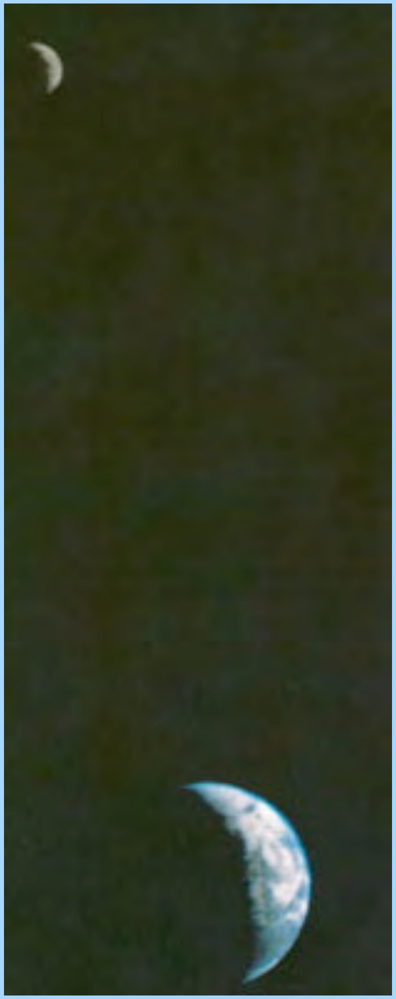
NASA Vision & Mission

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…

Al Bowers
NASA Dryden Flight Research Center

North Carolina State University
Raleigh, NC
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

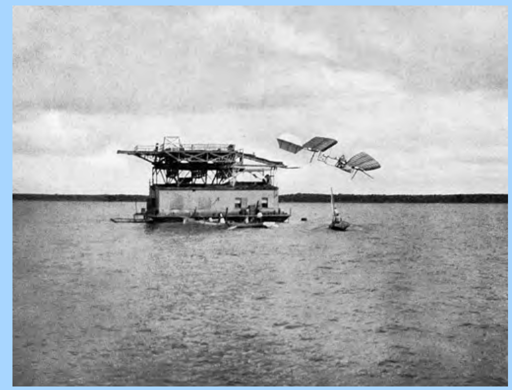
Otto Lilienthal

- Glider experiments 1891 - 1896




Dr Samuel Pierpont Langley

- Aerodrome experiments 1887-1903



Octave Chanute

- Gliding experiments 1896 to 1903

Wilbur and Orville

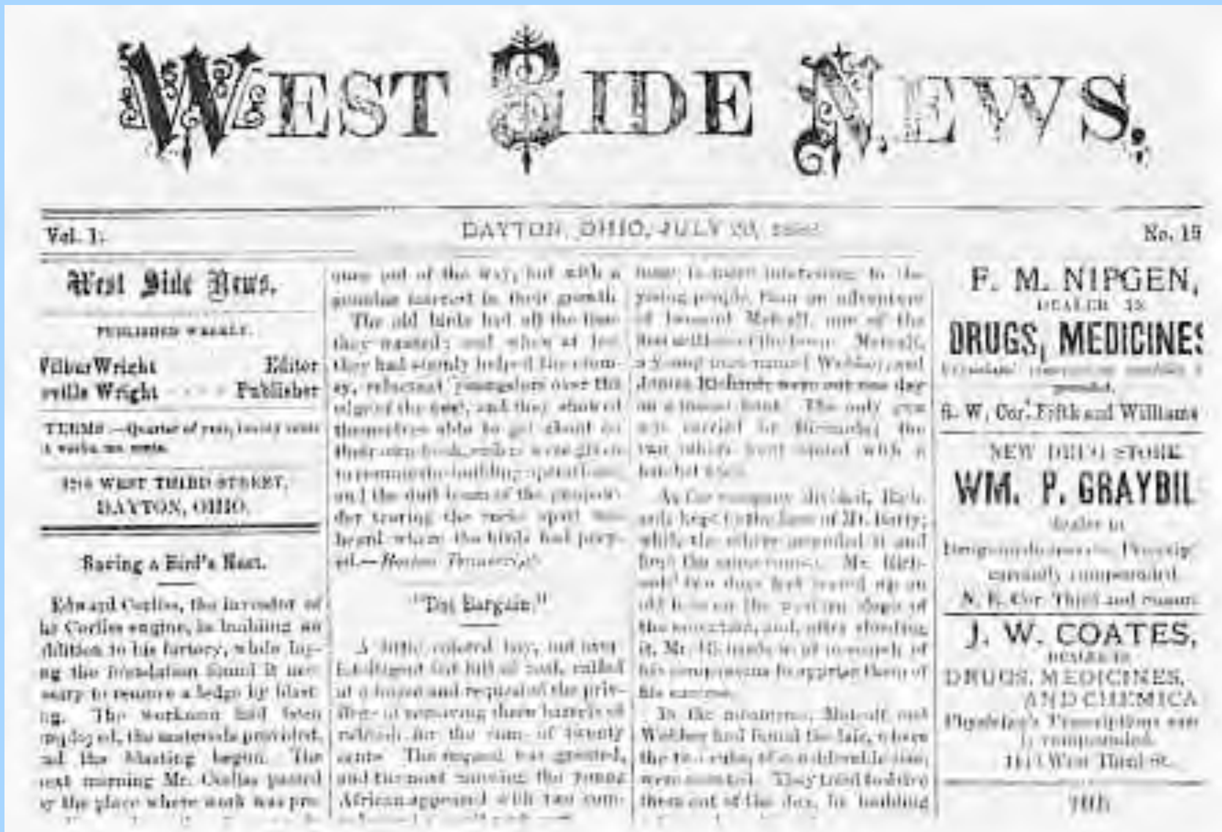
16 Apr 1867 – 30 May 1912

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


WEST SIDE NEWS.

Vol. 1. DAYTON, OHIO, JULY

West Side News.

PUBLISHED WEEKLY.

Wilbur Wright Editor

Orville Wright Publisher

WEST THIRD STREET,

DAYTON, OHIO.

Saving a Bird's Nest.

"The Bargain."

F. M. NIPGEN,

DRUGS, MEDICINES

NEW DRUG STORE

WM. P. GRAYBIL

J. W. COATES,

DRUGS, MEDICINES,

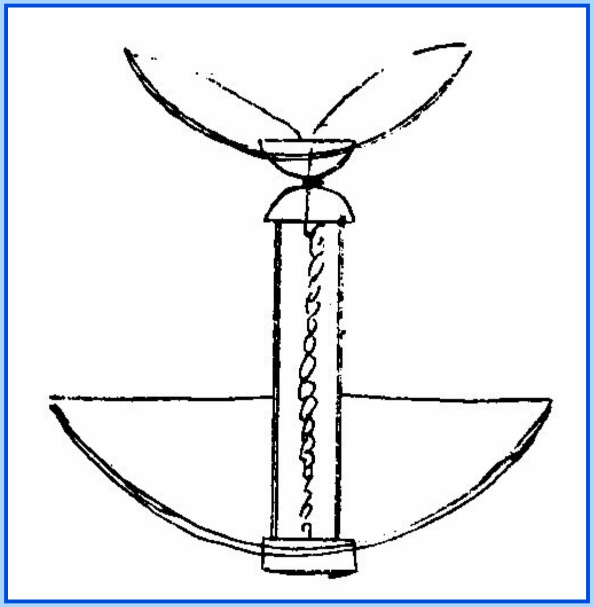
AND CHEMICA

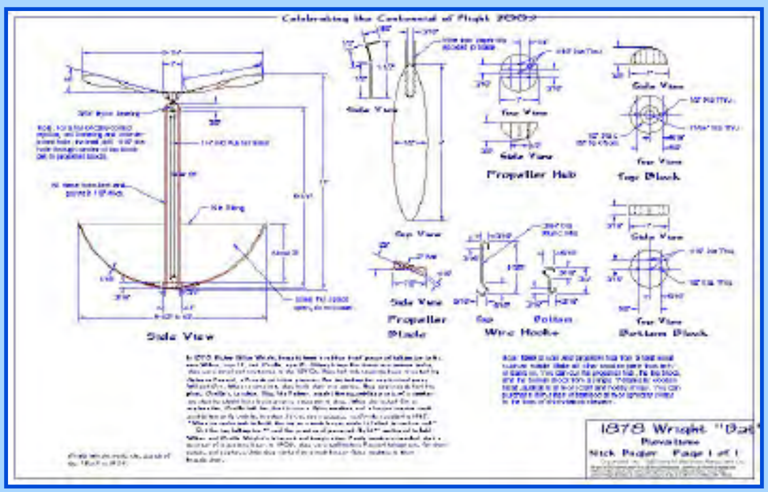
Dayton's "West Side News"

Wright Brothers' Cycle Company

- "single-track" vehicle mechanics

Inspiration: 1878

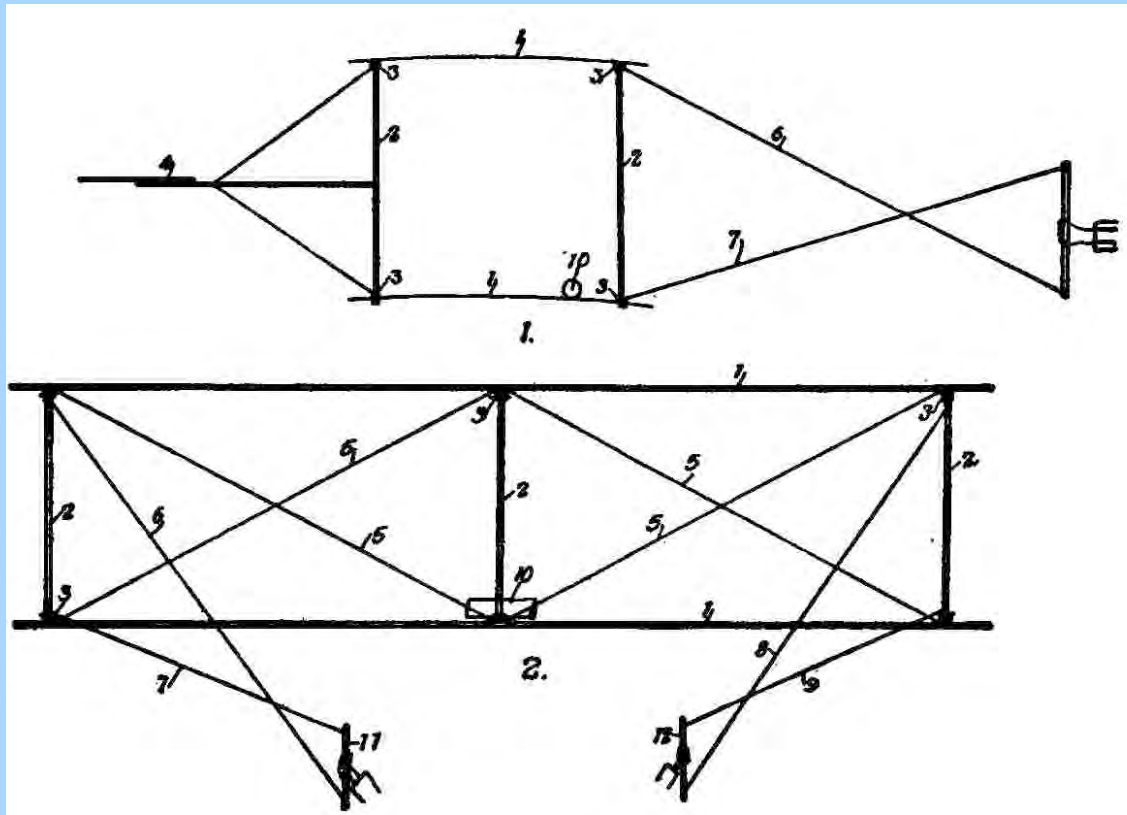




Inspiration: July 1899

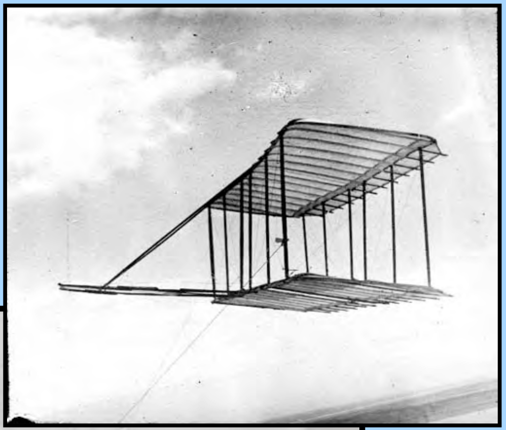
1899 Kite Experiments

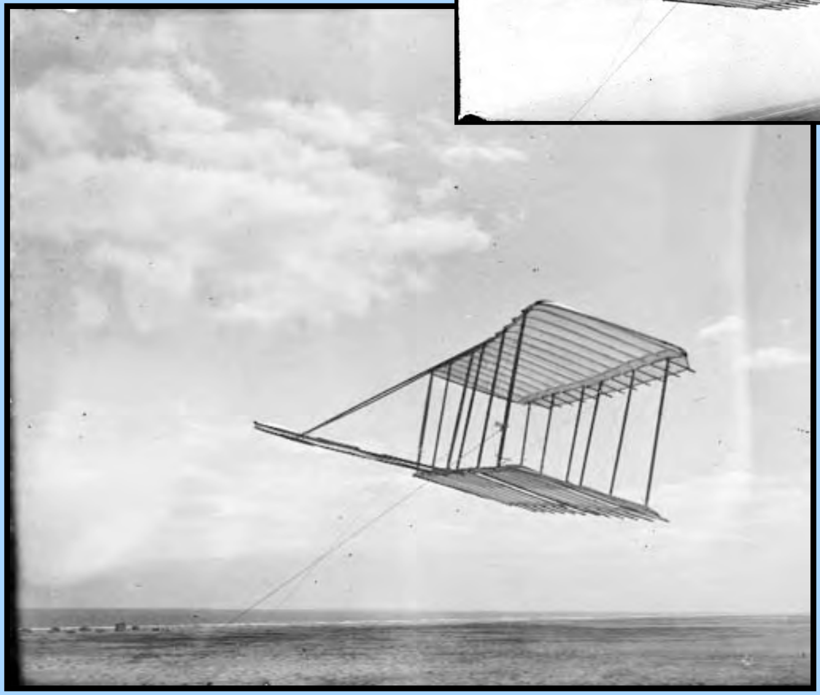
Dayton Ohio



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.

