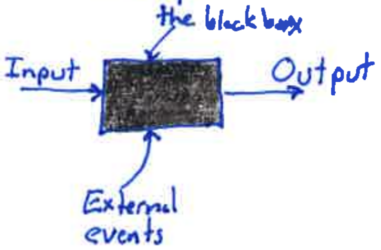
Lesson 26

Flying Qualities / Handling Qualities

Inertial Coupling

Flying Qualities

Aircraft are machines .... complex sometimes .... but deterministic.



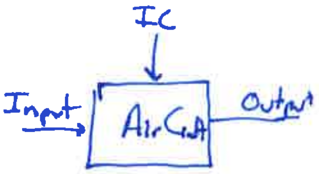
Same inputs → same outputs
<u>always</u>

Pilots are tempermental, inconsistent, imperfect, bored, hungry, distracted, picky, cautious, ...

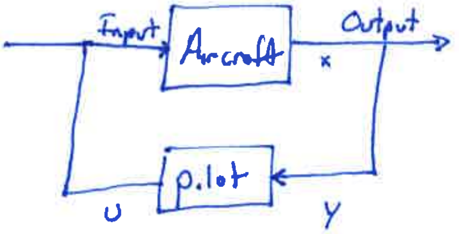
- Experience
- Value Scale
- Initial Conditions
- Emotional State

> Adding a pilot fundamentally changes flight dynamics and Control

Open loop



Closed loop



The pilot reacts to outputs to create inputs in a finite manner and time

The system dynamics are complex and non-deterministic.

Can you write the pilot as $u = f(y)$? **No**

A good pilot can stabilize an unstable aircraft. (Phugoid)

A bad/poor pilot can destabilize a stable aircraft.

Table 6.1 Definition of Airplane Classes

MIL–F–8785C	Examples	Civilian Equivalent	Examples
Class I **Small, light airplanes such as:** * Light utility * Primary trainer * Light observation	* Cessna T–41 * Beech T–34C * Rockwell OV–10A	Very Light Aircraft (VLA) and FAR 23 category airplanes	* Cessna 210 * Piper Tomahawk * Edgeley Optica
Class II **Medium weight, low–to–medium maneuverability airplanes such as:** * Heavy utility / search and rescue * Light or medium transport / cargo / tanker * Early warning / electronic counter–measures / airborne command, control or communications relay * Anti–submarine * Assault transport * Reconnaissance * Tactical Bomber * Heavy Attack * Trainer for Class II	* Fairchild C–26A/B * Fairchild C–123 * Grumman E–2C * Boeing E–3A * Lockheed S–3A * Lockheed C–130 * Fairchild OA–10 * Douglas B–60 * Grumman A–6 * Beech T–1A	FAR 25 category airplanes	* Boeing 737, * Airbus A 320 * McDD MD–80
Class III **Large, heavy, low–to–medium maneuverability airplanes such as:** * Heavy transport / cargo / tanker * Heavy bomber * Patrol / early warning / electronic counter–measures / airborne command, control or communications relay * Trainer for Class III	* McDD C–17 * Boeing B–52H * Lockheed P–3 * Boeing E–3D * Boeing TC–135	FAR 25 category airplanes	* Boeing 747, * Airbus 340, * McDD MD–11
Class IV **High maneuverability airplanes such as:** * Fighter / interceptor * Attack * Tactical reconnaissance * Observation * Trainer for Class IV	* Lockheed F–22 * McDD F–15E * McDD RF–4 * Lockheed SR–71 * Northrop T–38	FAR 23 aerobatic category airplanes	* Pitts Special, * Sukhoi Su–26M

