On the Minimum Induced Drag of Wings

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Lancaster, CA
16 August, 2007

Introduction

- The History of Spanload
  Development of the optimum spanload
  Winglets and their implications
- Horten Sailplanes
- Flight Mechanics & Adverse yaw
- Concluding Remarks

History

- Bird Flight as the Model for Flight
- Vortex Model of Lifting Surfaces
- Optimization of Spanload
  Prandtl
  Prandtl/Horten/Jones
  Klein/Viswanathan
- Winglets - Whitcomb

Birds

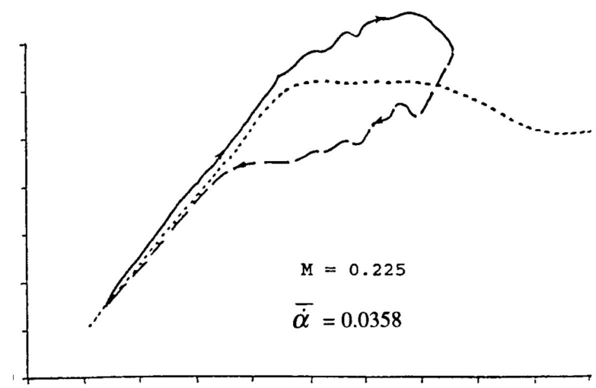
Bird Flight as a Model

or "Why don't birds have vertical tails?"

- Propulsion
  Flapping motion to produce thrust
  Wings also provide lift
  Dynamic lift - birds use this all the time (easy for them, hard for us)

- Stability and Control
  Still not understood in literature
  Lack of vertical surfaces

- Birds as an Integrated System
  Structure
  Propulsion
  Lift (performance)
  Stability and control



Dynamic Lift

Early Mechanical Flight

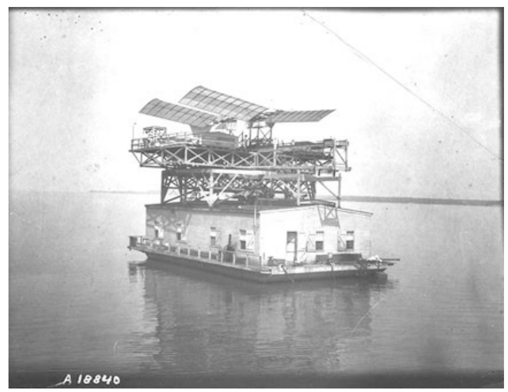
- Otto & Gustav Lilienthal (1891-1896)
- Octave Chanute (1896-1903)
- Samuel P Langley (1896-1903)
- Wilbur & Orville Wright (1899-1905)

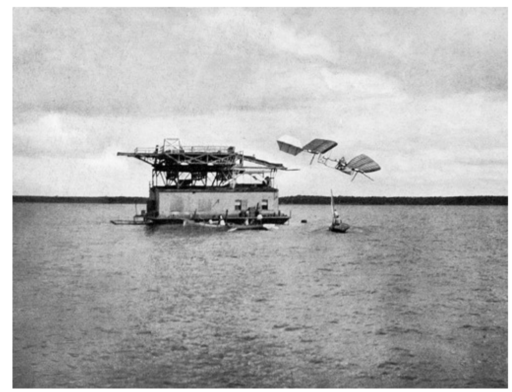
Otto Lilienthal

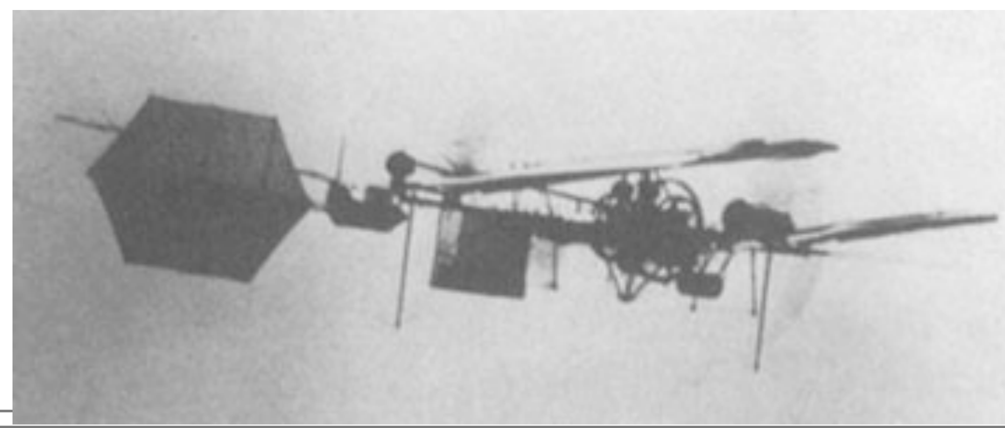
- Glider experiments 1891 - 1896

Dr Samuel Pierpont Langley

- Aerodrome experiments 1887-1903





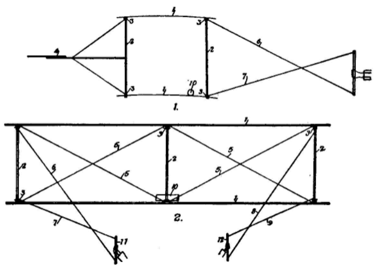


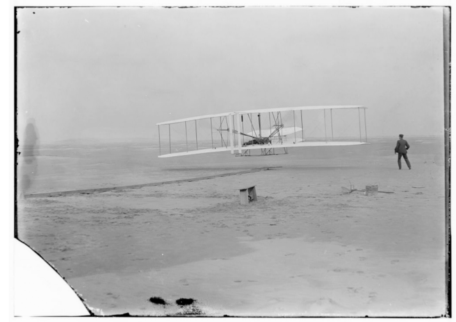
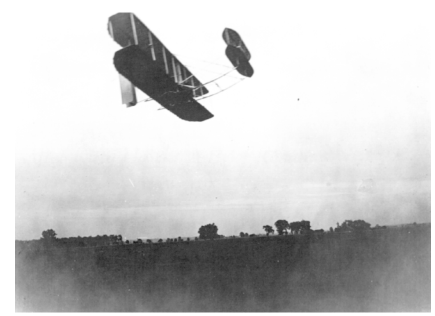
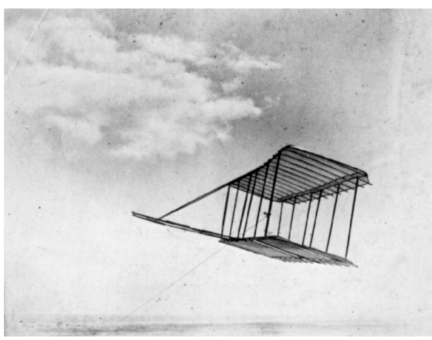
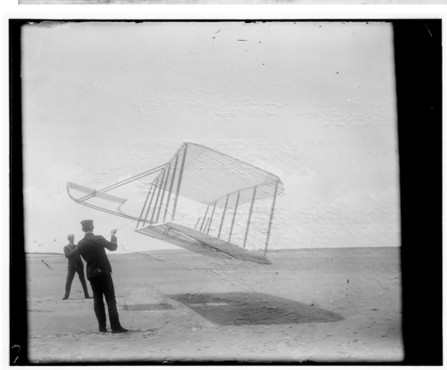
Octave Chanute

- Gliding experiments 1896 to 1903

Wilbur & Orville Wright

- Flying experiments 1899 to 1905




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

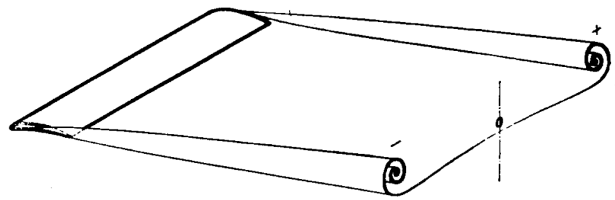
Practical Spanload Developments

- 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

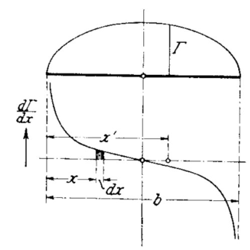
- Robert T Jones
  Spanload for minimum induced drag and wing root bending moment
  Application of wing root bending moment is less general than Prandtl's
  No prior knowledge of Prandtl's work, entirely independent (1950)

