Aircraft Flying Qualities

Robert Stengel, Aircraft Flight Dynamics
MAE 331, 2008

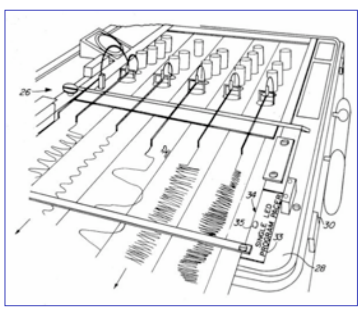
- Flight test instrumentation
- Flying qualities requirements
- Flying qualities specifications
- Pilot opinion ratings
- *CAP*, *C**, and other longitudinal criteria
- Pilot-induced oscillations

Flying (or Handling) Qualities

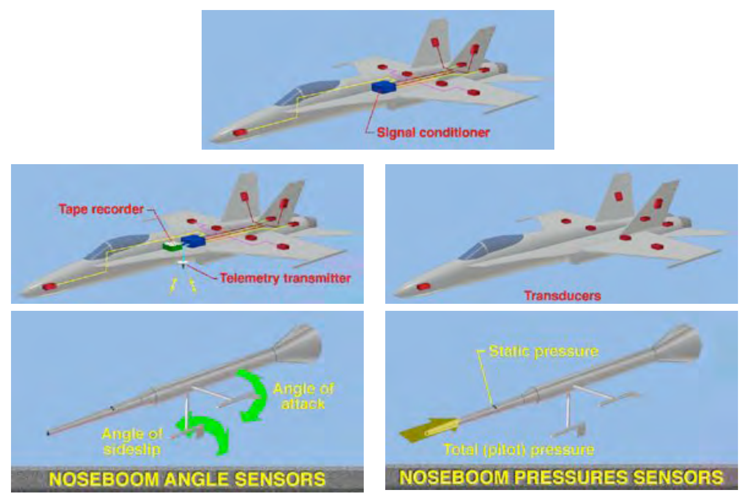
- Stability and controllability perceived by the pilot
- 1919 flight tests of *Curtiss JN-4H Jenny* at *NACA Langley Laboratory* by Warner, Norton, and Allen
  - Elevator angle and stick force for equilibrium flight
  - Correlation of elevator angle and airspeed with stability
  - Correlation of elevator angle and airspeed with wind tunnel tests of pitch moment

Flight Testing Instrumentation: Then

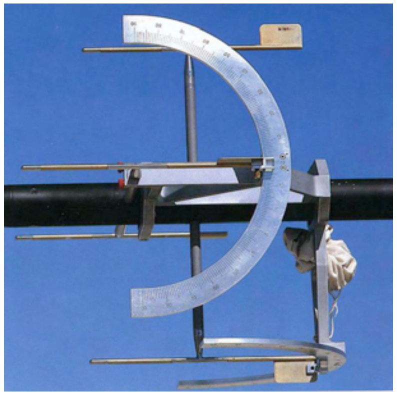
- Flight recording instruments: drum/strip charts, inked needles, film, galvanometers connected to air vanes, pressure sensors, clocks



Flight Testing Instrumentation: Now



Nose Boom and Calibration Quadrants



First Flying Qualities Specification

- First flying qualities specification: 1935, Edward Warner for *Douglas DC-4* transport
  - Interviews with pilots and engineers

Flying Qualities Research at NACA

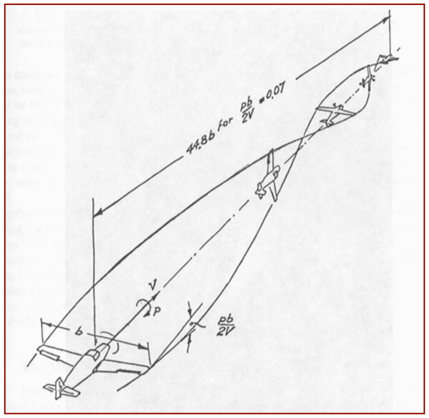
- Hartley Soulé and Floyd Thompson (late 1930s)
  - Long- and short-period motions
  - Time to reach specified bank angle
  - Period and damping of oscillations
  - Correlation with pilot opinion
- Robert Gilruth (1941-3)
  - Parametric regions and boundaries
  - Multi-aircraft criteria
  - Control deflection, stick force, and normal load factor
  - Roll helix angle
  - Lateral control power

Modern Flight Research and Development

- Application of control theory
- Variable-stability research aircraft, e.g., *TIFS, AFTI F-16, NT-33A, and VRA*
- The Princeton Connection [*Flight Research Laboratory*]