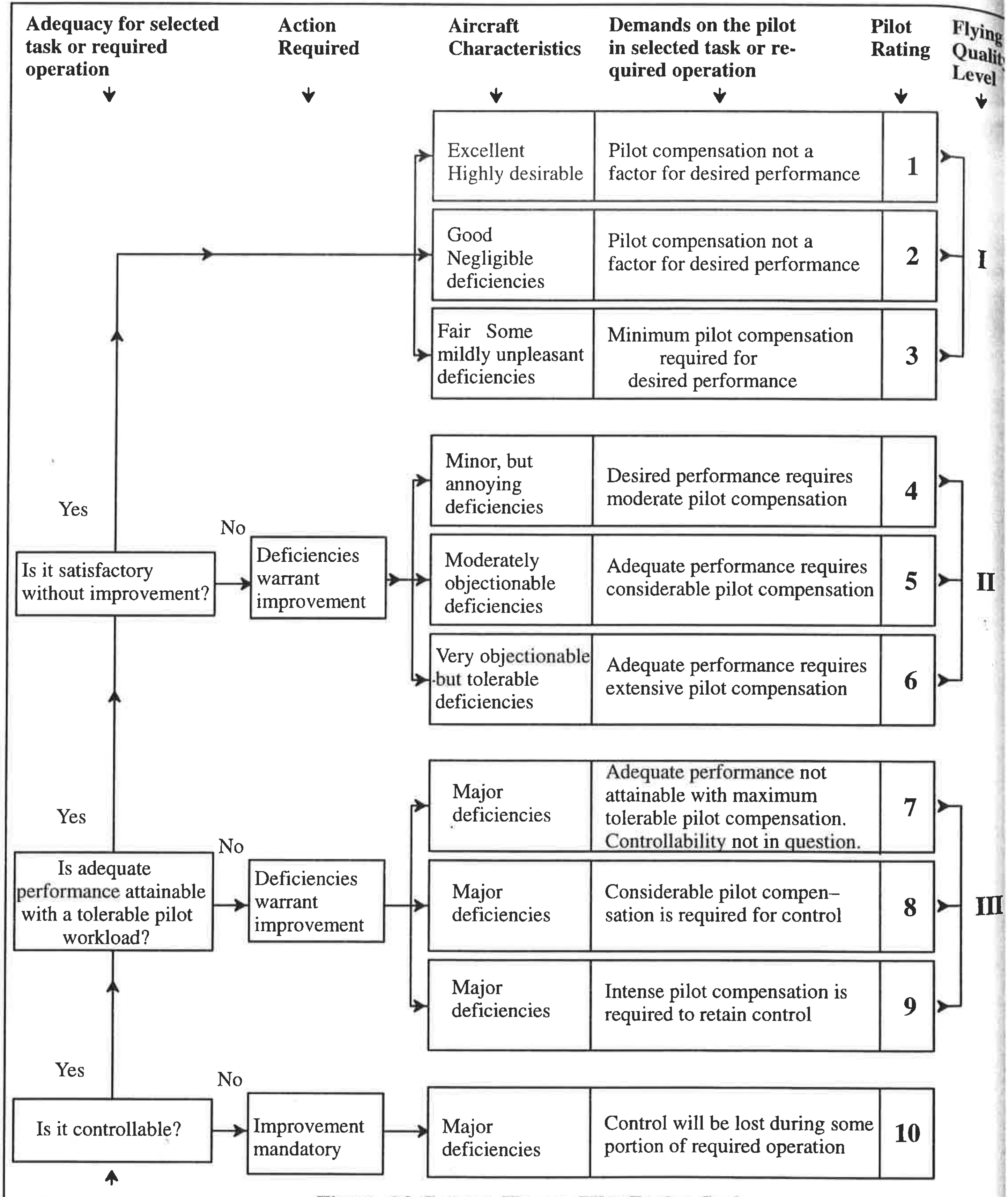


Figure 6.2 Cooper–Harper Pilot Rating Scale

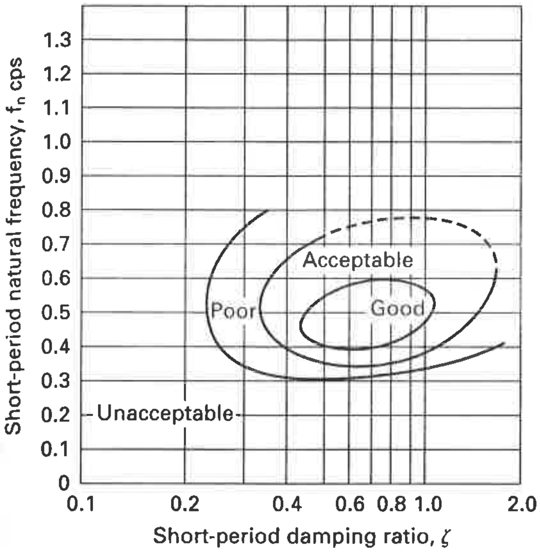


FIGURE 4.15
Short-period flying qualities.

