Problems of High Speed and Altitude
Robert Stengel, Aircraft Flight Dynamics
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- Effects of air compressibility on flight stability
- Variable sweep-angle wings
- Aero-mechanical stability augmentation
- Altitude/airspeed instability

High Mach Number Difficulties
Chapter 11, Airplane Stability and Control, Abzug and Larrabee

- What are the principal subject and scope of the chapter?
- What technical ideas are needed to understand the chapter?
- During what time period did the events covered in the chapter take place?
- What are the three main "takeaway" points or conclusions from the reading?
- What are the three most surprising or remarkable facts that you found in the reading?
Outrunning Your Own Bullets

• On Sep 21, 1956, Grumman test pilot Tom Attridge shot himself down, moments after this picture was taken

• Test firing 20mm cannons of F11F Tiger at M = 1

• The combination of events
  – Decay in projectile velocity and trajectory drop
  – 0.5-G descent of the F11F, due in part to its nose pitching down from firing low-mounted guns
  – Flight paths of aircraft and bullets in the same vertical plane
  – 11 sec after firing, Attridge flew through the bullet cluster, with 3 hits, 1 in engine

• Aircraft crashed 1 mile short of runway; Attridge survived

Effects of Air Compressibility on Flight Stability
Implications of Air Compressibility for Stability and Control

- Early difficulties with compressibility
  - Encountered in high-speed dives from high altitude, e.g., Lockheed P-38 Lightning
- Thick wing center section
  - Developed compressibility burble, reducing lift-curve slope and downwash
- Reduced downwash
  - Increased horizontal stabilizer effectiveness
  - Increased static stability
  - Introduced a nose-down pitching moment
- Solution
  - Auxiliary wing flaps that increased both lift and drag

P-38 Compressibility Limit on Allowable Airspeed

- Static margin increase with Mach number
  - Increases control stick force required to maintain pitch trim
  - Produces pitch down

- Pilots warned to stay well below speed of sound in steep dive
Mach Tuck

- Low-angle-of-attack phenomenon
  - Shock-induced change in wing downwash effect on horizontal tail
  - Pitch-down trim change, $C_m$, due to aft aerodynamic center shift with increasing Mach number
- F4D speed record flights ($M = 0.98$)
  - Low altitude, high temperature to increase the speed of sound
  - High dynamic pressure
  - 1.5 $g$ per degree of angle of attack, $M = 1$, dramatic trim changes with Mach number
  - Pilot used nose-up trim control
    - Pull to push for pitch control in turn at end of each run
    - Uncontrollable pitch-up to 9.1 $g$ during deceleration at end of one run, due to pilot’s not compensating fast enough

Abzug & Larrabee

$M_V$ Effect on 4th-Order Roots

\[
\Delta_{1\text{sw}}(s) = s^4 + \left( D_e + \frac{L_N}{V_N} - M_e \right) s^3
+ \left( (r - D_m) \frac{L_N}{V_N} + D_e \frac{L_N}{V_N} - M_e \frac{L_N}{V_N} - M_e \right) s^2
+ \left( M_4 \left( D_m - \frac{L_N}{V_N} - D_e \frac{L_N}{V_N} + D_e M_e - D_e M_e \right) + \frac{g}{V_N} \right) s
+ \frac{g}{V_N} M_e \left( D_m + \frac{L_N}{V_N} \right) = 0
\]

- Coupling derivative: Large positive value produces oscillatory phugoid instability
- Large negative value produces real phugoid divergence
Pitch-Up Instability

- High angle of attack phenomenon
- Center of pressure moves forward due to tip stall
- **F-86 trim change (right)**
  - At $t = 5$ s, $C_N$ and $A_z$ are increasing (pitch-up), although elevator deflection and control force are decreasing

Transonic Solutions

- Application of outboard *vortex generators* to delay tip separation (*Gloster Javelin* example)

- Mach number feedback to elevator on **F-100** to counteract transonic trim change
Supersonic Directional Instability