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

Prandtl Lifting Line Theory



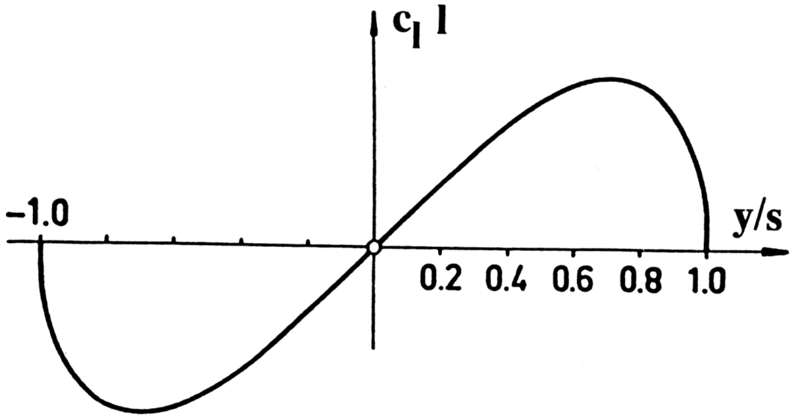
- Prandtl's "vortex ribbons"

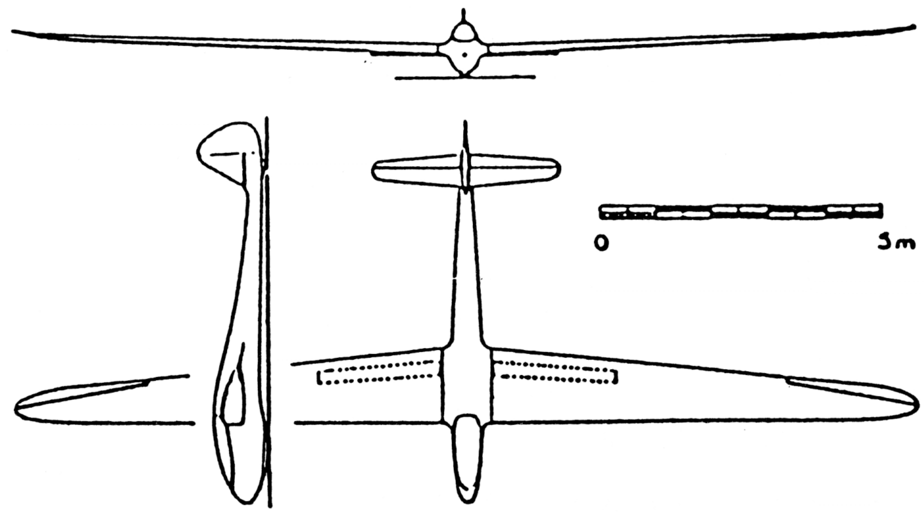


- Elliptical spanload (1914)
- "the downwash produced by the longitudinal vortices must be uniform at all points on the aerofoils in order that there may be a minimum of drag for a given total lift." y = c

Elliptical Half-Lemniscate

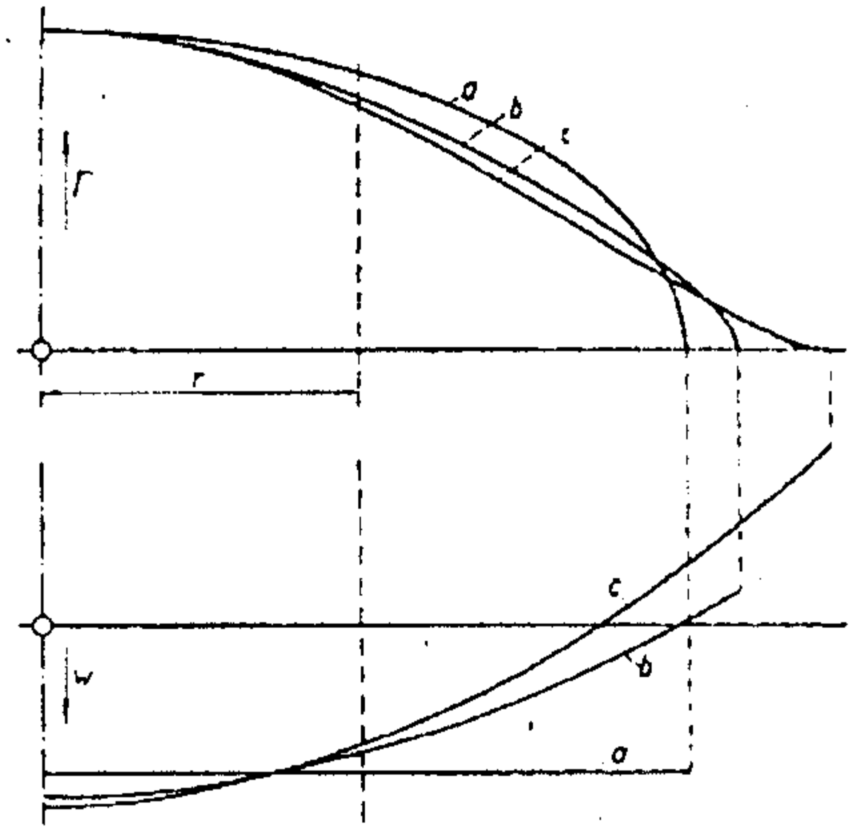
- Minimum induced drag for given control power (roll)
- Dr Richard Eppler: FS-24 Phoenix