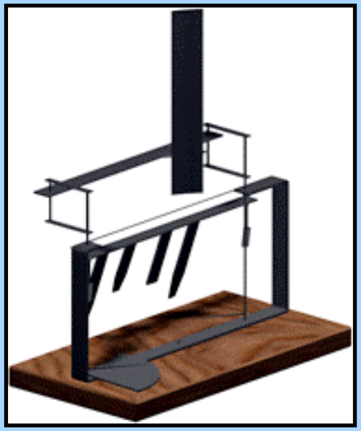
**On the train back to Dayton,
Wilbur tells Orville that men would
not fly for another fifty years...**

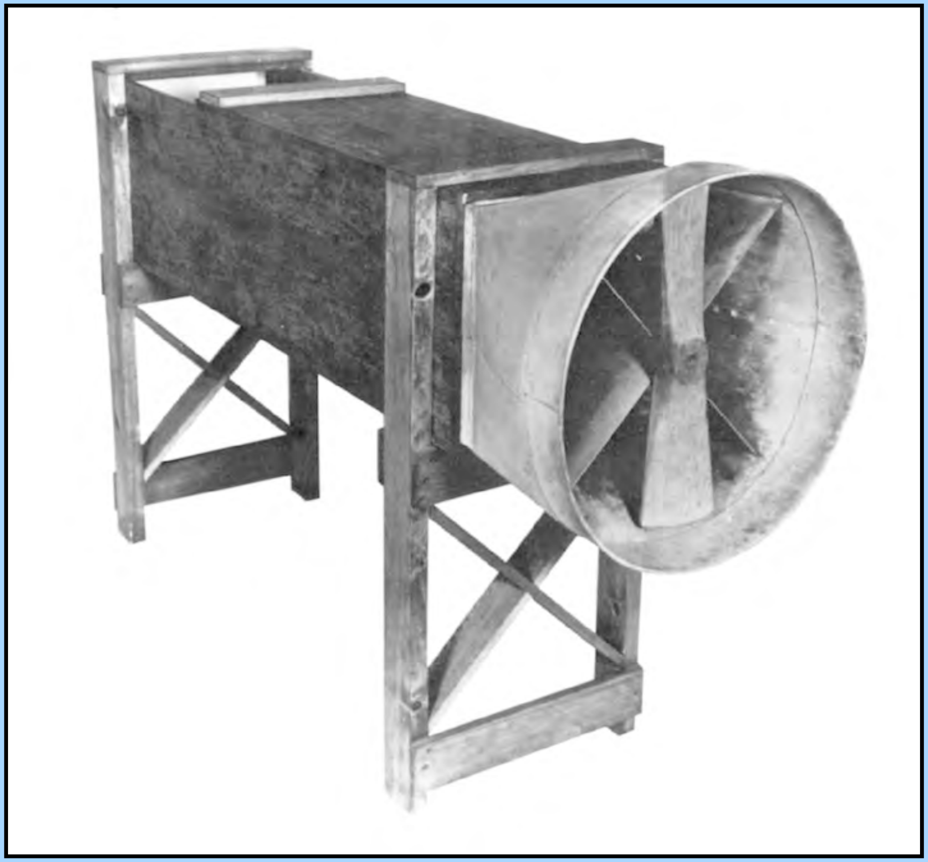
Dayton Experiments

October 1901

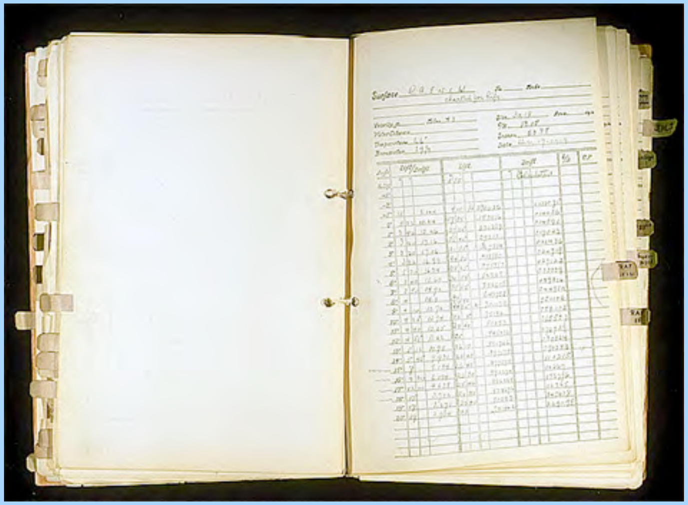
1901 Wind Tunnel

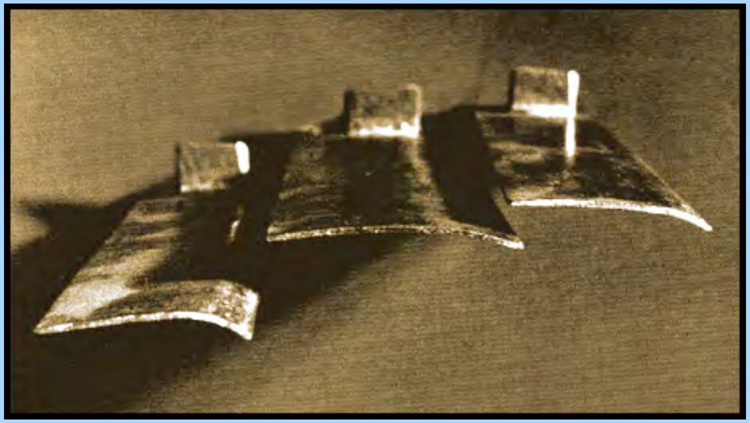
16 inch square section x 6 feet



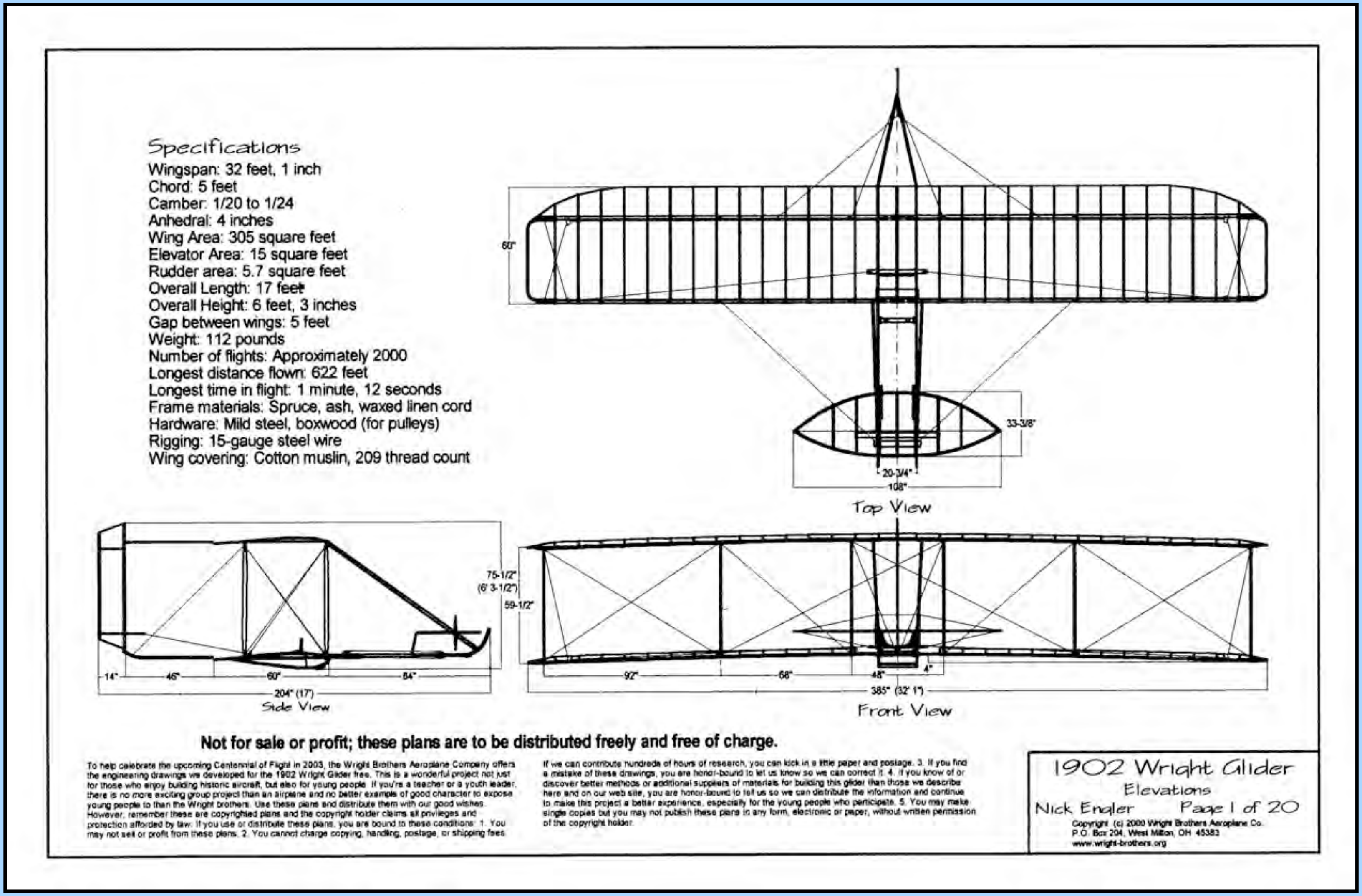


1901 Wright Wind Tunnel Results





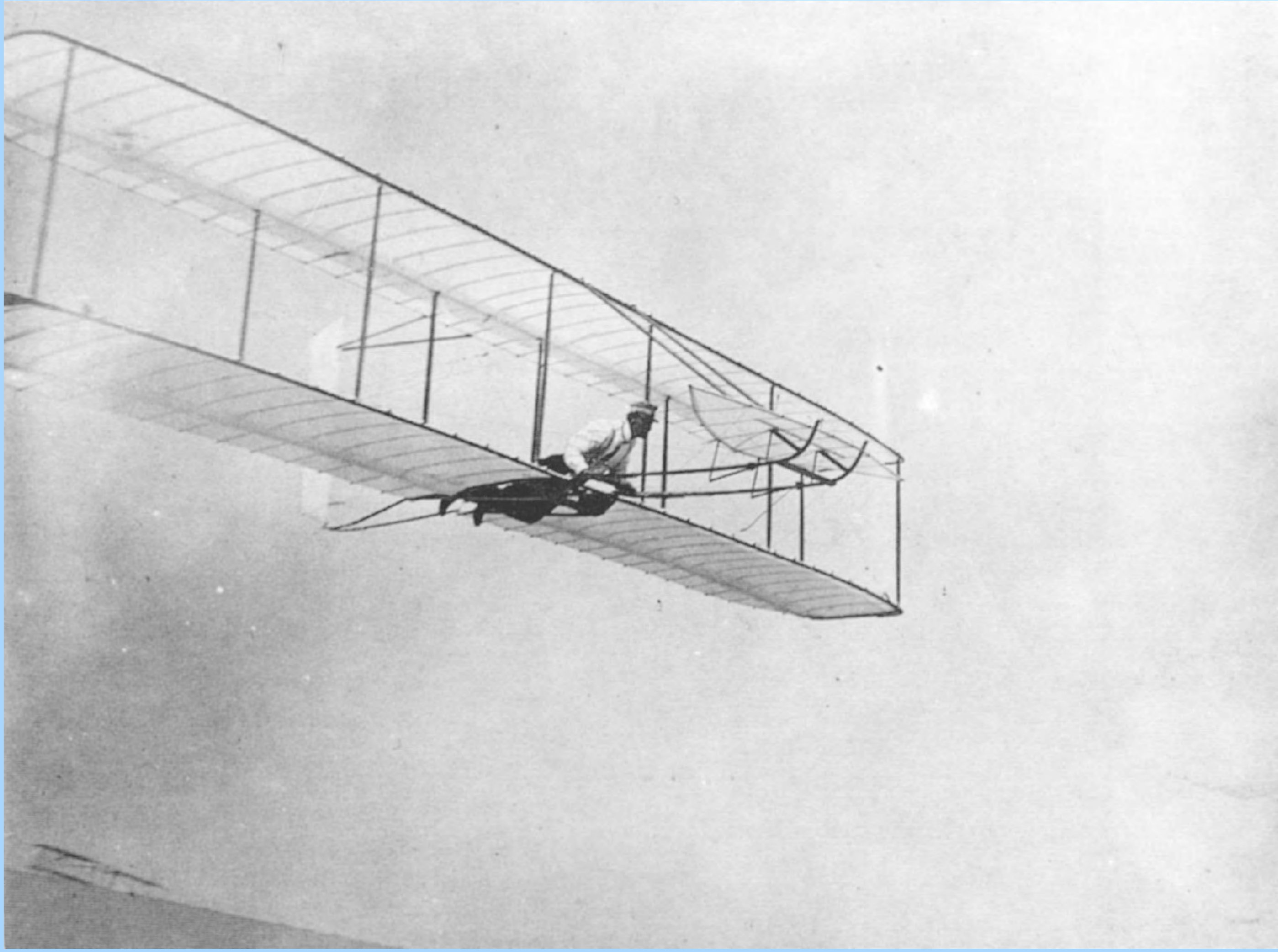
1902 Wright Glider



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

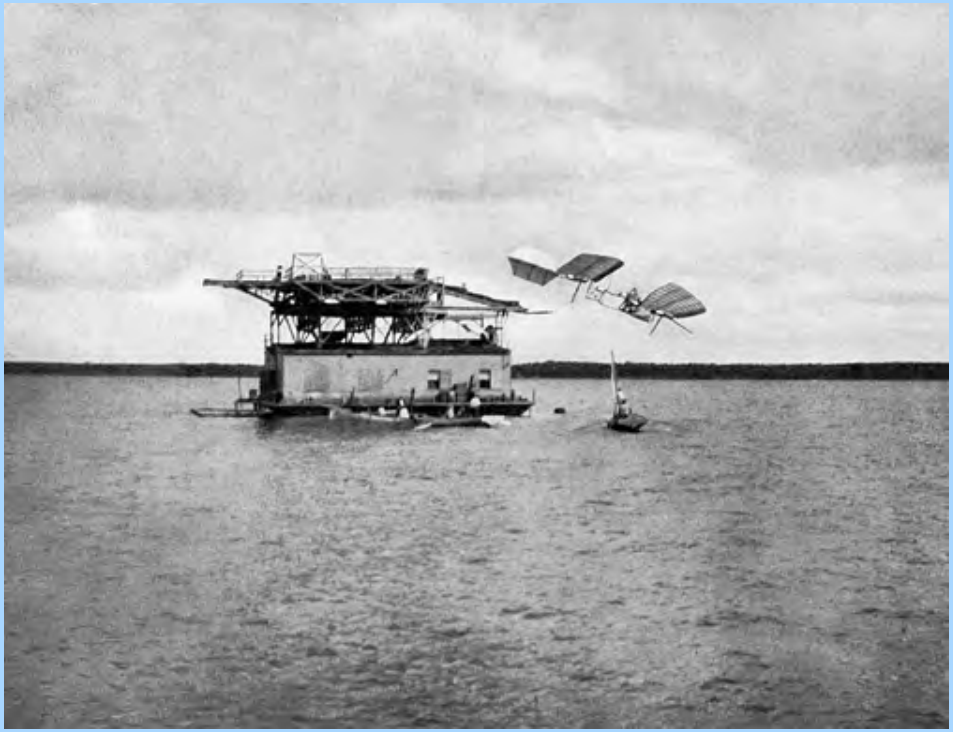
1902 Wright Glider



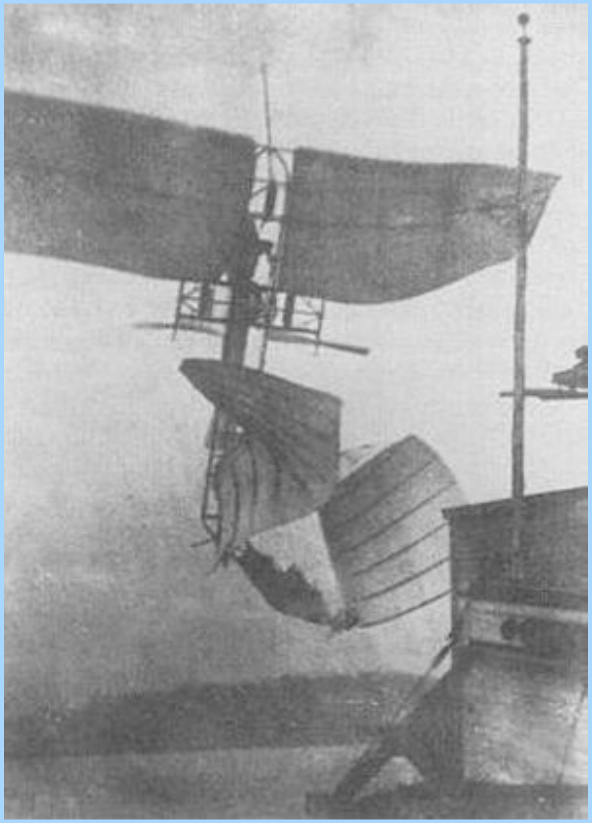
Centennial of Controlled Flight