- Reduced vertical stabilizer effectiveness with increasing Mach number
- Loss of X-2 on speed run
- F-100 solution: increased fin size
- X-15 solution: wedge-shaped tail
- XB-70: fold-down wing tips
  - Improved supersonic lift
  - Reduced excess longitudinal static stability

High-Altitude Stall-Mach Buffet

- Increased angle of attack and lift coefficient leads to “Stall buffet”
- Intermittent flow separation at transonic speed and “Mach buffet”
- The place where they meet = “Coffin Corner”
- Can induce an upset (loss of control)
- U-2 operates in Coffin Corner
- Citation X (M = 0.92) has wide buffet margin
Hypersonic Stability and Control

- Turbojet/rocket for launch/takeoff
- Ramjet/scramjet powerplant for cruise
- High degree of coupling, not only of phugoid and short period but of structural and propulsive modes
- Poor lateral-directional characteristics
- Extreme sensitivity to angular perturbations
- Low-speed problems for high-speed configurations, e.g., takeoff/landing

Altitude/Airspeed Instability
Supersonic Altitude/Airspeed Instability

- Inability of XB-70, Concorde, and YF-12A/SR-71 to hold both altitude and airspeed at high speed cruise
  - Phugoid mode is lightly damped
  - Height mode brought about by altitude-gradient effects
  - Exacerbated by temperature/density gradients of the atmosphere
- Engine unstart
  - Oblique engine-inlet shock is "spit out," decreasing thrust and increasing drag
  - Can trigger large longitudinal or lateral-directional oscillations
- Need for closed-loop, integrated control of altitude and airspeed

Effect of Supersonic Mach Number on Phugoid Mode Stability

- Characteristic polynomial for 2nd-order approximation

\[
\Delta(s) = s^2 + D_V s + gL_V / V_N = \left( s^2 + 2\zeta \omega_n s + \omega_n^2 \right)_{Ph}
\]

- In supersonic flight \((M > 1)\)

\[
D_V = 2\zeta \omega_n_{Ph} \propto \left( \frac{M^2}{M^2 - 1} \right)
\]

- \(D_V\) decreases as \(M\) increases
- Phugoid stability is reduced in supersonic flight
Effect of Atmosphere Variation on Aerodynamics

- Air density and sound speed vary with altitude, \(-z\)
  \[
  \rho(z) = \rho_0 e^{\beta z}, \quad \frac{\partial \rho}{\partial z} = \beta \rho_0 e^{\beta z}
  \]
  \[
  a(z) = a(z_{ref}) + \frac{\partial a}{\partial z}(z - z_{ref}) \quad \frac{\partial a}{\partial z} = \frac{\partial a}{\partial z}
  \]

- These introduce altitude effects on lift, drag, and pitching moment
  \[
  D_z = \frac{\partial}{\partial z} \left[ C_f(M) - C_d(M) \right] \left( \frac{1}{2m} \rho V^2 S \right), \quad L_z = \frac{\partial}{\partial z} \left[ C_L(M) \left( \frac{1}{2m} \rho V^2 S \right) \right], \quad M_z = \frac{\partial}{\partial z} \left( \frac{1}{2I_{yy}} V^2 S \right)
  \]

Third-Order Model for Phugoid-Height Model Dynamics

- Neglecting \(M_z\) and short-period dynamics
  \[
  \begin{bmatrix}
  \Delta V \\
  \Delta \gamma \\
  \Delta z
  \end{bmatrix} =
  \begin{bmatrix}
  -D_v & -g & -D_z \\
  L_x/V_N & 0 & L_x/V_N \\
  0 & -V_N & 0
  \end{bmatrix}
  \begin{bmatrix}
  \Delta V \\
  \Delta \gamma \\
  \Delta z
  \end{bmatrix} +
  \begin{bmatrix}
  T_{sr} \\
  0 \\
  0
  \end{bmatrix} \Delta \delta T
  \]