Gilruth Roll-Rate Criterion [*pb*/2*V*]

- **Helix angle formed by rotating wing tips, *pb/2V***
  - **Roll rate, *p*, rad/s**
  - **Wing semi-span, *b*/2, m**
  - **Velocity, *V*, m/s**
- ***Robert Gilruth criterion***
  - ***pb/2V* > 0.07 rad**



Simplified Roll-Rate Response

- **Tradeoff between high *pb*/2*V* and high lateral stick forces prior to powered controls:**

$$\dot{p}(t) = [C_{l_p} p(t) + C_{l_{\delta A}} \delta A(t)]\overline{q} Sb / I_{xx}$$
$$= a\, p(t) + c\, \delta A(t)$$
$$\overline{q} = \frac{1}{2}\rho V^2, \text{ dynamic pressure}, N/m^2$$

- **Initial-condition response (*δA* = 0)**

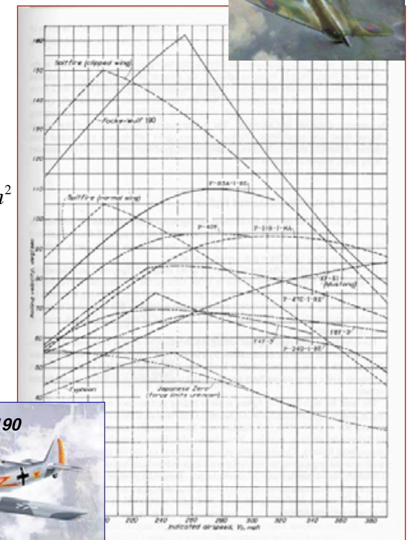
$$p(t) = p(0)e^{at}$$

- **Step response [*p(0)* = 0]**

$$p(t) = \frac{c}{a}\left(e^{at} - 1\right)\delta A^*$$

- **Steady state response**

$$p^* = -\frac{C_{l_{\delta A}}}{C_{l_p}}\delta A^*$$

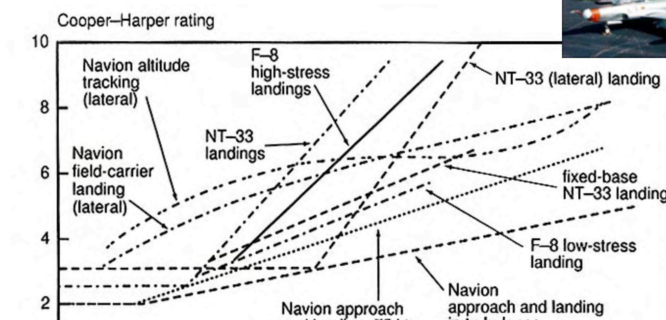


Cooper-Harper Handling Qualities Rating Scale

Aircraft characteristics	Demands on the pilot in selected task or required operation*	Pilot rating
Excellent Highly desirable	Pilot compensation not a factor for desired performance	1
Good Negligible deficiencies	Pilot compensation not a factor for desired performance	2
Fair – some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	3
Minor but annoying deficiencies	Desired performance requires moderate pilot compensation	4
Moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	5
Very objectionable but tolerable deficiencies	Adequate performance requires extensive pilot compensation	6
Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question	7
Major deficiencies	Considerable pilot compensation is required for control	8
Major deficiencies	Intense pilot compensation is required to retain control	9
Major deficiencies	Control will be lost during some portion of required operation	10

*Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions

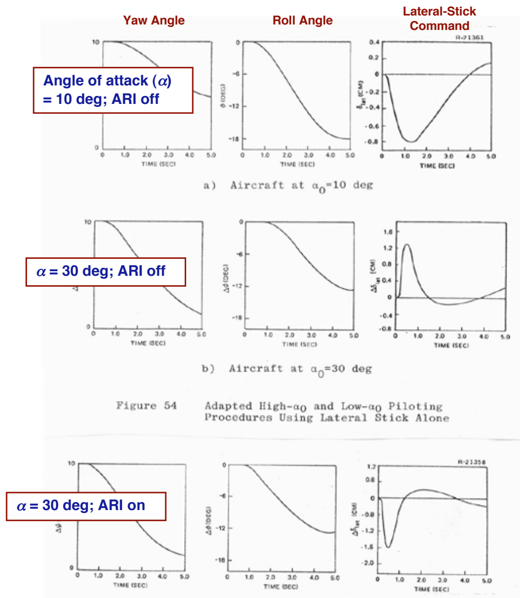
Effect of Equivalent Time Delay on Cooper-Harper Rating