24 October 1902

1903 Langley Aerodrome

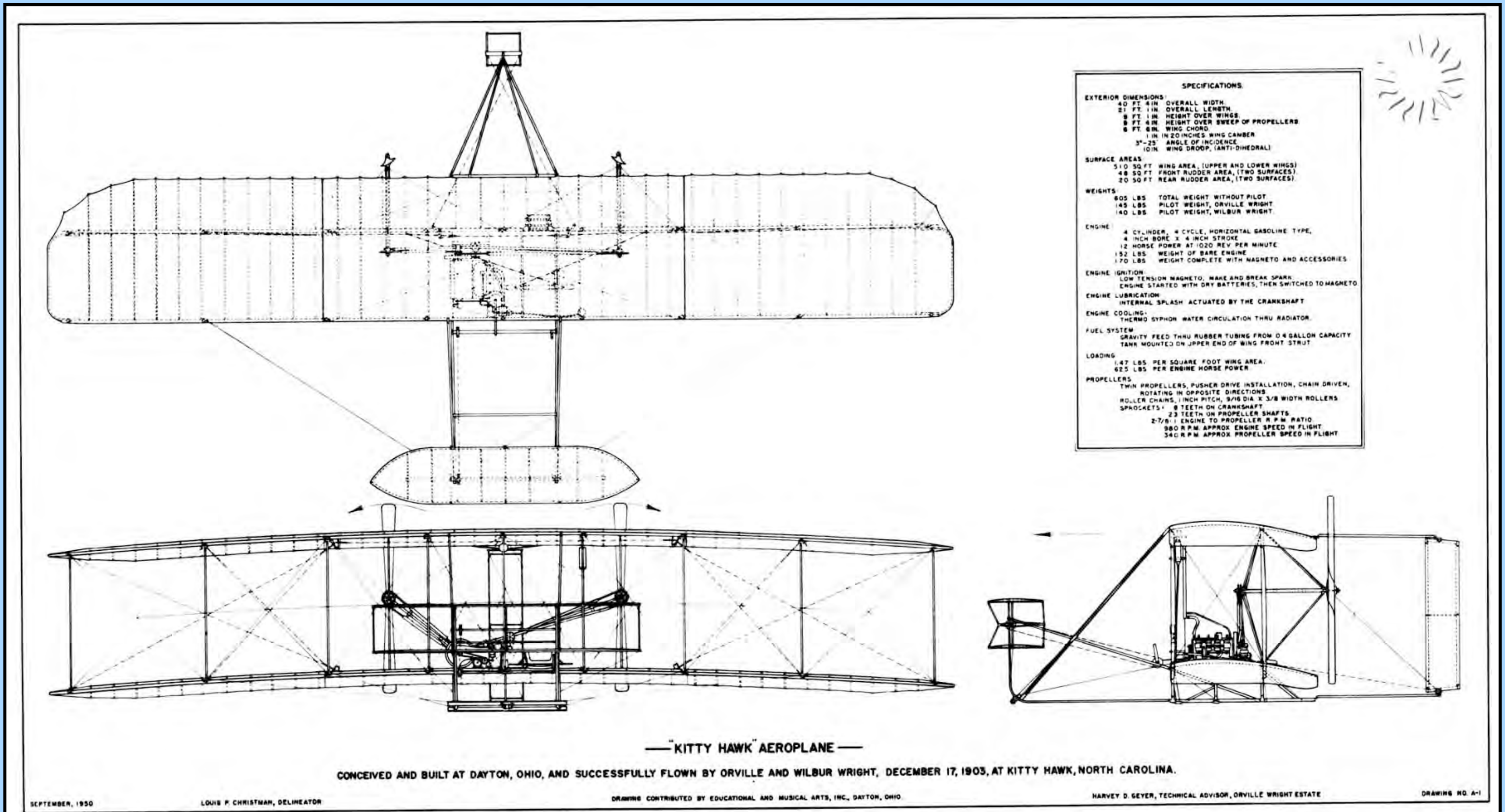


Oct 7, 1903



Dec 8, 1903

1903 Wright Flyer

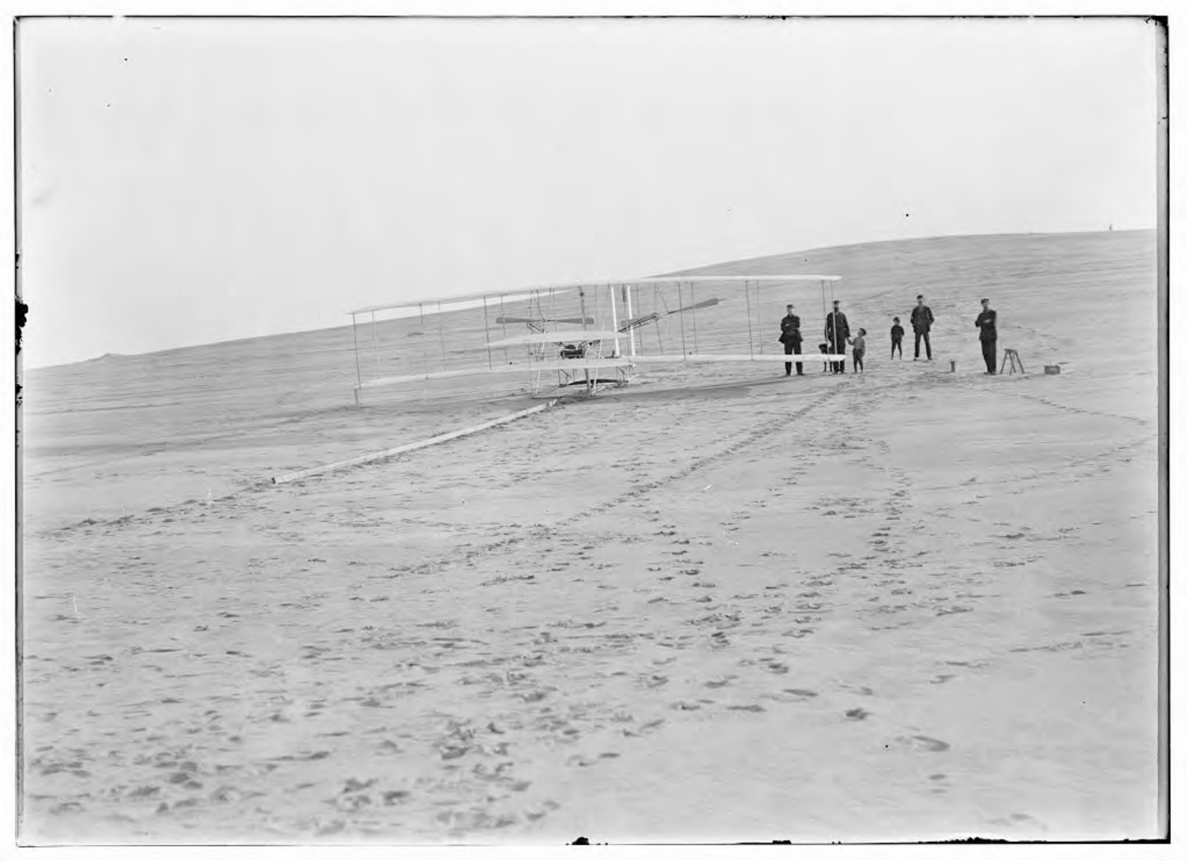


1903 Wright Flyer

- 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 21 sq ft
- Length 21 feet 1 inch
- Weight 605 lb

1903 Wright Flyer

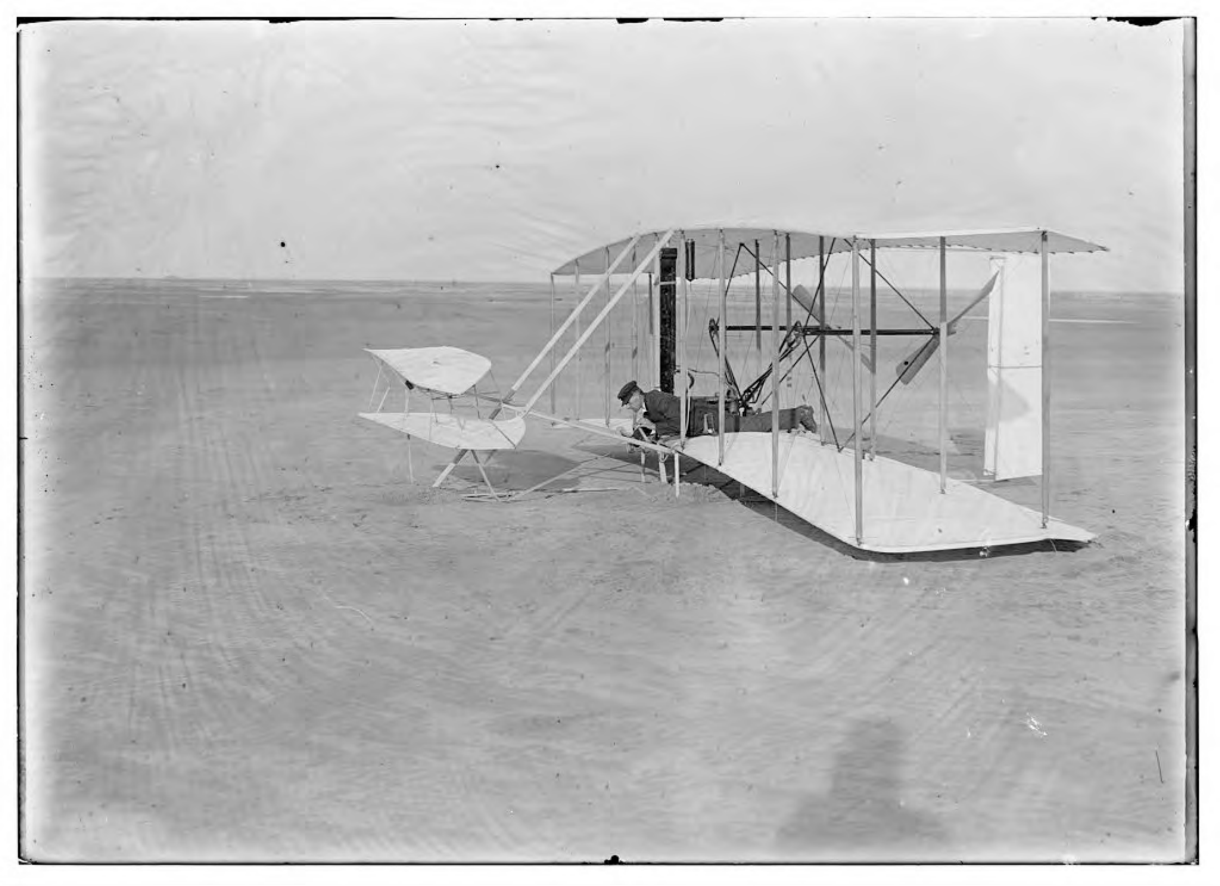
December 14, 1903



Wilbur wins the coin toss, and…

1903 Wright Flyer

December 14, 1903



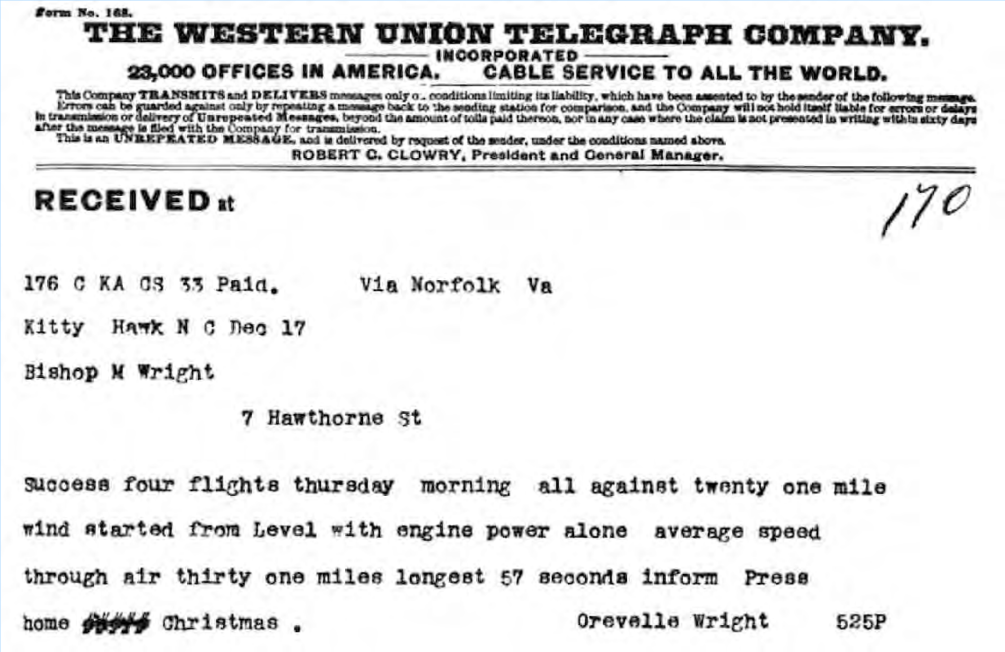
Oops!

1903 Wright Flyer

December 17, 1903

1903 Wright Flyer

They tell the world...



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ROBERT C. CLOWRY, President and General Manager.

