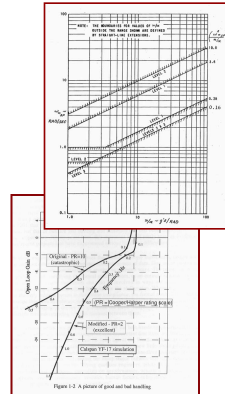# Flying Qualities Criteria
Robert Stengel, Aircraft Flight Dynamics
MAE 331, 2018

Learning Objectives

- **MIL-F-8785C criteria**
- ***CAP*, *C**, and other longitudinal criteria**
- **ϕ/β, ω_ϕ/ω_d, and other lateral-directional criteria**
- **Pilot-vehicle interactions**
- **Flight control system design**

Flight Dynamics
419–428, 525–533, 624–629
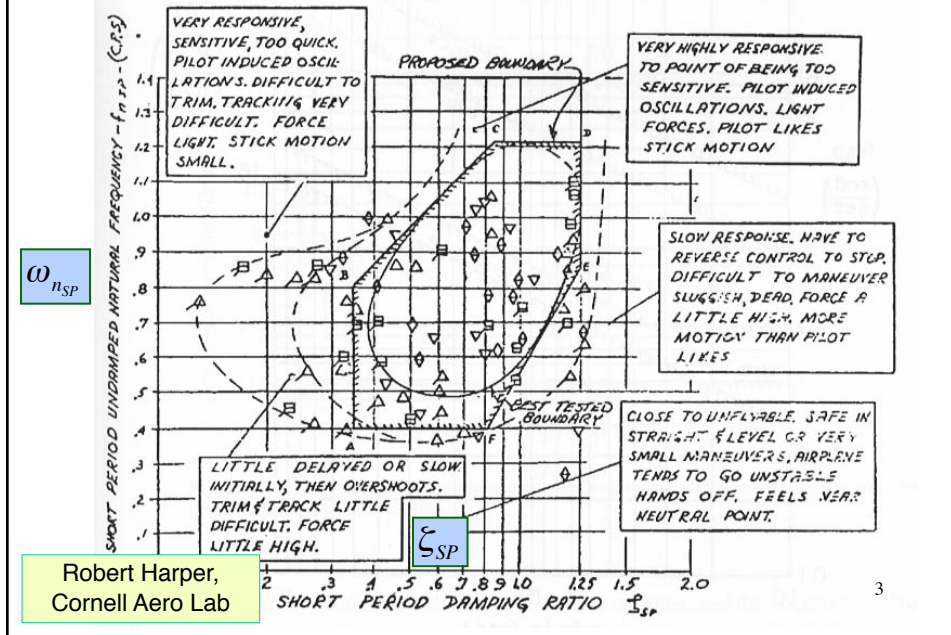*Airplane Stability and Control*
Chapter 21

1

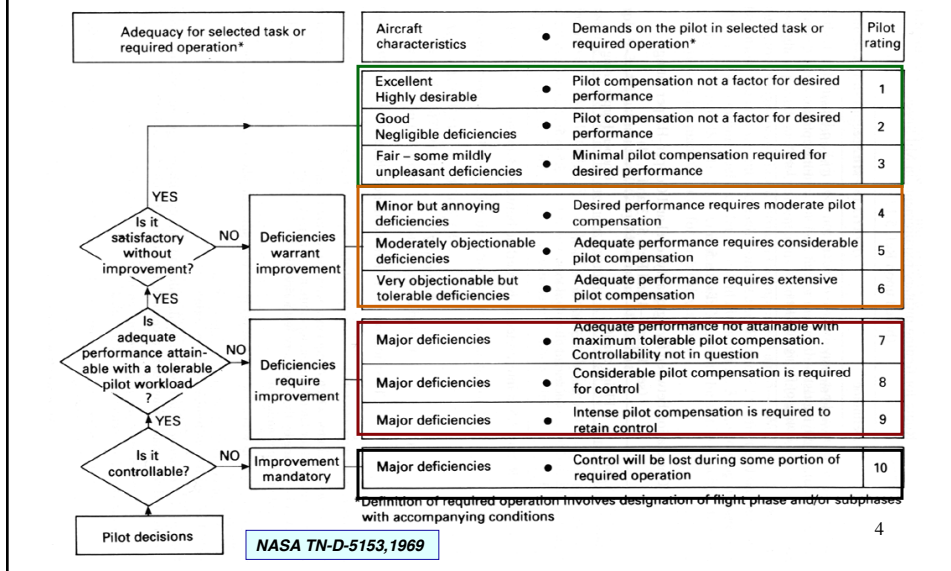# Design for Satisfactory Flying Qualities

