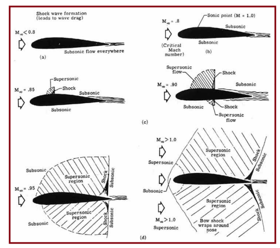
Problems of High Speed and Altitude

Robert Stengel, Aircraft Flight Dynamics
MAE 331, 2018



Learning Objectives

- **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

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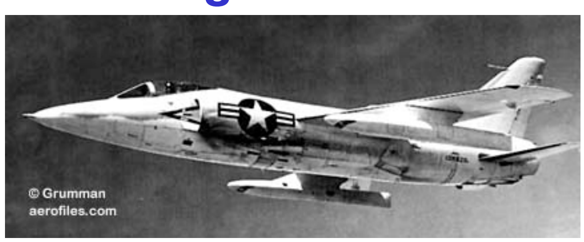
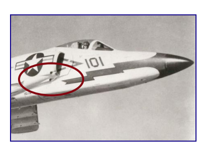
Outrunning Your Own Bullets



- **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**



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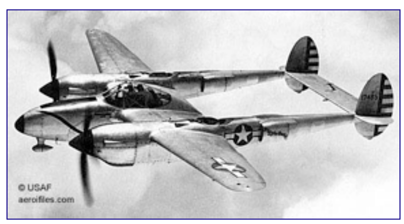
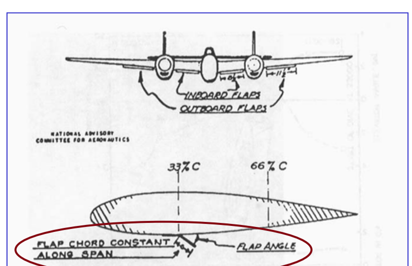
Effects of Air Compressibility on Flight Stability

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

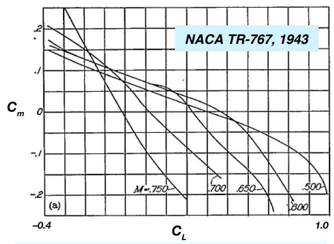




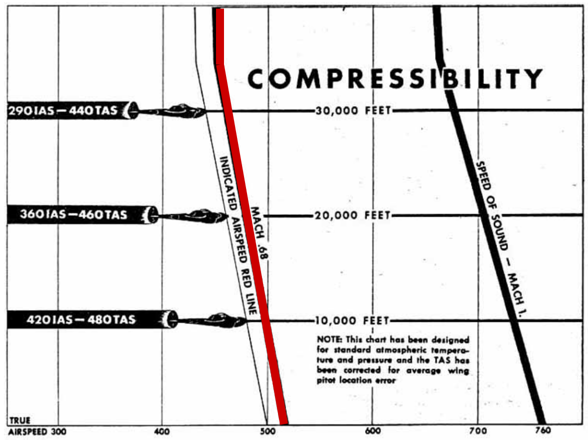
NACA WR-A-66, 1943

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

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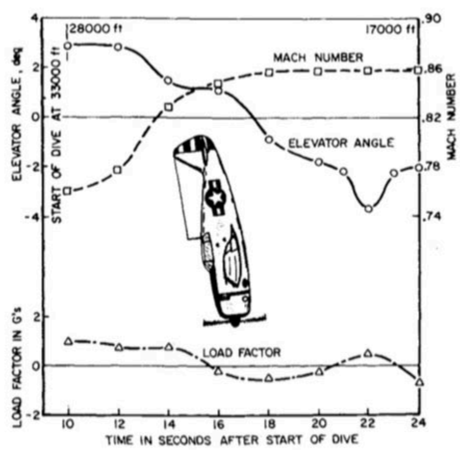
P-47 Mach Tuck

- Static margin increase with Mach number
  - Uncontrollable vertical dive
  - Reduction in elevator pitch control



- US Army Air Corps flight tests, 1944
  - Full aft stick produced ½ g load factor, rather than 20-30 g
  - Miraculous pullup at 15,000 ft – with bent wings