RECEIVED at 170

176 C KA CS 33 Paid. Via Norfolk Va

Kitty Hawk N C Dec 17

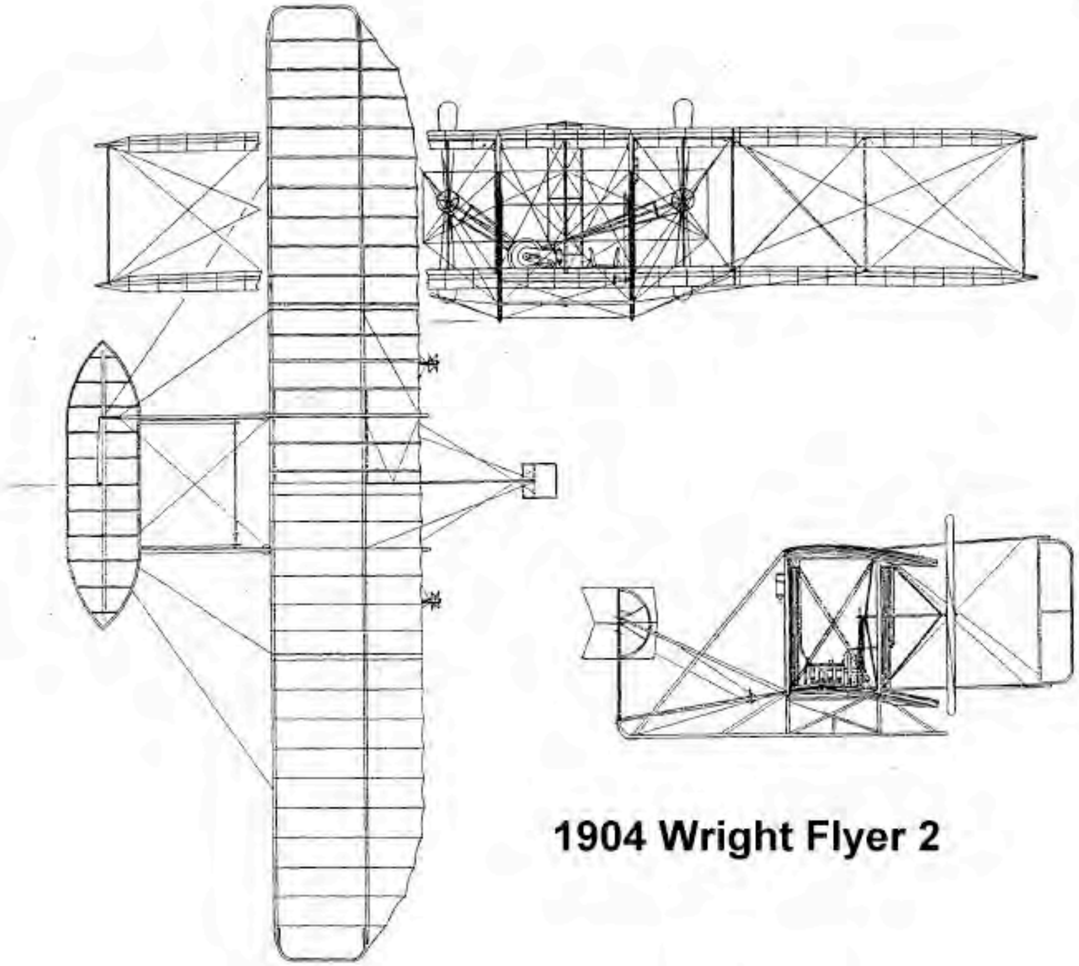
Bishop M Wright

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 525P

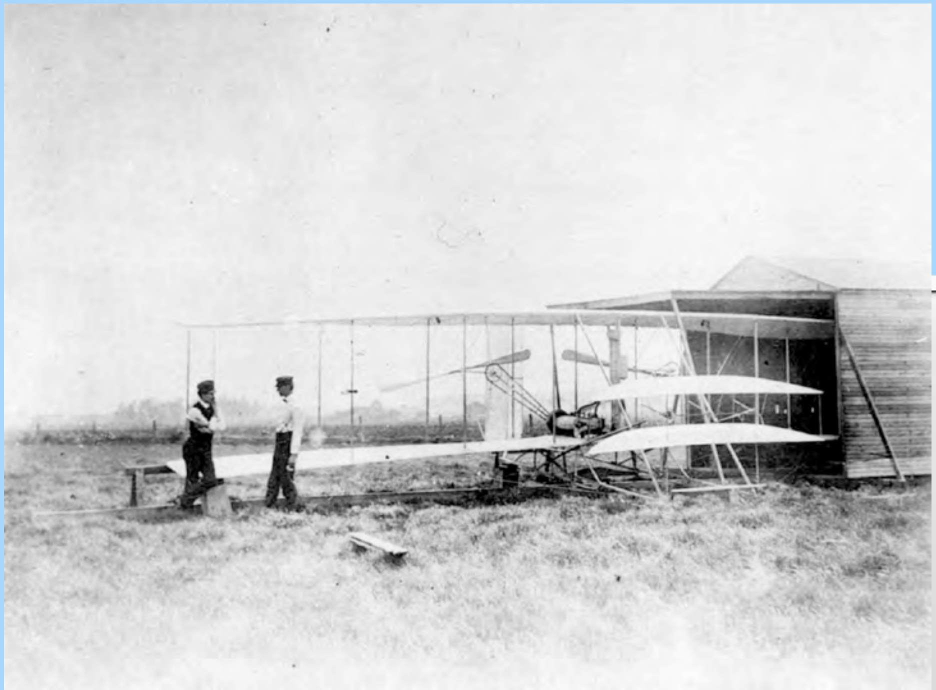
1904 Wright Flyer

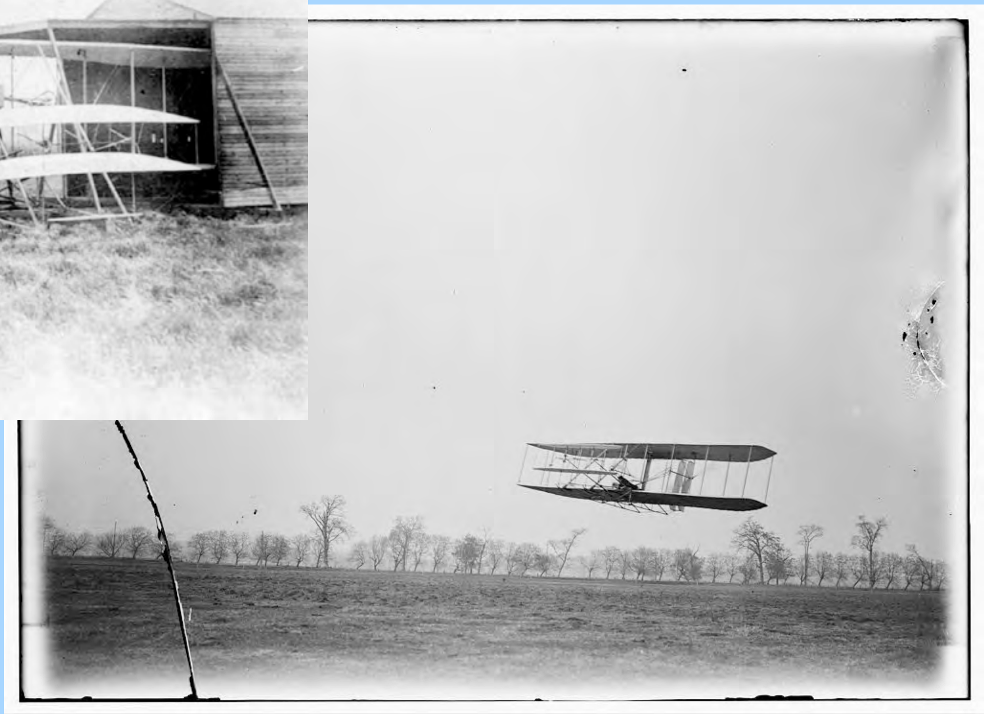


1904 Wright Flyer 2

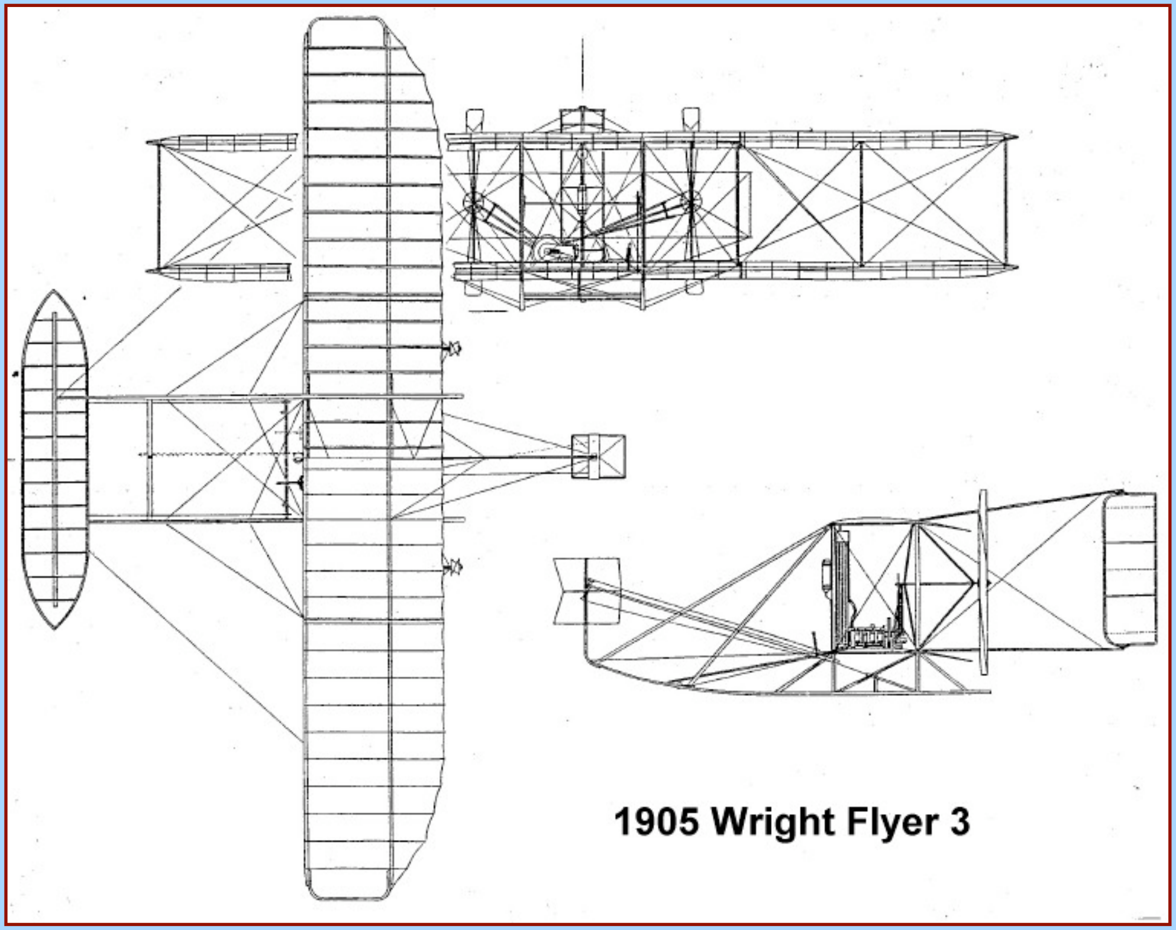
1904 Huffman Prairie Ohio

September 20, 1904 First Complete Circle in an Airplane





1905 Wright Flyer



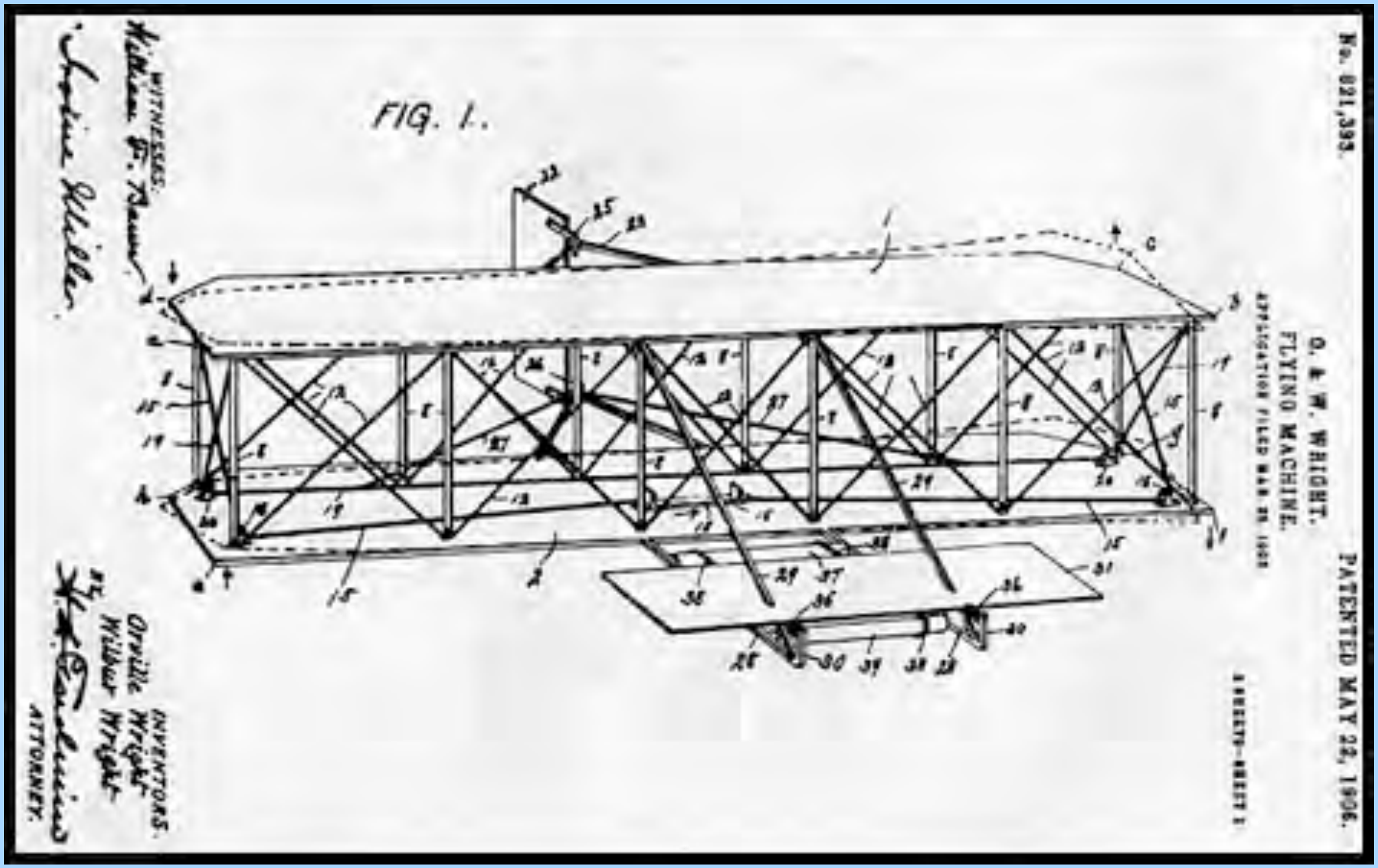
1905 Huffman Prairie OH

Oct 4, 1905 Extended Flight in an Airplane (38 minutes)

Wright Flying Machine Patent

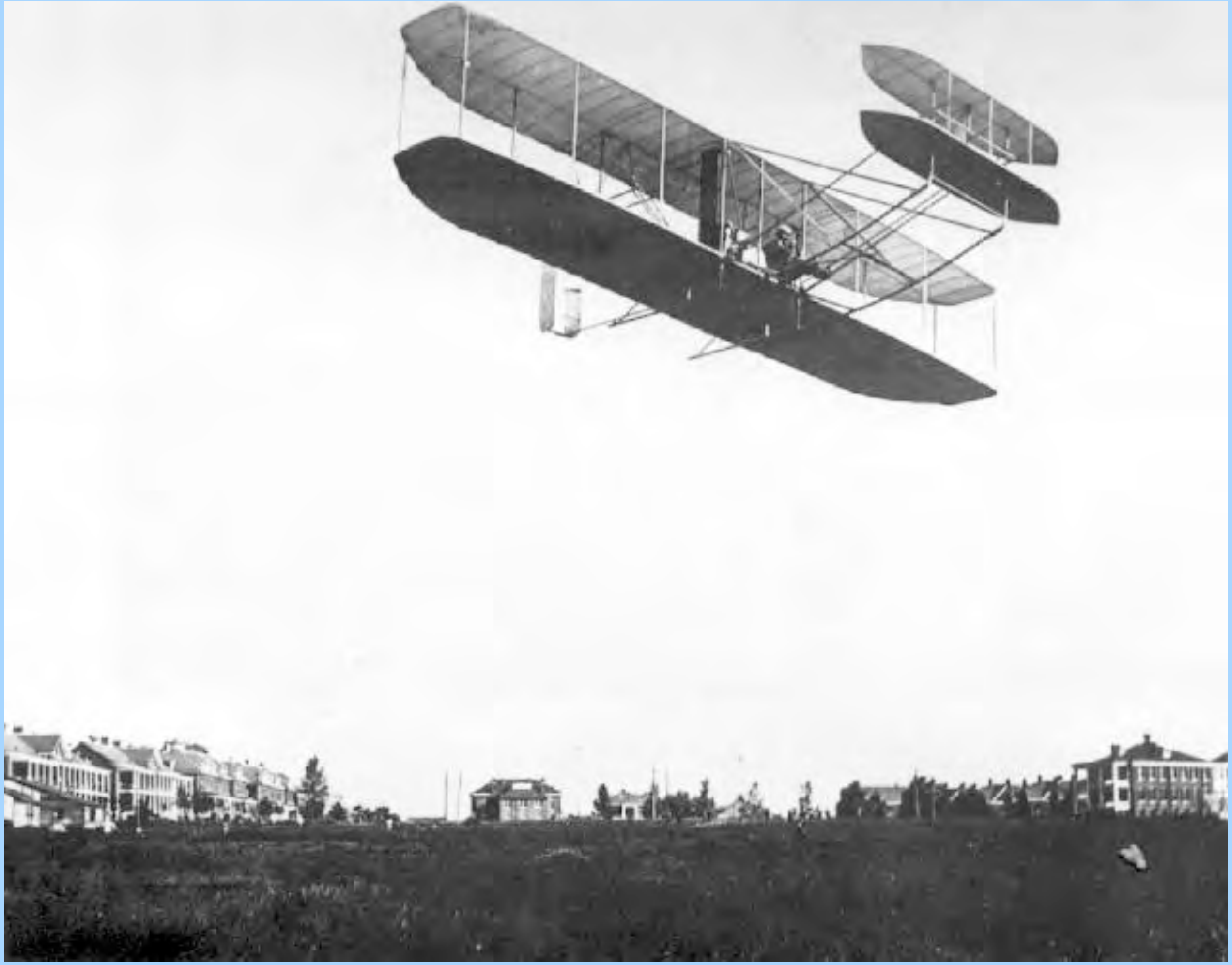
#821, 393

May 22, 1906



1908-1909 France & Virginia

Public trials of the first practical airplane

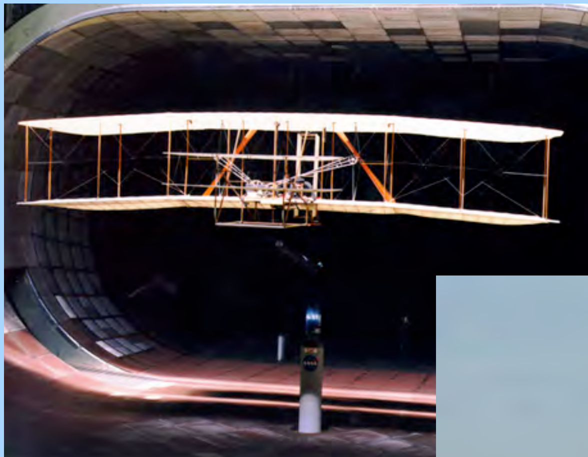


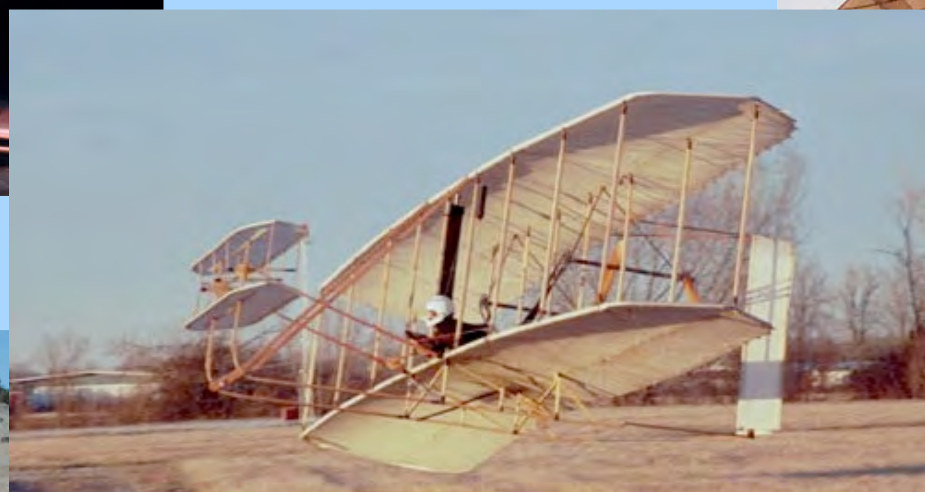
The Rest is History...