- **Satisfy procurement requirement (e.g., Mil Standard)**
- **Satisfy test pilots (e.g., *Cooper-Harper ratings*)**
- **Avoid pilot-induced oscillations (PIO)**
- **Minimize time-delay effects**
- **Time- and frequency-domain criteria**

2

Short-Period "Bullseye" or "Thumbprint"

SHORT PERIOD UNDAMPED NATURAL FREQUENCY f_{nSP} (C.P.S)

$\omega_{n_{SP}}$

PROPOSED BOUNDARY

VERY RESPONSIVE, SENSITIVE, TOO QUICK. PILOT INDUCED OSCILLATIONS. DIFFICULT TO TRIM, TRACKING VERY DIFFICULT. FORCE LIGHT, STICK MOTION SMALL.

VERY HIGHLY RESPONSIVE TO POINT OF BEING TOO SENSITIVE. PILOT INDUCED OSCILLATIONS. LIGHT FORCES. PILOT LIKES STICK MOTION

SLOW RESPONSE. HAVE TO REVERSE CONTROL TO STOP. DIFFICULT TO MANEUVER SLUGGISH, DEAD, FORCE A LITTLE HIGH. MORE MOTION THAN PILOT LIKES

BEST TESTED BOUNDARY

CLOSE TO UNFLYABLE. SAFE IN STRAIGHT & LEVEL OR VERY SMALL MANEUVERS, AIRPLANE TENDS TO GO UNSTABLE HANDS OFF, FEELS NEAR NEUTRAL POINT.

LITTLE DELAYED OR SLOW INITIALLY, THEN OVERSHOOTS. TRIM & TRACK LITTLE DIFFICULT. FORCE LITTLE HIGH.

ζ_{SP}

SHORT PERIOD DAMPING RATIO ζ_{SP}

Robert Harper, Cornell Aero Lab

3

Cooper-Harper Handling Qualities Rating Scale

Adequacy for selected task or required operation*	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

Is it satisfactory without improvement? — YES / NO → Deficiencies warrant improvement

Is adequate performance attainable with a tolerable pilot workload? — YES / NO → Deficiencies require improvement

Is it controllable? — YES / NO → Improvement mandatory

Pilot decisions

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

NASA TN-D-5153,1969

4

2

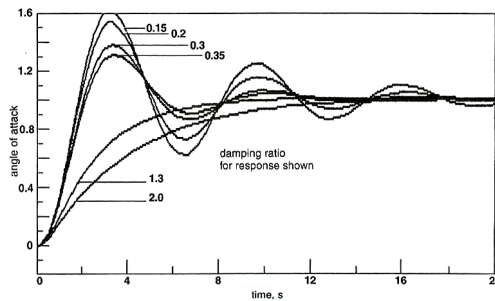## MIL-F-8785C Identifies Satisfactory, Acceptable, and Unacceptable Response Characteristics

Damping Ratio

	Category A and C Flight Phases		Category B Flight Phases	
Level	Minimum	Maximum	Minimum	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

Frequency Response

Step Response

5

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**
- **Replaced by Military Flying Qualities Standard, MIL-STD-1797A, with procurement-specific criteria**
- **MIL-F-8785C no longer "official," but still a good reference for analysis**

6

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**

7

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**

8

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

Longitudinal Criteria

11

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

Flight Phase	Level of Performance

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

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
    · Phugoid oscillation -> 2 real roots, 1 that is unstable
  – Stable control stick position and force gradients
    · e.g., Increasing "pull" position and force with decreasing speed