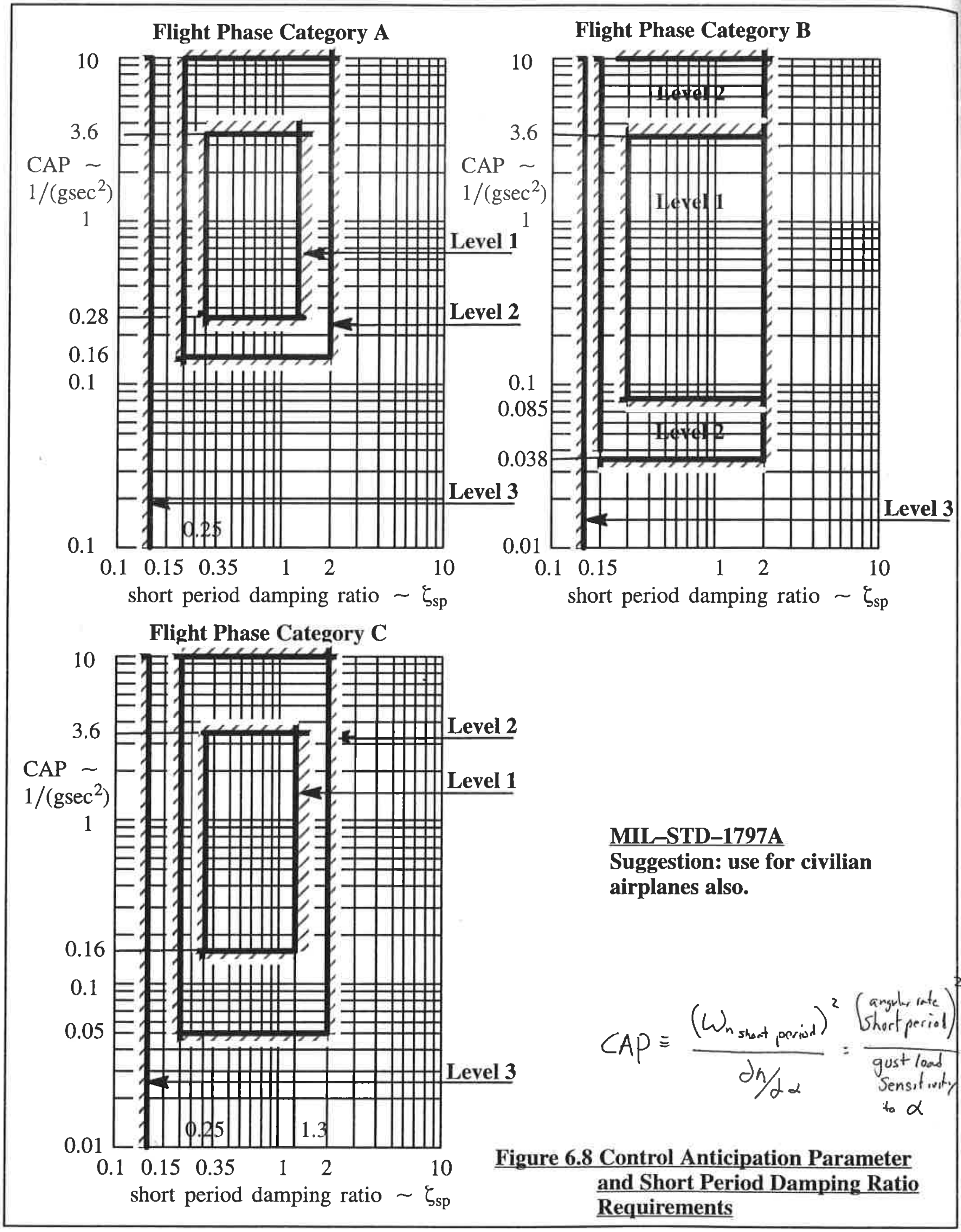
TABLE 4.10
Longitudinal flying qualities