- 3rd-degree characteristic polynomial
  \[
  |sI - \Gamma_{height}| = \Delta(s) = s^3 + D_v s^2 + \left( g \frac{L_x}{V_N} + L_x \right) s + V_N \left( D_v \frac{L_x}{V_N} - D_z \frac{L_x}{V_N} \right) = 0
  \]
  \[
  = (s - \lambda_0) (s^2 + 2 \zeta_p \omega_{nr} s + \omega_{nr}^2) = 0
  \]
  \[
  \left( \zeta_p, \omega_{nr}, \lambda_0 \right)
  \]

- Oscillatory phugoid mode
- Real height mode
Approximate Roots of the 3\textsuperscript{rd}-Order Equation

- Assume phugoid response is fast compared to height mode response

\[ |sI - F_{\text{height}}| = \Delta(s) = s^3 + D_v s^2 + \left( g \frac{L_v}{V_N} + L_z \right) s + V_N \left( D_v \frac{L_v}{V_N} - D_z \frac{L_z}{V_N} \right) = 0 \]

\[ s \left[ D_v s + \left( g \frac{L_v}{V_N} + L_z \right) \right] \left[ \left( \frac{L_v}{V_N} + L_z \right) \right] = 0 \]

\[ \omega_n = \sqrt{g \frac{L_v}{V_N} + L_z} \quad \zeta_p = \frac{D_v}{2 \sqrt{g \frac{L_v}{V_N} + L_z}} \]

\[ \lambda_n = -\frac{V_N \left( D_v \frac{L_v}{V_N} - D_z \frac{L_z}{V_N} \right)}{\left( g \frac{L_v}{V_N} + L_z \right)} \]

Equilibrium Response of Airspeed, Flight Path Angle, and Height

\[ \Delta x_{SS} = -F_{\text{height}}^3 G_{\text{height}} \Delta T_{SS} \]

\[ \begin{bmatrix} \Delta V_{SS} \\ \Delta Y_{SS} \\ \Delta \zeta_{SS} \end{bmatrix} = \begin{bmatrix} -D_v & -g & -D_z \\ L_v / V_N & 0 & L_z / V_N \\ 0 & -V_N & 0 \end{bmatrix} \begin{bmatrix} T_{SR} \\ -L_v / V_N \\ L_z / V_N \end{bmatrix} \Delta T_{SS} \]

- From Flight Dynamics, pp. 476-480, with negligible \( D_z \)

\[ 2\text{nd} - \text{order Approximation} \]

\[ \Delta V_{SS} = 0 \]

\[ \Delta Y_{SS} = \frac{T_{SR}}{g} \Delta T_{SS} \]

- Steady-state response to constant thrust increase
  - Bounded airspeed increase
  - Horizontal flight path
  - Bounded altitude increase
Variable-Sweep/Incidence Wings ("Morphing")

Searching for the Right Design: The Many Shapes of the XF-91 Thunderceptor

- Variable-incidence wing
- Tip chord > Root chord
- Full nose inlet
- Vee tail, large tip chord
- Radome above inlet
- Modified nose and tail
Early Swing-Wing Designs

- Translation as well as rotation of the wing (Messerschmitt P.1101, Bell X-5, and Grumman XF10F, below)
- Complicated, only partially successful
- Barnes Wallis’s Swallow (right) concept included “wing glove”, solution adopted by Polhamus and Toll at NACA Langley

Variable Sweep and Incidence

- **Variable sweep**
  - High aspect ratio for low-speed flight
    - Landing and takeoff
    - Loiter
  - Low aspect ratio for high-speed flight
    - Reduction of transonic and supersonic drag
- **Variable incidence**
  - Improve pilot’s line of sight for carrier landing
Boeing 2707-300
Supersonic Transport

- Variable-sweep wing dropped in favor of more conventional design
- Final configuration had weight and aeroelastic problems
- Project cancelled in 1971 due to sonic boom, takeoff sideline noise and cost problems

Future of High-Speed Flight

- Commercial transport is likely to be subsonic for the foreseeable future
  - Luxury, comfort, and cost trump speed