12

6

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

Steady-State Response to Elevator

$$\Delta V_{SS} = a\Delta\delta E_{SS}$$
$$\Delta\gamma_{SS} = c\Delta\delta E_{SS}$$

Ratio

$$\frac{\Delta\gamma_{SS}}{\Delta V_{SS}} = \frac{c}{a} \quad \text{(with appropriate scaling)}$$

- **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

13

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 ≥ 55 sec

Time to Double

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

14

Short Period Criteria

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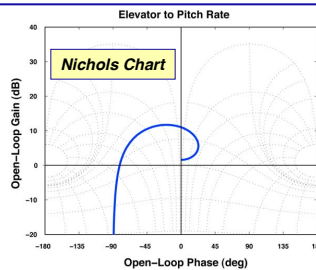 - **Flight path angle response (landing)**

Space Shuttle Pitch-Response Criterion

$\frac{q}{q_{SS}}$

Cooper–Harper rating

Navion altitude tracking (lateral)

F–8 high-stress landings

NT–33 (lateral) landing

NT–33 landings

Navion field-carrier landing (lateral)

fixed-base NT–33 landing

F–8 low-stress landing

Navion approach and landing, 75 kts

Navion approach and landing in turbulence

equivalent time delay, s

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

15

Short-Period Approximation Transfer Functions

- **Elevator to pitch rate**

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

Bode Plot

Pitch Rate Amplitude, dB

0 dB/dec

20 dB/dec   –20 dB/dec

Pitch Rate Phase Angle, deg

z_q ω_n

Frequency (rad/sec)

Nichols Chart

Elevator to Pitch Rate

Open–Loop Gain (dB)

Open–Loop Phase (deg)

Elevator to Pitch Rate

Root Locus

Imaginary Axis

Real Axis

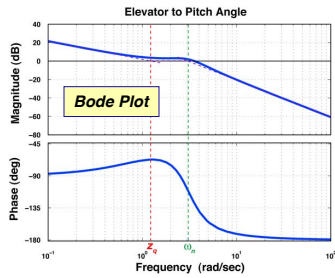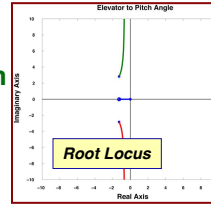- **Pure gain or phase change (< 90 deg) in feedback control cannot produce instability**

16

8

Short-Period Approximation Transfer Functions

- **Elevator to pitch angle**
- **Integral of prior example**

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

Elevator to Pitch Angle

Bode Plot

Elevator to Pitch Angle

Nichols Chart

Elevator to Pitch Angle

Root Locus

- **Pure gain or phase change (< 45 deg) in feedback control cannot produce instability**

17

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 ($L_{\delta E} = 0$)**

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

Asymptote =

0 dB/dec

−40 dB/dec

−90 deg

18

9

Control Anticipation Parameter, *CAP*

Inner ear senses angular acceleration about 3 axes

Initial Angular Acceleration

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

Desired Normal Load Factor

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

19

Control Anticipation Parameter, *CAP*

Inner ear cue should aid pilot in <u>anticipating commanded normal acceleration</u>

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

with $L_{\delta E} = 0$

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

20
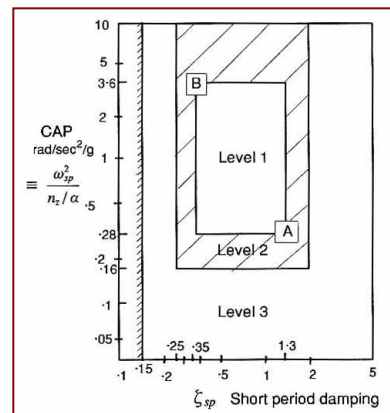
10

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

CAP =
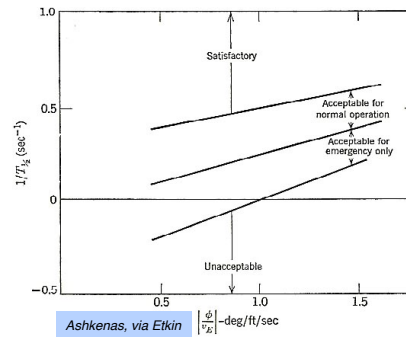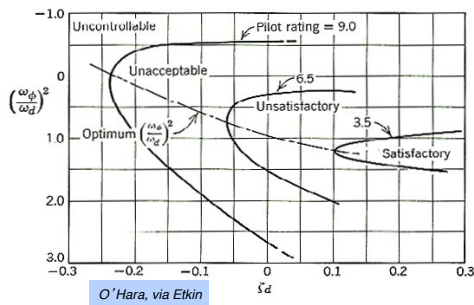**constant along**
Level Boundaries

