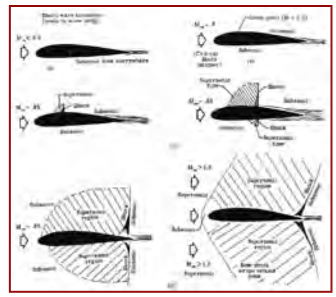
Problems of High Speed and Altitude

Robert Stengel, Aircraft Flight Dynamics
MAE 331, 2014

- **Effects of air compressibility on flight stability**
- **Variable sweep-angle wings**
- **Aero-mechanical stability augmentation**
- **Altitude/airspeed instability**

Flight Dynamics
470-480
Airplane Stability and Control
Chapter 11



http://www.princeton.edu/~stengel/MAE331.html
http://www.princeton.edu/~stengel/FlightDynamics.html

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?

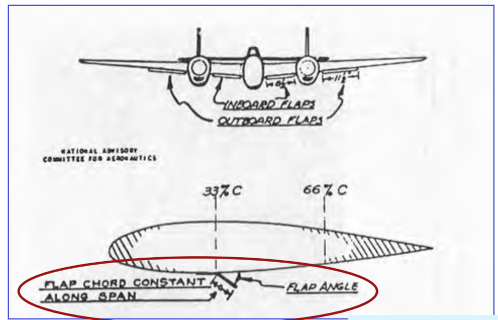
Outrunning Your Own Bullets

- 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

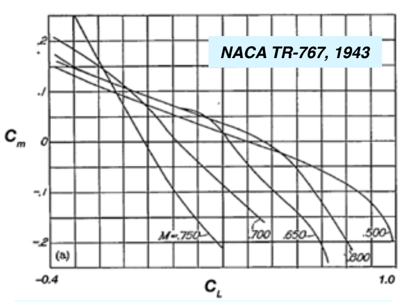
- Early difficulties with compressibility
  - Encountered in high-speed dives from high altitude, e.g., Lockheed *P-38 Lightning*
- Thick wing center section
  - Developed compressibility burble, reducing lift-curve slope and downwash
- Reduced downwash
  - Increased horizontal stabilizer effectiveness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



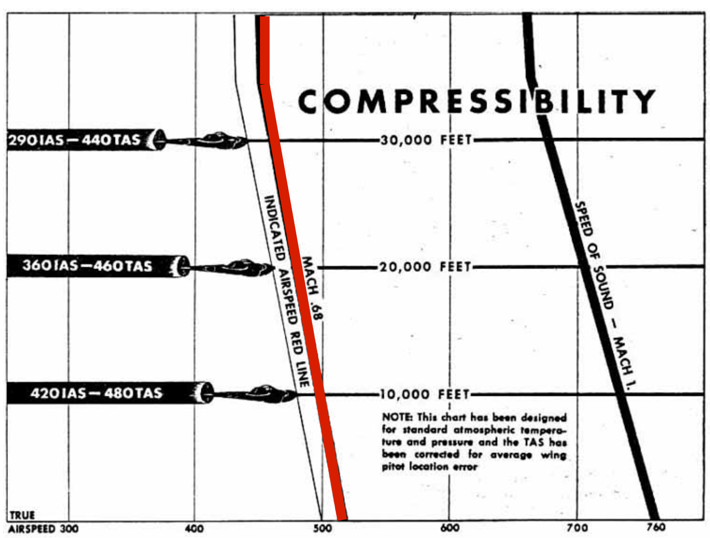
NACA WR-A-66, 1943

P-38 Compressibility Limit on Allowable Airspeed

from P-38 Pilot's Manual



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

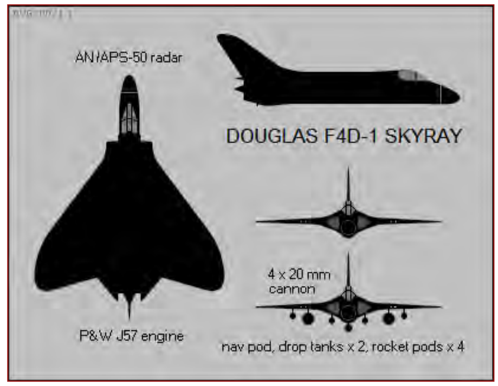


- Pilots warned to stay well below speed of sound in steep dive

Mach Tuck

- Low-angle-of-attack phenomenon
  - Shock-induced change in wing downwash effect on horizontal tail
  - Pitch-down trim change, C_{m_o} , due to aft aerodynamic center shift with increasing Mach number
- *F4D* speed record flights (*M* = 0.98)
  - Low altitude, high temperature to <u>increase</u> 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

