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NASA vision is:

• Innovation
• Inspiration
• Discovery

The NASA mission is:

• Technology innovation
• Inspiration for the next generation
• And discovery in our universe as only NASA can
The Wright Brothers and the Future of Bio-Inspired Flight
1899 through to the Future…

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28 November 2007
Background: The Times

Transcontinental Railroad...

- the great engineering achievement of the time
- understanding of “two-track” vehicle systems (buggys, carts, & trains)
- completed on 10 May 1869 (Wilbur was two years old)
Background: Progenitors

- Otto Lilienthal
  - experiments from 1891 to 1896
- Samuel P Langley
  - experiments from 1891-1903
- Octave Chanute
  - experiments from 1896-1903
Otto Lilienthal

- Glider experiments 1891 - 1896
Dr Samuel Pierpont Langley

- Aerodrome experiments 1887-1903
Octave Chanute

- Gliding experiments 1896 to 1903
Wilbur and Orville

16 Apr 1867 – 30 May 1912

19 Aug 1871 – 30 Jan 1948
Wright Brothers Timeline

- 1878 The Wrights receive a gift of a toy helicopter
- 1895 The Wrights begin to manufacture their own bicycles
- 1896 The Wrights take an interest in the "flying problem"
- 1899 Wilbur devises a revolutionary control system, builds a kite to test it; also writes the Smithsonian.
- 1900 The Wright brothers fly a glider at Kitty Hawk, NC
- 1901 The Wrights fly a bigger glider at Kitty Hawk, NC
- 1901 In Dayton, OH, they build a research wind tunnel
- 1902 The Wrights perfect their glider and learn to fly
- 1903 The Wright brothers make the first controlled, sustained powered flight at Kitty Hawk.
- 1905 In Dayton, the Wrights develop a practical airplane
Wright Brothers’ Paper

Dayton’s “West Side News”
Wright Brothers’ Cycle Company

- “single-track” vehicle mechanics
Inspiration: 1878
Inspiration: July 1899
1899 Kite Experiments

Dayton Ohio
1900 Wright Glider

- Span: 17 feet
- Chord: 5 feet
- Gap: 4 feet, 8 inches
- Camber: 1/23
- Wing Area: 165 sq ft
- Weight with operator: 190 lb
1901 Wright Glider

- Span: 22 feet
- Chord: 7 feet
- Gap: 4 feet, 8 inches
- Camber: 1/17
- Wing Area: 290 sq ft
- Horizontal Rudder Area: 18 sq ft
- Length: 14 feet
- Weight: 98 lb
They go home, very discouraged.

On the train back to Dayton, Wilbur tells Orville that men would not fly for another fifty years...
Dayton Experiments
October 1901
1901 Wind Tunnel
16 inch square section x 6 feet
1901 Wright Wind Tunnel Results
1902 Wright Glider

Specifications
Wingspan: 32 feet, 1 inch
Chord: 5 feet
Camber: 1/20 to 1/24
Aspect Ratio: 4 inches
Wing Area: 305 square feet
Elevator Area: 15 square feet
Rudder Area: 5.7 square feet
Overall Length: 17 feet
Overall Height: 6 feet, 3 inches
Gap between wings: 5 feet
Weight: 112 pounds
Number of Flights: Approximately 2000
Longest distance flown: 622 feet
Longest time in flight: 1 minute, 12 seconds
Frame materials: Spruce, ash, woven linen cord
Hardware: Mild steel, boxwood (for pulleys)
Rigging: 15-gauge steel wire
Wing covering: Cotton muslin, 209 thread count

Not for sale or profit; these plans are to be distributed freely and free of charge.
1902 Wright Glider

- Span: 32 feet 1 inch
- Chord: 5 feet
- Gap: 4 feet, 7 inches
- Camber 1/24
- Wing Area: 305 sq ft
- Horizontal Rudder Area: 15 sq ft
- Length 16 feet 1 inch
- Weight 112 lb
- Three configurations
Centennial of Controlled Flight
24 October 1902
1903 Langley Aerodrome

Oct 7, 1903

Dec 8, 1903
1903 Wright Flyer

- Span: 40 feet 4 inch
- Chord: 6 feet 6 inches
- Gap: 6 feet 2 inches
- Camber 1/20
- Wing Area: 510 sq ft
- Horizontal Rudder Area: 48 sq ft
- Vertical Rudder Area: 21 sq ft
- Length 21 feet 1 inch
- Weight 605 lb
Wilbur wins the coin toss, and...
1903 Wright Flyer
December 14, 1903

Oops!
1903 Wright Flyer
December 17, 1903
1903 Wright Flyer
They tell the world...

