Some High Alpha and Handling Qualities Aerodynamics

W.H. Mason
Configuration Aerodynamics Class
Issues in Hi-\(\alpha\) Aero

- **General Aviation**
  - Prevention/recovery from spins
  - **Beware:** Tail Damping Power Factor (TDPF)
    » Sometimes advocated for use in design
    » Has been shown to be inadequate!

- **Fighters**
  - Resistance to “departure” from controlled flight
  - Carefree hi-\(\alpha\) air combat maneuvering
    » Fuselage pointing
    » Velocity vector rolls
    » Supermaneuverability
    » etc.

- **Transports**
  - Control/prevention of pitchup and deep stall (the DC-9 case study)
High Angle of Attack

- **Aerodynamics are nonlinear**
  - complicated component interactions (vortices)
  - depends heavily on WT data for analysis
  - This means critical conditions outside linear aero range

- Motion is highly dynamic - often need unsteady aero

- Keys issues (from a fighter designer’s perspective):
  - adequate nose down pitching moment to recover
  - roll rate at high alpha
  - departure avoidance
  - adequate yaw control power
  - the role of thrust vectoring
The Hi-\(\alpha\) Story

Longitudinal

Typical unstable modern fighter – the envelope is the key thing to look at

\[ + \]

Max nose up moment

\[ Cm^* \]

Pinch often around \(\alpha \sim 30^\circ-40^\circ\)

\[ 0^\circ \]

\[ 90^\circ \]

Max nose down moment

Minimum \(Cm^*\) allowable is an open question
Issue of including credit for thrust vectoring

Suggested nose down req’ t: Pitch accel in 1st sec: -0.25 rad/sec\(^2\)
Example: F-16

Found in flight, and also in tests at the NASA Full Scale Tunnel, other tunnels didn’t find this, and so the design was made with this “issue.”

An $\alpha$-limiter was put in the control system to prevent pilots from going above about $28^\circ$.

NASA TP-1538, Dec. 1979
The Hi-$\alpha$ Story
Directional

[Graph showing the relationship between $Cn\beta$ and $\alpha$]
Example: F-5

Above 30°, the directional stability comes entirely from the forebody!

Sketch from NASA TN D-7716, 1974

Chine forebodies are even more effective!
At “high” angles of attack, vortices form over the forebody, producing additional, possibly restoring, forces and often interacting with the rest of the airplane flowfield.

F-5A forebody, $\alpha = 40^\circ$, $\beta = 5^\circ$

NASA CR 4465, Aug. 1992
Illustration of Forebody Vortices and a “Fix”

- Laser Light Sheet Video of the RFC forebody

- And Flow Asymmetries:
  - an amazing story
  - solve with nose strakes

X-29 forebody
Taken at the USAF Museum, WPAFB, Ohio
Rudder Lock and the B-17 Vertical Tail Mod

Vertical Tail Shaping II: “Subtle” Tail Changes

Lockheed “Constitution” Aviation Age Magazine Feb. 1952, pg. 37

Note that yaw is the negative of sideslip, thus the negative slope

Also note good use of labels to identify effects
Who’s on first?

A true story from the Grumman STAC Airplane program

The Stability and Control Group Plane


The Aerodynamics group plane
Some High Alpha and Handling Qualities Aerodynamics

Again

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The Hi-\(\alpha\) Story
Lateral

Drooping LE devices helps control severity

Dihedral Effect (also due to sweep)

Flow Separates on wing

“Stable”

“Unstable”

\(\alpha\)

\(0^\circ\)

\(90^\circ\)
Example: F-4

NASA TN D-7131, July 1973
Control Effectiveness Change with alpha

Example: F-16 Lateral/Directional Control

Conventional aero control surfaces lose effectiveness at high angles of attack

Subscripts:
- $r$ – rudder
- $a$ – aileron
- $d$ – differential horizontal tail

$\Delta C_n$ vs $\alpha$, deg
$\Delta C_l$ vs $\alpha$, deg

NASA TP 1538, Dec. 1979
A way to get yaw: differential canard

Differential deflection of the canard creates differential pressures on the side of the forebody, and hence yawing moment.