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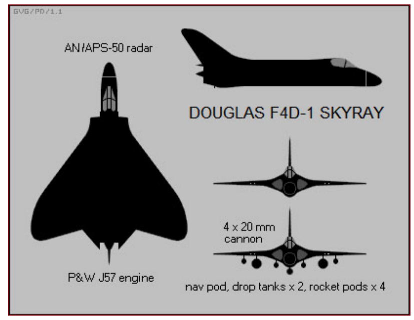
F4D Mach Tuck

- 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 increase the speed of sound
  - High dynamic pressure
  - 1.5 *g* per degree of angle of attack, $M \approx 1$, dramatic trim changes with Mach number
  - Pilot used nose-up trim control during high-speed run
    - 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

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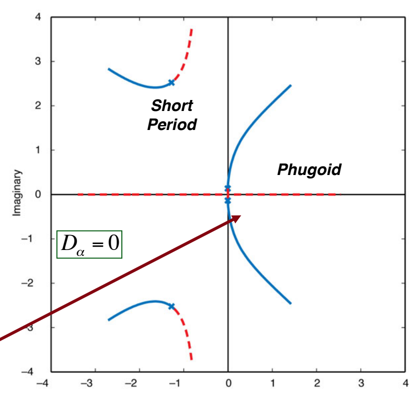
M_V Effect on 4th-Order Roots

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

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



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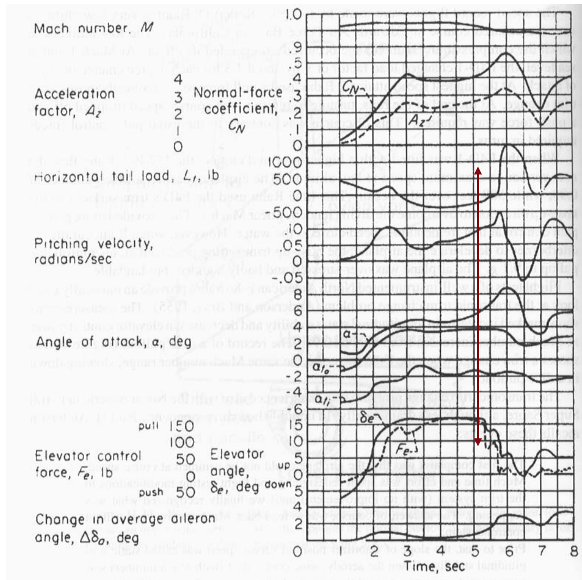
Pitch-Up Instability

- High angle of attack phenomenon
- Aft-swept wing
- 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

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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
- Mach Trim typical on current jet transports [$M > 0.6$]

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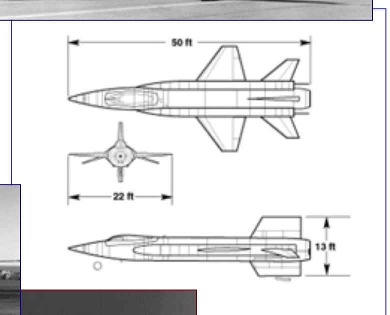
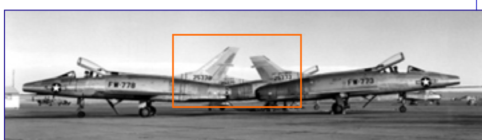
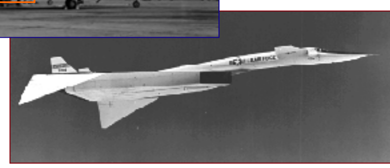
Supersonic Directional Instability

- **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**







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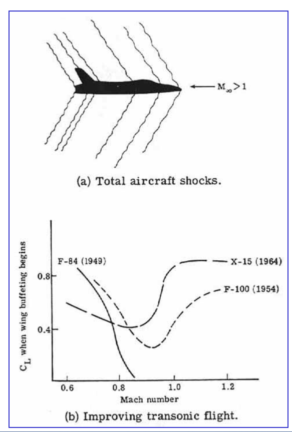
High-Altitude Stall-Mach Buffet