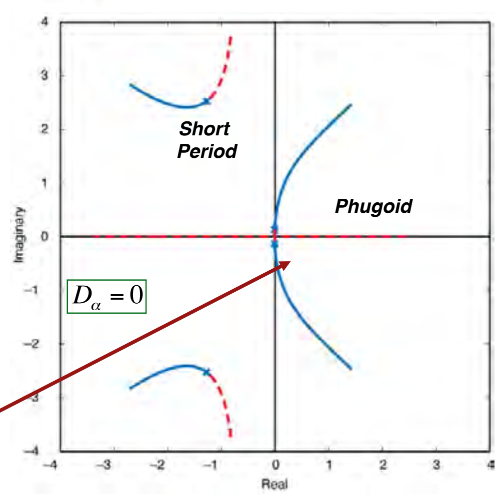
Abzug & Larrabee



M_V Effect on 4th-Order Roots

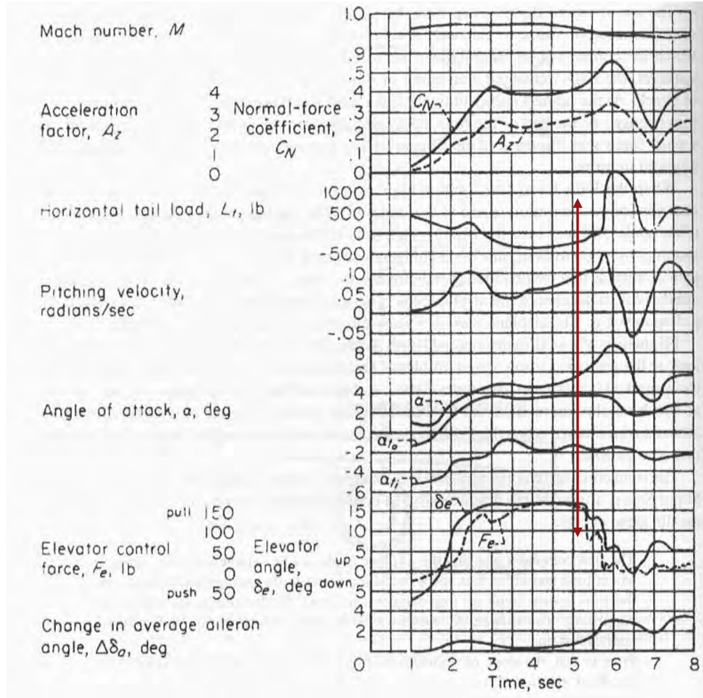
$$\begin{aligned}\Delta_{Lon}(s) = s^4 &+ \left(D_V + L_\alpha/V_N - M_q\right)s^3 \\ &+ \left[(g - D_\alpha)L_V/V_N + D_V\left(L_\alpha/V_N - M_q\right) - M_q L_\alpha/V_N - M_\alpha\right]s^2 \\ &+ \left\{M_q\left[(D_\alpha - g)L_V/V_N - D_V L_\alpha/V_N\right] + D_\alpha M_V - D_V M_\alpha\right\}s \\ &gM_\alpha L_V/V_N + \underline{M_V\left(D_\alpha s + g L_\alpha/V_N\right)} = 0\end{aligned}$$

- <u>Coupling derivative</u>: 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

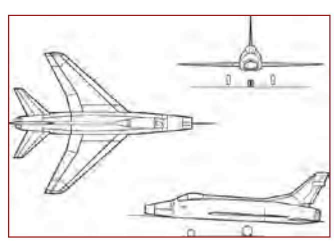


NACA TR-1237

Transonic Solutions

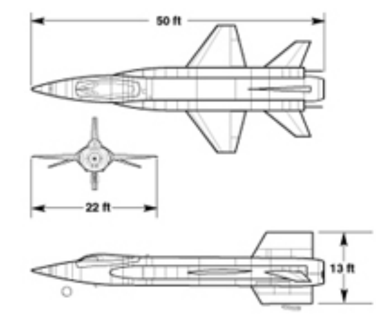
- Application of outboard *vortex generators* to delay tip separation (*Gloster Javelin* example)