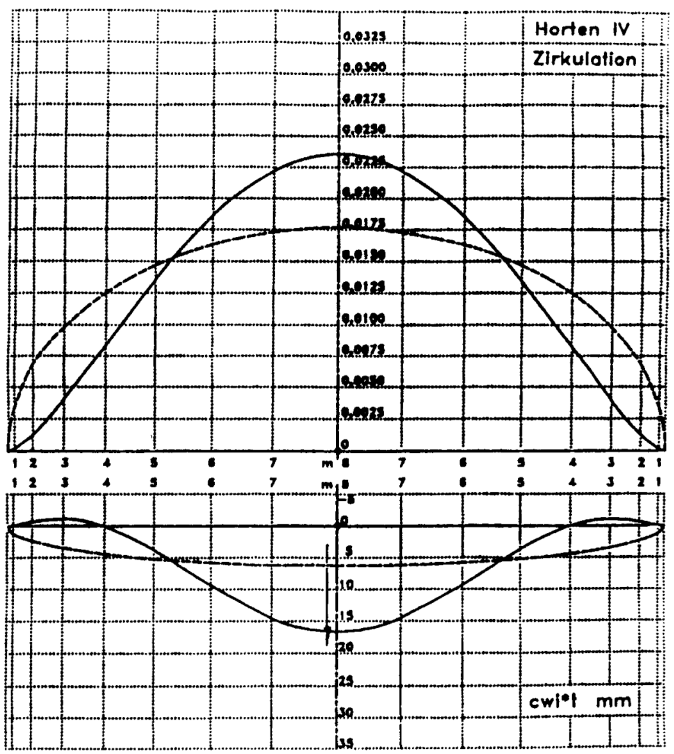
Elliptical Spanloads

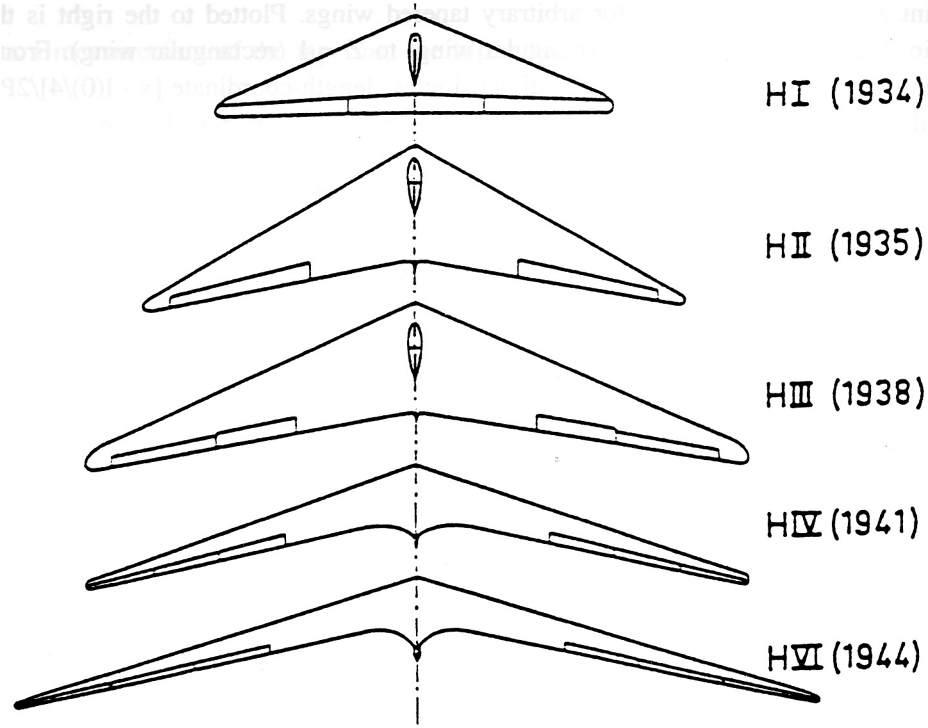
Minimum Induced Drag & Bending Moment



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

Horten Applies Prandtl's Theory

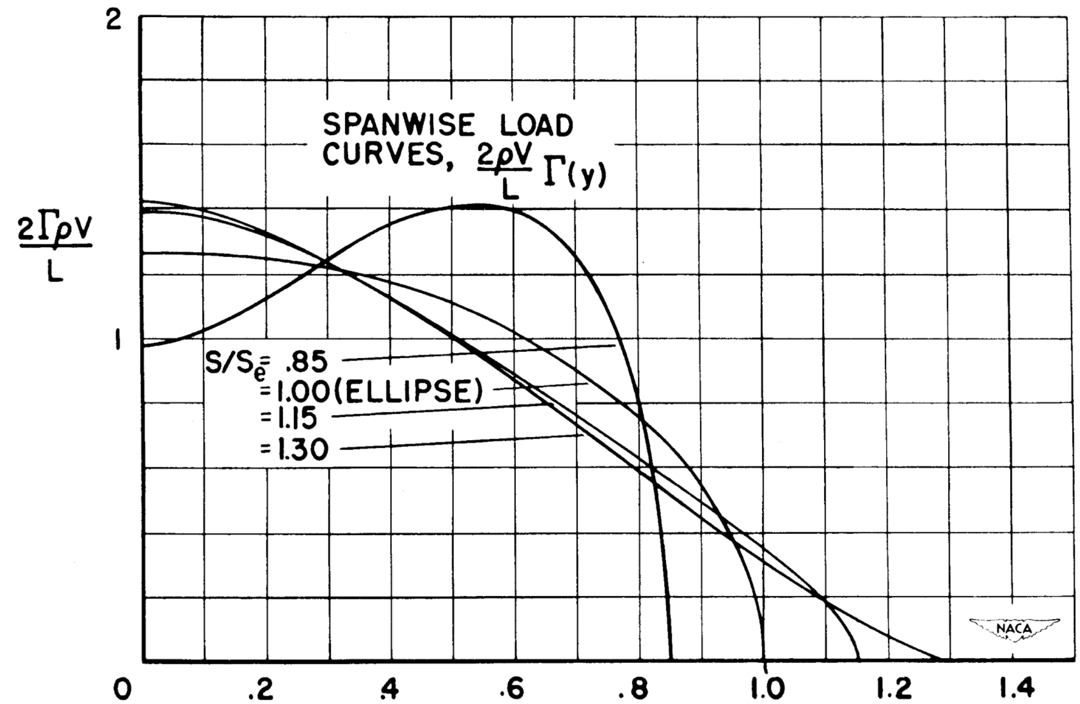




Horten Sailplanes

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

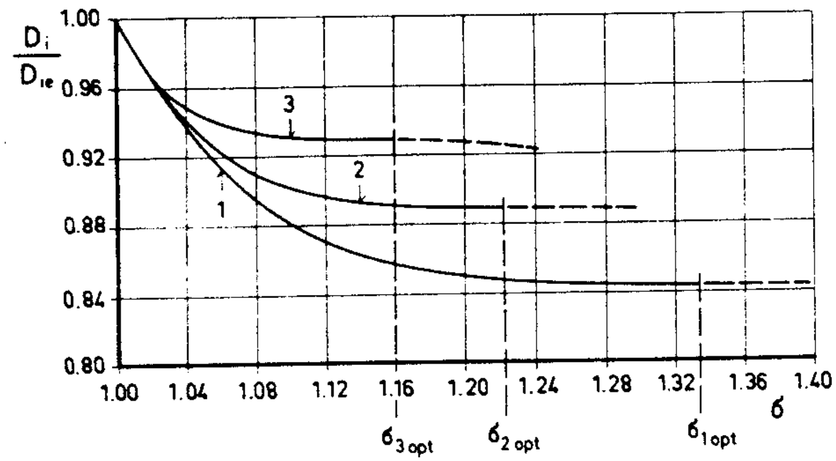
Jones Spanload



- λ Minimize induced drag (1950)
  Constrain wing root bending moment
  30% increase in span with 17% decrease in induced drag

- λ "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

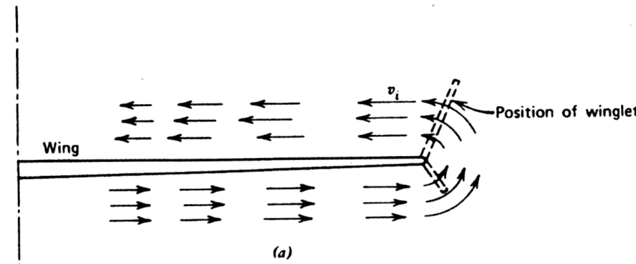


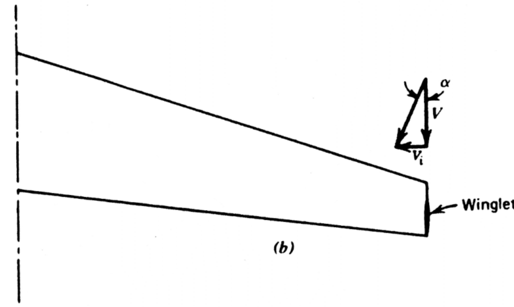
- Minimize induced drag (1975)
  Constrain bending moment
  Constrain shear stress
  16% increase in span with 7% decrease in induced drag

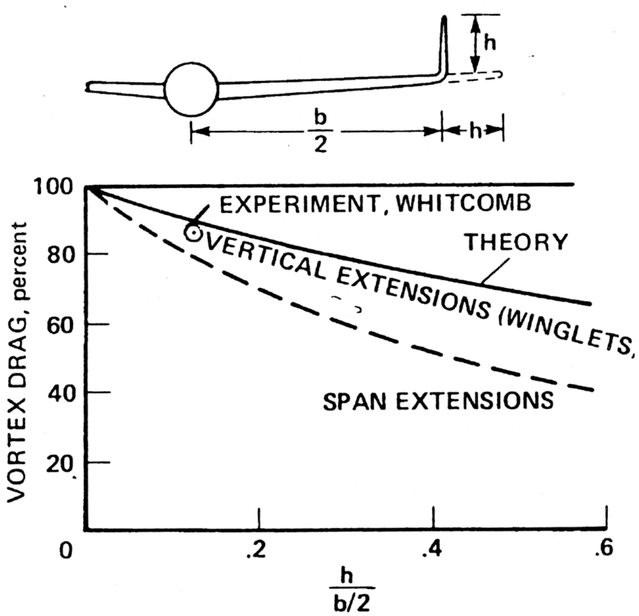
- "Hence the required downwash-distribution is parabolic."
  $y = ax^2 + bx + c$

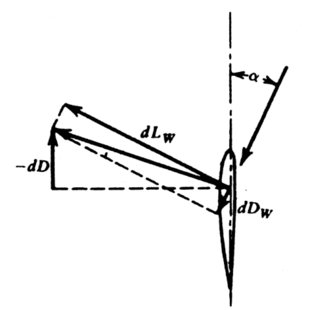
Winglets

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









Winglet Aircraft

Spanload Summary

λ Prandtl/Munk (1914)
Elliptical
Constrained only by span and lift
Downwash: $y = c$