Phugoid mode

Level 1	$\zeta > 0.04$
Level 2	$\zeta > 0$
Level 3	$T_2 > 55$ s

Short-period mode

	Categories A and C		Category B	
	ζ_{sp}	ζ_{sp}	ζ_{sp}	ζ_{sp}
Level	min	max	min	max
1	0.35	1.30	0.3	2.0
2	0.25	2.00	0.2	2.0
3	0.15	—	0.15	—



MIL–STD–1797A
Suggestion: use for civilian airplanes also.

$$CAP \approx \frac{(\omega_{n\ \text{short period}})^2}{\partial n/\partial \alpha} = \frac{\left(\begin{matrix}\text{angular rate}\\ \text{short period}\end{matrix}\right)^2}{\begin{matrix}\text{gust load}\\ \text{sensitivity}\\ \text{to } \alpha\end{matrix}}$$

Figure 6.8 Control Anticipation Parameter and Short Period Damping Ratio Requirements

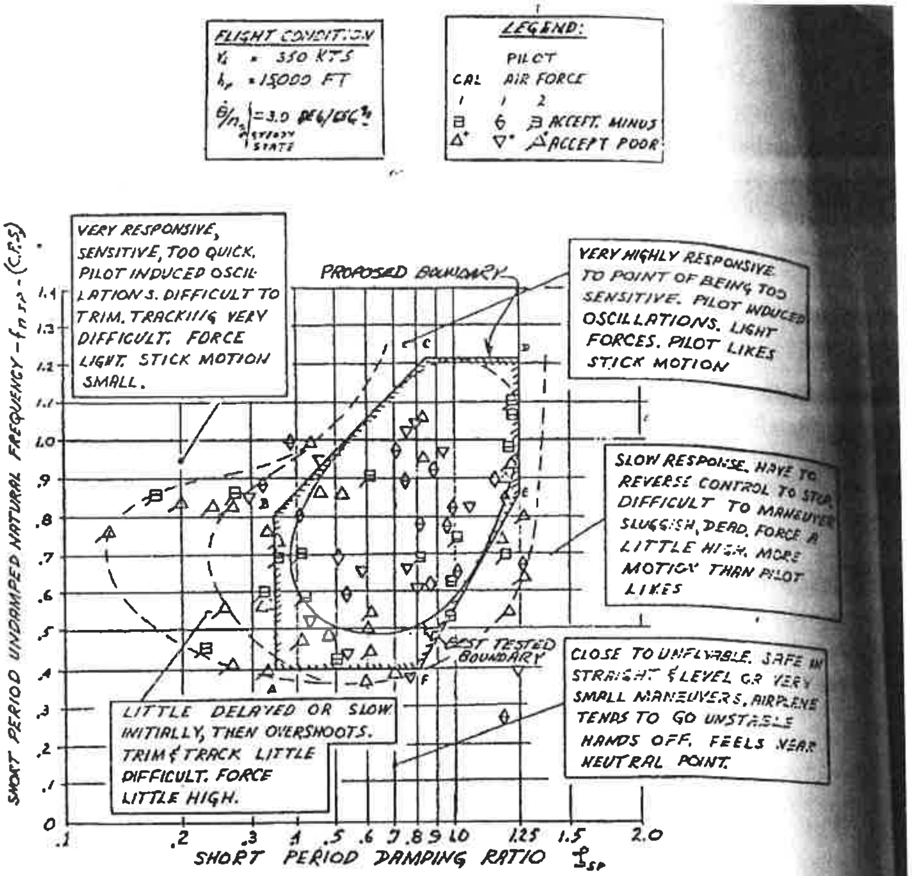
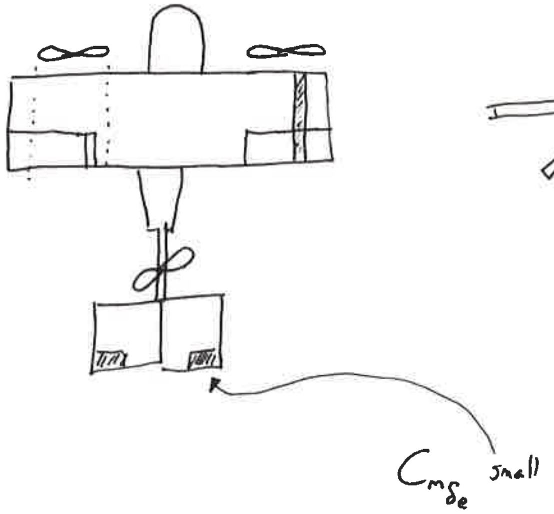
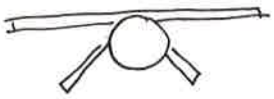