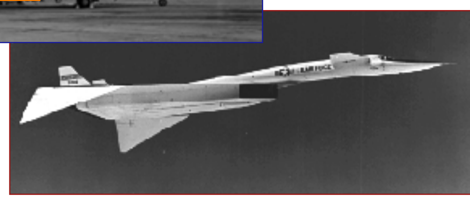
- Mach number feedback to elevator on *F-100* to counteract transonic trim change



Supersonic Directional Instability

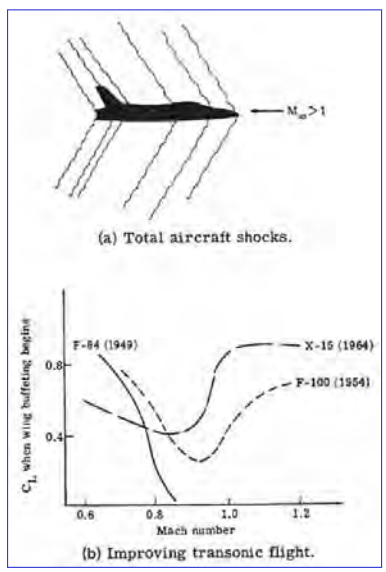
- **Reduced vertical stabilizer effectiveness with increasing Mach number**
- **Loss of *X-2* on speed run**
- ***F-100 solution*: increased fin size**
- ***X-15 solution*: wedge-shaped tail**
- ***XB-70*: fold-down wing tips**
  - **Improved supersonic lift**
  - **Reduced excess longitudinal static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





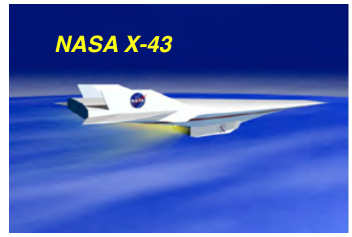
High-Altitude Stall-Mach Buffet

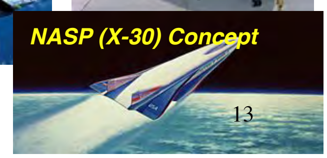
- **Increased angle of attack and lift coefficient leads to "Stall buffet"**
- **Intermittent flow separation at transonic speed and "Mach buffet"**
- **The place where they meet = "Coffin Corner"**
- **Can induce an upset (loss of control)**
- ***U-2* operates in Coffin Corner**
- ***Citation X* (M = 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





http://www.youtube.com/watch?v=liBsD-cafH8

http://www.youtube.com/watch?v=VZUwKX3_uE4

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

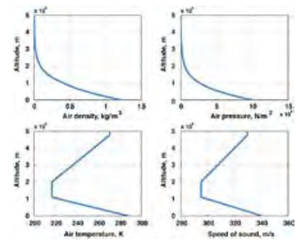
$$\Delta(s) = s^2 + D_V s + gL_V / V_N = \left(s^2 + 2\zeta\omega_n s + \omega_n^2\right)_{Ph}$$

- 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, $-z$**

$$\rho(z) = \rho_{SL} e^{\beta z}$$
$$\frac{\partial \rho(z)}{\partial z} = \beta \rho_{SL} e^{\beta z}$$

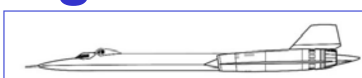
$$a(z) = a(z_{ref}) + \frac{\partial a}{\partial z}(z - z_{ref})$$
$$\frac{\partial a(z)}{\partial z} = \frac{\partial a}{\partial z}$$

- **These introduce altitude effects on lift, drag, and pitching moment**

$$D_z \triangleq \frac{\partial \left\{ \left[C_T(M) - C_D(M) \right] \left(\frac{1}{2m} \rho V^2 S \right) \right\}}{\partial z}; \quad L_z = \frac{\partial \left[C_L(M) \left(\frac{1}{2m} \rho V^2 S \right) \right]}{\partial z};$$

$$M_z = \frac{\partial \left[C_m(M) \left(\frac{1}{2 I_{yy}} \rho V^2 S \bar{c} \right) \right]}{\partial z} \qquad M = \frac{V}{a}$$

Third-Order Model for Phugoid-Height Model Dynamics



$$\Delta \dot{\mathbf{x}}_{height}(t) = \mathbf{F}_{height} \Delta \mathbf{x}_{height}(t) + \mathbf{G}_{height} \Delta \delta T(t)$$