λ Prandtl/Horten/Jones (1932)
Bell shaped
Constrained by lift and bending moment
Downwash: $y = bx + c$

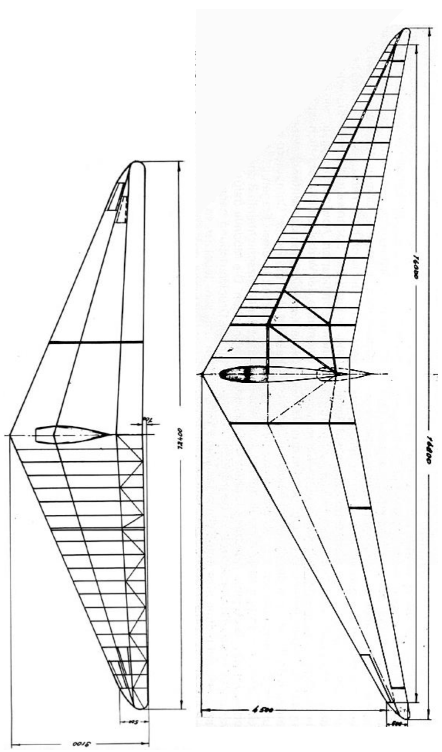
λ Klein/Viswanathan (1975)
Modified bell shape
Constrained by lift, moment and shear (minimum structure)
Downwash: $y = ax^2 + bx + c$

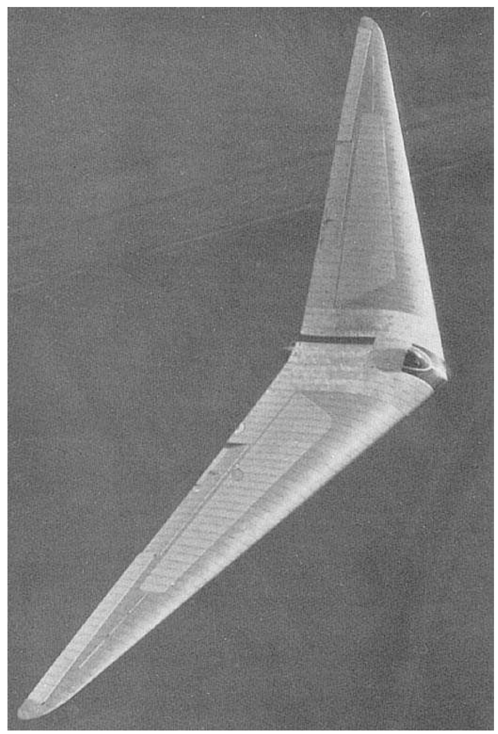
λ Whitcomb (1975)
Winglets

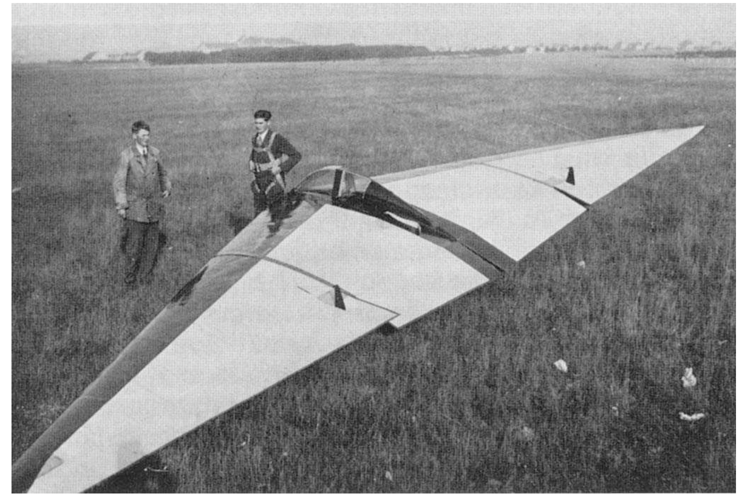
λ Summarized by Jones (1979)

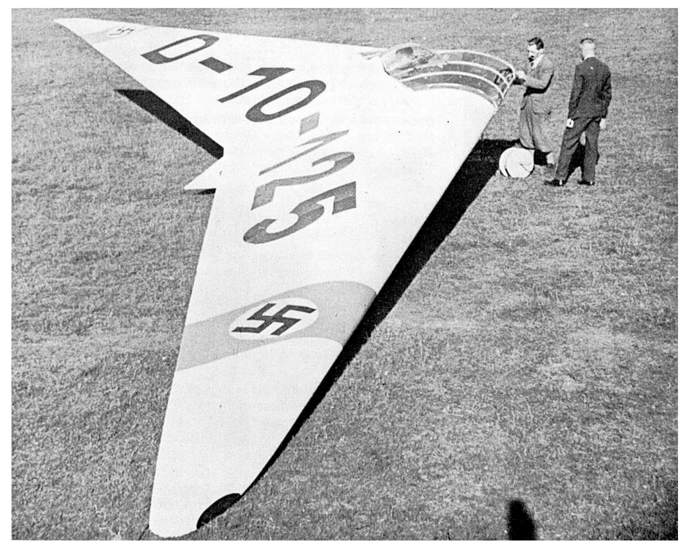
Early Horten Sailplanes (Germany)

- Horten I - 12m span
- Horten II - 16m span
- Horten III - 20m span



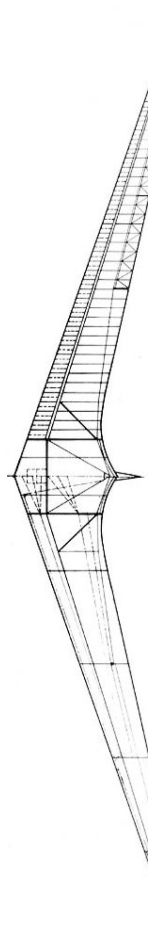


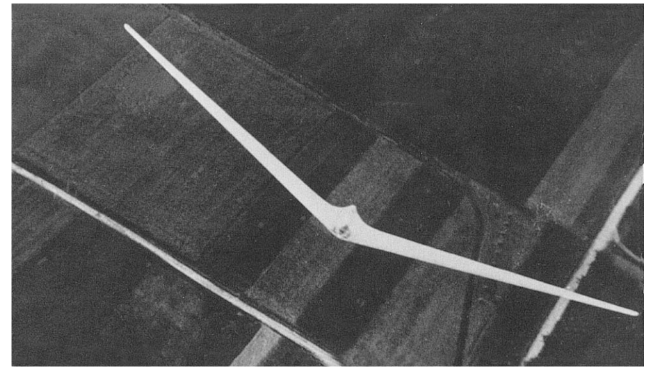


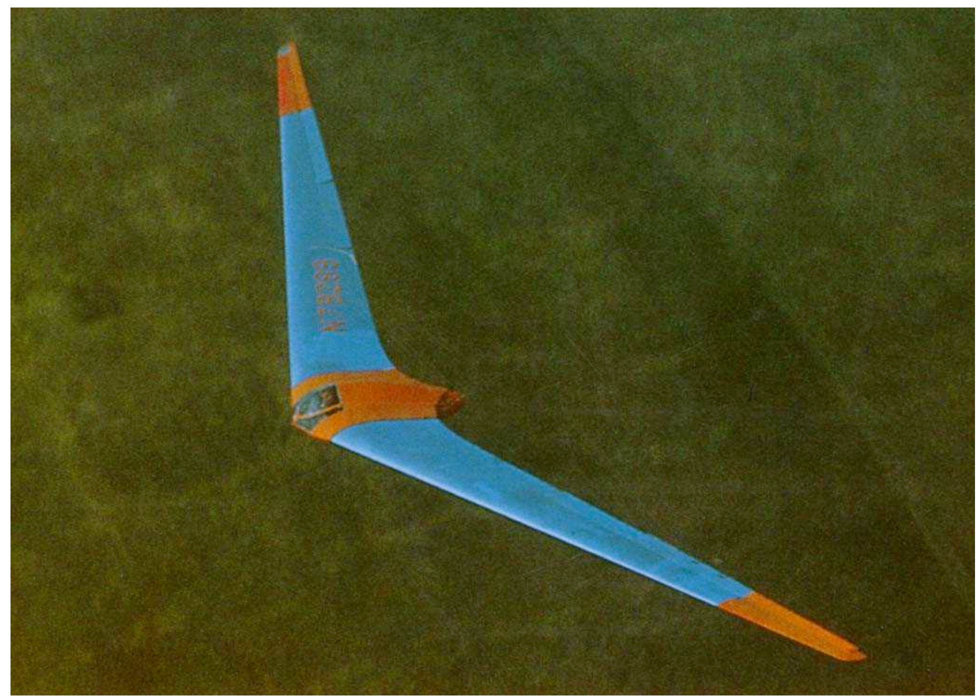


Horten Sailplanes (Germany)