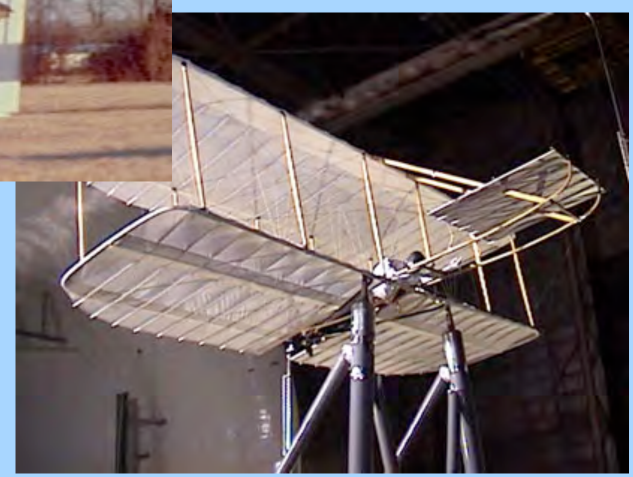
NACA Board, 1938

- 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

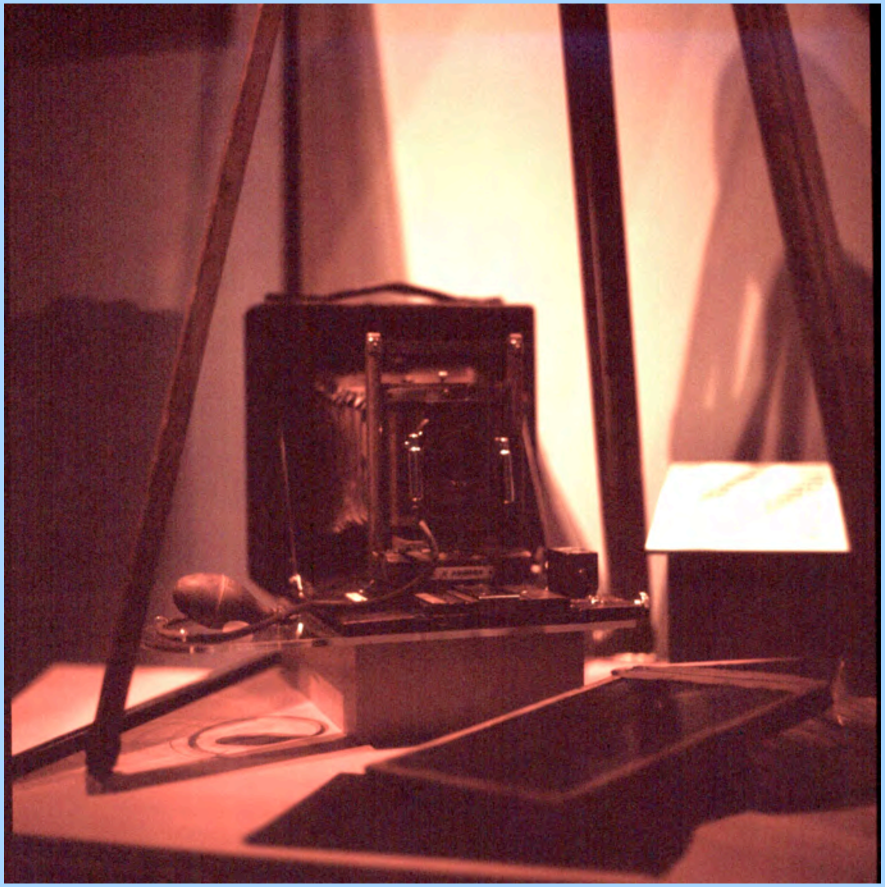
1903 Wright Flyer I
National Air & Space Museum

1905 Wright Flyer III
Carillon Hall

Orville Wright

Wilbur Wright.

Orville’s Camera: 1902 to 1905

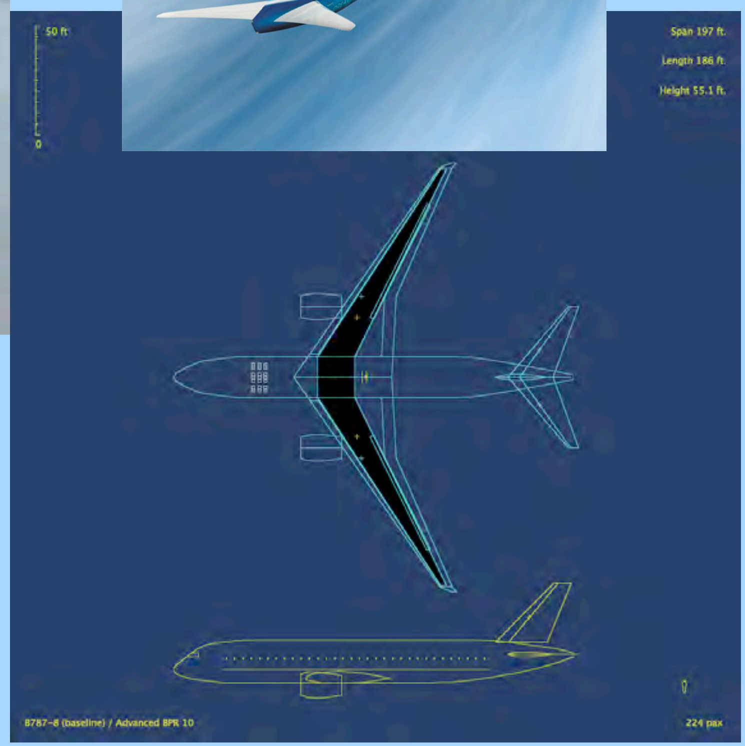


The Wrights to Today

- 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

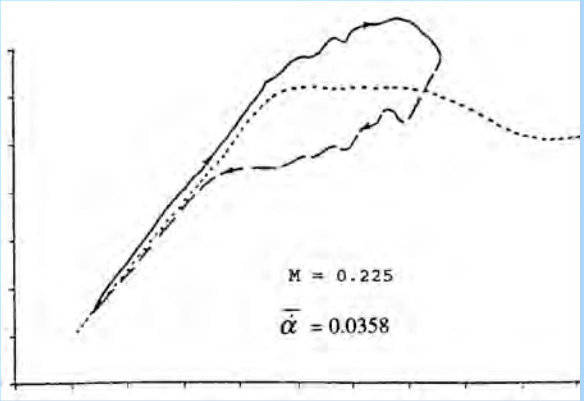
- The Wrights dis-integrated the bird
- It is time to re-integrate the bird

"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



Dynamic Lift

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

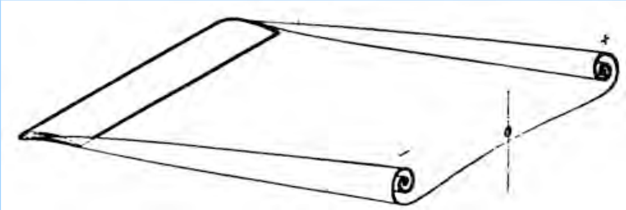
Practical Spanload Developments

- 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

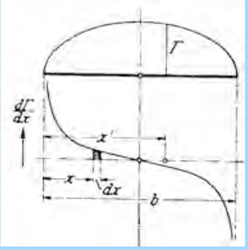
- Robert T Jones
  Spanload for minimum induced drag and wing root bending moment
  Application of wing root bending moment is less general than Prandtl's
  No prior knowledge of Prandtl's work, entirely independent (1950)

- 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”

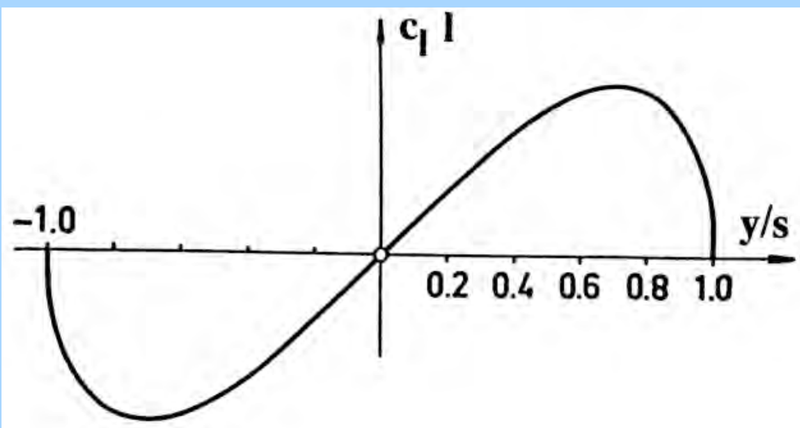


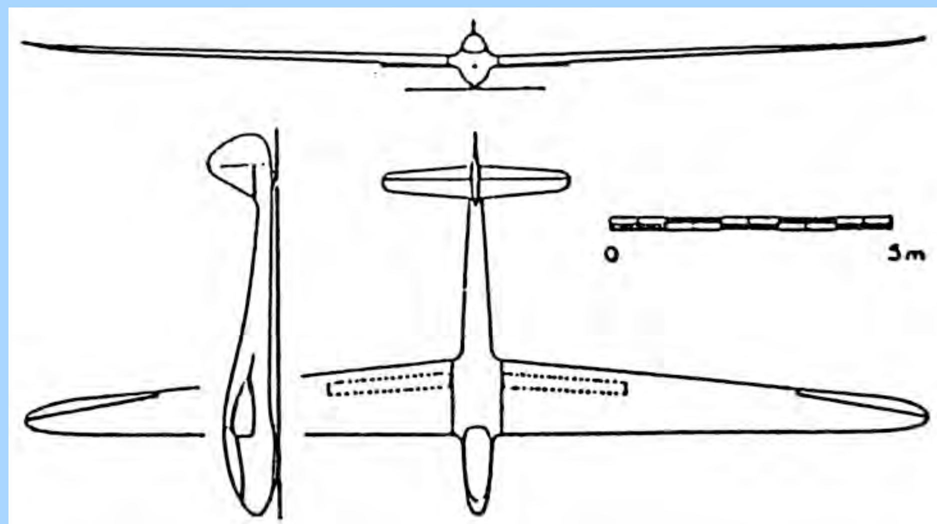
- Elliptical spanload (1914)

- “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

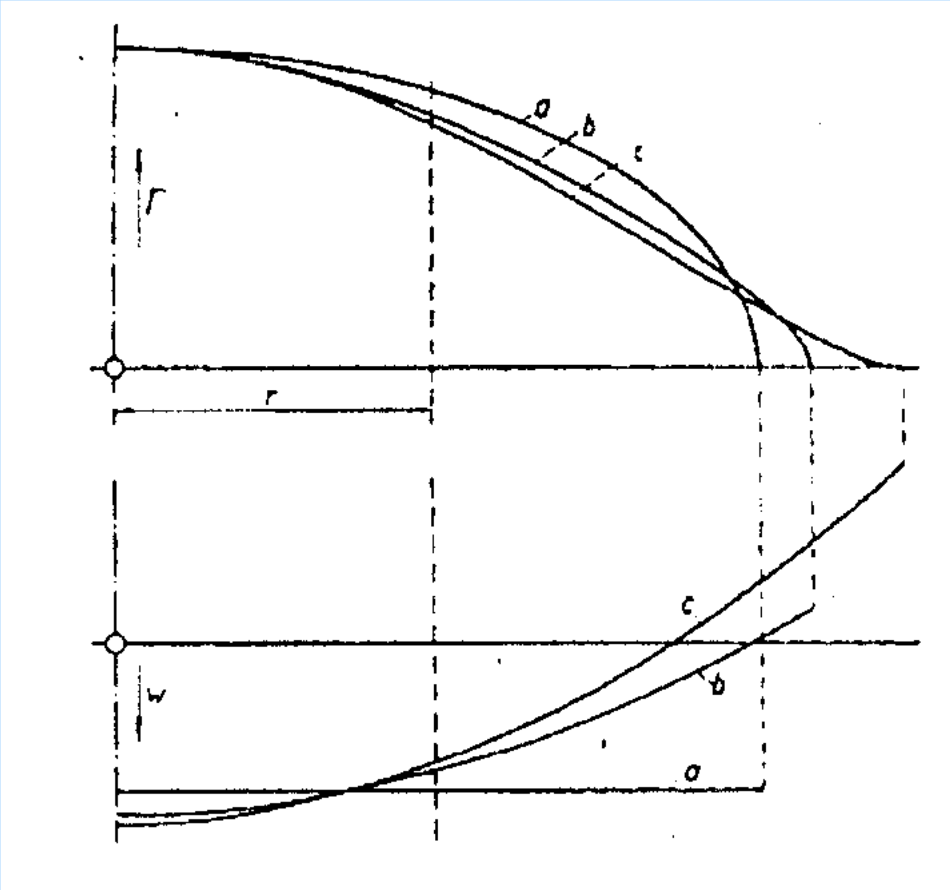
- Minimum induced drag for given control power (roll)
- Dr Richard Eppler: FS-24 Phoenix