- **Increased angle of attack and lift coefficient leads to "Stall buffet"**
- **Intermittent flow separation at transonic speed leads to "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**



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Variable-Sweep/Incidence Wings ("Morphing")

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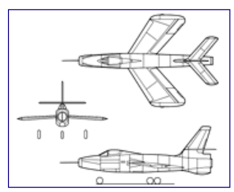
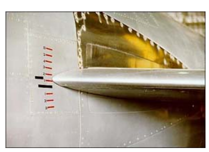
Searching for the Right Design: The Many Shapes of the XF-91 *Thunderceptor*



- Variable-incidence wing
- Tip chord > Root chord



- Full nose inlet

- Vee tail, large tip chord

- Radome above inlet

- Modified nose and tail

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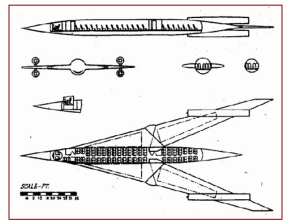
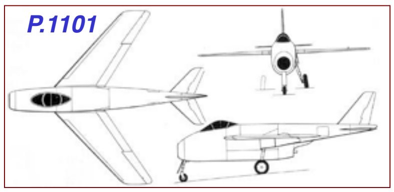
Early Swing-Wing Designs

- **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**





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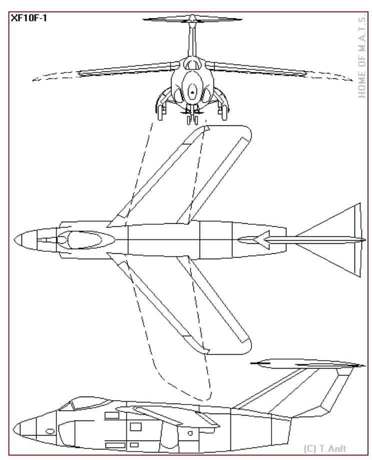
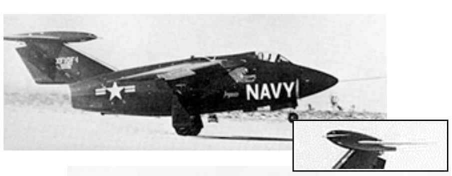
Flying Tail of the *XF10F*

- **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**





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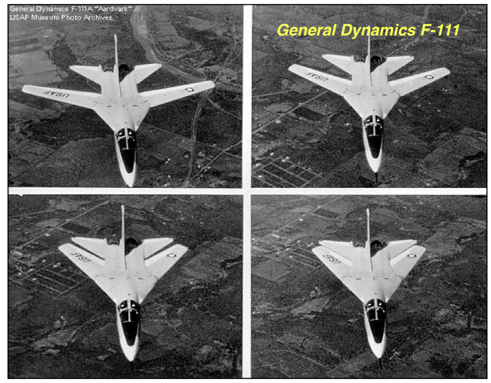
Variable Sweep and Incidence

- 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



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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

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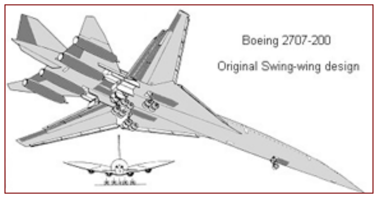
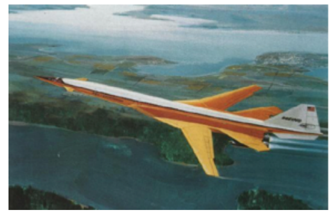
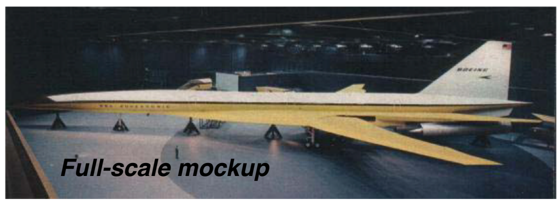
Boeing 2707-200
Supersonic Transport Concept

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







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

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Altitude/Airspeed Instability