Figure 10.3 Example of an early iso-opinion chart for the longitudinal short-period mode. This one was derived from flight tests of the variable-stability F-94F airplane. (Mazza, Becker, Cohen, and Spector, NADC Report ED-6282, 1963)

Analysis of Senior Design Aircraft

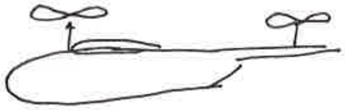




$$= \eta V_H \left(1 - \frac{d\epsilon}{d\alpha}\right)$$

$$C_{L_{\delta_a}} = \eta \; \ddot{c}\, C_{L_\alpha} T \cancel{\delta_a}\, \delta_a$$

$$\eta = \frac{\frac{1}{2}\rho U^2}{\frac{1}{2}\rho V_\infty^2}$$



$\approx 10^{\text{lbf}}$ $\approx 10^{\text{in}}$ prop $\approx 0.5\ \text{ft}^2$

$\approx 1^{\text{ft}}$

$$T = \dot{m}(\overset{V-V}{V}) = \rho V A \cdot V = \rho V^2 A$$

$$V = \sqrt{\frac{T}{\rho A}} = \sqrt{\frac{10\ \text{lbf}}{0.0023\ \text{slugs}} \cdot \frac{\text{ft}^3}{} \cdot \frac{}{\text{ft}^2} \cdot \frac{\text{slugs ft}}{\cancel{\text{lbf}}\ s^2}}$$

$= 65\ \frac{ft}{s}$ at $V_\infty = 0$

$\approx 100\ \frac{ft}{s}$ at $V_\infty \approx 35\frac{ft}{s}$

$$\eta = \frac{\frac{1}{2}\rho\,(100^2)}{\frac{1}{2}\rho\ (30^2)} = 10$$

$$p = 1200\ ^{\circ}/s$$

Step Change

What is the response to a step input to the ailerons?

Neglecting non-linear effects,

$$I_x \ddot{\phi} = \Sigma L$$

$$\approx \frac{dL}{d\delta_a}\delta_a + \frac{dL}{dp}\cancelto{\dot{\phi}}{p}$$

$$\underbrace{I_x \dot{p} = \frac{dL}{d\delta_a}\delta_a + \frac{dL}{dp}p}_{1^{st} \text{ order ODE with forcing function } \left(\frac{dL}{d\delta_a}\delta_a\right)}$$

Convert to canonical form

$$\dot{p} = \underbrace{\frac{1}{I_x}\frac{dL}{d\delta_a}}_{L_{\delta_a}}\delta_a + \underbrace{\frac{1}{I_x}\frac{dL}{dp}}_{L_p}p$$

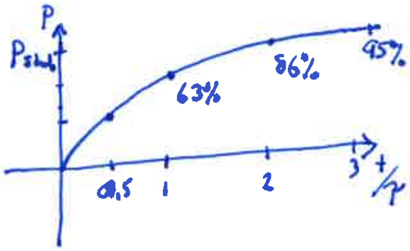
$$L_{\delta_a} \equiv \frac{qSbC_{l_{\delta_a}}}{I_x}$$

$$L_p \equiv \underbrace{\frac{qSb^2C_{l_p}}{2I_x u_0}}_{C_{l_p} < 0}$$ table 3.6

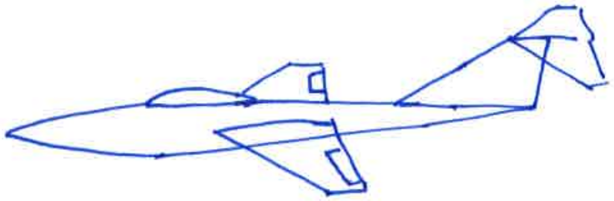
Soln (step response 1st order)

$$\tau \equiv \text{time constant} \equiv -\frac{1}{L_p}$$

$$p = \frac{-L_{\delta_a}}{L_p}\left(1 - e^{+L_p t}\right)\delta_a$$



Inertial Coupling



Take a long slender (supersonic) aircraft and enter a sustained high roll rate, what happens?