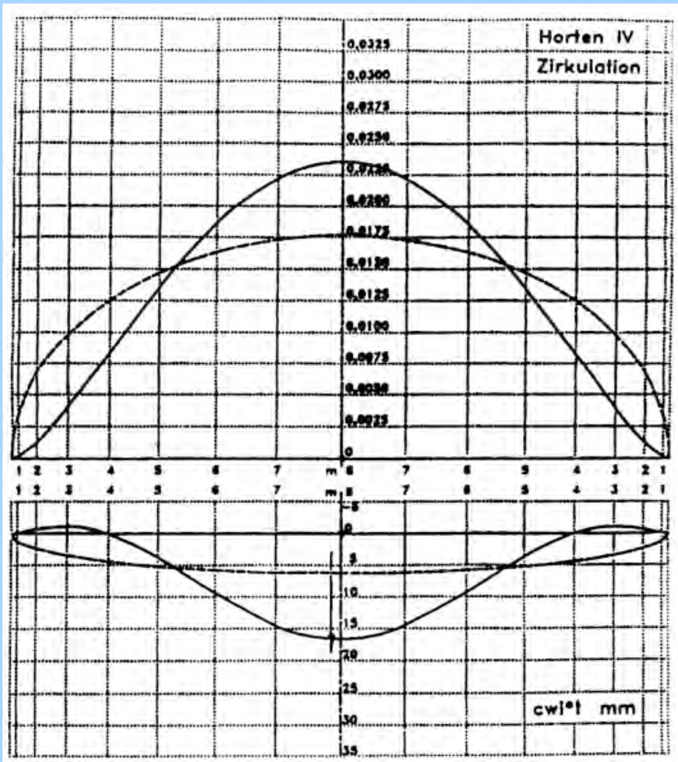
Elliptical Spanloads

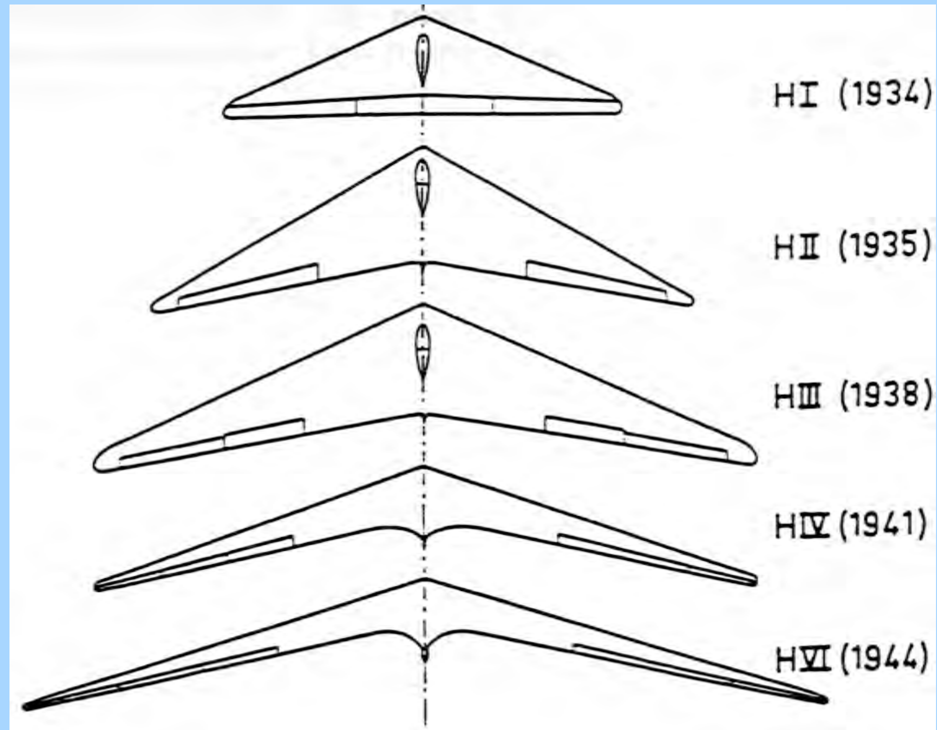
Minimum Induced Drag & Bending Moment



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

Horten Applies Prandtl's Theory

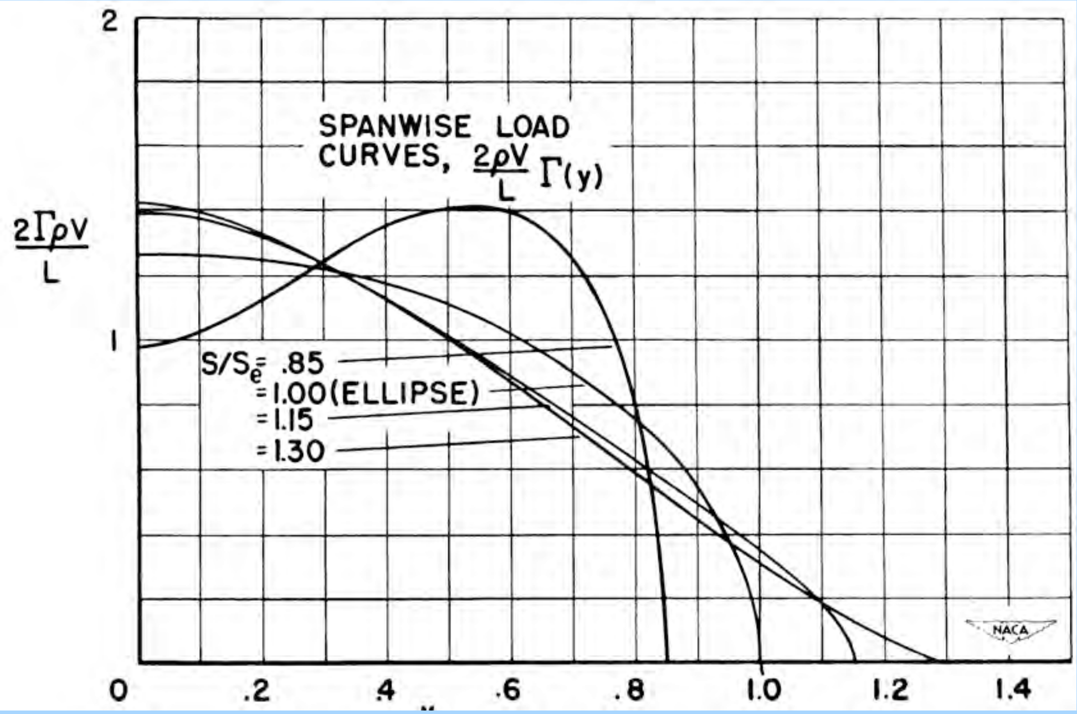




Horten Sailplanes

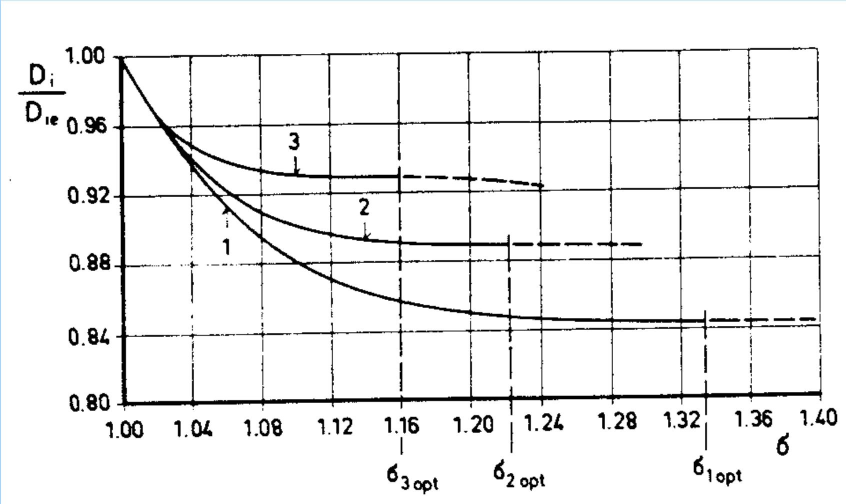
- Horten Spanload (1940-1955)
  induced thrust at tips
  wing root bending moment

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

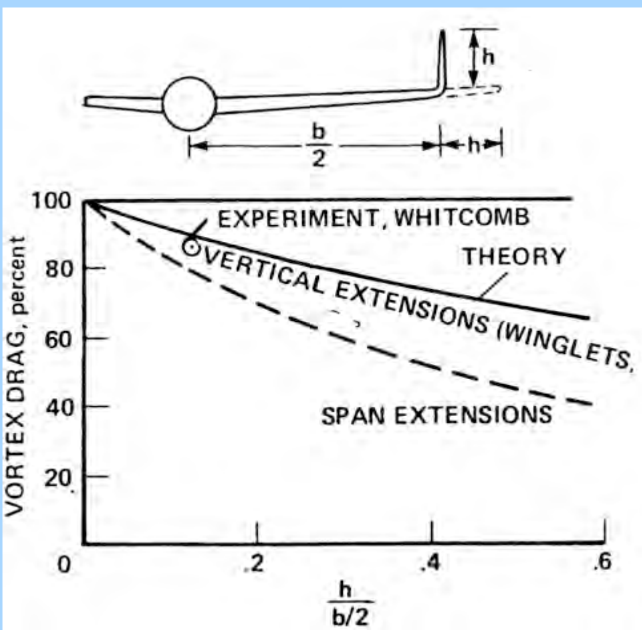
Klein and Viswanathan

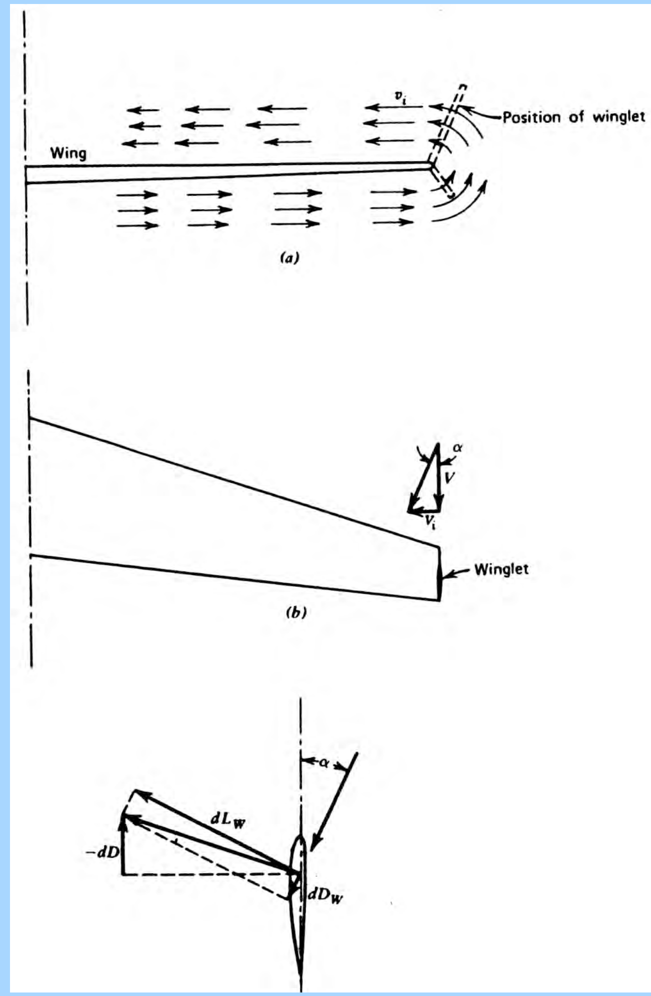


- Minimize induced drag (1975)
  Constrain bending moment
  Constrain shear stress
  16% increase in span with 7% decrease in induced drag
- "Hence the required downwash-distribution is parabolic." $y = ax^2 + bx + c$

Winglets

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





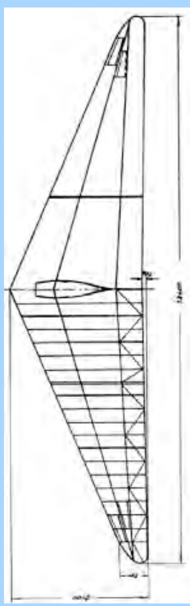
Winglet Aircraft

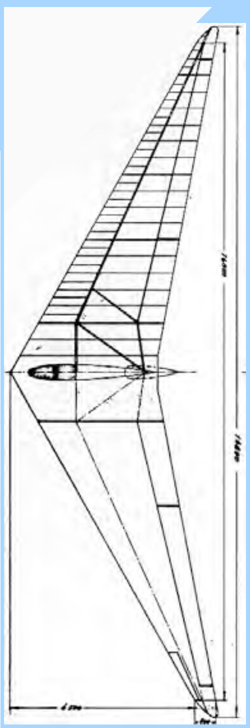
Spanload Summary

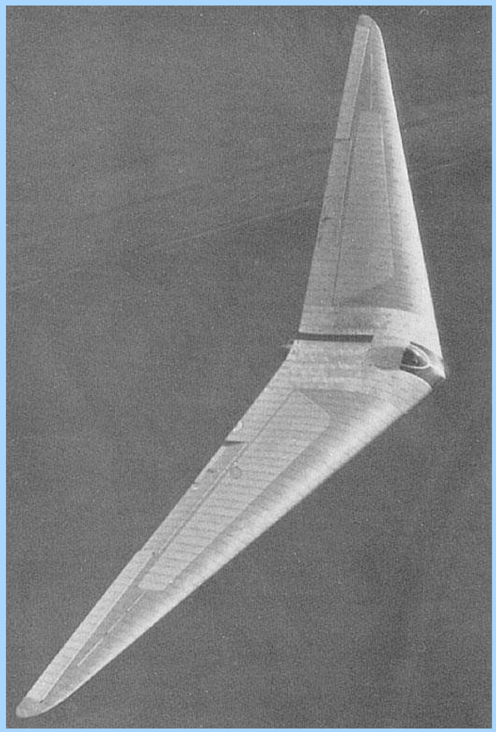
- Prandtl/Munk (1914)
  Elliptical
  Constrained only by span and lift
  Downwash: $y = c$
- Prandtl/Horten/Jones (1932)
  Bell shaped
  Constrained by lift and bending moment
  Downwash: $y = bx + c$
- Klein/Viswanathan (1975)
  Modified bell shape
  Constrained by lift, moment and shear (minimum structure)
  Downwash: $y = ax^2 + bx + c$
- Whitcomb (1975)
  Winglets
- Summarized by Jones (1979)

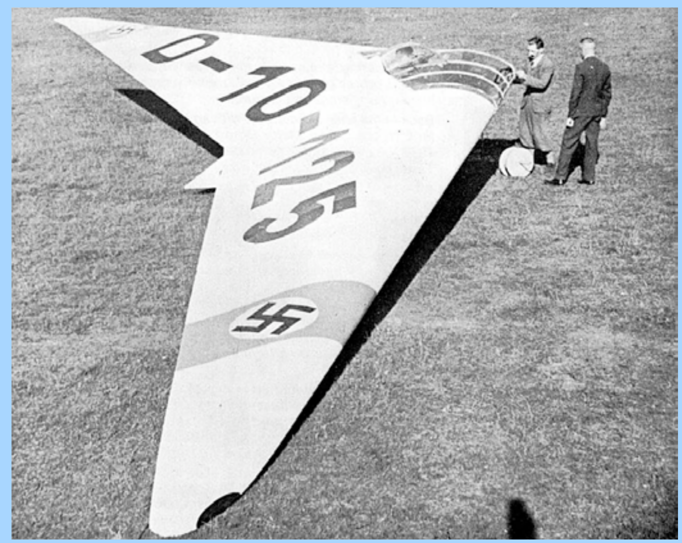
Early Horten Sailplanes (Germany)

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



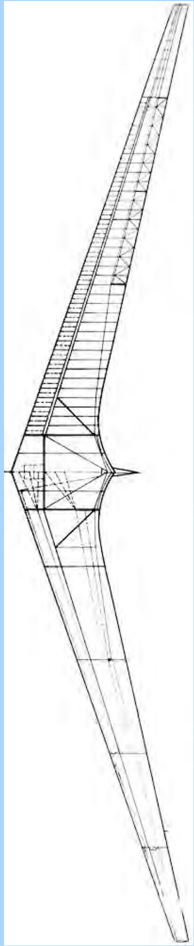


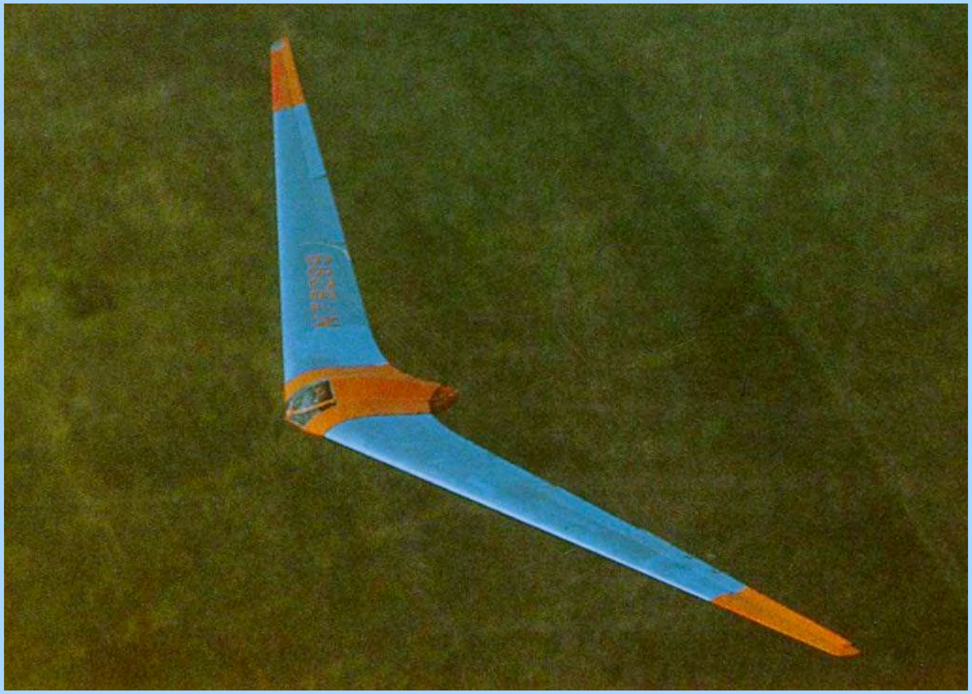




Horten Sailplanes (Germany)