Rate of degraduation of Cooper–Harper pilot ratings increases with difficulty of task

Inverse Problem of Lateral Control

- Given a flight path, what is the control history that generates it?
  - Necessary piloting actions
  - Control-law design
- Aileron-rudder interconnect (ARI) simplifies pilot input



Aerial Refueling

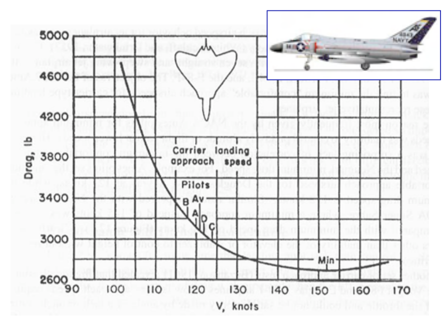
- Difficult flying task
- High potential for PIO
- Alternative designs
  - Rigid boom (USAF)
  - Probe and drogue (USN)

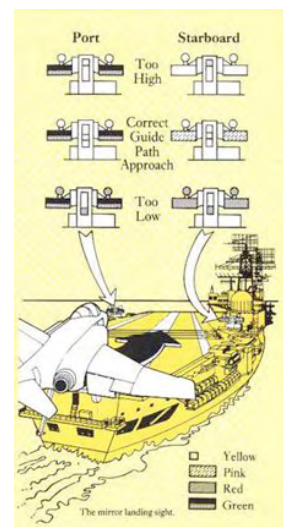
Formation Flying

- Coordination and precision
- Potential aerodynamic interference
- *US Navy Blue Angels* (*F/A-18*)

Carrier Approach on Back Side of the Power/Thrust Curve

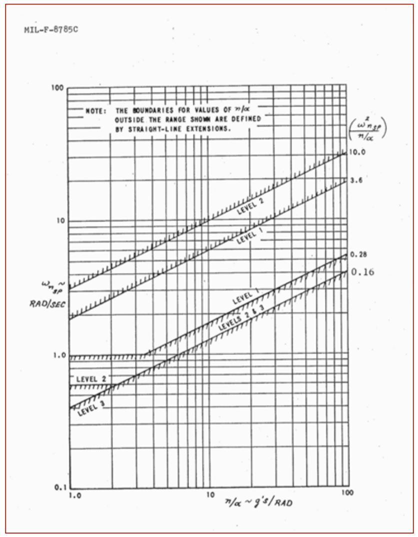
- Precise path and airspeed control while on the *back side of the power curve*
  - Slower speed requires higher thrust
  - Lightly damped phugoid mode requires coordination of pitch and thrust control
- *Reference flight path* generated by optical device, which projects a *meatball* relative to a datum line





Military Flying Qualities Specifications, MIL-F-8785C

- Specifications established during WWII
- US Air Force and Navy coordinated efforts beginning in 1945
- First version appeared in 1948, last in 1980
- Distinctions by flight phase, mission, and aircraft type



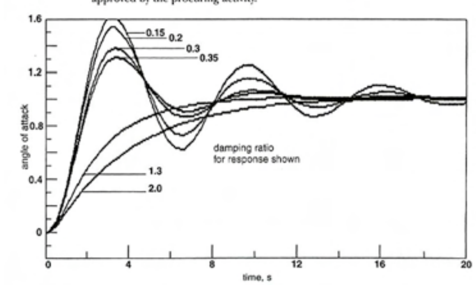
MIL-F-8785C Identifies Satisfactory, Acceptable, and Unacceptable Response Characteristics

Damping Ratio

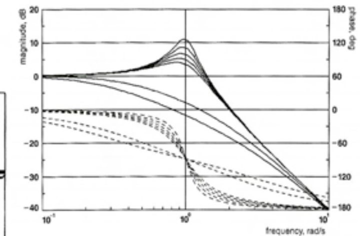
Level	Category A and C Flight Phases Minimum	Category A and C Flight Phases Maximum	Category B Flight Phases Minimum	Category B Flight Phases Maximum
1	0.35	1.30	0.30	2.00
2	0.25	2.00	0.20	2.00
3	0.15*	–	0.15	–

* May be reduced at altitudes above 20 000 feet if approved by the procuring activity.