CAP

$$\omega_{n_{SP}} \ vs. \ \frac{n_z}{\alpha}$$

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)

$$CAP = \frac{-\left(M_q \frac{L_\alpha}{V_N} + M_\alpha\right)}{L_\alpha / g}$$

$$\approx \frac{\omega_{n_{SP}}^2}{n_z / \alpha}$$

Early Lateral-Directional Flying Qualities Criteria

O'Hara, via Etkin

Ashkenas, via Etkin $\left|\frac{\phi}{v_E}\right|$ -deg/ft/sec

$$T_{1/2} = 0.693 / \zeta\, \omega_n$$
$$v = V_N \beta$$

Time to Half

23

Lateral-Directional Flying Qualities Parameters

- **Lateral Control Divergence Parameter, *LCDP***
- ϕ/β **Effect**
- ω_ϕ/ω_d **Effect**

24

Lateral Control Divergence Parameter (*LCDP*)

- **Aileron deflection produces yawing as well as rolling moment**
  - "Favorable yaw" aids the turn command
  - "Adverse yaw" opposes it
- **Equilibrium response to constant aileron input**

$$\frac{\Delta\phi_S}{\Delta\delta A_S} = \frac{\left(N_\beta + N_r \dfrac{Y_\beta}{V_N}\right)L_{\delta A} - \left(L_\beta + L_r \dfrac{Y_\beta}{V_N}\right)N_{\delta A}}{\dfrac{g}{V_N}\left(L_\beta N_r - L_r N_\beta\right)}$$

- **Large-enough $N_{\delta A}$ effect can reverse the sign of the response**
  - Can occur at high angle of attack
  - Can cause "departure from controlled flight"
- **Lateral Control Divergence Parameter provides simplified criterion**

$$\frac{\left(N_\beta\right)L_{\delta A} - \left(L_\beta\right)N_{\delta A}}{L_{\delta A}} = N_\beta - \frac{N_{\delta A}}{L_{\delta A}}L_\beta$$

$$LCDP \equiv C_{n_\beta} - \frac{C_{n_{\delta A}}}{C_{l_{\delta A}}}C_{l_\beta}$$

25

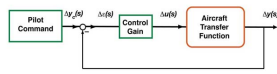
ω_ϕ/ω_d Effect

- **Aileron-to-roll-angle transfer function**

$$\frac{\Delta\phi(s)}{\Delta\delta A(s)} = \frac{k_\phi\left(s^2 + 2\zeta_\phi\omega_\phi s + \omega_\phi^2\right)}{\left(s - \lambda_S\right)\left(s - \lambda_R\right)\left(s^2 + 2\zeta_{DR}\omega_{n_{DR}}s + \omega_{n_{DR}}^2\right)}$$
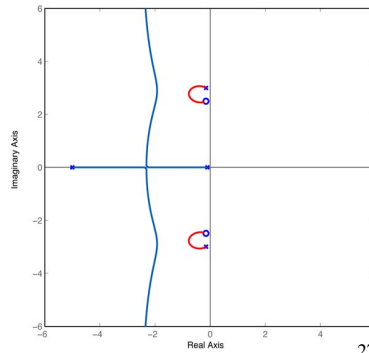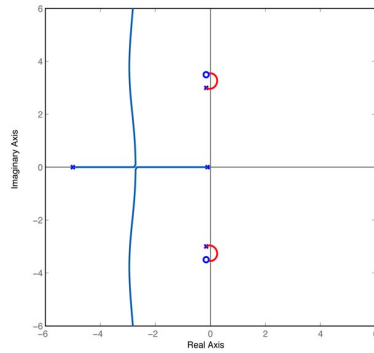
  - ω_ϕ is the "natural frequency" of the complex zeros
  - $\omega_d = \omega_{nDR}$ is the natural frequency of the Dutch roll mode
- **Conditional instability** may occur with closed-loop control of roll angle, even with a <u>perfect pilot</u>