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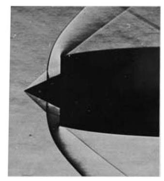
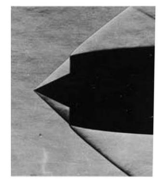
Supersonic Altitude/Airspeed Instability

- **Inability of *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**



Unstarted inlet



Started Inlet

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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**

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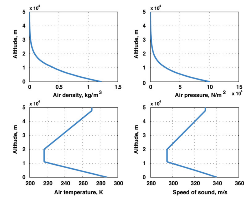
Effect of Atmosphere Variation on Aerodynamics



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

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

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

$$M = \frac{V}{a}$$

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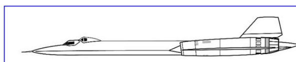
Third-Order Model for Phugoid-Height Model Dynamics



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

Neglecting M_z and short-period dynamics

$$\begin{bmatrix} \Delta \dot{V} \\ \Delta \dot{\gamma} \\ \Delta \dot{z} \end{bmatrix} = \begin{bmatrix} -D_V & -g & -D_z \\ L_V / V_N & 0 & L_z / V_N \\ 0 & -V_N & 0 \end{bmatrix} \begin{bmatrix} \Delta V \\ \Delta \gamma \\ \Delta z \end{bmatrix} + \begin{bmatrix} T_{\delta T} \\ 0 \\ 0 \end{bmatrix} \Delta \delta T$$

3rd-degree characteristic polynomial

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

- **Oscillatory phugoid mode** $\left(\zeta_P, \omega_{n_P} \right)$
- **Real height mode** λ_h

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Approximate Roots of the 3rd-Order Equation

Assume phugoid response is fast compared to height mode response

Phugoid Mode | Height Mode

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

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

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

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

$$\begin{bmatrix}\Delta V_{SS}\\ \Delta\gamma_{SS}\\ \Delta z_{SS}\end{bmatrix} = -\begin{bmatrix}-D_V & -g & -D_z\\ \frac{L_V}{V_N} & 0 & \frac{L_z}{V_N}\\ 0 & -V_N & 0\end{bmatrix}^{-1}\begin{bmatrix}T_{\delta T}\\ 0\\ 0\end{bmatrix}\Delta\delta T_{SS}$$

- **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

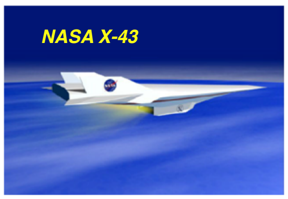
$$\Delta V_{SS} = 0$$

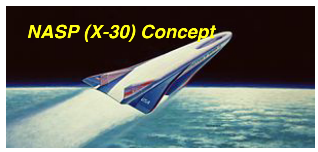
$$\Delta\gamma_{SS} = \frac{T_{\delta T}}{g}\Delta\delta T_{SS}$$

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

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





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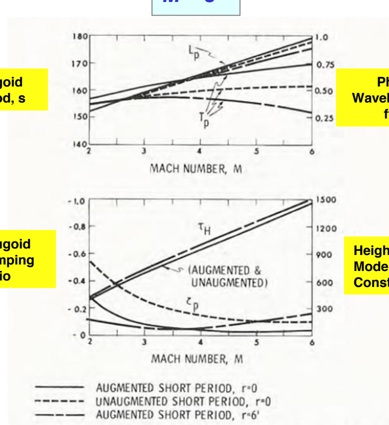
Phugoid and Height Modes of 5th-Order Longitudinal Model*