- H IV - 20m span
- H VI - 24m span

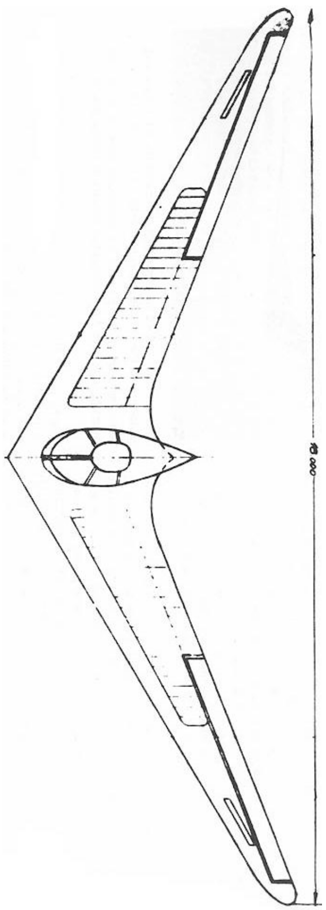


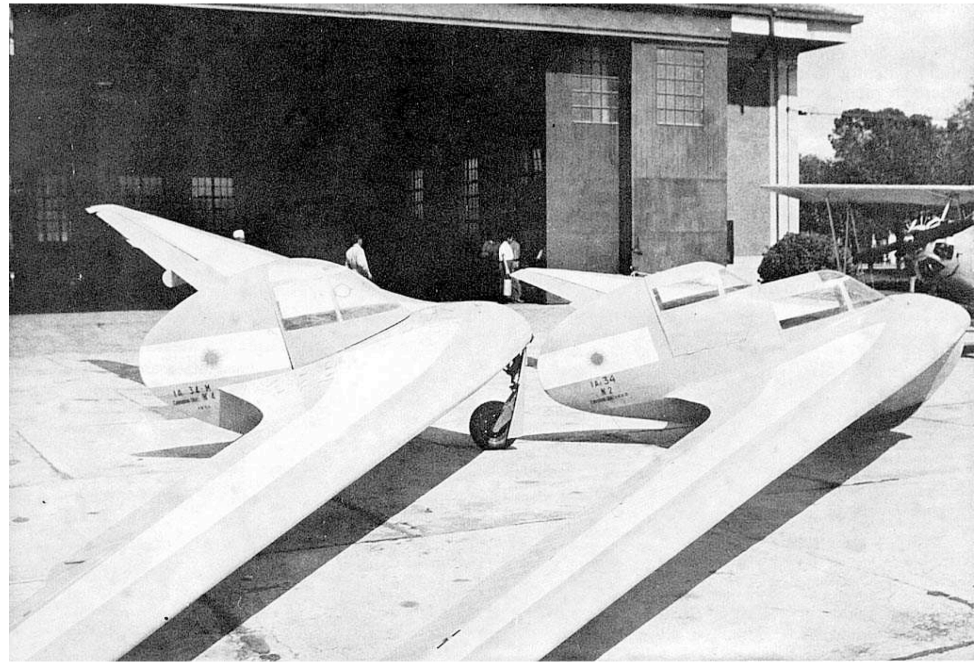


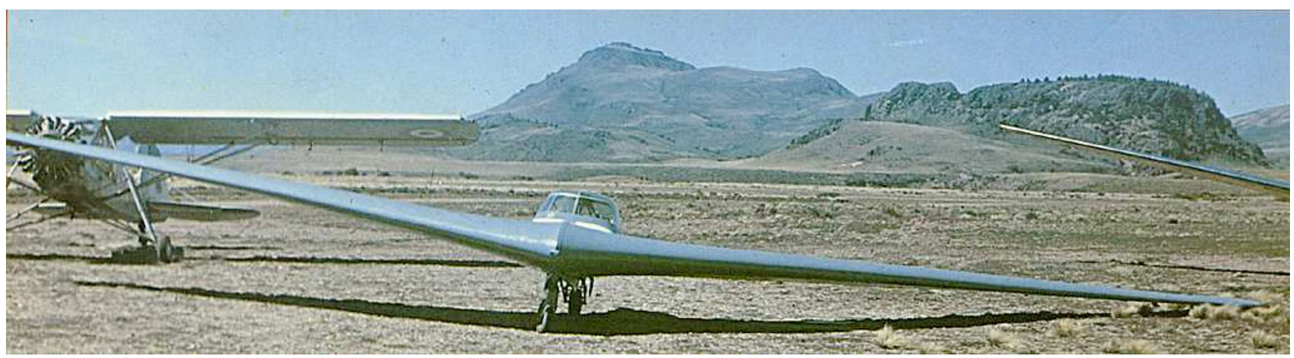


Horten Sailplanes (Argentina)

- H I b/c - 12m span
- H XV a/b/c - 18m span

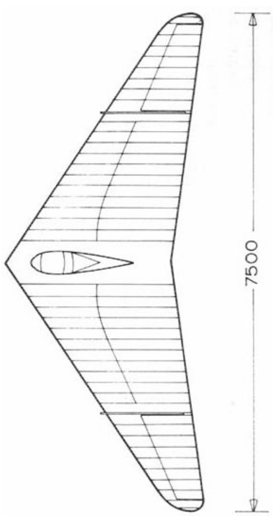


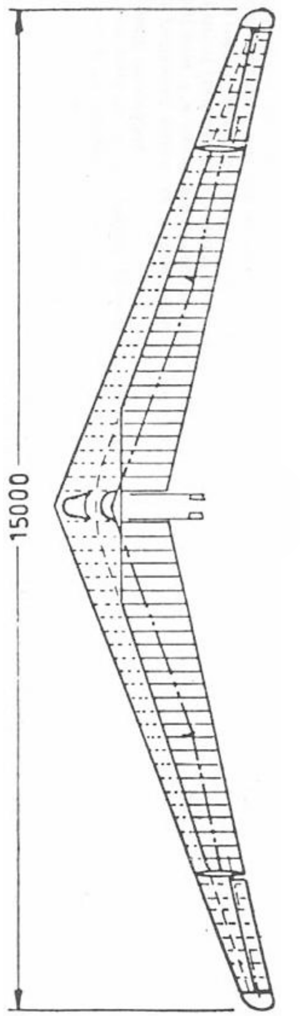


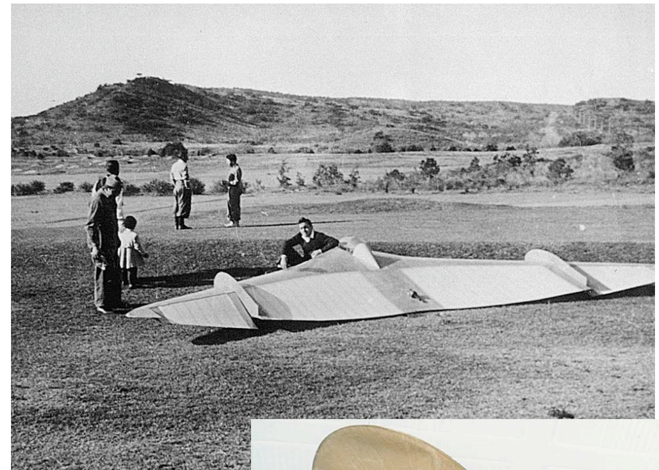


Later Horten Sailplanes (Argentina)

