AOE 2104
A Lecture on
Airplanes/Aerodynamics

W.H. Mason
October 31, 2006
What’s It all About?

Propulsion (Thermo)

Thrust

Aerodynamics
High Speed Aero Boundary Layer

Lift

And we need to fly it
- Dynamics
- Stability & Control

Drag

And make it green
- Noise
- Emissions

Weight

Materials Structures

Horizon

V
Making it Quantitative

From *Performance Class*, the specific range:

\[
\frac{mn\text{ range}}{lb\text{ of fuel}} = sr = \frac{V}{sfc} \left( \frac{L}{D} \right) \frac{1}{W}
\]

- \(V =\) velocity - speed!
- \(sfc =\) lbs of fuel burned per lb of thrust - efficient propulsion!
- \(L/D =\) Lift/Drag ratio - high L/D!
- \(W =\) weight of the plane - low weight!
Putting it All Together

• First: *Design the plane - Senior Design Class*
• Then *Test the Concept - Aero Lab Classes*
  – Computational simulations
  – Wind tunnel testing for aerodynamics
  – Subscale flight tests
  – Full scale flight testing
• Note: Lots of other tests:
  – Systems
  – Structures
  – Flight Control: The Iron Bird
Some Connections: Mason’s Classes

- Aircraft Design Class - 2 semester senior class
- Configuration Aerodynamics - a senior elective
- A Common Theme
  - Why are airplanes different shapes and sizes?
Why Airplanes Look Like They Do

W. H. Mason

collage from John McMasters
Aerospace and Ocean Engineering

Technology advances?

Designer

A new capability someone might pay to have?

How to exploit technology for capability?

Configuration Concept

Airplane Shapes Have Changed to Exploit Advances in Technology
Configuration Concept:

- Payload
- Lifting surface arrangement
- Control surface(s) location
- Propulsion system selection
- Landing Gear

Wright Brothers:

- Innovative control concept (more important than stability)
- “Light weight” propulsion
- Continual design evolution/refinement

Amazingly Tricky to Integrate Advances in Each Technology
Conventional Subsonic - A Baseline

- Payload distributed around cg (center of gravity)
- Longitudinal control power from tail (with moment arm)
- Vertical Tail for directional stability, rudder for control
- Wing/Fuselage/Landing Gear setup works
- Minimum trimmed drag at near neutral stability

Boeing 747-400, source: www.boeing.com
Why Sweep the Wing?

Subsonic (usually small)
- Adjust wing aerodynamic center* relative to cg
- On flying wing, get moment arm length for control

Transonic (significant, 30°-35°)
- Delay drag rise Mach (compressibility effect)
  - definition of the drag divergence Mach no.?

Supersonic (large, 45°-70°)
- Wing concept changes,
  - must distribute load longitudinally as well as laterally
- reduce cross-sectional area and area variation

*the aerodynamic center, ac, is the longitudinal station about which the pitching moment is constant as the lift changes.
The classic large airplane: The Boeing 747

source: www.boeing.com
Why Canards?

• said that trim surface carries positive load for positive g maneuvers
• reduces subsonic-supersonic $ac$ shift
• drawback: downwash from canard unloads wing
  (for forward swept wing this is good)
• if balanced stable,* $C_L$ on canard is much higher than the wing
• balanced unstable, control system design very expensive
• acceptable high angle of attack lateral/directional characteristics hard to obtain
• When to use?
  - severe supersonic cruise/transonic maneuver requirement

*Stability is important. A stable airplane returns to its basic flight condition when disturbed, while an unstable airplane needs a flight computer, a so-called stability augmentation system, to fly well.
The Grumman Research Fighter
designed by Nathan Kirschbaum, Ron Hendrickson in pix
Why a Flying Wing?

• removing fuselage must improve aero efficiency
  – But, payload volume distribution is still an issue
• synergistic effect with relaxed static stability
• military: stealth
• commercial: distribute load, reduce weight

Example: XB-35, YB-49, B-2
The B-2 Stealth Bomber
Computational Design Used Today

- Disciplines integrated:
  - Not the optimum aerodynamic design
  - Not the optimum structural design
  - The Best Total System Design
- Known as MDO
  - Multidisciplinary Design Optimization
So Will the Computer Eliminate the WT?

E.N. Tinoco, (Boeing) “The Impact of CFD in Aircraft Design,”
*Canadian Aeronautics and Space Journal*, Sept., 1998, pp. 132-144

One complete airplane development requires about 2.5 million aerodynamic simulations.
Comptational Simulations and WT Testing are Complimentary

- Both have strengths and weaknesses
- Solving a real problem requires both
Key Idea of a Wind Tunnel Test

Simulate the full scale design at reduced scale, low cost, and controlled conditions

Key Concept:

- Model is fixed, air moves

  *Same as?*

- Air fixed, airplane moves
Similarity

• **Reynolds Number (Re)**
  – To simulate the viscous effects correctly, match the Reynolds Number.
  – But you most likely can’t match the Reynolds number, we’ll show you why and what aeros do about the problem.