Short-period angle-of-attack response to elevator input



Step Response



Frequency Response

MIL-F-8785C Aircraft Types

I. Small, light airplanes, e.g., utility aircraft and primary trainers
II. Medium-weight, low-to-medium maneuverability airplanes, e.g., small transports or tactical bombers
III. Large, heavy, low-to-medium maneuverability airplanes, e.g., heavy transports, tankers, or bombers
IV. Highly maneuverable aircraft, e.g., fighter and attack airplanes

MIL-F-8785C Flight Phase

A. Non-terminal flight requiring rapid maneuvering precise tracking, or precise flight path control
   - air-to-air combat
   - ground attack
   - in-flight refueling (receiver)
   - close reconnaissance
   - terrain following
   - close formation flying
B. Non-terminal flight requiring gradual maneuvering
   - climb, cruise
   - in-flight refueling (tanker)
   - descent
C. Terminal flight
   - takeoff (normal and catapult)
   - approach
   - wave-off/go-around
   - landing

MIL-F-8785C Levels of Performance

1. Flying qualities clearly adequate for the mission flight phase
2. Flying qualities adequate to accomplish the mission flight phase, with some increase in pilot workload or degradation of mission effectiveness
3. Flying qualities such that the aircraft can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate

Principal MIL-F-8785C Metrics

- Longitudinal flying qualities
  - static speed stability
  - phugoid stability
  - flight path stability
  - short period frequency and its relationship to command acceleration sensitivity
  - short period damping
  - control-force gradients
- Lateral-directional flying qualities
  - natural frequency and damping of the Dutch roll mode
  - time constants of the roll and spiral modes
  - rolling response to commands and Dutch roll oscillation
  - sideslip excursions
  - maximum stick and pedal forces
  - turn coordination

Long-Period Flying Qualities Criteria (MIL-F-8785C)

Flight Phase

A.	Non-terminal flight requiring rapid maneuvering
B.	Non-terminal flight requiring gradual maneuvering
C.	Terminal flight

Level of Performance

1.	Clearly adequate for the mission
2.	Adequate to accomplish the mission, with some increase in workload
3.	Aircraft can be controlled safely, but workload is excessive

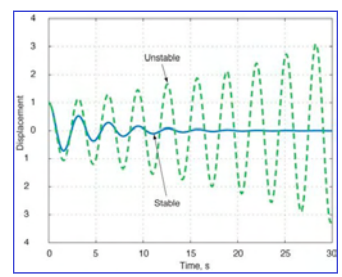
- Static speed stability
  - No tendency for aperiodic divergence
  - Stable control stick gradient
  - Increasing "pull" force with decreasing speed

- Flight path stability [Phase C]
  1. $(\Delta\gamma/\Delta V)_{SS} < 0.06$ deg/kt
  2. $(\Delta\gamma/\Delta V)_{SS} < 0.15$ deg/kt
  3. $(\Delta\gamma/\Delta V)_{SS} < 0.24$ deg/kt

Long-Period Flying Qualities Criteria (MIL-F-8785C)

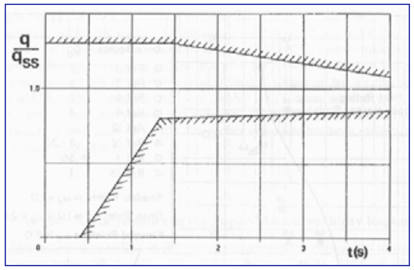
- Phugoid stability
  1. Damping ratio ≥ 0.04
  2. Damping ratio ≥ 0
  3. "Time to double", $T_2 \geq 55$ sec

$$T_{2_{Ph}} = -0.693/\zeta_{Ph}\omega_{n_{Ph}}$$

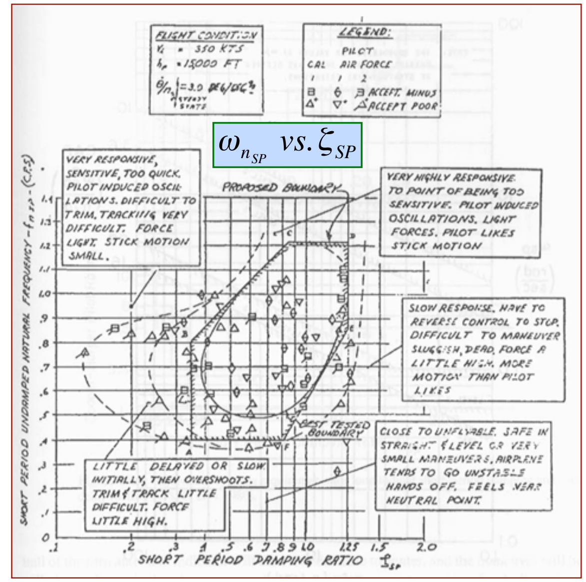


Short Period Criteria

- **Important parameters**
  - Short-period natural frequency
  - Damping ratio
  - Lift slope
  - Step response
    - Initial lag
    - Rise time
    - Over-/under-shoot
    - Settling time
    - Pure time delay
  - Pitch angle response
  - Normal load factor response
  - Flight path angle response (landing)