- **Neglecting M_z and short-period dynamics**

$$\begin{bmatrix} \Delta \dot{V} \\ \Delta \dot{\gamma} \\ \Delta \dot{z} \end{bmatrix} = \left[\begin{array}{cc|c} -D_V & -g & -D_z \\ L_V / V_N & 0 & L_z / V_N \\ \hline 0 & -V_N & 0 \end{array}\right] \begin{bmatrix} \Delta V \\ \Delta \gamma \\ \Delta z \end{bmatrix} + \begin{bmatrix} T_{\delta T} \\ 0 \\ 0 \end{bmatrix} \Delta \delta T$$

- **3rd-degree characteristic polynomial**

$$\left| s\mathbf{I} - \mathbf{F}_{height} \right| = \Delta(s) = s^3 + D_V s^2 + \left(g \frac{L_V}{V_N} + L_z \right) s + V_N \left(D_V \frac{L_z}{V_N} - D_z \frac{L_V}{V_N} \right) = 0$$
$$= (s - \lambda_h)\left(s^2 + 2\zeta_P \omega_{n_P} s + \omega_{n_P}^2 \right) = 0$$

- **Oscillatory phugoid mode**
- **Real height mode**

$$\left(\zeta_P, \omega_{n_P} \right)$$
$$\lambda_h$$

Approximate Roots of the 3rd-Order Equation

- **Assume phugoid response is fast compared to height mode response**

Phugoid Mode Height Mode

$$\left| s\mathbf{I} - \mathbf{F}_{height} \right| = \Delta(s) = s^3 + D_V s^2 + \left(g \frac{L_V}{V_N} + L_z \right) s + V_N \left(D_V \frac{L_z}{V_N} - D_z \frac{L_V}{V_N} \right) = 0$$

$$s\left[\Delta s^2 + D_V s + \left(g \frac{L_V}{V_N} + L_z \right)\right] \quad \left(g \frac{L_V}{V_N} + L_z \right)\left[s + \frac{V_N \left(D_V \frac{L_z}{V_N} - D_z \frac{L_V}{V_N} \right)}{\left(g \frac{L_V}{V_N} + L_z \right)} \right]$$

Phugoid Mode

$$\omega_{n_P} \approx \sqrt{g \frac{L_V}{V_N} + L_z}; \quad \zeta_P \approx \frac{D_V}{2\sqrt{g \frac{L_V}{V_N} + L_z}}$$

Height Mode

$$\lambda_h \approx -\frac{V_N \left(D_V \frac{L_z}{V_N} - D_z \frac{L_V}{V_N} \right)}{\left(g \frac{L_V}{V_N} + L_z \right)}$$

Equilibrium Response of Airspeed, Flight Path Angle, and Height

$$\Delta \mathbf{x}_{SS} = -\mathbf{F}_{height}^{-1} \mathbf{G}_{height} \Delta \delta T_{SS}$$

$$\begin{bmatrix} \Delta V_{SS} \\ \Delta \gamma_{SS} \\ \Delta z_{SS} \end{bmatrix} = -\left[\begin{array}{cc|c} -D_V & -g & -D_z \\ \frac{L_V}{V_N} & 0 & \frac{L_z}{V_N} \\ \hline 0 & -V_N & 0 \end{array}\right]^{-1} \begin{bmatrix} T_{\delta T} \\ 0 \\ 0 \end{bmatrix} \Delta \delta T_{SS}$$

- **From *Flight Dynamics*, pp. 476-480, with negligible D_z**

$$\begin{bmatrix} \Delta V_{SS} \\ \Delta \gamma_{SS} \\ \Delta z_{SS} \end{bmatrix} = \begin{bmatrix} \frac{T_{\delta T}}{D_V} \\ 0 \\ -\left(\frac{T_{\delta T}}{D_V} \right) \frac{L_V / V_N}{L_z / V_N} \end{bmatrix} \Delta \delta T_{SS}$$

2nd - order Approximation

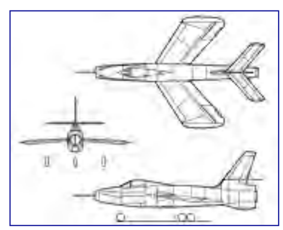
$$\Delta V_{SS} = 0$$

$$\Delta \gamma_{SS} = \frac{T_{\delta T}}{g} \Delta \delta T_{SS}$$

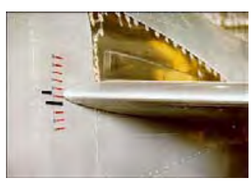
- **Steady-state response to constant thrust increase**
  - **Bounded airspeed increase**
  - **Horizontal flight path**
  - **Bounded altitude increase**