26

13

$\omega_\phi/\omega_\delta$ **Effect is Important in Roll Angle Control**

$$\frac{\Delta\phi(s)}{\Delta\delta A(s)} = \frac{k_\phi\left(s^2 + 2\zeta_\phi\omega_\phi s + \omega_\phi^2\right)}{\left(s - \lambda_S\right)\left(s - \lambda_R\right)\left(s^2 + 2\zeta_{DR}\omega_{n_{DR}} s + \omega_{n_{DR}}^2\right)}$$

- **As feedback gain increases, Dutch roll roots go to numerator zeros**
- **If zeros are over poles, conditional instability results**

27

ϕ/β **Effect**

- ϕ/β **measures the degree of rolling response in the Dutch roll mode**
  - **Large ϕ/β: Dutch roll is primarily a rolling motion**
  - **Small ϕ/β: Dutch roll is primarily a yawing motion**
- **Eigenvectors, e_i, indicate the degree of participation of the state component in the ith mode of motion**

$$\det\left(s\mathbf{I} - \mathbf{F}\right) = \left(s - \lambda_1\right)\left(s - \lambda_2\right)...\left(s - \lambda_n\right)$$

$$\left(\lambda_i\mathbf{I} - \mathbf{F}\right)\mathbf{e}_i = \mathbf{0}$$

28

14

Eigenvectors

· **Eigenvectors, $\mathbf{e}_i$, are solutions to the equation**

$$\left(\lambda_i\mathbf{I}-\mathbf{F}\right)\mathbf{e}_i = \mathbf{0}, \quad i=1,n$$

$$or$$

$$\lambda_i\mathbf{e}_i = \mathbf{F}\mathbf{e}_i, \quad i=1,n$$

· **For each eigenvalue, the corresponding eigenvector can be found (within an arbitrary constant) from**

$$Adj\left(\lambda_i\mathbf{I}-\mathbf{F}\right)=\left(\begin{array}{cccc} a_1\mathbf{e}_i & a_2\mathbf{e}_i & \dots & a_n\mathbf{e}_i \end{array}\right), \quad i=1,n$$

MATLAB

$(\mathbf{V},\mathbf{D})=eig(\mathbf{F})$

V: Modal Matrix (i.e., Matrix of Eigenvectors)

D: Diagonal Matrix of Corresponding Eigenvalues

29

ϕ/β Effect

With λ_i chosen as a complex root of the Dutch roll mode, the corresponding eigenvector is

$$\mathbf{e}_{DR+}=\begin{bmatrix} e_r \\ e_\beta \\ e_p \\ e_\phi \end{bmatrix}_{DR+}=\begin{bmatrix} (\sigma+j\omega)_r \\ (\sigma+j\omega)_\beta \\ (\sigma+j\omega)_p \\ (\sigma+j\omega)_\phi \end{bmatrix}_{DR+}=\begin{bmatrix} \left(AR\,e^{j\phi}\right)_r \\ \left(AR\,e^{j\phi}\right)_\beta \\ \left(AR\,e^{j\phi}\right)_p \\ \left(AR\,e^{j\phi}\right)_\phi \end{bmatrix}_{DR+}$$

ϕ/β is the magnitude of the ratio of the ϕ and β eigenvectors
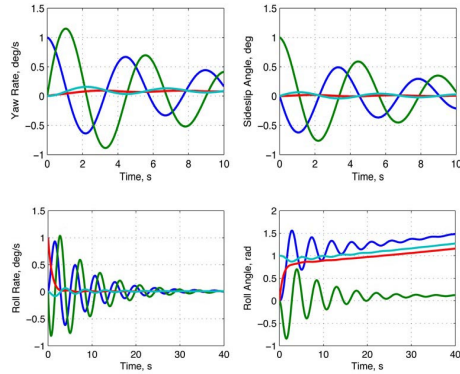
$$\phi/\beta = \left|\frac{(AR)_\phi}{(AR)_\beta}\right| = \left(\frac{V_N}{g}\right)\left[\left(\zeta_{DR}\omega_{n_{DR}}+\frac{Y_\beta}{V_N}+\frac{L_\beta}{L_r}\right)^2+\left(\omega_{n_{DR}}\sqrt{1-\zeta_{DR}^2}\right)\right]^{1/2}$$