Not a single axis roll!

Why? Look at the pitch moment/dynamics equation

$$\underbrace{M = -I_{xy}\cancelto{0\ \text{steady}}{\dot p} + I_y \dot q - I_{yz}\cancelto{0}{\dot r} + \cancelto{0}{rp}I_x - \cancelto{0}{rq}I_{xy} - \cancelto{0}{r^2}I_{xz} + p^2 I_{xz} + \cancelto{0}{pq}I_{yz} - \cancelto{0}{pr}I_z}$$

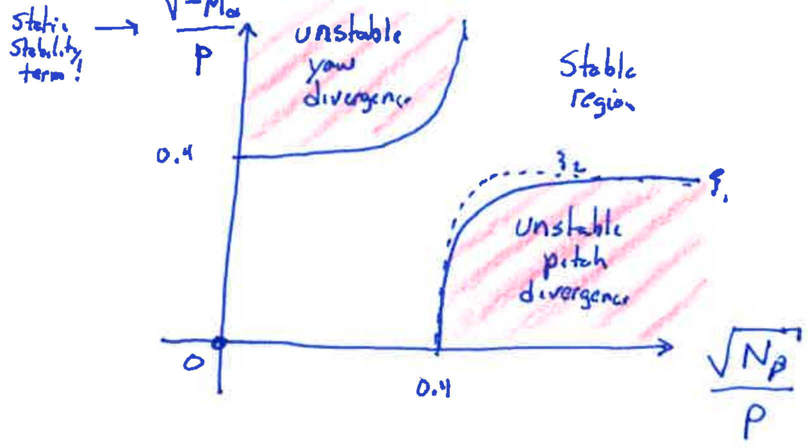
$$\cancelto{0}{M} = I_y \dot q + p^2 I_{xz} \Rightarrow \underbrace{\dot q = \frac{p^2 I_{xz}}{I_y}}$$

The roll rate coupled with $I_{xz} \neq 0$ causes a pitch rate acceleration.

Inertia

$$I_{xz} = \int xz \, dm$$

From stability anaysis (see Roskam's books)



Also, pitch rate maneuvers can destabilize lateral + longitudinal stability!

$q > 0$ makes DR less damped!