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

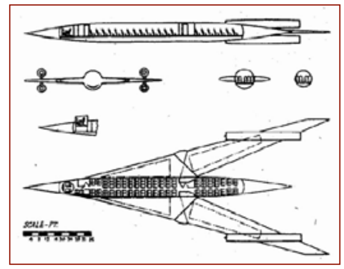
- Vee tail, large tip chord

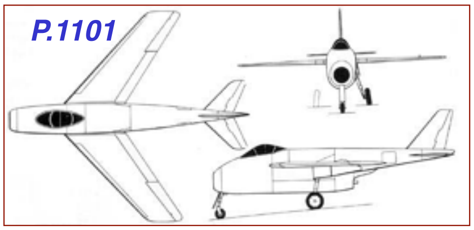
- Radome above inlet

- Modified nose and tail

Early Swing-Wing Designs

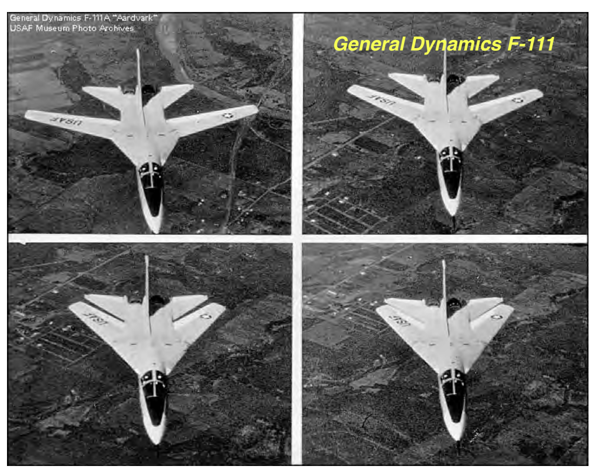
- Translation as well as rotation of the wing (*Messerschmitt P.1101*, *Bell X-5*, and *Grumman XF10F*, below)
- Complicated, only partially successful
- Barnes Wallis's *Swallow* (right) concept included "wing glove", solution adopted by Polhamus and Toll at NACA Langley





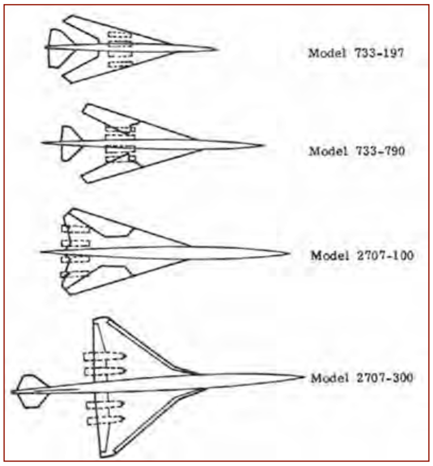
Variable Sweep and Incidence

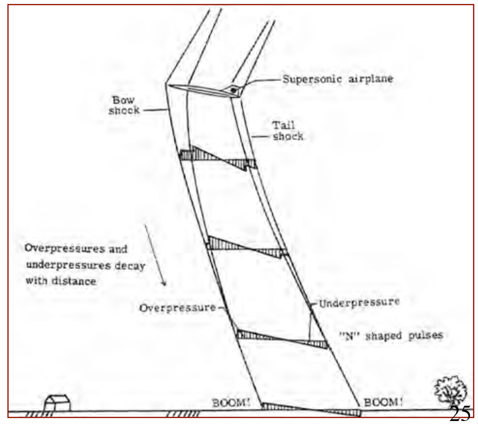
- Variable sweep
  - High aspect ratio for low-speed flight
    - Landing and takeoff
    - Loiter
  - Low aspect ratio for high-speed flight
    - Reduction of transonic and supersonic drag
- Variable incidence
  - Improve pilot's line of sight for carrier landing



Boeing 2707-300 Supersonic Transport

- Variable-sweep wing dropped in favor of more conventional design
- Final configuration had weight and aeroelastic problems
- Project <u>cancelled</u> 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