- H Xa/b/c 7.5m, 10m, & 15m





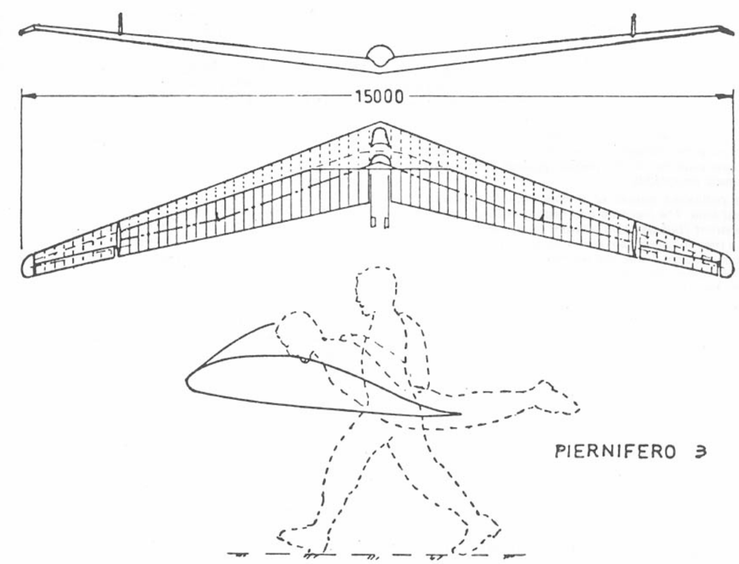


Bird Flight Model

- Minimum Structure
- Flight Mechanics Implications
- Empirical evidence
- How do birds fly?

Horten H Xc Example

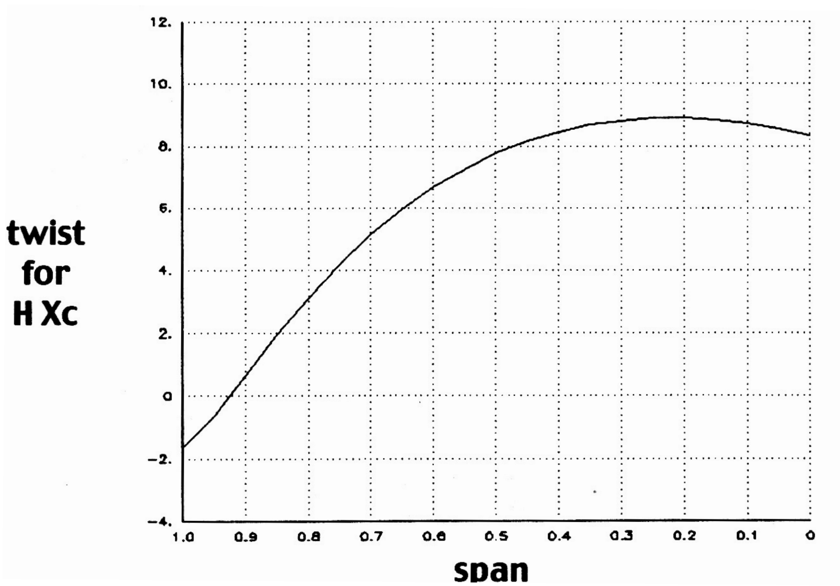
- Horten H Xc footlaunched ultralight sailplane 1950

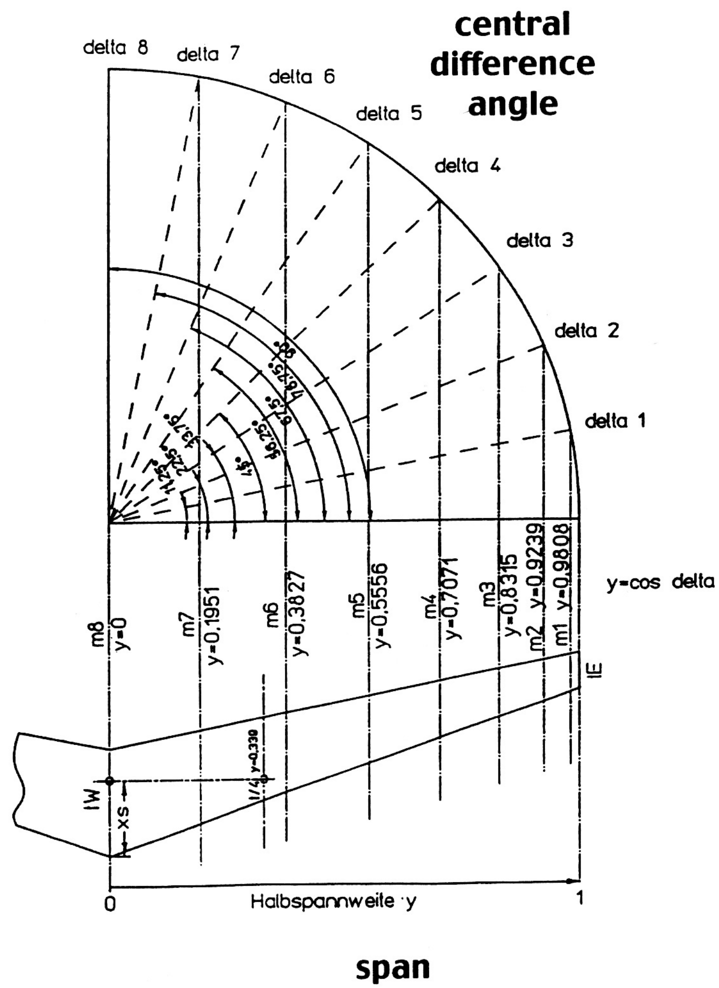


Skizze der H X c mit 15 Meter Spannweite. (Zeichnung Jan Scott)

