On the Minimum Induced Drag of Wings

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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

\[
N = 0.225
\]
\[
\bar{a} = 0.0358
\]
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

- Horten Spanload (1940-1955)
  - induced thrust at tips
  - wing root bending moment
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." \( y = bx + c \)
λ. Minimize induced drag (1975)
Constrain bending moment
Constrain shear stress
16% increase in span with 7% decrease in induced drag

λ. “Hence the required downwash-distribution is parabolic.”
y = ax^2 + bx + c
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

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

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

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

- Whitcomb (1975)
  Winglets

- 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
Calculation Method

- Taper
- Twist
- Control Surface Deflections
- Central Difference Angle
Dr Edward Udens’ Results

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

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“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

- $\lambda$ Cl $\delta a$ (roll due to aileron)
- $\lambda$ Cn $\delta a$ (yaw due to aileron)
  - induced component
  - profile component
  - change with lift
- $\lambda$ Cn $\delta a$/Cl $\delta a$
- $\lambda$ CL (Lift Coefficient)
  - Increased lift:
    - increased Cl $\beta$
    - increased Cn $\beta^*$
  - Decreased lift:
    - decreased Cl $\beta$
    - decreased Cn $\beta^*$

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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
Predicted 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 the first model for flight
- Theoretical 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?