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

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

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: Now

- Tape recorder
- Telemetry transmitters
- Transducers
- Strain gauges
- High-side accessories
- Noseboom angle sensors
- Noseboom pressures sensors
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 \([pb/2V]\)

- 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

Cooper-Harper Handling Qualities Rating Scale

Simplified Roll-Rate Response

- Tradeoff between high \(pb/2V\) and high lateral stick forces prior to powered controls:
  \[
  p(t) = \left[ C_{\alpha, p}(t) + C_{\alpha, q}(\Delta t) \right] \bar{q} Sb / I_v
  \]
- Initial-condition response \((\Delta A = 0)\)
  \[
  p(t) = p(0)e^{\alpha t}
  \]
- Step response \([p(0) = 0]\)
  \[
  p(t) = \frac{1}{\alpha} \left( e^{\alpha t} - 1 \right) \Delta A
  \]
- Steady state response
  \[
  p^* = \frac{C_{\alpha, p}}{C_{\alpha, q}} \Delta A
  \]

Effect of Equivalent Time Delay on Cooper-Harper Rating

- Rate of degradation 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

Formation Flying

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

Aerial Refueling

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

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 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

Damping Ratio

<table>
<thead>
<tr>
<th>Category</th>
<th>Flight Phase</th>
<th>Level</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
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<tr>
<td>A and C</td>
<td>Flight Phase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>1.5</td>
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<tr>
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<td>1.2</td>
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<tr>
<td>3</td>
<td>0.05</td>
<td>0.5</td>
<td>-</td>
<td>0.8</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
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

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. \((\Delta y/\Delta V)_{SS} < 0.06 \text{ deg/kt}\)
  2. \((\Delta y/\Delta V)_{SS} < 0.15 \text{ deg/kt}\)
  3. \((\Delta y/\Delta V)_{SS} < 0.24 \text{ deg/kt}\)

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

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

\[ T_{2p_h} = -0.693/\xi_{p_h}\omega_{n_{p_h}} \]
**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)

**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, \( \omega \), for which \( \phi(j\omega) = -180^\circ \), the difference between 0 dB and the transfer function magnitude, \( 20 \log_{10} AR(j\omega) \)

- **Phase Margin**: At the input frequency, \( \omega \), for which \( 20 \log_{10} AR(j\omega) \) is 0 dB, the difference between the phase angle \( \phi(j\omega) \), and \(-180^\circ\)

- **Axis intercepts on the Nichols Chart**
  - Identify GM and PM
Examples of Gain and Phase Margins

- **Bode Plot**
  - Third Order Frequency Responses
  - Third Order Nichols Charts

- **Nichols Chart**
  - Phase Margin
  - Gain Margin

Short-Period Approximation Transfer Functions

- **Elevator to pitch rate**
  - \[ \Delta \phi(s) = \frac{k_e(s-z)}{s^3 + 2z_1 s^2 + \zeta_1 s + \frac{1}{\tau_e}} \]

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

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, \( Ke/h \), 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 \( \phi \) that causes unstable control

Short-Period Approximation Transfer Functions

- **Elevator to pitch angle**
  - \[ \Delta \phi(s) = \frac{k_e(s-z)}{s^3 + 2z_1 s^2 + \zeta_1 s + \frac{1}{\tau_e}} \]

- **Pure gain or phase change in feedback control cannot produce instability**
Normal Load Factor

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

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

\[ \frac{\partial \Delta n_z(s)}{\partial \Delta \delta E(s)} = \frac{1}{g} \left( \frac{L_{ae}}{V_n} \frac{\partial \Delta \alpha(s)}{\partial \Delta \delta E(s)} + \frac{L_{ae}}{V_n} \right) = \frac{L_{ae}}{g} \frac{\partial \Delta \alpha(s)}{\partial \Delta \delta E(s)} \]

- Elevator to angle of attack (\( L_{ae} = 0 \))

\[ \Delta \alpha(s) = \frac{k_n}{\Delta \delta E(s)} s^2 + 2 \xi_{SP} \omega_{n_{SP}} s + \omega_{n_{SP}}^2 \]

\[ \omega_{n_{SP}} = \sqrt{C_{0} \frac{n_z / \alpha}{\Delta \delta E(s)}} \]

Control Anticipation Parameter, \( CAP \)

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

\[ \Delta q(0) = \left( \frac{M_{ae}}{V_n + L_{ae}} \right) \Delta \delta E \]

\[ \Delta n_{SS} = \frac{V_n}{g} \Delta q_{SS} = \left( \frac{V_n}{g} \right) \left( \frac{M_{ae} L_{/V_n} - M_{ao} L_{eo} / V_n}{M_{ae} L_{/V_n} + M_{ao}} \right) \Delta \delta E \]

\[ CAP = \frac{\Delta q(0)}{\Delta n_{SS}} = \left( \frac{M_{ae}}{V_n + L_{ae}} \right) \left( \frac{M_{ae} L_{/V_n} - M_{ao} L_{eo} / V_n}{M_{ae} L_{/V_n} + M_{ao}} \right) \]

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

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)

\[ \omega_{n_{SP}} = \sqrt{CAP \frac{n_z / \alpha}{\Delta \delta E(s)}} \]
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,

\[
\Delta q(s) = \frac{k \left( s - c \right)}{s^3 + 2\omega_n\omega_s s + \omega_n^2}
\]

\[
\Delta E(s) = \frac{k \left( s + \omega_s \right)}{s^3 + 2\omega_n\omega_s s + \omega_n^2}
\]


C* Criterion

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

\[
= \frac{l_{\text{pilot}} \Delta q + \Delta A \text{ or } + \frac{V_{\text{crossover}}}{g} \Delta q}{g}
\]

- Hypothesis
  - C* blends normal load factor and pitch rate
  - Step response of C* should lie within acceptable envelope
  - Below \( V_{\text{crossover}} \), \( \Delta q \) is pilot’s primary control objective
  - Above \( V_{\text{crossover}} \), \( \Delta \eta_{\text{pilot}} \) 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)
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

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

Pilot-Induced Oscillations

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

Next Time: Fourth-Order Longitudinal Dynamics