M = 3

Phugoid Period, s

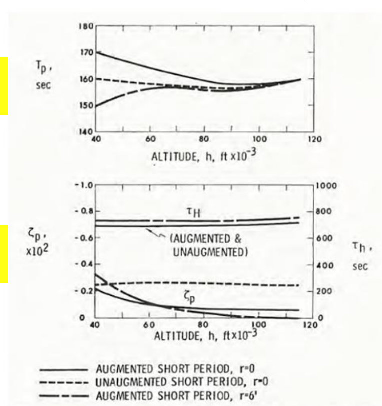
Phugoid Wavelength, ft x 10-6

Phugoid Damping Ratio



Altitude = 70,000 ft

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

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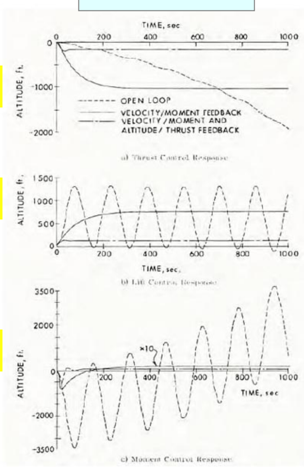
Altitude Response of 5th-Order Longitudinal Model

Control Effects

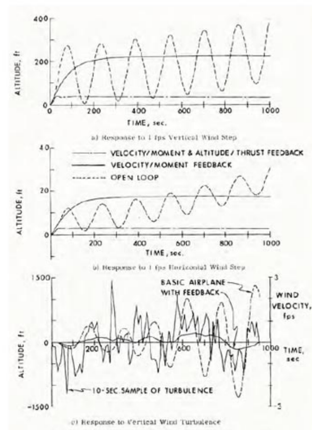
Thrust Control

Lift Control

Moment Control



Disturbance Effects



Vertical Wind Step

Horizontal Wind Step

Random Vertical Wind

Stengel, 1970

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Future of High-Speed Flight

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

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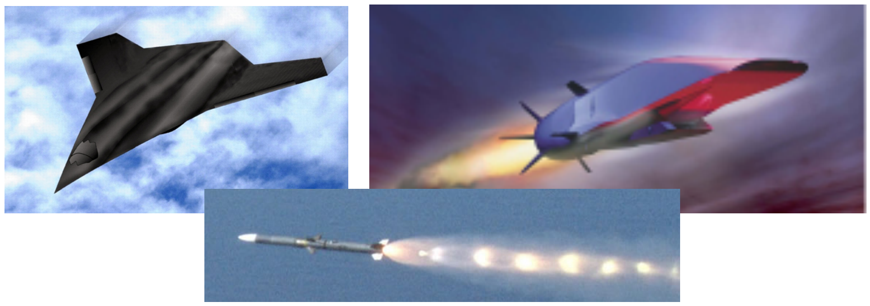
Future of High-Speed Flight



- 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

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Supplemental Material

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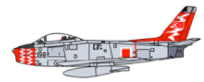
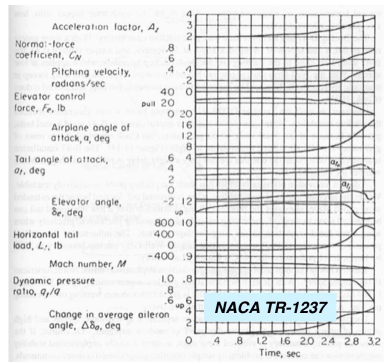
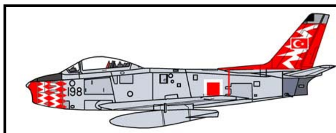
Transonic Pitchup Problem

