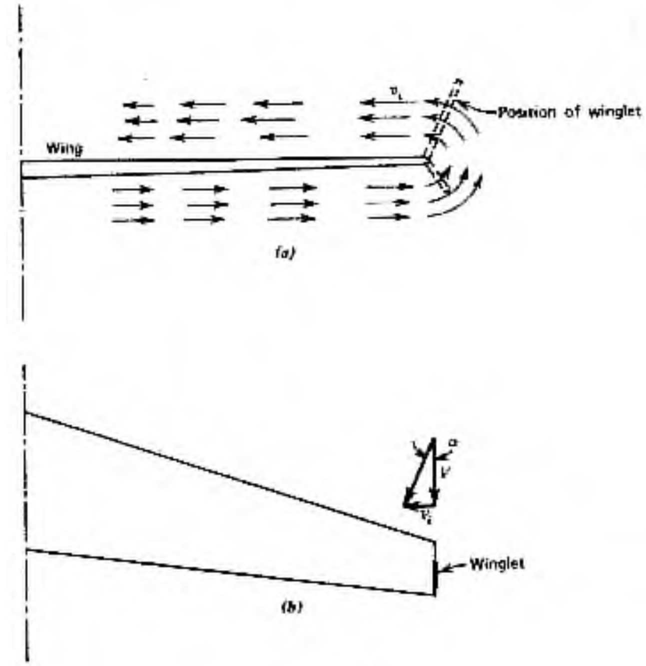


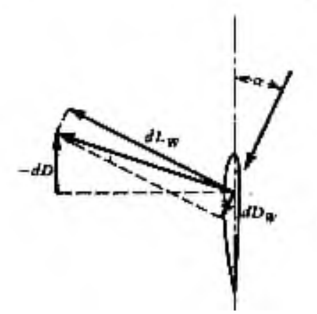
- Minimize induced drag (1975)
  Constrain bending moment
  Constrain shear stress
  16% increase in span with 7% decrease in induced drag
- “Hence the required downwash-distribution is parabolic.” $y = ax^2 + bx + c$

Winglets

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







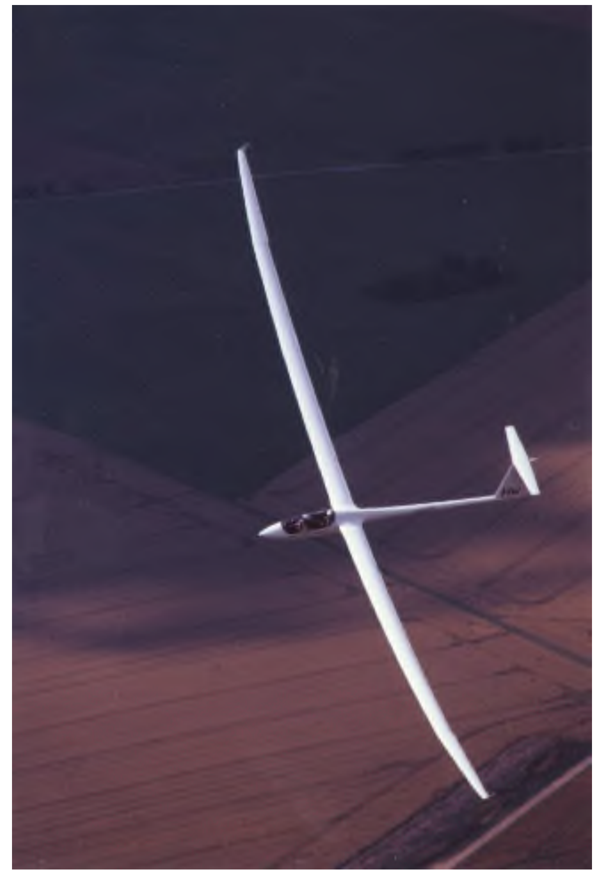
Design Solutions

•! Minimum induced drag for a given span (Std or 15m Class): elliptical span load (or winglets)