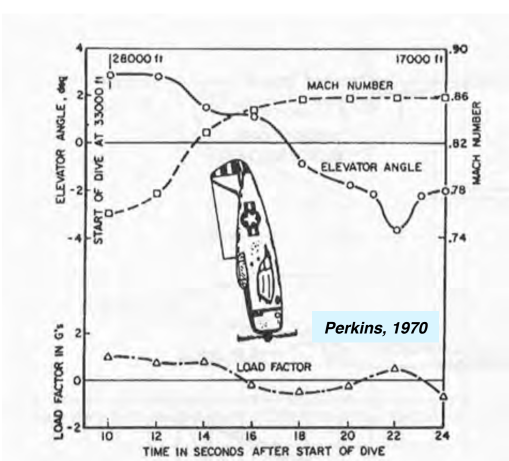
Blackboard, Lecture 23

Virtual Textbook, Part 23

Supplemental Material

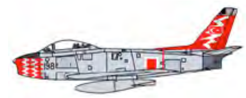
Compressibility Problems

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

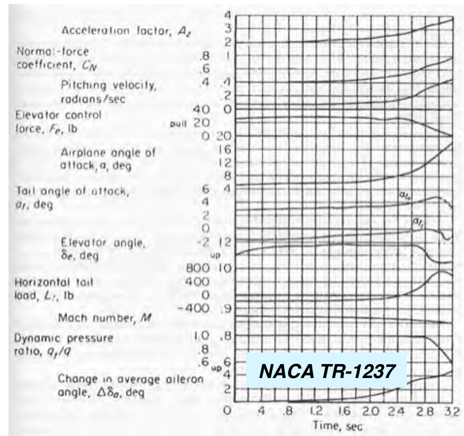


Perkins, 1970

Transonic Pitchup Problem



- **Sign reversal** of C_{m_α} 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



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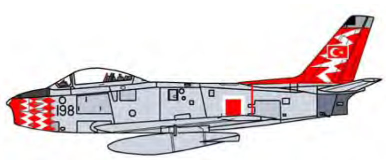
F-86 Flight Test: Attempt to Hold Load Factor at 3 in Transonic Windup Turn



Just below Pitch-up

Just above Pitch-up

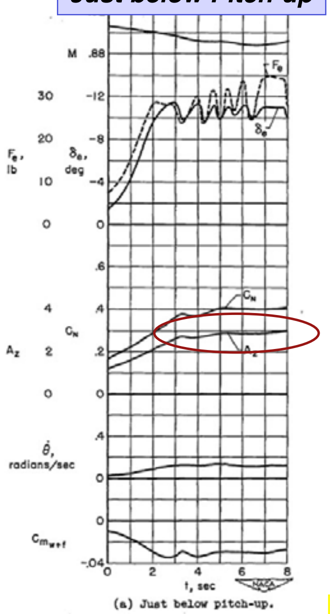
Mach number

Stick force, F_E
Elevator deflection, δE

Normal force coefficient, C_N
Normal load factor, A_z

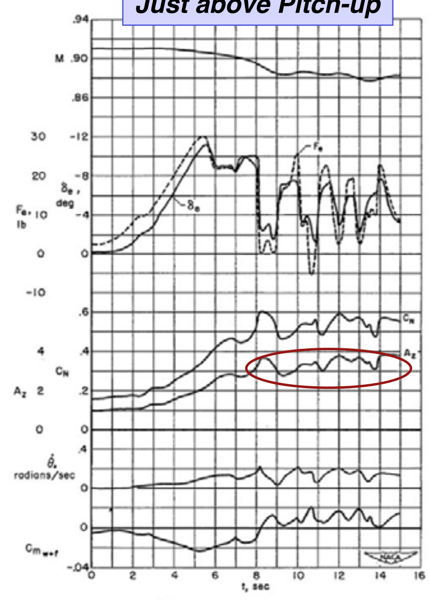
Pitch rate

Pitch moment coefficient, C_m



(a) Just below pitch-up.

Time, s

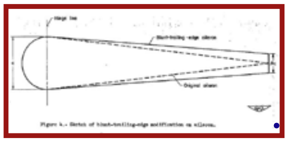


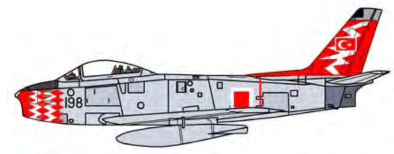
(b) Just above pitch-up.

Time, s

NACA RM-A54C31, 1954

Effects of F-86 Blunt-Trailing-Edge Aileron





- Mach Effect on Control of Wings-Level Flight
- Effect of Aileron Modification on Roll-Control Effectiveness and Response

Stick force

Aileron

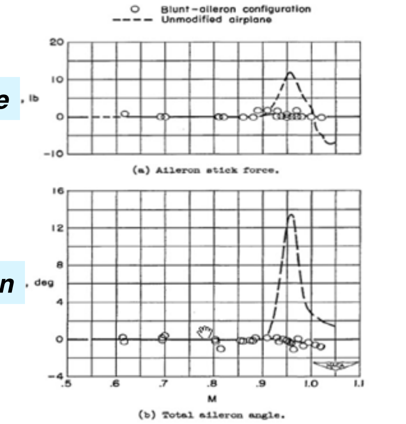


Figure 18.- Variation with Mach number of aileron stick force and total aileron angle to maintain wings-level flight.