Calculation Method

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

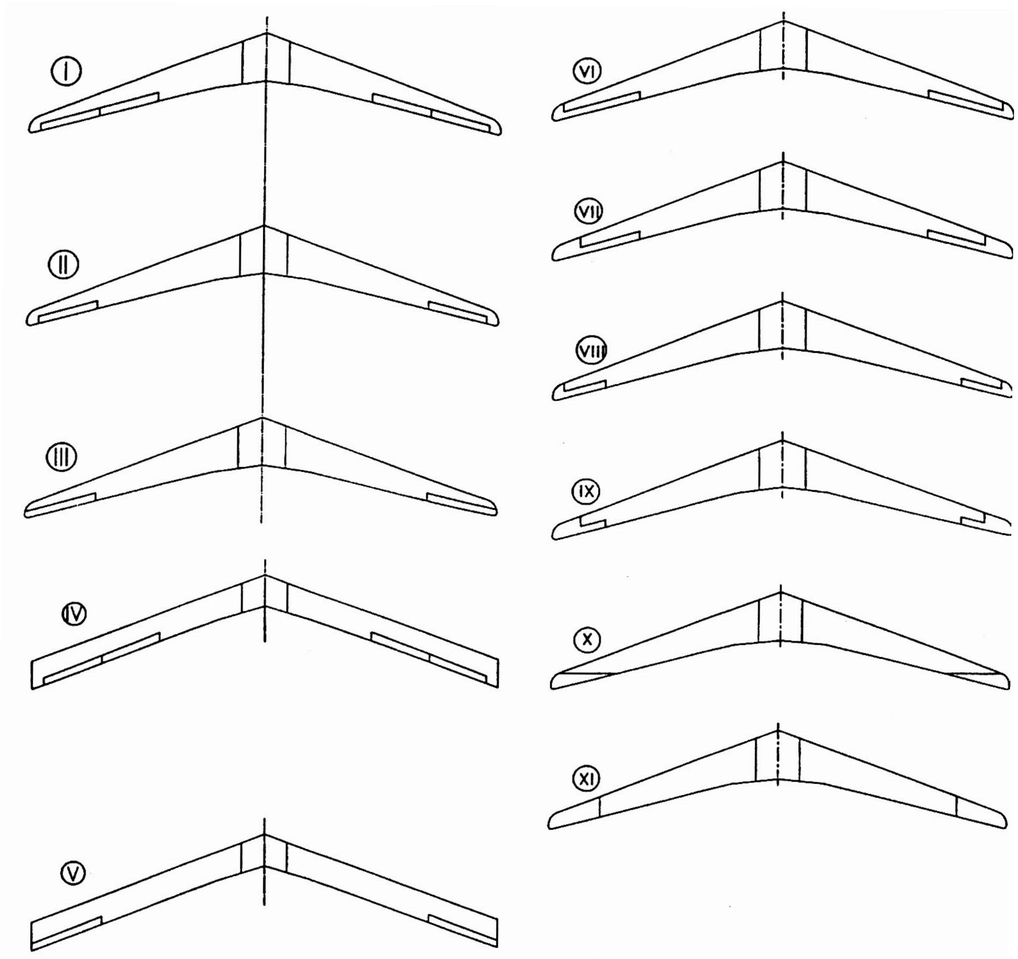




Dr Edward Udens' Results

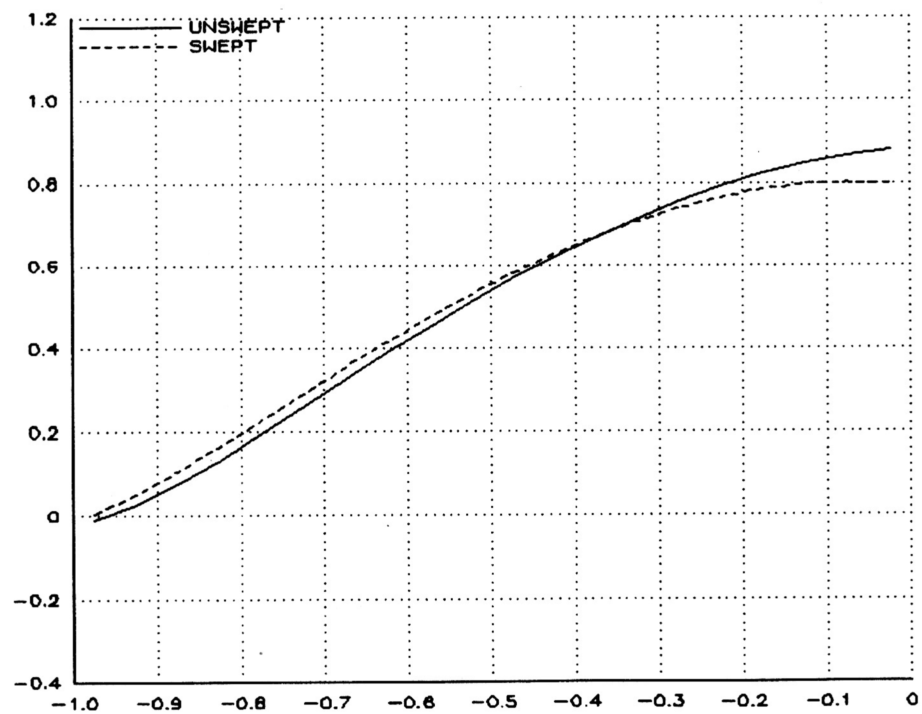
- Spanload and Induced Drag
- Elevon Configurations
- Induced Yawing Moments

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



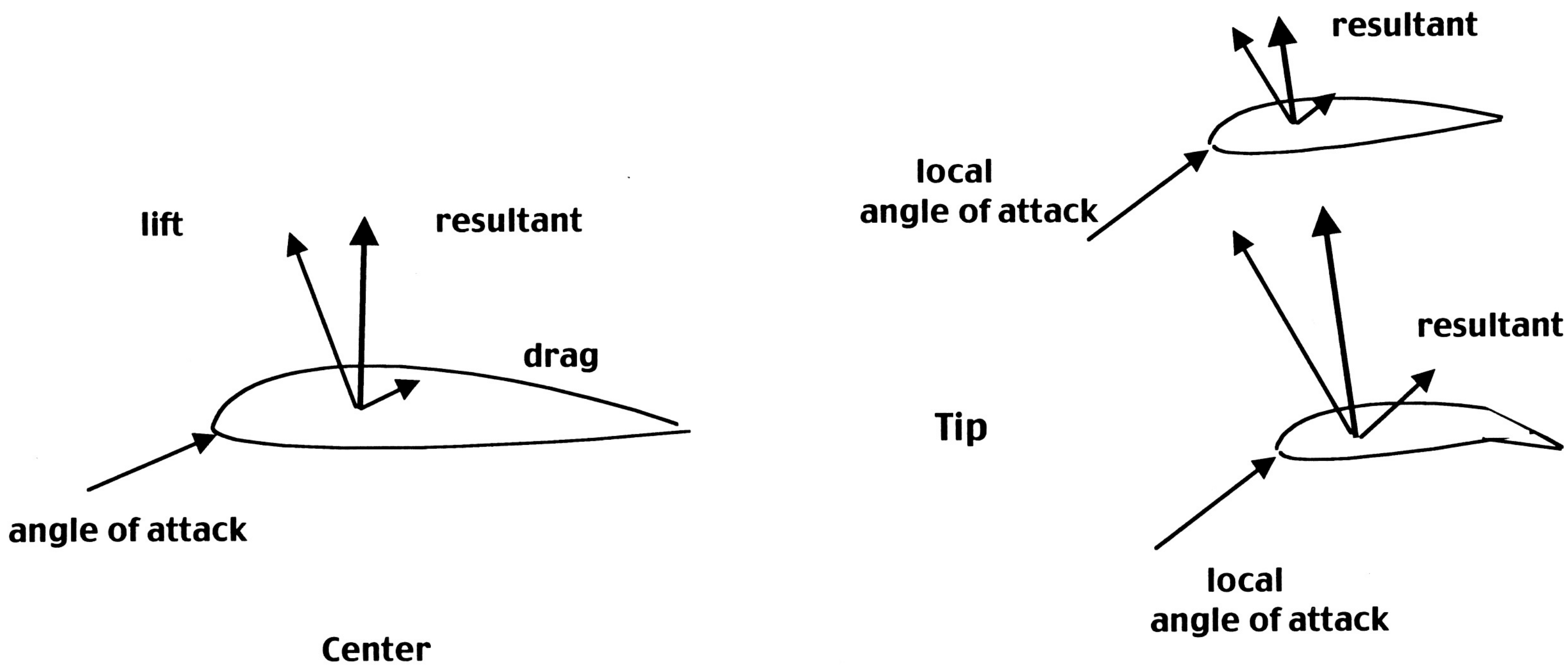
“Mitteleffekt”