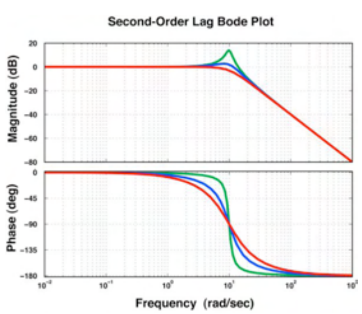


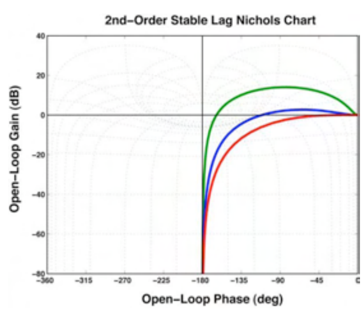
Short-Period "Bullseye" or "Thumbprint"



Nichols Chart: Gain vs. Phase Angle

- Bode Plot
  - Two plots
  - Open-Loop Gain (dB) vs. $\log_{10}\omega$
  - Open-Loop Phase Angle vs. $\log_{10}\omega$
- Nichols Chart
  - Single crossplot; input frequency not shown
  - Open-Loop Gain (dB) vs. Open-Loop Phase Angle





Gain and Phase Margins

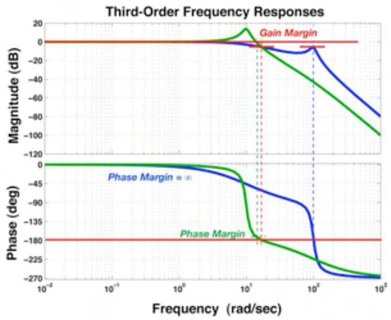
- **Gain Margin:** At the input frequency, ω, for which $\phi(j\omega)$ is –180°,the difference between 0 dB and the transfer function magnitude, $20 \log_{10} AR(j\omega)$
- **Phase Margin:** At the input frequency, ω, for which $20 \log_{10} AR(j\omega)$ is 0 dB, the difference between the phase angle $\phi(j\omega)$, and –180°
- Axis intercepts on the Nichols Chart identify GM and PM

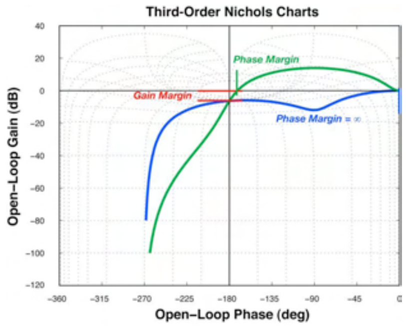
Examples of Gain and Phase Margins

$$H_{blue}(j\omega) = \left[\frac{10}{(j\omega + 10)}\right]\left[\frac{100^2}{(j\omega)^2 + 2(0.1)(100)(j\omega) + 100^2}\right]$$

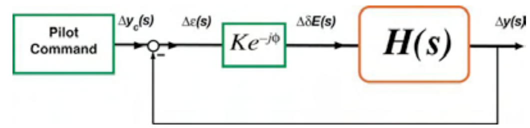
$$H_{green}(j\omega) = \left[\frac{10^2}{(j\omega)^2 + 2(0.1)(10)(j\omega) + 10^2}\right]\left[\frac{100}{(j\omega + 100)}\right]$$

- Bode Plot
- Nichols Chart

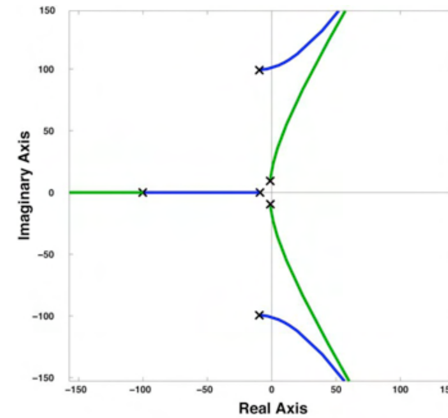


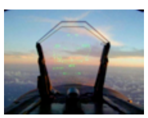


Significance of Gain and Phase Margins



- Assume
  - Pilot tracks a single output using the elevator
  - Plant has 3rd-order transfer function
- Gain/phase-changing element, $Ke^{-j\phi}$, in the forward loop
- Gain margin = value of K that causes unstable control (e.g., root loci at right)
  - Crossover frequency predicted by open-loop Bode plot
- Phase margin = value of ϕ that causes unstable control