Mach number

$C_{l_{\delta_{a_T}}}$, per radian

$\frac{\partial(pb/2V)}{\partial\delta_{a_T}}$, per radian

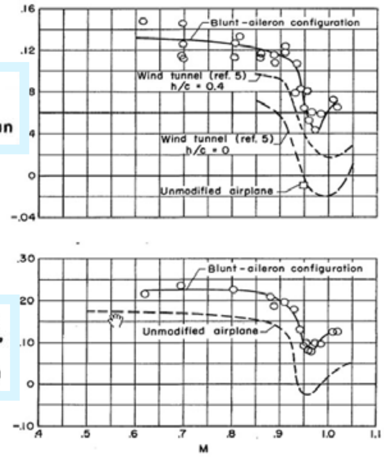


Figure 17.- Variation of aileron effectiveness parameters $C_{l_{\delta_{a_T}}}$ and $\partial(pb/2V)/\partial\delta_{a_T}$ with Mach number.

Mach number

NACA RM-A54C31, 1954

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

M = 3

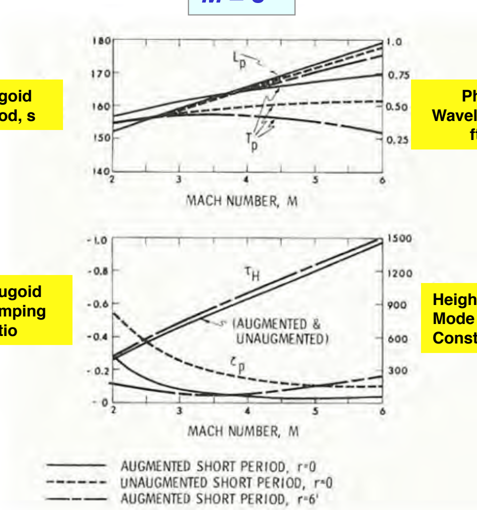
Altitude = 70,000 ft

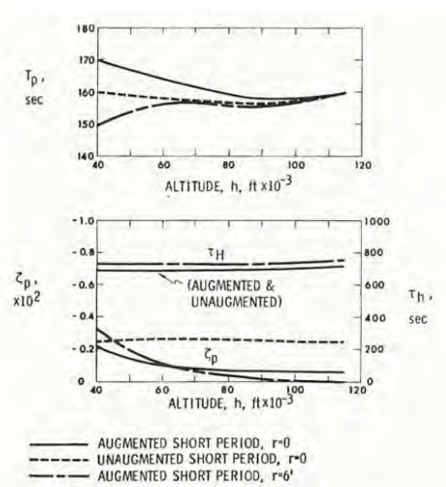
Phugoid Period, s

Phugoid Wavelength, ft x 10^{-6}

Phugoid Damping Ratio

Height Mode Time Constant, s





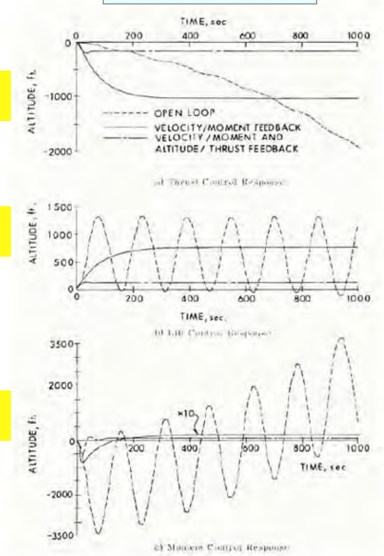
* Short-period, phugoid, and height modes

$$\Delta x^T = \left[\Delta V \ \Delta\gamma \ \Delta q \ \Delta\alpha \ \Delta z \right]$$