• **Mach Number (M)**
  – You are not going to get accurate aero data for supersonic flight with a subsonic test!
  – To match model to full scale compressibility effects, test at the same Mach number, sub-scale and full scale.
Example of the Re Issue

"The Need for developing a High Reynolds Number Transonic WT"
Astronautics and Aeronautics, April 1971, pp. 65-70
Matching the Reynold’s Number?

\[ Re = \frac{\rho V L}{\mu} \]

\( \rho \): density, \( V \): velocity, \( L \): length, \( \mu \): viscosity,

\[ \frac{Re_{fs}}{Re_m} = \left( \frac{\rho_{fs}}{\rho_m} \right) \left( \frac{V_{fs}}{V_m} \right) \left( \frac{L_{fs}}{L_m} \right) \frac{1}{\mu_{fs} \mu_m} \]

\( fs \): full scale
\( m \): model
WT vs Flight
- why the NTF was built -

"The Large Second Generation of Cryogenic Tunnels"
Astronautics and Aeronautics, October 1971, pp. 38-51
What’s the Problem?

• Suppose we have a 20th scale model: \( \frac{L_m}{L_{fs}} = 0.05 \)
  – Can we make \( V_m = 20V_{fs} \)? - Mach number would be different!
  – Can we change \( \rho \) ? \( \mu \)? - yes: make air cold or high pressure

• Ways to help Reynolds number match:
  – \textbf{Cold} Wind Tunnels
    » Also keeps dynamic pressure “reasonable”
    » Also reduces power requirements
  – \textbf{Big} Wind Tunnels
  – Games with the boundary layer
    » Force transition from laminar to turbulent flow: “trips”
Trying to match flight Re using cryogenic nitrogen:
The NTF at NASA Langley, Hampton, VA

Performance: $M = 0.2$ to $1.20$
$P_T = 1$ to $9$ atm
$T_T = 77°$ to $350°$ Kelvin

Feb. 1982
Big Models: Full Scale WT at NASA Ames

40x80 Foot Test Section

80x120 Foot Test Section
Sue Grafton with RFC at NASA Langley
RFC in the 30x60 at Langley: static tests
Free Flight Setup: A complicated activity
RFC Model in Free Flight at Langley
Flight Test

Subscale demonstration of an oblique wing airplane
Flight Test

• The X-45A from last November

Find movies on the NASA Dryden web site:
http://www.dfrc.nasa.gov/gallery/Movie/index.html
Flight Test at VT: March 14, 2003

A senior ME/AE Design Team
Full scale flight test the X-29
X-35 Flight Test Leading to the F-35!
Tech’s Human Powered Airplane Model

http://www.aoe.vt.edu/design/hpa/video.php

October 26, 2006
And A Few Novel Concepts

• **Blended Wing-Body Concept**
  • Concept from Bob Liebeck (Douglas A/C)
  • Less wetted area (no fuselage)
  • Possibly more efficient structure

• **Oblique Wing Supersonic Transport**
  – concept by R.T. Jones
  – fore-aft symmetry of lift/better area distribution
  – possibly only “practical” SST
  – flying wing version also

AD-1, Circa 1980
SpaceShipOne

Burt Rutan: Still imagineering!

The White Knight

Pictures from the Scaled Composites web site
Our Current Favorite: the Strut Braced Wing

- Werner Pfenninger’s strut-braced wing concept from 1954

- We need MDO to make it work

- The strut allows a thinner wing without a weight penalty
  - and also a higher aspect ratio, less induced drag
- Reduced $t/c$ allows less sweep without a wave drag penalty
- Reduced sweep leads to even lower wing weight
- Reduced sweep allows for some natural laminar flow
  - reduced skin friction drag

Was proposed as an X-plane
Lockheed, Virginia Tech, NASA Team

Compared to a conventional cantilever design:
- 12-15% less takeoff weight
- 20-29% less fuel
- less noise and emissions
And Hope for Low-Sonic Boom Noise Flight

A modified F-5E demonstrated a low-noise boom on Aug. 27, 2003

So-called “boom shaping” can be used to reduce the part of the boom that hits the ground.

And Hypersonics - The X-43

Scramjet Features

Important Terms/Concepts for the X-43 Experiment

Inlet starting
Ignition/Flameout/Flameholding
Combustor/isolator interaction
Fuel equivalence ratio/Φ
The Latest: UCAVs
This one is based on Nastasi/Kirschbaum/Burhans Patent 5,542,625

Northrop Grumman Corporation, reprinted by Aviation Week, June 16, 1997

The vertical tail is eliminated for stealth, directional control comes from specially coordinated trailing edge deflections
And finally, Micro AVs!

Black Widow
AeroVironment, Inc.

- 6-inch span fixed-wing aircraft
- Live video downlink
- Portable launch/control box
- Pneumatic launcher
- 60 gram mass
- 22-minute endurance
- Estimated 10 km range
- Electric propulsion

Achievements

- World MAV endurance record of 22 minutes
- Smallest video camera ever flown on a UAV: 2 grams
- Smallest live video downlink ever flown on a UAV
- World’s smallest, lightest multi-function, fully proportional radio control system: 3 grams
- First aircraft to be flown “heads-down” indoors

Joel Grasmeyer, MS VT 1998 - team member!
To Conclude: There is Still Room for Dreamers

*We don’t yet know what the ultimate airplane concept is.*