•! Minimum induced drag for a given structural weight (Open Class): bell shaped span load (16% greater span and 7% less drag than elliptical - Klein & Viswanathan)

Design Solutions

- Applying bell shaped span load to Eta-class sailplane
- 710 kg We (plus two 70 kg pilots)
- 7% less induced drag
- 16% more span (36m!)
- Max L/D = ~72:1



Design Solutions

- ! What if we could build a flying wing?
- ! Decrease viscous drag by 15% (can't take full credit for 25%)
- ! Decrease induced drag by 7%

Flying Wing

- Balance between induced and viscous drag gives about 12% total drag decrease
- Optimistic due to additional constraint of pitching moment from wing
- Max L/D = 78:1
- Even if the airfoil Cdo was 40% of the total, & all credit was taken: Max L/D ~ 94:1

Horten H VI

Conclusions

- Open Class performance limits (under current rules and technologies) is very close to absolute limits
- Some gains remain to be explored
- Possible gains from unexplored areas and new technologies, even using existing materials.

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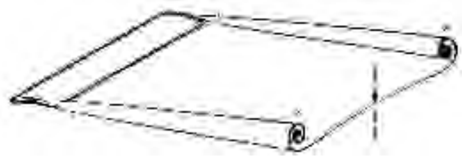
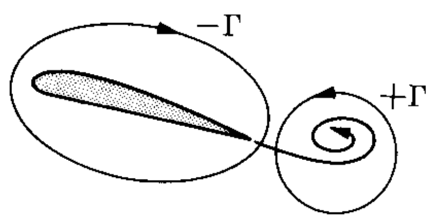
What does the future hold?

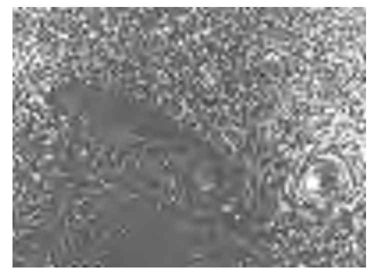
NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: ED01-0230-4 Date: August 13, 2001 Photo by: Carla Thomas
The Helios Prototype aircraft at approximately 10,000 feet flying above cloud cover northwest of Kauai, Hawaii.

Start-Up Vortex

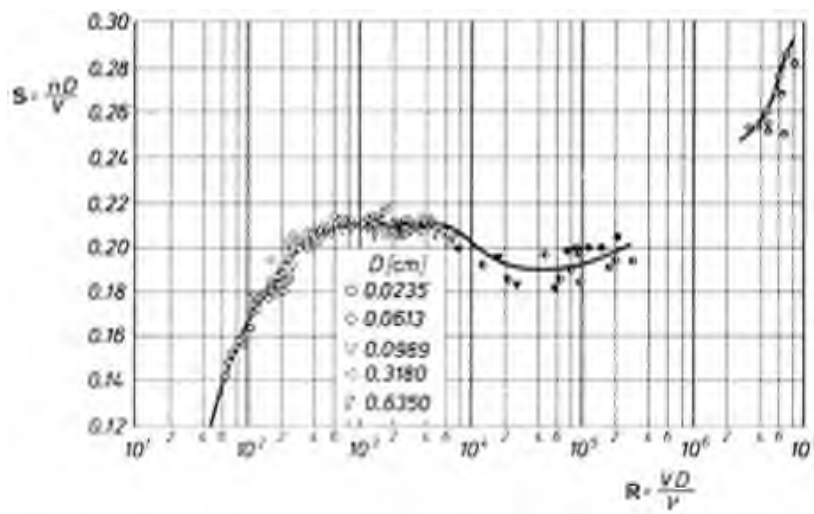


- Prandtl's lifting-line theory - conservation of momentum (angular)





- Oscillating vortex shedding - Strouhal (nondimensional vortex shedding)



And what are we still missing?

Thanks to Phil Barnes and Bob Hoey for reminding us…