Lapins, Martorella, Klein, Meyer and Sturm, NASA CR 3738, Nov. 1983

See also, Re and Capone, NASA TN D-8510, July 1977
Example: the Evolution of the SCAMP

- How and Why the modified F-16 supercruiser SCAMP became the F-16XL

Original Concept

The Final Airplane


Low Speed Tests Mandated Planform Mods

Baseline low speed configuration (note crank)

The “Apex” mod

The TE extension mod

Grafton, NASA TM 85776, May 1984

One more not shown: a “Wing fence”
The F-16XL

Note “Wing Fence” called a sensor fairing

WT data: Grafton, NASA TM 85776, May 1984
Hi-\(\alpha\) Flight Mechanics I

- **Departure**
  - Aircraft “departs” from controlled flight
  - May develop into a spin

- **Wing drop**
  - Uncommanded motion: asymmetric wing stall
    - Typical spin entry for straight wing GA airplanes, a wing roll-off
      - *Became famous again as the F-18E Abrupt Wing Stall Problem*

- **Wing rock**
  - “Damping” characteristics generate wing roll oscillations

- **Nose slice**
  - Yawing moments from airplane (mainly forebody) greater than rudder power
  - May develop into a yaw-type entry into a spin
    - Swept wing fighter, with totally different inertial characteristics
      - So-called “fuselage heavy”, as oppose to “wing heavy” light planes

- **Tumbling**
  - Typically associated with flying wings
Hi-α Flight Mechanics II

- Becomes closely integrated with flight control system
- Requires extensive ground and flight simulation


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<tr>
<th>Determinants of High α Flying Qualities</th>
<th>Approach</th>
<th>Example</th>
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<td>Aerodynamic Dominance</td>
<td>Aerodynamics must provide an all around solution with respect to performance, stability and controllability. FCS may give fine tuning, but is not required for basic stability and control.</td>
<td>F-5</td>
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<tr>
<td>Balanced Aerodynamics and FCS</td>
<td>Aerodynamic design favors performance with some regions of undesirable flying qualities. FCS necessary to enhance or provide acceptable stability and control.</td>
<td>F-15</td>
</tr>
<tr>
<td>FCS Dominance</td>
<td>Aerodynamic design favors performance FCS to provide good flying qualities up to maximum usable lift coefficient.</td>
<td>F-16</td>
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The problem: configurations have changed from WWII

The fuselage is longer and heavier, the wings relatively smaller

Figure from Joe Chambers, “High-Angle-of-Attack Aerodynamics: Lessons Learned,” AIAA Paper 1986-1774
Departure Criteria I

• Really need dynamic data and piloted simulation
  – Needs to be connected to flight mechanics analysis
  – Simulation math model requires massive amount of data from WT(s)

• Issue: can we do anything w/o dynamic data?

• Some rough approximations to get started (note inertia ratio):
  – Open loop: (actually a very rough approximation): $C_{n\beta \text{ dynamic}} > 0$
    
    $C_{n\beta, \text{ dyn}} = C_{n\beta} \cos \alpha - \left( I_z/I_x \right) C_{l\beta} \sin \alpha$
  
  » Several forms depending on coordinate system, this is essentially body axis (actually principal axis) - see Calico, *Journal of Aircraft*, Vol. 16, No. 12, Dec. 1979, pp 895-896.
  
  » Comes from the lateral-directional equations of motion linearized about steady, rectilinear flight, and an examination of the resulting stability quartic (ignoring rate derivatives) – see Greer, NASA TN D-6993, 1972. Essentially a Dutch Roll Approx

Departure Criteria II

• Closed loop: \( LCDP \), the lateral control departure parameter > 0

\[
\begin{align*}
LCDP &= C_{n\beta} - C_{l\beta} \left( \frac{C_{n\delta_a} + G_{ARI} C_{n\delta_r}}{C_{l\delta_a} + G_{ARI} C_{l\delta_r}} \right)
\end{align*}
\]

• Where \( G_{ARI} \) is the ratio of rudder to aileron deflection for an airplane with an aileron-rudder interconnect (ARI)

• When yaw due to aileron gets large, commanded roll produces a motion in the opposite direction!