$q < 0$ creates a "lateral phugoid" motion

AEM 668 for more info

Data taken from NACA RM H55A13

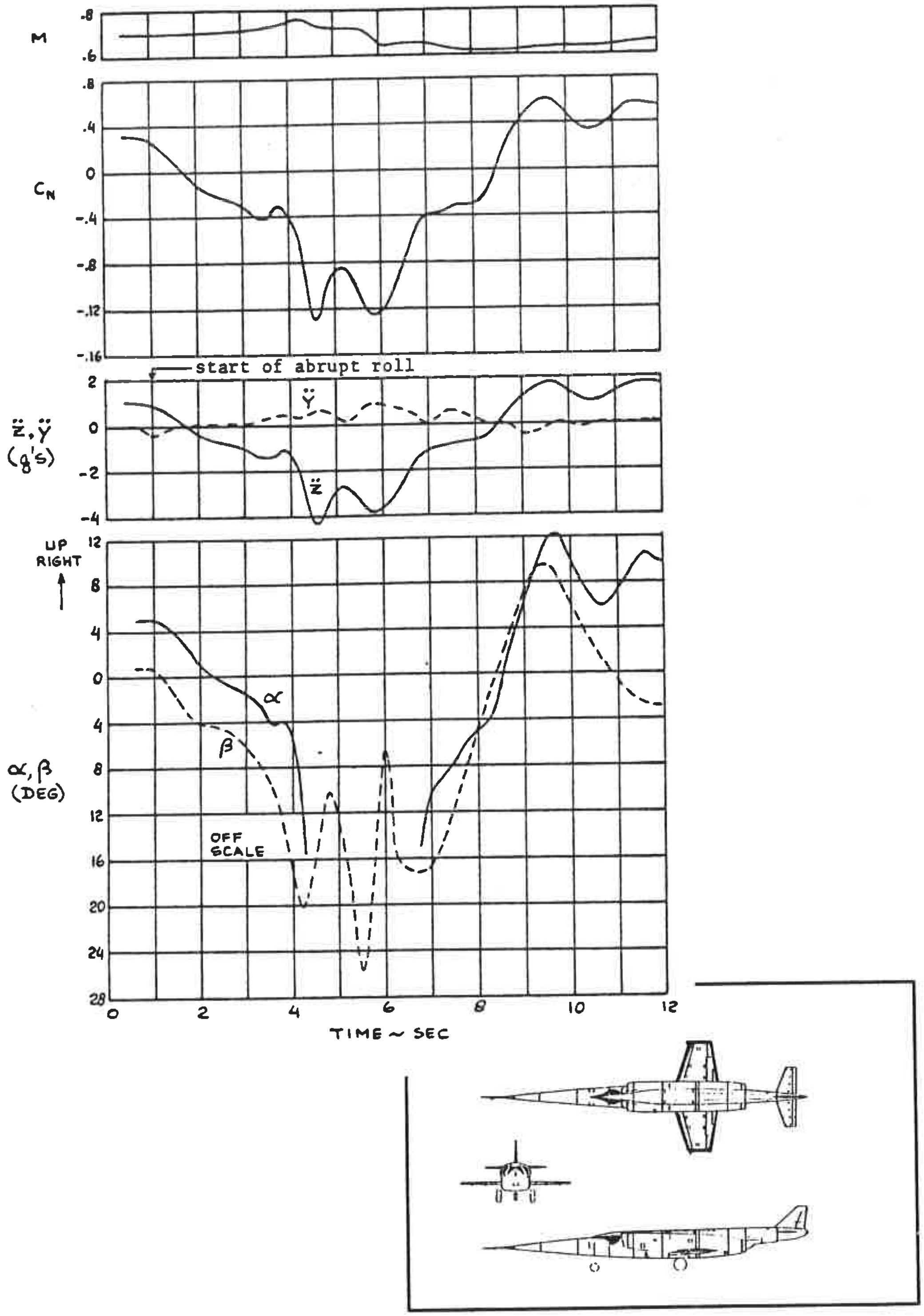


Figure 5.46 Time History of Motion Parameters Measured During an Abrupt Aileron Roll in the NACA X–3 at M=0.70 and h=30,000 ft