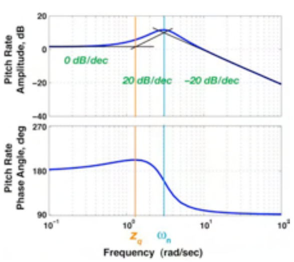


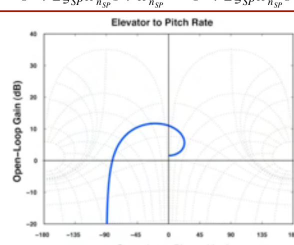


Short-Period Approximation Transfer Functions

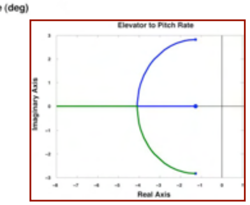
- Elevator to pitch rate

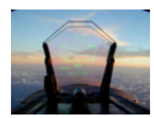
$$\frac{\Delta q(s)}{\Delta\delta E(s)} = \frac{k_q\left(s - z_q\right)}{s^2 + 2\zeta_{SP}\omega_{n_{SP}}s + \omega_{n_{SP}}^{\;2}} = \frac{k_q\left(s - \frac{1}{T_{\theta_2}}\right)}{s^2 + 2\zeta_{SP}\omega_{n_{SP}}s + \omega_{n_{SP}}^{\;2}}$$



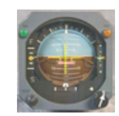


- Pure gain or phase change in feedback control cannot produce instability



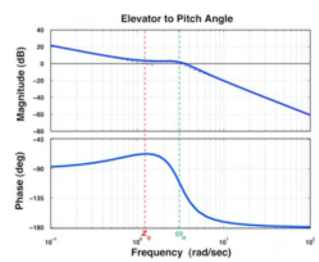


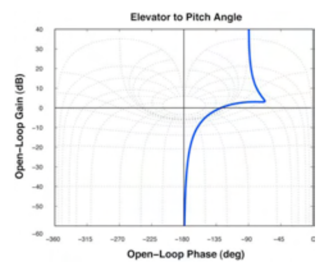
Short-Period Approximation Transfer Functions



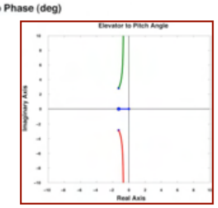
- Elevator to pitch angle

$$\frac{\Delta\theta(s)}{\Delta\delta E(s)} = \frac{k_q\left(s - z_q\right)}{s\left(s^2 + 2\zeta_{SP}\omega_{n_{SP}}s + \omega_{n_{SP}}^{\;2}\right)}$$





- Pure gain or phase change in feedback control cannot produce instability



Normal Load Factor

$$\Delta n_z = \frac{V_N}{g}\left(\Delta\dot{\alpha} - \Delta q\right) = -\frac{V_N}{g}\left(\frac{L_\alpha}{V_N}\Delta\alpha + \frac{L_{\delta E}}{V_N}\Delta\delta E\right)$$

positive down

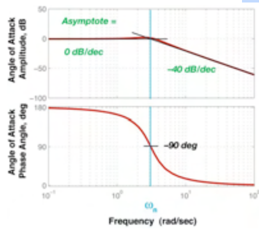
- Therefore, with negligible $L_{\delta E}$ (aft tail/canard effect)

$$\frac{\partial \Delta n_z(s)}{\partial \Delta\delta E(s)} = \frac{1}{g}\left(L_\alpha \frac{\partial\Delta\alpha(s)}{\partial\Delta\delta E(s)} + L_{\delta E}\right) \approx \left(\frac{L_\alpha}{g}\right)\frac{\partial\Delta\alpha(s)}{\partial\Delta\delta E(s)}$$

positive up

- Elevator to angle of attack ($L_{\delta E} = 0$)

$$\frac{\Delta\alpha(s)}{\Delta\delta E(s)} \approx \frac{k_\alpha}{s^2 + 2\zeta_{SP}\omega_{n_{SP}} s + \omega_{n_{SP}}^2}$$



Control Anticipation Parameter, *CAP*

- Inner ear senses angular acceleration
- Inner ear cue should aid pilot in anticipating commanded normal acceleration

$$\Delta\dot{q}(0) = \left(M_{\delta E} - \frac{M_\alpha}{V_N + L_\alpha}L_{\delta E}\right)\Delta\delta E_{SS}$$