• See AFWAL-TR-81-3108 for examples

Note: the value (and drawback) of \( C_{n\beta,\text{dyn}} \) and \( LCDP \) are that they are based on static aero coefficients

Damping derivatives:

• \( C_{nr} < 0 \) (yaw damping), but not too negative

• \( C_{lp} < 0 \) (roll damping), to prevent wing rock
F-16 Hi-\(\alpha\) characteristics

\[c_{n_\beta}, c_{l_\beta}, c_{n_\beta,dyn}\]

deped deg

\[\alpha, \text{deg}\]

NASA TP-1538, Dec. 1979
F-16 LCDP and augmented LCDP

NASA TP-1538, Dec. 1979
Integrated Bihrlle-Weissman Chart

E - Weak spin tendency, moderate departure and roll reversals, affected by secondary factors
F - Weak departure and spin resistance, no roll reversals, heavily influenced by secondary factors
Ways to get aero data, including dynamic data

Wind Tunnels

- Basic static, Hi-$\alpha$ WT data
  - Beware of support interference and Reynolds Number issues
- Forced oscillation data
- Virginia Tech’s DyPPiR
- Rotary balance data (typically use NASA Langley Spin Tunnel)
  - Bihrlie Applied Research

CFD

- not there yet in general, VLM gives low $\alpha$ damping derivatives
Wind Tunnel Testing for Hi-\(\alpha\) Data

The RFC in the Full Scale (30x60) wind tunnel at NASA Langley for static WT tests

Sue Grafton with the NASA-Grumman 1/7th scale Research Fighter Configuration (RFC) at NASA Langley - mid ’80s

Note: orange surfaces can move, note also the nozzle thrust vectoring deflectors
And Trying to Understand the Flowfield

Kurt Chankaya, in the Grumman 7x10 tunnel
Forced Oscillation Testing
Virginia Tech’s DyPPIR for Dynamic Data

A unique system for the study of unsteady aerodynamics
Movies of the DyPPiR in motion

F-18 Rapid Plunge and Roll Maneuvers

Submarine (0.3 sec) Pitchdown Maneuver

For these and other Quicktime movies, see http://www.aoe.vt.edu/research/facilities/dyppir/
Rotary Balance Acquires Aero Data

Typically obtained in a spin tunnel, with the air moving vertically, the balance rotates, and the alpha and offset can be varied.

NASA Langley spin tunnel
French Rotary Balance
Testing of a Fighter
The Abrupt Wing Stall Problem

Movie from *Modeling Flight*
by Joe Chambers, NASA SP 2009-575
The F-18 E/F Abrupt Wing Stall Problem

- In the midst of the maneuvering envelope the F-18E/F developed a sudden drop of a wing. The problem made the airplane unacceptable to the Navy.

Kevin Waclawicz, MS, 2001
Mike Henry, MS, 2001

Chordwise pressure distributions, showing effect of LE and TE device deflection

The “solution”: a porous wing fold fairing
But, CFD is starting to be useful

Jim Forsythe DES Calculations, NASA CP-2004-213028
The next step

- Build a math model of the aero
- Develop the flight control system
- Simulate Hi-\(\alpha\) flight with “free-flight” testing

Disclaimer

Note: a lot of what has been shown is based on linear aerodynamic approaches – the real world requires complete nonlinear aerodynamics to be included in the simulations, not classical stability derivatives, but tables of coefficients as a function of \(\alpha\), \(\beta\), etc.

*Jacob Kay, of JKayVLM, does this for a living, and wanted me to emphasize this.*
Free Flight Setup: A complicated activity

This was the setup in the LaRC Full Scale Tunnel, now torn down
RFC Model in Free Flight at Langley
RFC Free Flight in the Full Scale Tunnel
And Finally, Flight Test

Software Bugs revealed in flight: the Gripen
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*Again and Final*

W.H. Mason
Configuration Aerodynamics Class
Spins

- Normally viewed slightly differently than Hi-α
- General aviation airplanes have often been the focus of the work
- Types of simulations include spin tunnels, rotary balance data, and RC model testing
- Bihrle Applied Research is the main center of excellence
- Various airplanes demonstrate different (multiple) spin “modes” – different equilibrium motions
  – The worst, the famous flat spin!


• Do not use TDPF, but certain principles still valid:
  – Important to provide damping to the spin
  – Very important to provide exposed rudder for spin recovery

• Tail configuration can have an appreciable influence on the spin recovery (but so can just about everything else!)
Tail-design characteristics for improved spin recovery

Better

Worse

James Bowman, NASA TN D-6575 (1971)
Simulating spins on the ground

- NASA has a spin tunnel at Langley: also does tumbles

Air flows vertically

Models “tossed in” and the spin modes are examined

A rotary balance rig is available to acquire forces and moments while the model rotates
French Spin Tunnel
A way to improve spin characteristics of General Aviation Airplanes

NASA Ames: *The Interrupted Leading Edge*
  - Terry Feistel and Seth Anderson, AIAA 78-1476