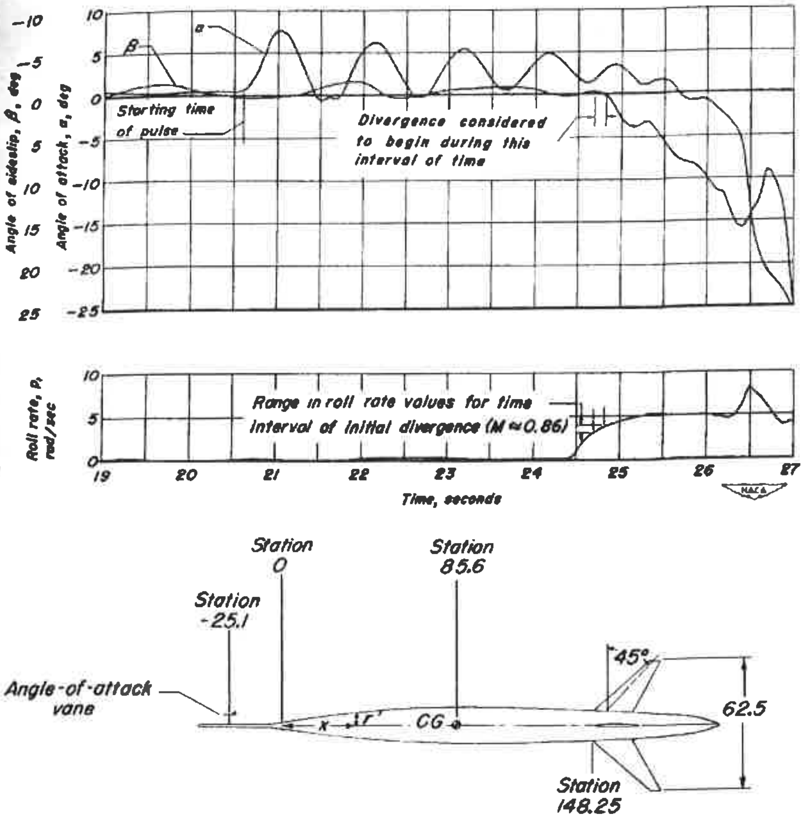


Figure 8.3 First flight confirmation of the Phillips inertial coupling theory, made on a rolling body–tail combination. A divergence begins at a roll rate of 3.5 radians per second. (From Bergrun and Nickel, NACA TN 2985, 1953)

Fuel Slosh

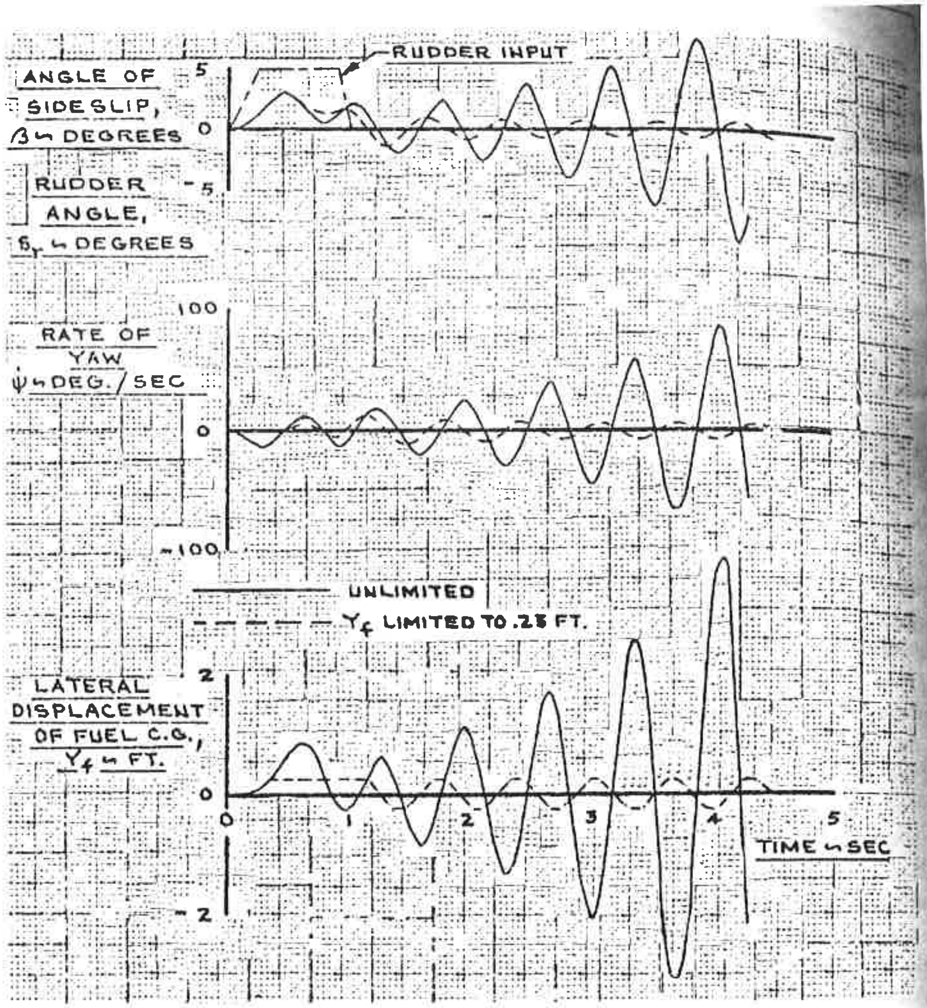


Figure 14.1 Calculated effect of fuselage tank slosh in the Douglas A-4 Skyhawk before installation of a fuselage tank baffle. Fuel motion couples with the Dutch roll mode of motion. With the fuel mass motion limited by the tank sides (dotted curves), a steady limit cycle "snaking" motion results. (From Abzug, Douglas Rept. ES 29551, 1959)