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



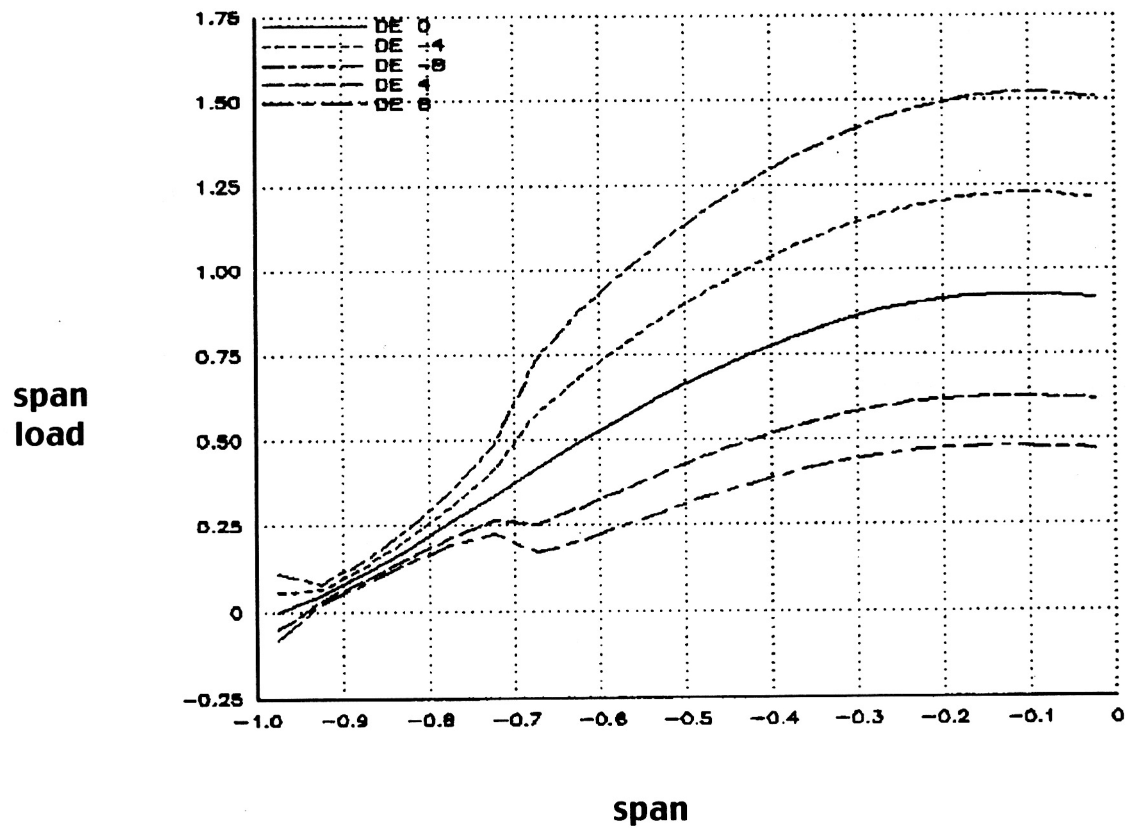
Horten H Xc Wing Analysis

- Vortex Lattice Analysis
- Spanloads (longitudinal & lateral-directional) - trim & asymmetrical roll
- Proverse/Adverse Induced Yawing Moments
  handling qualities
- Force Vectors on Tips - twist, elevon deflections, & upwash
- 320 Panels: 40 spanwise & 8 chordwise



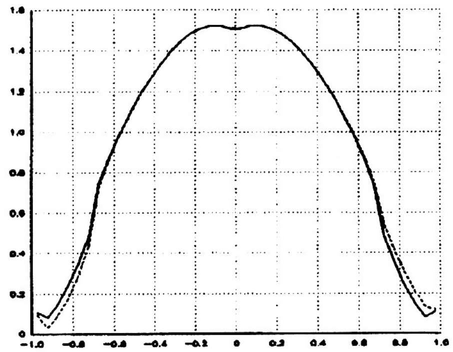
Symmetrical Spanloads

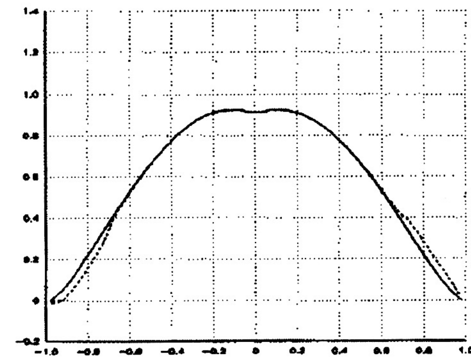
- Elevon Trim
- CG Location

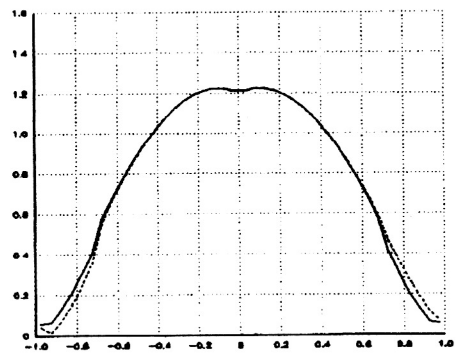


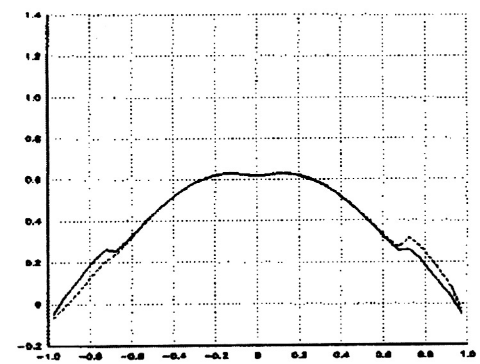
Asymmetrical Spanloads

- 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*

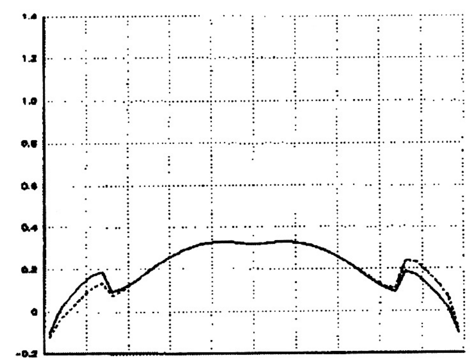








CL	Cl	Cn
.966	.01384	.00055
.774	.01384	.00037
.582	.01345	.00021
.390	.01384	.00003
.198	.01345	-.00015



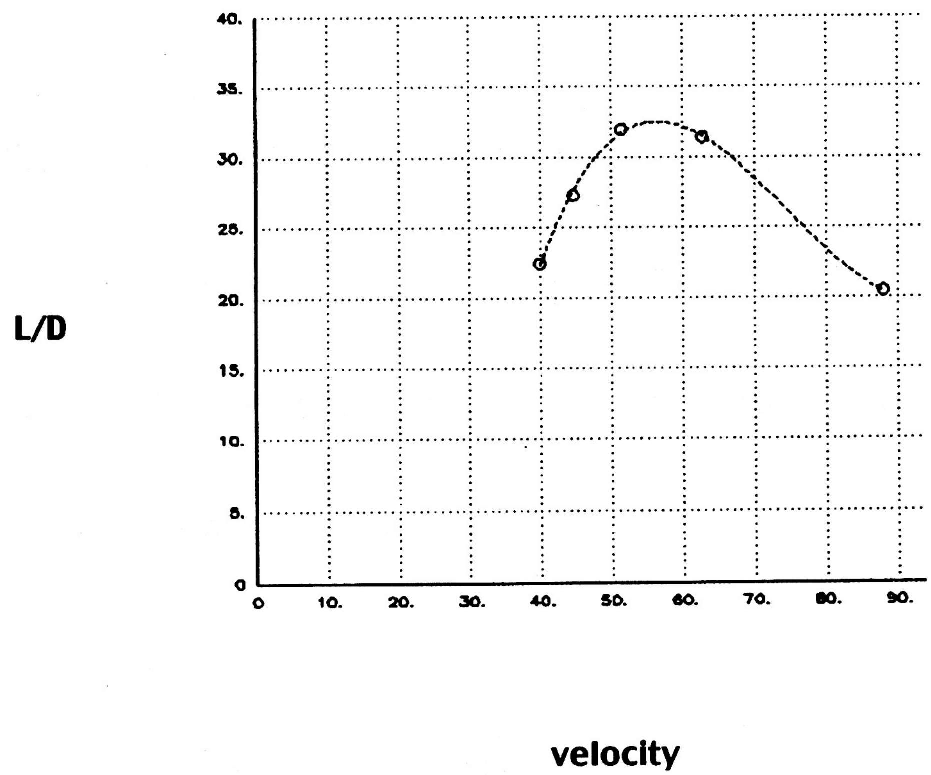
Airfoil and Wing Analysis

- Profile code (Dr Richard Eppler)
- Flap Option (elevon deflections)
- Matched Local Lift Coefficients
- Profile Drag
- Integrated Lift Coefficients
  match Profile results to Vortex Lattice
  separation differences in lift
- Combined in MatLab

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



Horten Spanload Equivalent to Birds

- Horten spanload is equivalent to bird span load (shear not considered in Horten designs)
- Flight mechanics are the same - turn components are the same
- Both attempt to use minimum structure
- Both solve minimum drag, turn performance, and optimal structure with one solution

Concluding Remarks

- Birds as as the first model for flight
- Theortical developments independent of applications
- Applied approach gave immediate solutions, departure from bird flight
- Eventual meeting of theory and applications (applied theory)
- Spanload evolution (Prandtl/Munk, Prandtl/Horten/Jones, Klein & Viswanathan)
- Flight mechanics implications
- Hortens are equivalent to birds
- Thanks: John Cochran, Nalin Ratenyake, Kia Davidson, Walter Horten, Georgy Dez-Falvy, Bruce Carmichael, R.T. Jones, Russ Lee, Dan & Jan Armstrong, Dr Phil Burgers, Ed Lockhart, Andy Kesckes, Dr Paul MacCready, Reinhold Stadler, Edward Udens, Dr Karl Nickel & Jack Lambie

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How do birds fly?