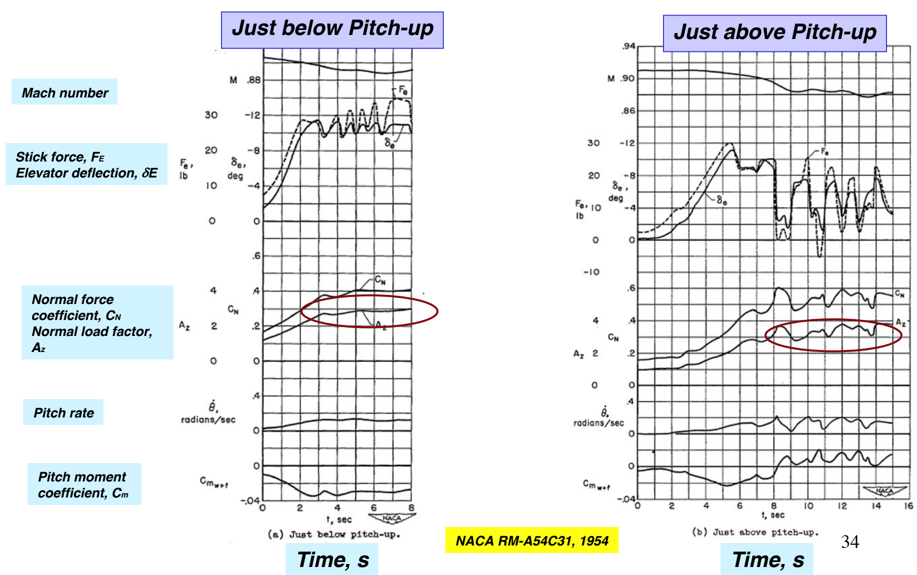


- **Sign reversal of C_{m_α} with increasing angle of attack**
  - **Combined effect of Mach number and changing downwash effects on horizontal tail**
- ***F-86 Sabre* wind-up turn**
  - **Turn at high bank angle, constant load factor, decreasing velocity, and increasing angle of attack**

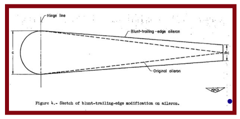


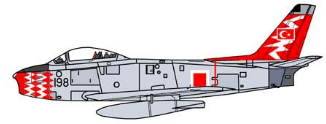


F-86 Flight Test: Attempt to Hold Load Factor at 3 in Transonic Windup Turn



Effects of F-86 Blunt-Trailing-Edge Aileron





Effect of Aileron Modification on Roll-Control Effectiveness and Response

- Mach Effect on Control of Wings-Level Flight

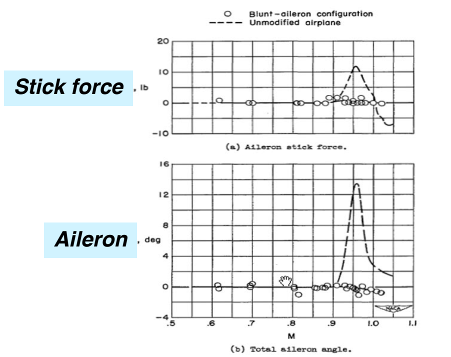


Figure 16.- Variation with Mach number of aileron stick force and total aileron angle to maintain wings-level flight.

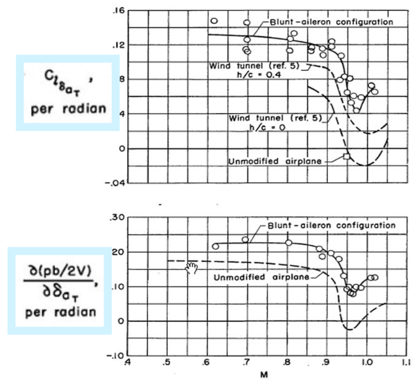


Figure 17.- Variation of aileron effectiveness parameters $C_{l_{\delta_{a_T}}}$ and $\partial(pb/2V)/\partial\delta_{a_T}$ with Mach number.

NACA RM-A54C31, 1954

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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

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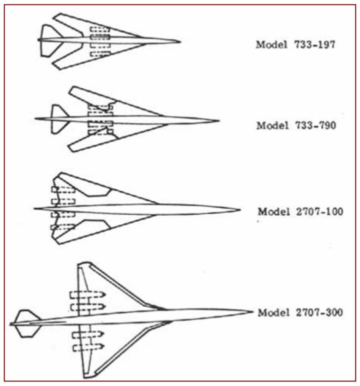
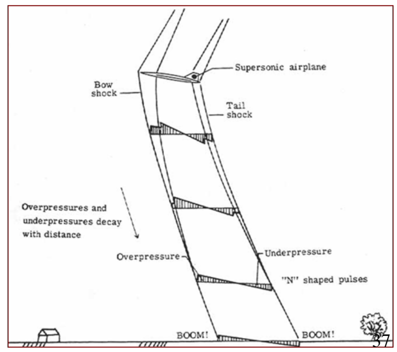
Boeing 2707-300 Supersonic Transport

- 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





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