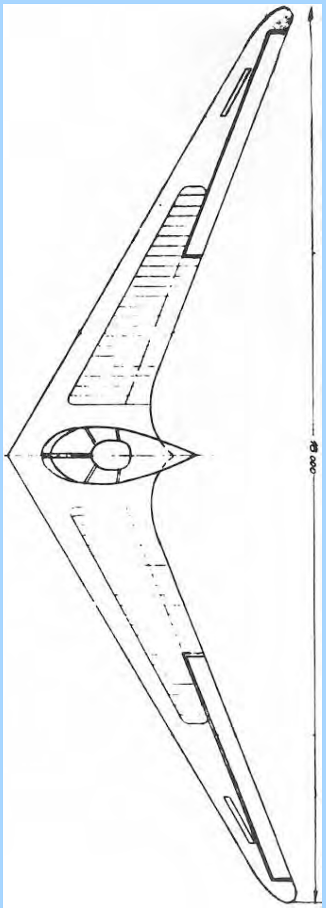
- H IV - 20m span
- H VI - 24m span

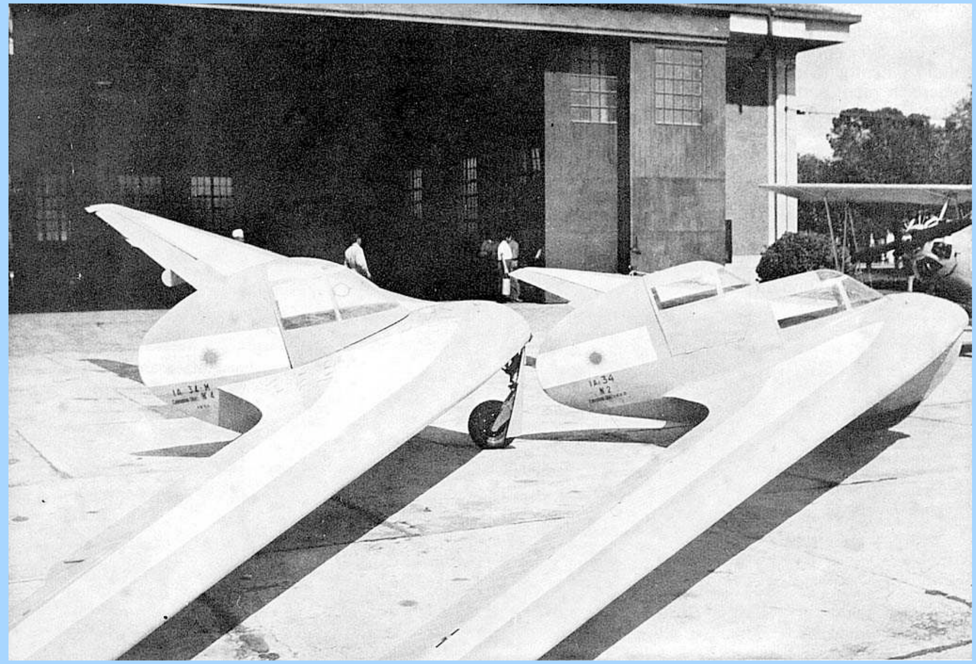




Horten Sailplanes (Argentina)

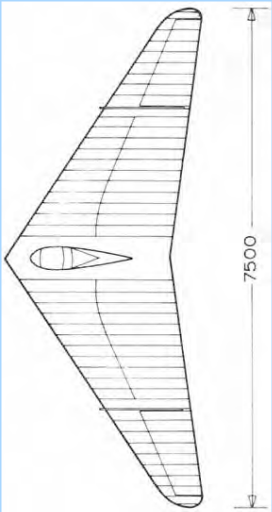
- H I b/c - 12m span
- H XV a/b/c - 18m span

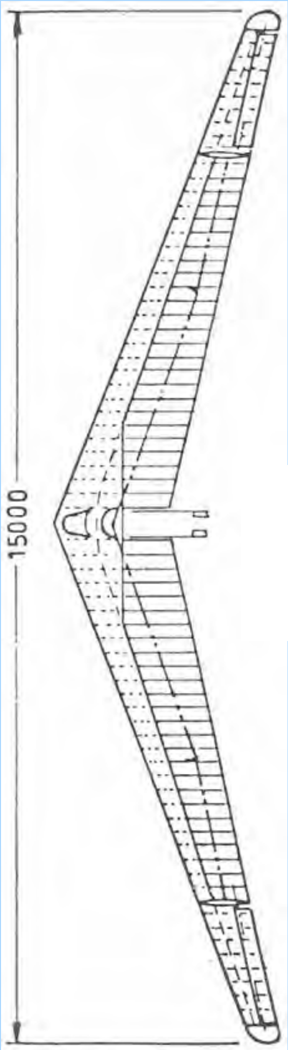


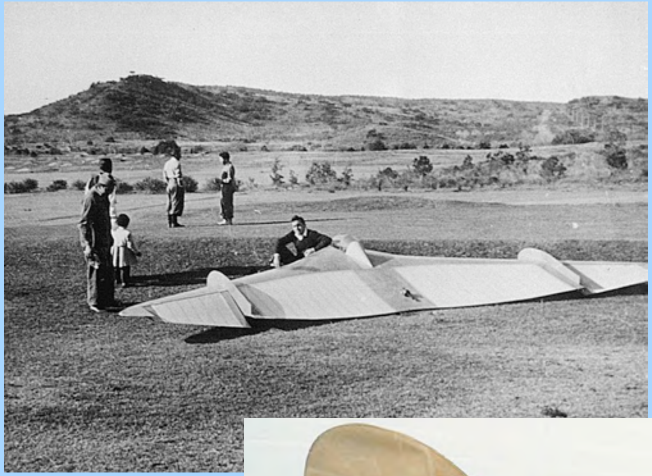


Later Horten Sailplanes (Argentina)

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





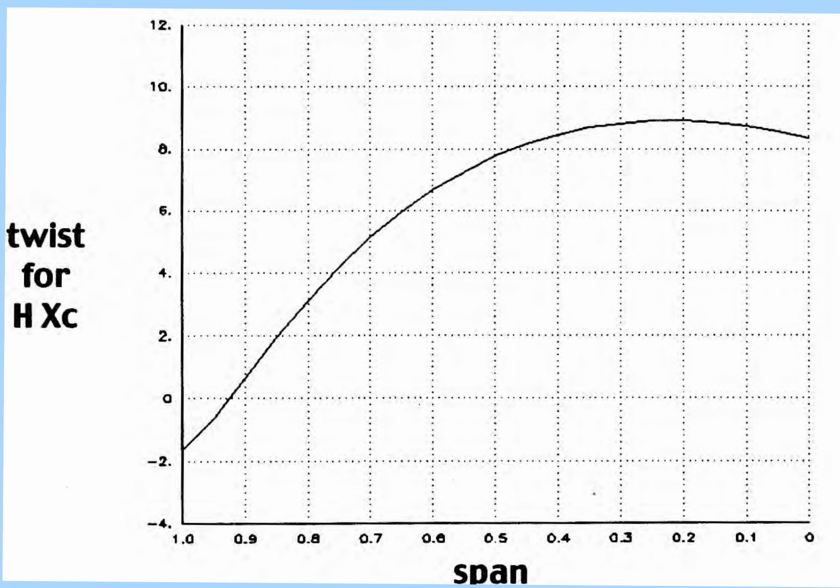


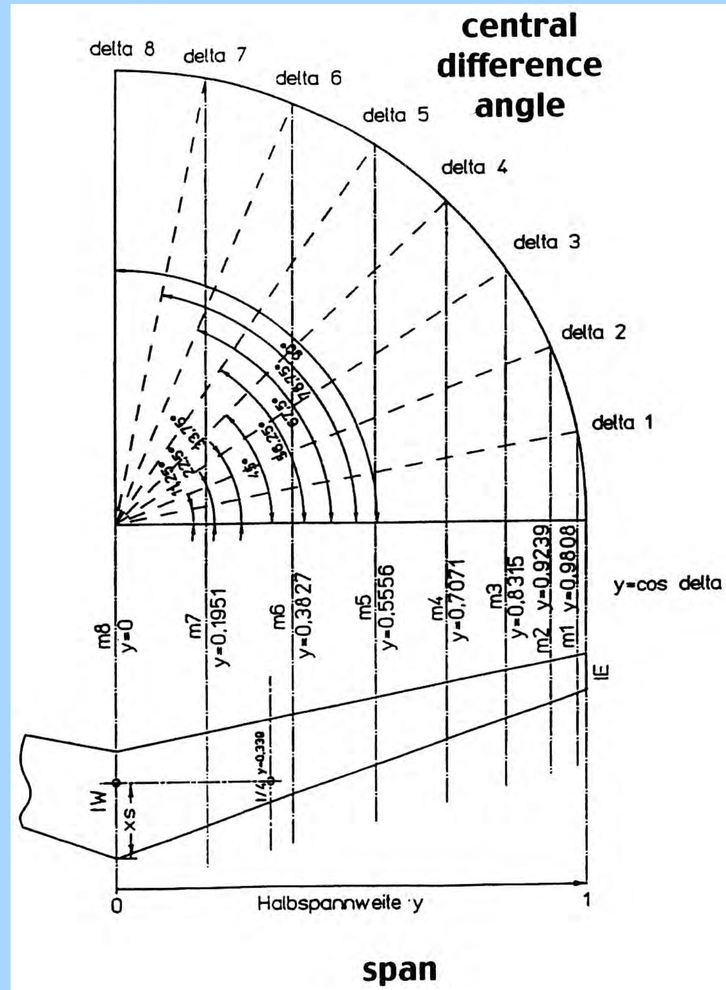
Bird Flight Model

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

Calculation Method

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

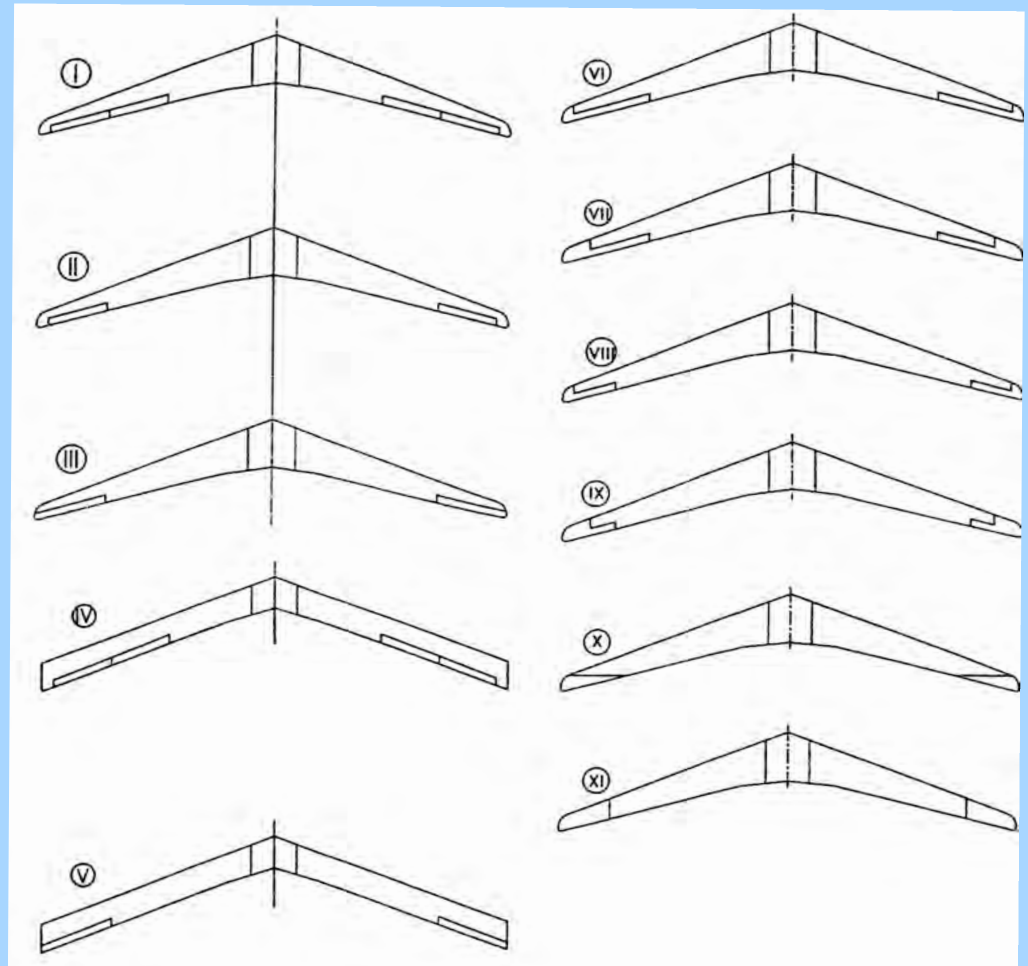




Dr Edward Udens' Results

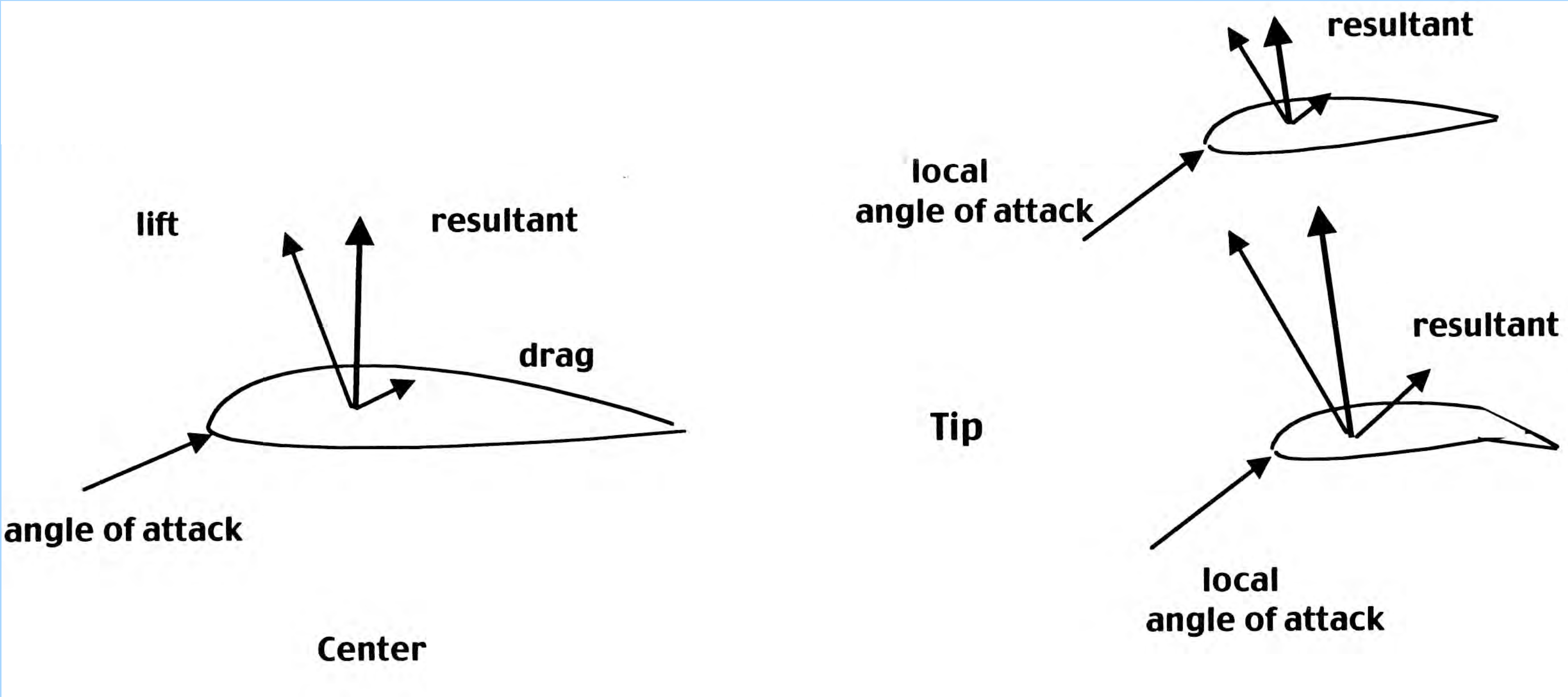
- Spanload and Induced Drag
- Elevon Configurations
- Induced Yawing Moments

