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

- 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)

<table>
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<th>Model</th>
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<th>L/D</th>
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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
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 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: elliptical span load (or winglets)

• Minimum induced drag for a given structural weight: 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 = \sim 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.
References

- Prandtl, Ludwig: "Uber Tragflugel kleinsten induzierten Widerstandes"; Zeitschrift fur Flugtecknik und Motorluftschiffahrt, 28 XII 1932; Munchen, Deustchland.
- Horten, Reimar; and Selinger, Peter; with Scott, Jan (translator): “Nurflugel: the Story of Horten Flying Wings 1933 - 1960”; Weishapt Verlag; Graz, Austria; 1985.
- Klein, Armin and Viswanathan, Sathy; “Approximate Solution for Minimum induced Drag of Wings with a Given Structural Weight”; Journal of Aircraft, Feb 1975, Vol 12 No 2, AIAA.
- Jones, Robert T; “Minimizing Induced Drag.”; Soaring, October 1979, Soaring Society of America.
- http://www.alexander-schleicher.de/index_e.htm
What does the future hold?
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…