Longitudinal Flying Qualities Criteria
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Learning Objectives

- Cooper-Harper Ratings
- MIL-F-8785C criteria
- Normal load factor
- $CAP$, $C^*$, and other longitudinal criteria

Review Questions

- What is the advantage of using one 4th-order model over using two 2nd-order models for analysis?
- What are gain and phase margins?
- What is a Nichols chart?
- What are some general characteristics of a pilot's feedback control effects on aircraft dynamics?
- What are the principal dynamic effects of thrust and power on longitudinal stability?
- How are angle-of-attack-rate effects different from pitch-rate effects?
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

Short-Period “Bullseye” or “Thumbprint”
Cooper-Harper Handling Qualities
Rating Scale

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

Damping Ratio

<table>
<thead>
<tr>
<th>Category A and G Flight Phases</th>
<th>Category B Flight Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level</td>
<td>Minimum</td>
</tr>
<tr>
<td>1</td>
<td>0.35</td>
</tr>
<tr>
<td>2</td>
<td>0.35</td>
</tr>
<tr>
<td>3</td>
<td>0.15</td>
</tr>
</tbody>
</table>

* 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
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 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)

<table>
<thead>
<tr>
<th>Flight Phase</th>
<th>Level of Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Non-terminal flight requiring rapid maneuvering</td>
<td>1. Clearly adequate for the mission</td>
</tr>
<tr>
<td>B. Non-terminal flight requiring gradual maneuvering</td>
<td>2. Adequate to accomplish the mission, with some increase in workload</td>
</tr>
<tr>
<td>C. Terminal flight</td>
<td>3. Aircraft can be controlled safely, but workload is excessive</td>
</tr>
</tbody>
</table>

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

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

Steady-State Response to Elevator

\[
\begin{align*}
\Delta V_{SS} &= a \Delta \delta E_{SS} \\
\Delta \gamma_{SS} &= c \Delta \delta E_{SS}
\end{align*}
\]

Ratio

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

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

• Phugoid stability
  1. Damping ratio \(\zeta \geq 0.04\)
  2. Damping ratio \(\zeta \geq 0\)
  3. “Time to double”, \(T_2 \geq 55 \text{ sec}\)

\[
T_{2, Ph} = -0.693 / \zeta_{ph} \omega_{n, ph}
\]
Short Period Criteria

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

Elevator to Pitch Rate 2\textsuperscript{nd}-Order Transfer Function

\[
\frac{\Delta \dot{q}(s)}{\Delta \delta E(s)} = \frac{k_s (s - z_g)}{s^2 + 2 \xi \omega_n s + \omega_n^2} = \frac{k_s (s + \frac{1}{\tau_h})}{s^2 + 2 \zeta \omega_n s + \omega_n^2}
\]
**Elevator to Pitch Angle Transfer Function**

\[
\frac{\Delta \theta(s)}{\Delta \delta E(s)} = \frac{k_\alpha (s - z_q)}{s \left( s^2 + 2\zeta_{_{SP}}\omega_{n_{_{SP}}} s + \omega_{n_{_{SP}}}^2 \right)}
\]

**Bode Plot**

**Nichols Chart**

**Root Locus for Pitch-Angle Feedback**

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**Normal Load Factor**

\[
\Delta n_z = \frac{V_N}{g} (\Delta \alpha - \Delta q) \simeq -\frac{V_N}{g} \left( \frac{L_{\alpha}}{V_N} \Delta \alpha + \frac{L_{SE}}{V_N} \Delta \delta E \right)
\]

With \( L_{SE} \sim 0 \) (aft tail/canard effect)

\[
\frac{\partial \Delta n_z(s)}{\partial \Delta \delta E(s)} = -\frac{1}{g} \left( \frac{L_{\alpha}}{V_N} \frac{\partial \Delta \alpha(s)}{\partial \Delta \delta E(s)} + L_{SE} \right) \approx -\left( \frac{L_{\alpha}}{g} \right) \frac{\partial \Delta \alpha(s)}{\partial \Delta \delta E(s)}
\]

\[
\frac{\Delta \alpha(s)}{\Delta \delta E(s)} \approx \frac{k_\alpha}{s^2 + 2\zeta_{_{SP}}\omega_{n_{_{SP}}} s + \omega_{n_{_{SP}}}^2}
\]
Control Anticipation Parameter, CAP

Inner ear senses angular acceleration 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**

\[ \Delta n_{zSS} = \frac{V_N}{g} \Delta q_{SS} = - \left( \frac{V_N}{g} \right) \left[ \frac{M_{\delta E}}{V_N} L_\alpha - \frac{M_\alpha L_{\delta E}}{V_N} \right] \Delta \delta E_{SS} \]

Control Anticipation Parameter, CAP

Inner ear cue should aid pilot in anticipating commanded normal acceleration

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

with \( L_{\delta E} = 0 \)

\[ CAP = - \left( \frac{M_q L_\alpha}{V_N} + M_\alpha \right) \approx \frac{\omega_{nsp}^2}{\Delta n_z / \Delta \alpha} \]
MIL-F-8785C
Short-Period
Flying
Qualities
Criterion

\[ CAP = \text{constant along Level Boundaries} \]

Control Anticipation Parameter vs. Short-Period Damping Ratio
(MIL-F-8785C, Category A)

\[ CAP = \frac{1}{\Delta n_z / \Delta \alpha} = \frac{\omega_n^{SP}}{\Delta n_z / \Delta \alpha} \]

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
**C* Criterion**

- **Hypothesis**
  - $C^*$ blends normal load factor at pilot’s location and pitch rate
  - Step response of $C^*$ should lie within acceptable envelope

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

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

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

- Below $V_{crossover}$, $\Delta q$ is pilot’s primary control objective
- Above $V_{crossover}$, $\Delta n_{pilot}$ is the primary control objective

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

**Gibson Dropback Criterion for Pitch Angle Control**

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

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

\[
= \frac{k_q \left( s + \frac{\omega_{nsp}}{\zeta_{SP}} \right)}{s^2 + 2 \zeta_{SP} \omega_{nsp} s + \omega_{nsp}^2}
\]

- Criterion is satisfied when

\[
\zeta_q \triangleq - \frac{1}{T_{\theta_2}} = - \left( \frac{\omega_{nsp}}{\zeta_{SP}} \right)
\]

**Figure 3-3:** Generic short period pitch transient response

Gibson, 1997
YF-17 Landing Approach Simulation

- Original design
  - Low short-period natural frequency
  - Overdamped short period
  - Rapid roll-off of phase angle
  - PIO tendency, CHR = 10

- Revised DFCS design
  - Higher short-period natural frequency
  - Lower short-period damping
  - Reduced time delay in DFCS
  - CHR = 2

Elevator-to-pitch angle *Nichols chart* (gain vs. phase angle)

Next Time: Advanced Problems of Lateral-Directional Dynamics

*Flight Dynamics* 595–627

Learning Objectives

Fourth-order dynamics
- Steady-state response to control
- Transfer functions
- Frequency response
- Root locus analysis of parameter variations

Residualization
- Roll-spiral oscillation
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
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