30

15

ϕ/β Effect for the Business Jet Example

$$\mathbf{e}_{DR+} = \begin{bmatrix} |e_r| \\ |e_\beta| \\ |e_p| \\ |e_\phi| \end{bmatrix}_{DR+} = \begin{bmatrix} 0.525 \\ \boxed{0.416} \\ 0.603 \\ \boxed{0.433} \end{bmatrix}_{DR+}$$

$$\boxed{\dfrac{\phi}{\beta} = 1.04}$$

Roll/Sideslip Angle ratio in the Dutch roll mode

31

Criteria for Lateral-Directional Modes
(MIL-F-8785C)

TABLE VII. Maximum roll-mode time constant, seconds.

Maximum Roll-Mode Time Constant

Flight Phase Category	Class	Level 1	Level 2	Level 3
A	I, IV	1.0	1.4	
	II, III	1.4	3.0	
B	All	1.4	3.0	10
C	I, II-C, IV	1.0	1.4	
	II-L, III	1.4	3.0	

TABLE VIII. Spiral stability - minimum time to double amplitude.

Minimum Spiral-Mode Time to Double

Flight Phase Category	Level 1	Level 2	Level 3
A & C	12 sec	8 sec	4 sec
B	20 sec	8 sec	4 sec

32

16

Minimum Dutch Roll Natural Frequency and Damping (MIL-F-8785C)

TABLE VI. Minimum Dutch roll frequency and damping.

Level	Flight Phase Category	Class	Min ζ_d*	Min $\zeta_d\omega_{n_d}$* rad/sec.	Min ω_{n_d} rad/sec.
	A (CO and GA)	IV	0.4	–	1.0
	A	I, IV	0.19	0.35	1.0
		II, III	0.19	0.35	0.4**
1	B	All	0.08	0.15	0.4**
	C	I, II-C, IV	0.08	0.15	1.0
		II-L, III	0.08	0.10	0.4**
2	All	All	0.02	0.05	0.4**
3	All	All	0	–	0.4**

* The governing damping requirement is that yielding the larger value of ζ_d, except that a ζ_d of 0.7 is the maximum required for Class III.

** Class III airplanes may be excepted from the minimum ω_{n_d} requirement, subject to approval by the procuring activity, if the requirements of 3.3.2 through 3.3.2.4.1, 3.3.5 and 3.3.9.4 are met.

33

Pilot-Vehicle Interactions

34

YF-16 Test Flight Zero

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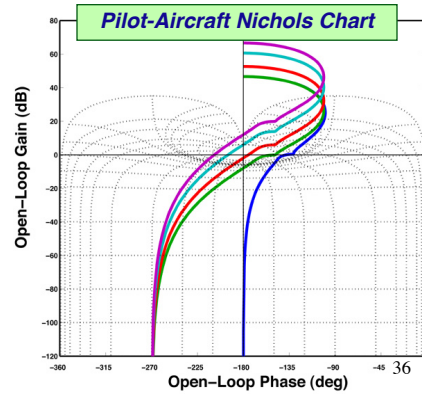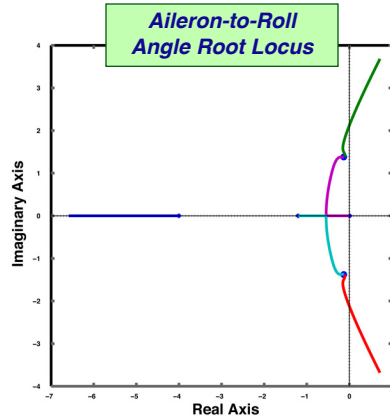- **Pilot elected to go around rather than eject**