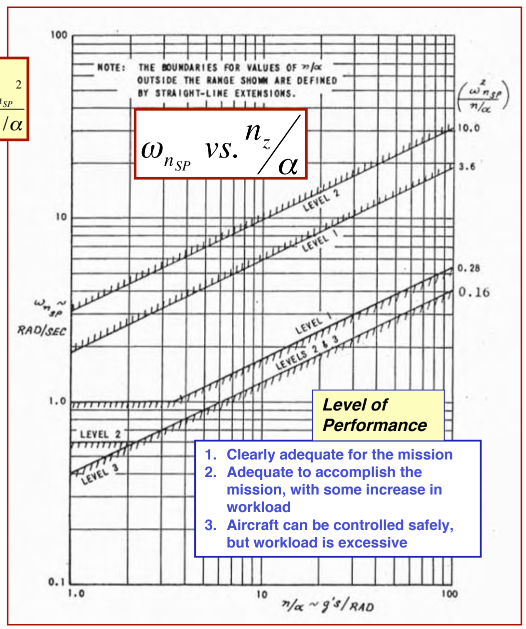
$$\Delta n_{SS} = \frac{V_N}{g}\Delta q_{SS} = -\left(\frac{V_N}{g}\right)\frac{\left(M_{\delta E}\,{}^{L_\alpha}\!/_{V_N} - M_\alpha\,{}^{L_{\delta E}}\!/_{V_N}\right)}{\left(M_q\,{}^{L_\alpha}\!/_{V_N} + M_\alpha\right)}\Delta\delta E_{SS}$$

$$CAP = \frac{\Delta\dot{q}(0)}{\Delta n_{SS}} = \frac{-\left(M_{\delta E} - \frac{M_\alpha}{V_N + L_\alpha}L_{\delta E}\right)\left(M_q\,{}^{L_\alpha}\!/_{V_N} + M_\alpha\right)}{\left(L_\alpha M_{\delta E} - L_{\delta E}M_\alpha\right)/g}$$

with $L_{\delta E} = 0$

$$CAP = \frac{-\left(M_q\,{}^{L_\alpha}\!/_{V_N} + M_\alpha\right)}{L_\alpha/g} \approx \frac{\omega_{n_{SP}}^2}{n_z/\alpha}$$

MIL-F-8785C Short-Period Flying Qualities Criterion



$$\omega_{n_{SP}}\ vs.\ {}^{n_z}\!/_{\alpha}$$

Level of Performance

1. Clearly adequate for the mission
2. Adequate to accomplish the mission, with some increase in workload
3. Aircraft can be controlled safely, but workload is excessive

Control Anticipation Parameter vs. Short-Period Damping Ratio

(MIL-F-8785C, Category A)

$$\omega_{n_{SP}} = \sqrt{CAP\,{}^{n_z}\!/_{\alpha}}$$

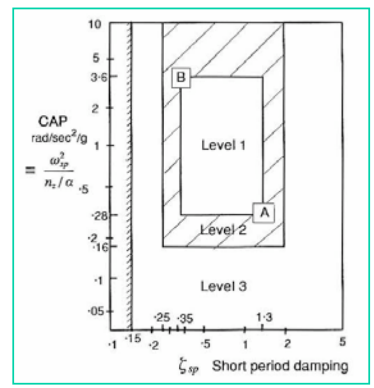
$${}^{n_z}\!/_{\alpha} \approx {}^{L_\alpha}\!/_{g}$$

Flight Phase

A. Non-terminal flight requiring rapid maneuvering
B. Non-terminal flight requiring gradual maneuvering
C. Terminal flight

Level of Performance

1. Clearly adequate for the mission
2. Adequate to accomplish the mission, with some increase in workload
3. Aircraft can be controlled safely, but workload is excessive



Gibson Dropback Criterion for Pitch Angle Control

- Step response of pitch rate should have overshoot for satisfactory pitch and flight path angle response
- When criterion is satisfied,

$$\frac{\Delta q(s)}{\Delta \delta E(s)} = \frac{k_q\left(s - z_q\right)}{s^2 + 2\zeta_{SP}\omega_{n_{SP}} s + \omega_{n_{SP}}^2} = \frac{k_q\left(s + \omega_{n_{SP}}/\zeta_{SP}\right)}{s^2 + 2\zeta_{SP}\omega_{n_{SP}} s + \omega_{n_{SP}}^2}$$