NASA Langley: *The Discontinuous Leading Edge*
  - Dan DiCarlo and Paul Stough, AIAA 80-1843

- Both done about the same time
- Making the leading edge “discontinuous” allows the wing to behave like two lower aspect ratio wings as the wing approaches stall, and then stalls
Physics of Interrupted Leading Edges

The NASA Ames version

The NASA Langley version

The Cirrus as well as the Adam A500 and Columbia 400 have adopted this wing concept


DiCarlo, Stough and Patton, JA Sept. 1981
Cirrus wing – showing discontinuous LE

At the Virginia Tech Airport, Sept. 21, 2012
Spin Recovery Controls Depend on Mass Distribution

Note: specific controls differ for each airplane

James Bowman, NASA TN D-6575 (1971)
Finally, flight tests required for Hi-$\alpha$, including spins
Tumbling: A Related Problem
Shown in the NASA Spin Tunnel
Another related problem: Coupling

- Rolling the airplane especially at hi-$\alpha$, leads to coupling

  **Kinematic coupling: roll 90°**

  ![Diagram](image1)
  ![Diagram](image2)
  **Now $\alpha$ is $\beta$!**

  ![Diagram](image3)
  ![Diagram](image4)

  **Inertia Coupling:** rolling forces nose up!

  ![Diagram](image5)
  ![Diagram](image6)

  ![Diagram](image7)

  ![Diagram](image8)
Famous case attributed to inertial coupling: the F-100 and the vertical tail size change

The F-100 suffered from inertial coupling problems and general lack of directional stability: George Welch, NAA Chief Test Pilot was killed Oct 12, 1954 – and the F-100s were grounded until fixed.

The fix: 27% more VT area, 26 inch wingspan increase
F-22 FLIGHT CONTROL SURFACES

**Case Study**

- **Deceleration Device** Uses Combined Aileron, Flaperon, and Rudder Deflections.

- **Ailerons**
  - 70°/sec
  - +25°

- **Rudders**
  - 80°/sec
  - ±30°

- **Flight Test Boom**

- **Inlet Bleed Doors**
  - 50°/sec
  - 0° to +45°

- **Leading Edge Flaps**
  - 30°/sec
  - 0° to +35°

- **Pitch Control Provided by Integrated Horizontal Tails and Thrust Vectoring Nozzles.**

- **Vectoring Nozzles**
  - 40°/sec
  - ±20°

- **Horizontal Tails**
  - 60°/sec
  - -25° to +30°

- **Lateral Control Provided by Combined Aileron, Flaperon, and Horizontal Tail Deflections.**

- **Asymmetric Leading Edge Flaps Added at High AOA**

- **Flapersons**
  - 70°/sec
  - -20° to +35°

Charles M. Wilson
F-22 Stability and Control
Lockheed–Martin Corp.
F-22 Provides the Pilot with:
-- Carefree Maneuver Capability
-- Departure Resistance
-- Automatic Recovery
HIGH AOA MANEUVERABILITY

THRUST VECTORING DOUBLES LONGITUDINAL CONTROL POWER AND SIGNIFICANTLY EXTENDS USEABLE ANGLE OF ATTACK RANGE

Note: no scales
Leading Edge Flaps are Powerful Devices for Flow Improvement

Note: no scales
THRUST VECTORING PROVIDES F-22 ROLL RATE ADVANTAGE

PITCH THRUST VECTORING INCREASES LONGITUDINAL CONTROL POWER
-- CONTROL INERTIAL ROLL COUPLING
-- REPOSITION HORIZONTAL TRIM FOR EFFICIENT ROLL CONTROL

CHARLES M. WILSON
F-22 STABILITY AND CONTROL
LOCKHEED–MARTIN CORP.

STABILITY AXIS
MACH < 0.6

NO RUDDER PEDAL INPUTS
AIR-TO-AIR CONFIGURATIONS
Comment on Thrust Vectoring

• Thrust vectoring mainly provides moments at high thrust
  - a problem if you don’t want lots of thrust!
• Thrust vectoring moment is near constant with speed
• Ratio of aero to propulsive moments:
  - propulsion dominates at low $q$
  - aero dominates at high $q$
**Conclusion**

- High-\(\alpha\) is a somewhat special area in configuration aerodynamics
- Development of good aero characteristics at high-\(\alpha\) is a critical aspect of modern tactical aircraft design


Two Special Sections in the *Journal of Aircraft* on the Abrupt Wing Stall Problem (and suggested solutions)
- May-June 2004
- May-June 2005