35

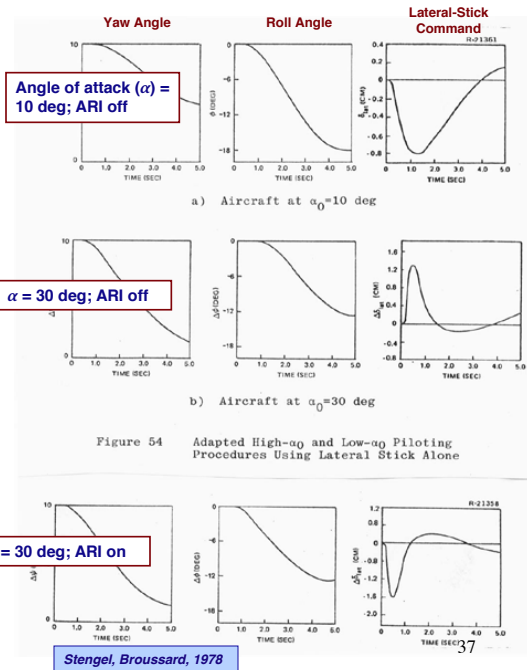## Pilot-Induced Roll Oscillation

YF-16

Pilot Transfer Function   Aircraft Transfer Function

$$\frac{\Delta\phi(s)}{\Delta\delta A(s)}_{pilot\ in\ loop} = \left(\frac{K_p/T_p}{s+1/T_p}\right)\left[\frac{k_\phi\left(s^2+2\zeta_\phi\omega_\phi s+\omega_\phi^2\right)}{\left(s-\lambda_S\right)\left(s-\lambda_R\right)\left(s^2+2\zeta_{DR}\omega_{n_{DR}}s+\omega_{n_{DR}}^2\right)}\right]$$

Aileron-to-Roll Angle Root Locus

Pilot-Aircraft Nichols Chart

36

18

Inverse Problem of Lateral Control

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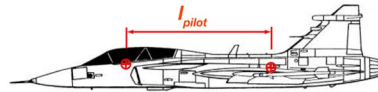- Aileron-rudder interconnect (ARI) simplifies pilot input

Grumman F-14 Tomcat

Yaw Angle   Roll Angle   Lateral-Stick Command

Angle of attack (α) = 10 deg; ARI off

α = 30 deg; ARI off

α = 30 deg; ARI on

a) Aircraft at α_0=10 deg

b) Aircraft at α_0=30 deg

Figure 54   Adapted High-α_0 and Low-α_0 Piloting Procedures Using Lateral Stick Alone

Stengel, Broussard, 1978

37

Next Time:
Maneuvering at High Angle of Attack and Angular Rate

38

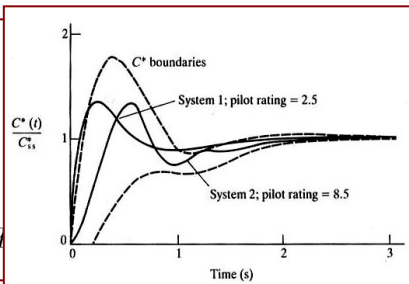# SUPPLEMENTAL MATERIAL

39

C* Criterion

I_{pilot}

- **Hypothesis**
  - *C** blends <u>normal load factor at pilot's location</u> and pitch rate
  - Step response of *C** should lie within acceptable envelope

$$C^* = \Delta n_{pilot} + \frac{V_{crossover}}{g}\Delta q$$

$$= \left(l_{pilot}\Delta\dot{q} + \Delta n_{cm}\right) + \frac{V_{crossover}}{g}\Delta q$$

$$= \left[l_{pilot}\Delta\dot{q} + \frac{V_N}{g}\left(\Delta q - \Delta\dot{\alpha}\right)\right] + \frac{V_{crossover}}{g}\Delta q$$

- Below $V_{crossover}$, Δq is pilot's primary control objective
- Above $V_{crossover}$, Δn_{pilot} is the primary control objective

Fighter Aircraft: $V_{crossover} \approx 125 \ m/s$

40

20

Slide 1

Gibson Dropback Criterion for Pitch Angle Control

- **Step response of pitch rate should have overshoot for satisfactory pitch and flight path angle response**