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



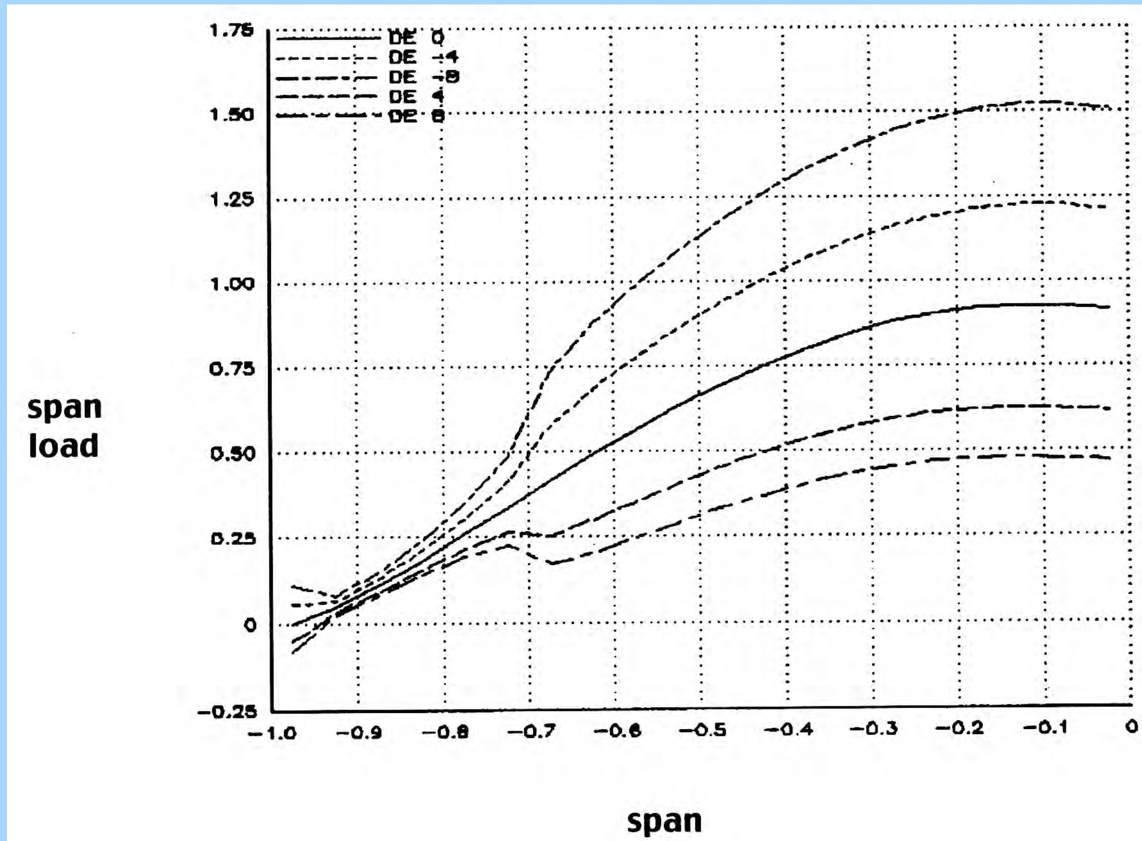
Horten H Xc Wing Analysis

- 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



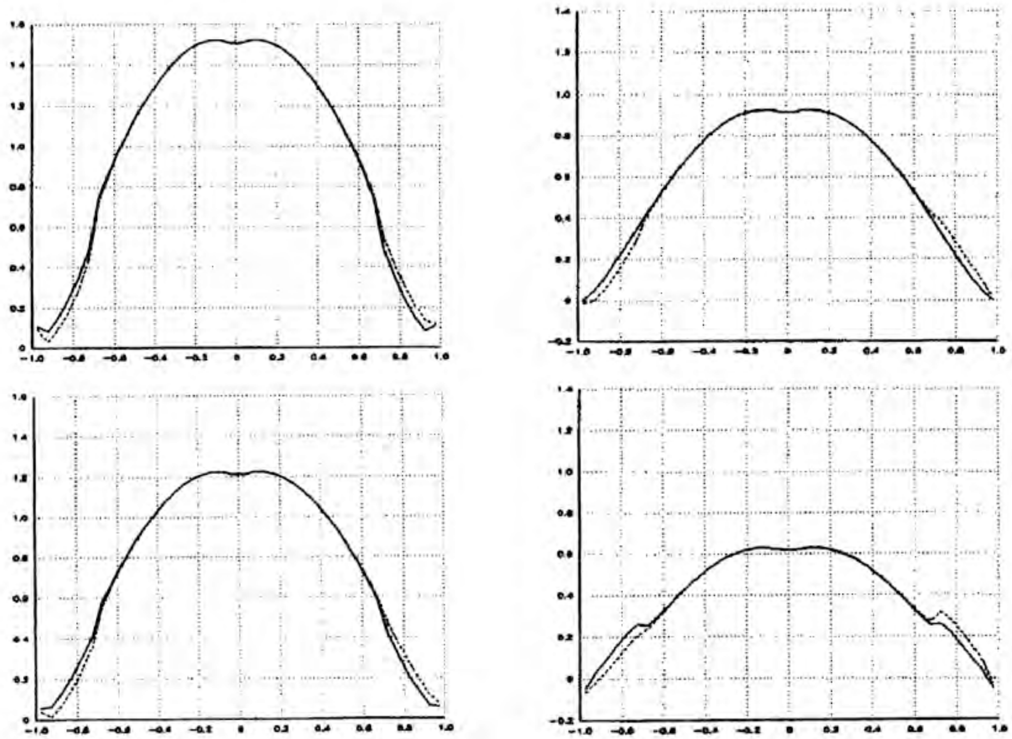
Symmetrical Spanloads

- Elevon Trim
- CG Location

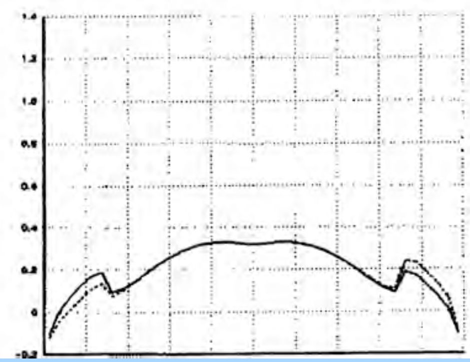


Asymmetrical Spanloads

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



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



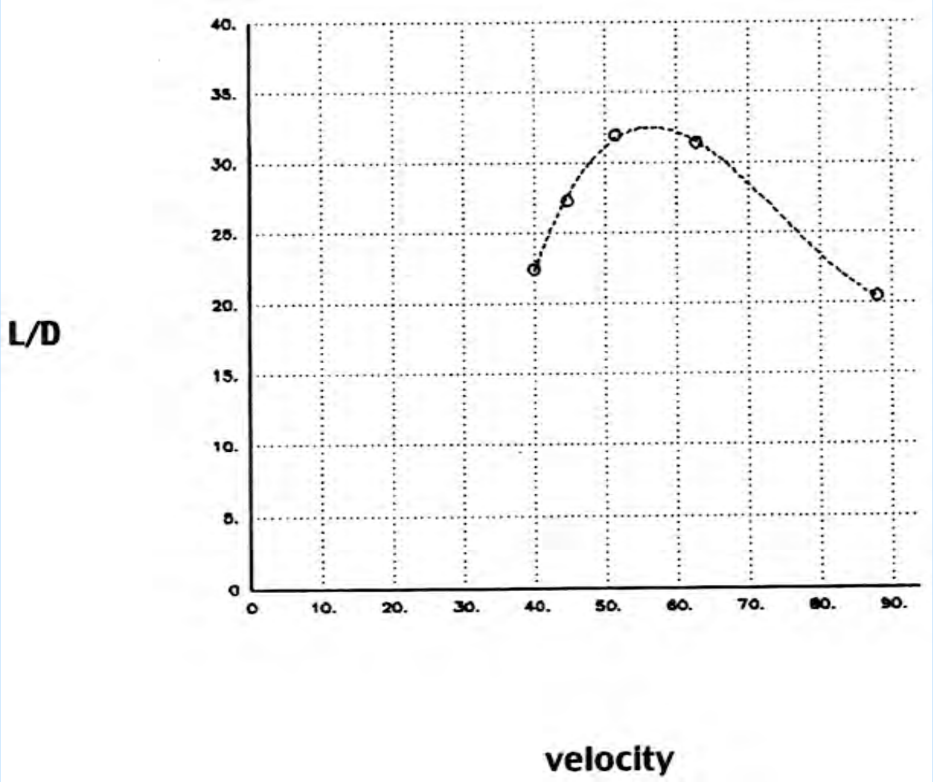
Airfoil and Wing Analysis

- 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

Dynamic Lift: Flapping Wings

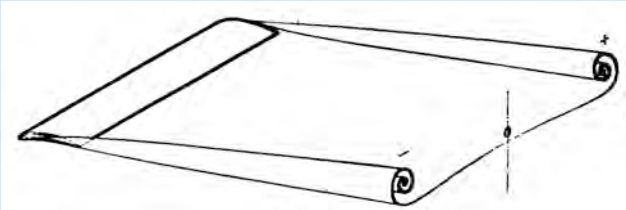
- What is the mechanism for flapping flight?
  - dynamic lift
  - start-up vortex
  - Strouhal number

Dynamic Lift

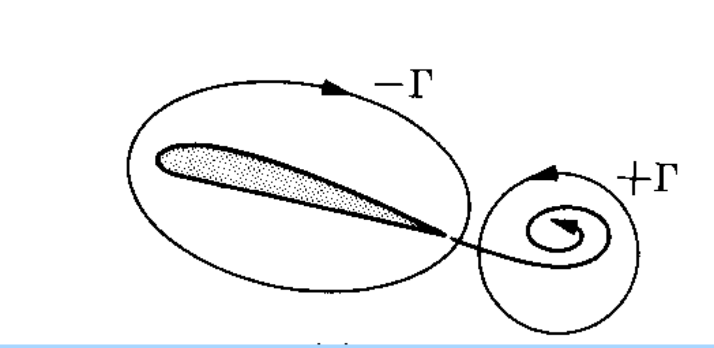
- Riddle of the bumblebee

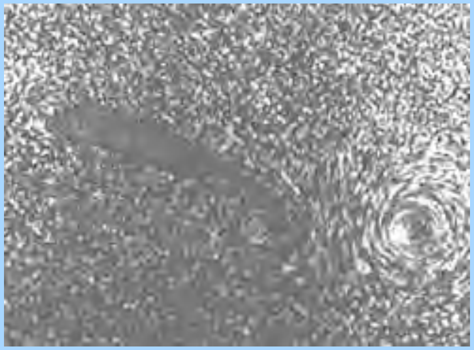
- Dynamic lift or delayed stall
  - transient lift coefficient in excess of steady-state maximum lift coefficient

Start-Up Vortex



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





Start-Up Vortex

- Rowing
- Paddling
- Sailing
- Swimming

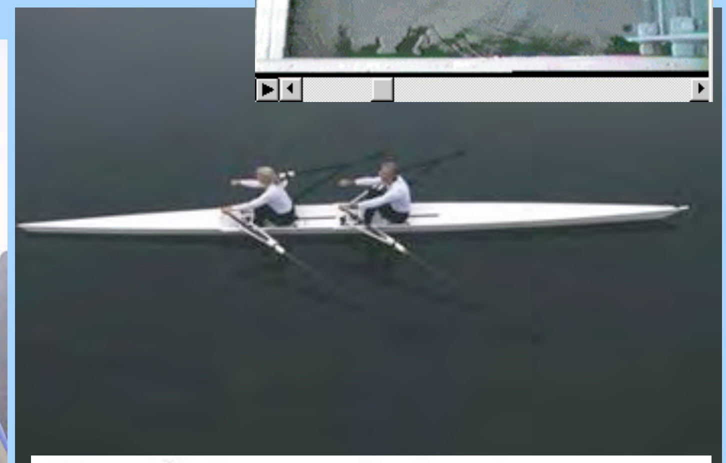


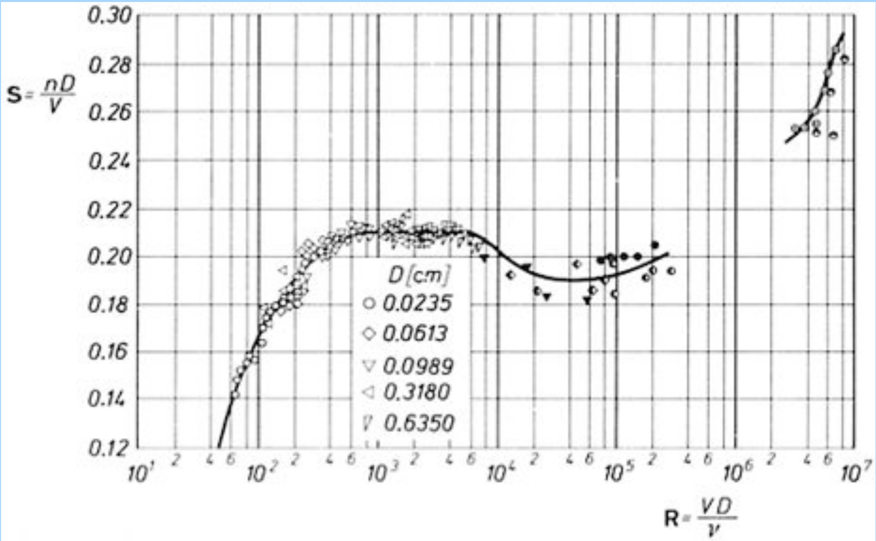
Figure 2 Sketches of the vortex ring formed at each paddle stroke for the drag blade (a) and for the wing blade (b).

Karman Vortex Street

- Oscillating vortex shedding

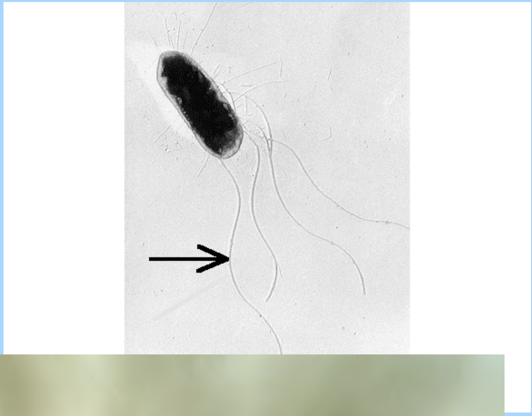
Strouhal Number

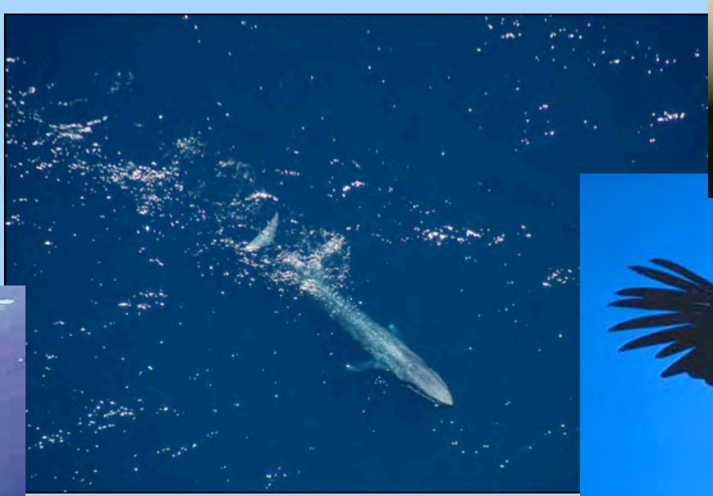
- Nondimensional measure of vortex shedding frequency

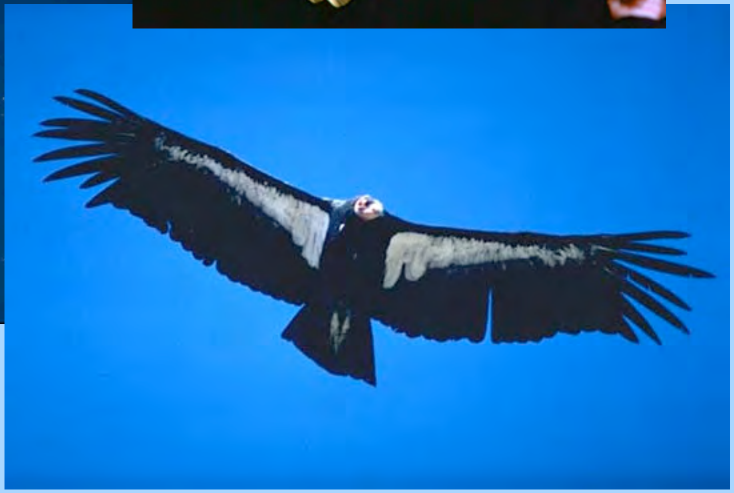


Strouhal

- Governs ALL biological periodic propulsion
  - bacteria
  - birds
  - fish
  - whales







Concluding Remarks

- Birds as 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/Horten/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

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What are we still missing?