Stengel, 1970

Altitude Response of 5th-Order Longitudinal Model

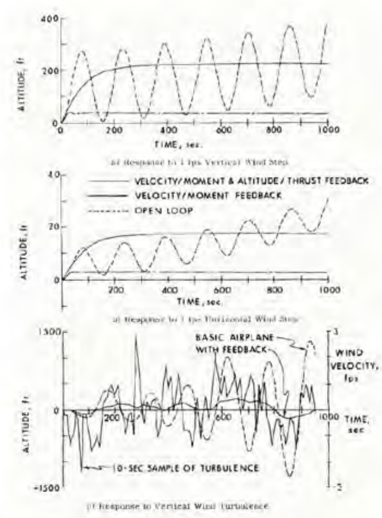
Control Effects | **_Disturbance Effects_**



Thrust Control

Lift Control

Moment Control



Vertical Wind Step

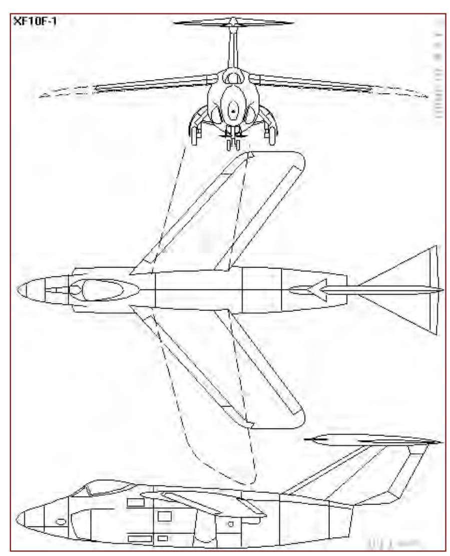
Horizontal Wind Step

Random Vertical Wind

Stengel, 1970

Flying Tail of the *XF10F*

- **Variable-sweep** successor to the ***F9F-6 Cougar*** and precursor to the ***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


BAE Tornado


Grumman F-14 Tomcat

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

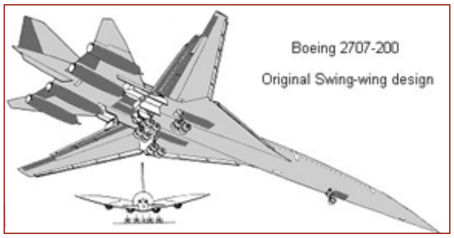
Rockwell B-1

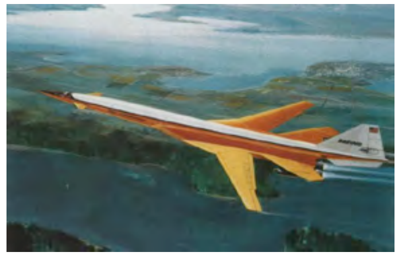

Grumman F-14 Tomcat

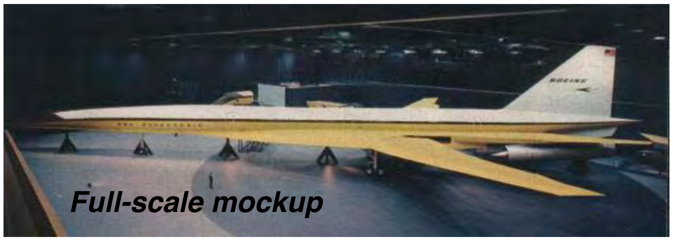

Dassault Mirage G8

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





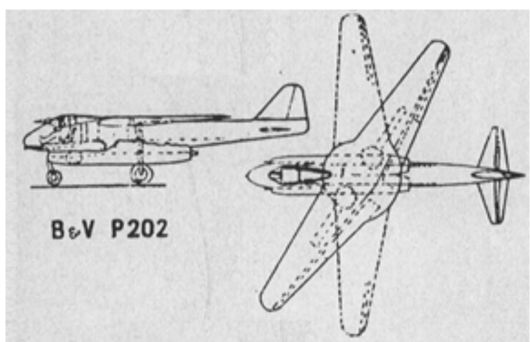


Full-scale mockup

http://www.youtube.com/watch?v=65gsjHhwV_8

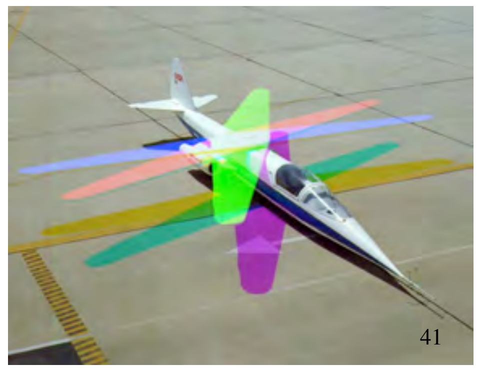
Oblique Wing Concepts

- 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



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?**