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

$$= \frac{k_q\left(s + \dfrac{\omega_{n_{SP}}}{\zeta_{SP}}\right)}{s^2 + 2\zeta_{SP}\omega_{n_{SP}}s + \omega_{n_{SP}}{}^2}$$

- **Criterion is satisfied when**

$$z_q \triangleq -\frac{1}{T_{\theta_2}} = -\left(\frac{\omega_{n_{SP}}}{\zeta_{SP}}\right)$$
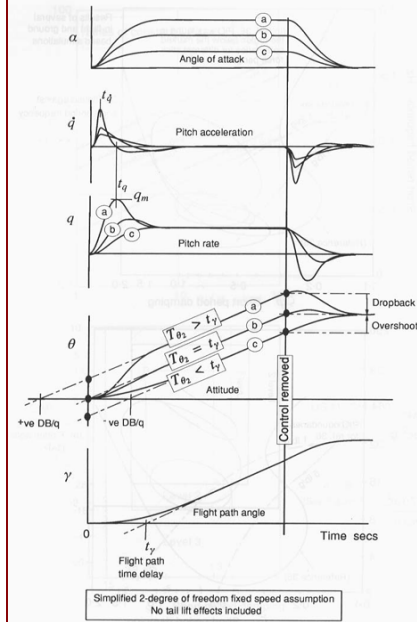
Gibson, 1997

Figure 7-3 Generic short period pitch transient response 41

Slide 2

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**

42

Criteria for Oscillations and Excursions
(MIL-F-8785C)

3.3.2.2 _Roll rate oscillations._ Following a yaw-control-free step roll control command, the roll rate at the first minimum following the first peak shall be of the same sign and not less than the following percentage of the roll rate at the first peak:
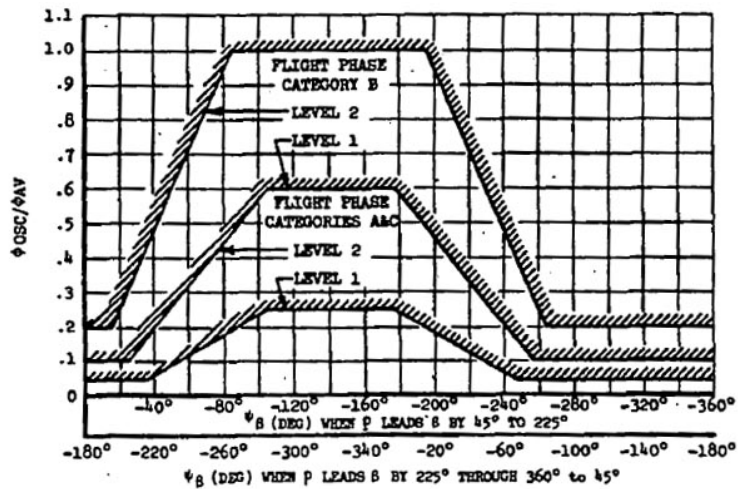
Level	Flight Phase Category	Percent
1	A & C	60
	B	25
2	A & C	25
	B	0

3.3.2.4 _Sideslip excursions._ Following a yaw-control-free step roll control command, the ratio of the sideslip increment, Δβ, to the parameter k (6.2.6) shall be less than the values specified herein. The roll command shall be held fixed until the bank angle has changed at least 90 degrees.

Level	Flight Phase Category	Adverse Sideslip (Right roll command causes right sideslip)	Proverse Sideslip (Right roll command causes left sideslip)
1	A	6 degrees	2 degrees
	B & C	10 degrees	3 degrees
2	All	15 degrees	4 degrees

43

Criteria for Oscillations and Excursions
(MIL-F-8785C)

44

Flight Testing Videos

TSR2 Test Flight

http://www.youtube.com/watch?v=GXdJxjvQZW4

Neil Armstrong, Test Pilot

http://www.youtube.com/watch?v=t6DdlPoPOE4

NASA Dryden (now Armstrong) Flight Research Center

http://www.youtube.com/watch?v=j85jlc1Zfk4

Avro Arrow Revisited

https://www.youtube.com/watch?v=S74zf0YZX20

45