176 C KA 03 33 Paid. Via Norfolk Va
Kitty Hawk N C Dec 17
Bishop M Wright
7 Hawthorne St

Success four flights Thursday morning all against twenty one mile wind started from Level with engine power alone average speed through air thirty one miles longest 57 seconds inform Press home Christmas.

Orevelle Wright E25P
1904 Wright Flyer
1904 Huffman Prairie Ohio

September 20, 1904 First Complete Circle in an Airplane
1905 Wright Flyer

1905 Wright Flyer 3
1905 Huffman Prairie OH

Oct 4, 1905 Extended Flight in an Airplane (38 minutes)
Wright Flying Machine Patent

#821, 393

May 22, 1906
1908-1909 France & Virginia
Public trials of the first practical airplane
The Rest is History...

- 1904 Flights of 5+ minutes duration
- 1905 Flights to 38 minutes duration
- 1906 - 1907 Commercialization
- 1908 - 1909 Flight Demonstrations
  - Wilbur in France, Italy and Germany
  - Orville in United States
- 1909 The Wright Company is established
  - Clarke-Wright glider in England
  - Established Flying School in Alabama, OH
- 1911 Glider Experiments with autopilot
- Orville serves on NACA board from 1920 to 1948
Understanding the Wright’s Accomplishments Through Evaluation
Wright Flyers Today

1903 Wright Flyer I
National Air & Space Museum

1905 Wright Flyer III
Carillon Hall
Orville’s Camera: 1902 to 1905
The Wrights to Today

• We still solve problems the same as the Wrights today
• We reduce the system to individual problems
  - aero
  - controls
  - propulsion
  - structures
How Did We Get Here?

• What are our assumptions?
• What are we missing?
An Integrated Approach: Towards More Bird-like Flight

- The Wrights dis-integrated the bird
- It is time to re-integrate the bird

“When was the last time you saw a bird with a vertical tail?”
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
Early Mechanical Flight

- Otto & Gustav Lilienthal (1891-1896)
- Octave Chanute (1896-1903)
- Samuel P Langley (1896-1903)
- Wilbur & Orville Wright (1899-1905)
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 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
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.” $y = ax + bx + c$
Winglets

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

![Diagram of Winglets](image)
Winglet Aircraft
Spanload Summary

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

• Prandtl/Horten/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: \( y = ax^2 + bx + c \)

• 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?
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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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

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

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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
Dynamic Lift: Flapping Wings

- What is the mechanism for flapping flight?
  - dynamic lift
  - start-up vortex
  - Strouhal number
Dynamic Lift

- Riddle of the bumblebee

- Dynamic lift or delayed stall
  - transient lift coefficient in excess of steady-state maximum lift coefficient
Start-Up Vortex

- Back to Prandtl’s lifting-line theory
  - conservation of momentum (angular)
Start-Up Vortex

- Rowing
- Paddling
- Sailing
- Swimming
Karman Vortex Street

- Oscillating vortex shedding
Strouhal Number

- Nondimensional measure of vortex shedding frequency
Strouhal

• Governs ALL biological periodic propulsion
  - bacteria
  - birds
  - fish
  - whales
Concluding Remarks

• Birds as the first model for flight, and maybe the ultimate model?
• 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/Horton/Jones, Klein & Viswanathan)
• Flight mechanics implications
• Hortens are equivalent to birds
• Flapping is important, but how much?

• Thanks: Dr FK Yuan, Chris, Moussain Mousavi, Nalin Ratenyake, Kia Davidson, Walter Horten, Georgy Dez-Falvy, Bruce Carmichael, R.T. Jones, Russ Lee, Geoff Steele, Dan & Jan Armstrong, Dr Phil Burgers, Ed Lockhart, Andy Kesckes, Dr Paul MacCready, Reinhold Stadler, Edward Udens, Dr Karl Nickel & Jack Lambie
References

- Prandtl, Ludwig: ”Uber Tragflugel kleinsten induzierten Widerstandes”; Zeitschrift fur Flugtechnik und Motorluftschifffahrt, 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.
- Horten, Reimar; unpublished personal notes.
- Udens, Edward; unpublished personal notes.
- 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.
- Koford, Carl; “California Condor”; Audobon Special Report No 4, 1950, Dover, NY.
What are we still missing?