- Military requirements for human supersonic flight are limited
  - Selected missions require supersonic flight
  - Majority of operational flight time is subsonic
  - No new variable-sweep designs in development
Future of High-Speed Flight

- Military requirement for UAV/Missile high-speed flight is significant
  - Many missions do not require human presence
  - Major weight reduction
  - Major increase in payload ratio
  - Current generation of low-and-slow UAVs inadequate for high-intensity conflict

Next Time:
Atmospheric Hazards to Flight

Reading
- Blackboard, Lecture 23
- Virtual Textbook, Part 23
Compressibility Problems

- Similar problems with P-39 Aircobra, P-47 Thunderbolt, and P-51 Mustang
  - Led to flight tests and greater understanding of compressibility effects
Transonic Pitchup Problem

- **Sign reversal of** $C_{m}$ **with increasing angle of attack**
  - Combined effect of Mach number and changing downwash effects on horizontal tail
- **F-86 Sabre wind-up turn**
  - Turn at high bank angle, constant load factor, decreasing velocity, and increasing angle of attack

F-86 Flight Test: Attempt to Hold Load Factor at 3 in Transonic Windup Turn

![Graphs illustrating F-86 flight test](image-url)
Effects of F-86 Blunt-Trailing-Edge Aileron

- Mach Effect on Control of Wings-Level Flight

Phugoid and Height Modes of 5th-Order Longitudinal Model*

\[ \Delta x^T = [\Delta V \ \Delta \gamma \ \Delta q \ \Delta \alpha \ \Delta \zeta] \]
Altitude Response of 5\textsuperscript{th}-Order Longitudinal Model

**Control Effects**
- Thrust Control
- Lift Control
- Moment Control

**Disturbance Effects**
- Vertical Wind Step
- Horizontal Wind Step
- Random Vertical Wind

Flying Tail of the \textit{XF10F}

- Variable-sweep successor to the \textit{F9F-6 Cougar} and precursor to the \textit{F-14 Tomcat}
- T-tail assembly with controllable canard and no powered control
  - Like a small airplane affixed to the fin
  - Pitching moment was inadequate during landing
Advanced Variable-Sweep Designs

- Fairing of wing trailing edge to stabilizer leading edge at high sweep
  - reduces downwash at the tail and corresponding pitch stability
  - effectively forms a delta wing
- Wing glove/leading-edge extension and outboard rotation point
  - provides greater percentage of lift at high Mach number and angle of attack

Milestones in Flight History
Dryden Flight Research Center

Swing-Wing Solutions

- Fuel shift to move center of mass aft as wing sweeps aft
- Forward wing surface that extends as wing sweeps aft
- Advanced stability augmentation systems
Boeing 2707-200
Supersonic Transport Concept

- Length = 318 ft; 300 passengers; larger than the B-747
- M = 2.7 (faster than Concorde)
- Cancelled before construction

Oblique Wing Concepts

- High-speed benefits of wing sweep without the heavy structure and complex mechanism required for symmetric sweep
- Blohm und Voss, R. T. Jones, Handley-Page concepts
- Improved supersonic L/D by reduction of shock-wave interference and elimination of the fuselage in flying-wing version

http://www.youtube.com/watch?v=65gsjHhwV_8
NASA Oblique Wing Test Vehicles

- **Stability and control issues abound**: The fact that birds and insects are symmetric should give us a clue (though they use huge asymmetry for control)
  - Strong aerodynamic and inertial longitudinal-lateral-directional coupling
  - High side force at zero sideslip angle
  - Torsional divergence of the leading wing
- **Test vehicles**: Various model airplanes, *NASA AD-1*, and *NASA DFBW F-8* (below, not built)

Handley-Page Oblique Wing Concepts

- **Advantages**
  - 10-20% higher L/D @ supersonic speed (compared to delta planform)
  - Flying wing: no fuselage
- **Issues**
  - Which way do the passengers face?
  - Where is the cockpit?
  - How are the engines and vertical surfaces swiveled?
  - What does asymmetry do to stability and control?