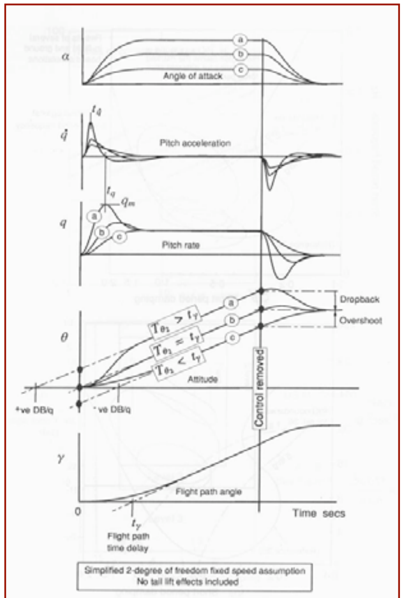
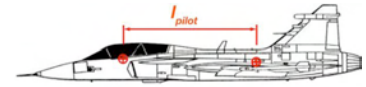
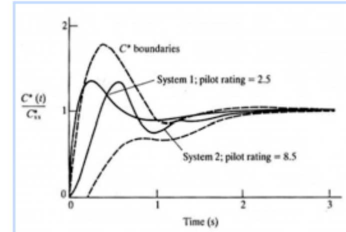


Figure 7-3 Generic short period pitch transient responses

C* Criterion



$$C^* = \Delta n_{pilot} + \frac{V_{crossover}}{g}\Delta q \qquad V_{crossover} \approx 125\ m/s$$
$$= l_{pilot}\Delta\dot{q} + \Delta n_{cm} + \frac{V_{crossover}}{g}\Delta q$$
$$= l_{pilot}\Delta\dot{q} + \frac{V_N}{g}\left(\Delta q - \Delta\dot{\alpha}\right) + \frac{V_{crossover}}{g}\Delta q$$



- Hypothesis
  - *C** blends normal load factor and pitch rate
  - Step response of *C** should lie within acceptable envelope
  - Below $V_{crossover}$, Δq is pilot's primary control objective
  - Above $V_{crossover}$, Δn_{pilot} is the primary control objective
- Pilot opinion does not always support the hypothesis

Large Aircraft Flying Qualities

- High wing loading, W/S
- Distance from pilot to rotational center
- Slosh susceptibility of large tanks
- High wing span -> short relative tail length
  - Higher trim drag
  - Increased yaw due to roll, need for rudder coordination
  - Reduced rudder effect
- Altitude response during approach
  - Increased non-minimum-phase delay in response to elevator
  - Potential improvement from canard
- Longitudinal dynamics
  - Phugoid/short-period resonance
- Rolling response (e.g., time to bank)
- Reduced static stability
- Off-axis passenger comfort in BWB turns

Control Design for Satisfactory Flying Qualities

- Satisfy procurement requirement (e.g., Mil Standard)
- Satisfy test pilots (e.g., *Cooper-Harper ratings*)
- Avoid pilot-induced oscillations (PIO)
- Minimize time-delay effects
- Frequency domain criteria
  - Crossover model
  - *Neal-Smith* criterion
  - Bandwidth-phase delay criteria
  - Smith-Geddes PIO criterion
- Elevator-to-pitch angle *Nichols chart* (gain vs. phase angle)

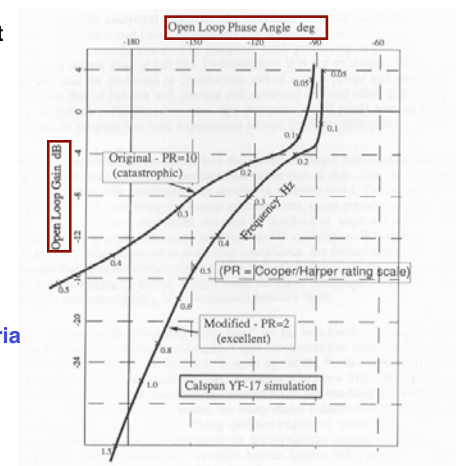


Figure 1-2 A picture of good and bad handling

Pilot-Induced Oscillations

- **MIL-F-8785C specifies no tendency for *pilot-induced oscillations* (PIO)**
  - **Uncommanded aircraft is stable but piloting actions couple with aircraft dynamics to produce instability**

Pilot-Induced Oscillations

- **Category I: Linear pilot-vehicle system oscillations**
- **Category II: Quasilinear events with nonlinear contributions**
- **Category III: Nonlinear oscillations with transients**

Hodgkinson, Neal, Smith, Geddes, Gibson et al

YF-16 Test Flight Zero

- **High-speed taxi test; no flight intended**
- ***Pilot-induced oscillations* induced by overly sensitive roll control**
- **Tail strike**
- **Pilot elected to go around rather than eject**

Next Time: Fourth-Order Longitudinal Dynamics