Bandwidth Criteria for Category I and II PIOs

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Background

• Phase II SBIR from Air Force Research Labs
  – Development of Methods & Devices to Predict & Prevent PIO
  – Contract monitor is Tom Cord
  – In process of writing final report

• Goals:
  – Gather data (Lockheed Martin, Northrop Grumman, McDonnell Douglas subcontractors)
  – Analyze all available PIO data
  – Develop criteria for prevention by design
  – Develop test methods for detection in flight test
  – Develop devices for real-time monitoring and detection
Outline

- Pitch criteria based on airplane Bandwidth for
  - Handling qualities
  - PIO
- Apply research, experimental, operational data
- Compare Smith-Geddes, Gibson, Neal-Smith criteria
- Bandwidth criteria for Category II PIO
- Control/response sensitivity and PIO
- Extension to roll axis
- Recommendations

Analytical Criteria

- Category I PIOs (linear):
  - Many criteria exist
  - Bandwidth-based criteria show most promise
    - AIAA-98-4335 show them to be effective
    - Amenable to initial design through flight test
- Category II PIOs (rate limiting):
  - Only a handful of criteria
  - Most are complex to apply
    - Require closed-loop analysis
    - Applicable to analytical models only, not in flight
    - Must make assumptions about pilot, frequency, or amplitude
  - Recent work on Bandwidth criteria shows promise
Handling Qualities Criteria

- Criteria developed for draft MIL standard (AFWAL-TR-82-3081, 1982)
  - Requirements more stringent than "classical" (CAP) criteria
  - Almost didn't make it into MIL-STD-1797 (1987)
- Primary short-term response criteria in rotorcraft handling-qualities standard ADS-33D-PRF
- For airplanes, adopted revised version of Gibson's requirements on dropback/overshoot
  - Relaxed Bandwidth limits (WL-TR-94-3162)
  - USAF TPS project found dropback untestable in flight (AFFTC-TR-95-78)
  - Dropback secondary in importance to pitch rate overshoot
  - Current criteria use frequency-domain measure of overshoot

Process for Obtaining Bandwidth Information from Flight

Frequency sweep... → Fast-Fourier Transform... → Bode plot... → Criteria
Attitude Bandwidth Parameters

Pitch Rate Overshoot

\[ \frac{q}{\omega_{ss}} \] (dB)

\[ \text{Frequency } \omega \text{ (rad/sec)} \]

\[ \Delta Q(q) \]
Nonlinearities Can Cause Data Quality to Degrade

- Example data from in-flight frequency sweep
- Coherence drops as a result of rate limiting
  - $p^2$ is a measure of linear correlation between input and output
- Input power high
- Frequency response looks reasonable
- Examined in AIAA-99-0639 (Reno)

Bandwidth Criteria for Handling Qualities (Fighters -- Landing)
Bandwidth Criteria for PIO
(Fighters -- Landing)

Level 3
"Severe" PIO

Level 2
"Mild" PIO if Flight Path Bandwidth
\( \omega_{BWY} < 0.7 \) rad/sec

Level 2
No PIO
[Bobble if \( \Delta G(q) > 12 \) dB]
[Pitch Bobble if Pitch Rate
Overshoot Ratio \( \Delta G(q) > 9 \) dB]

Level 1
No PIO

 "Mild" PIO if \( \Delta G(q) > 9 \) dB

Criteria Applied to Research Data
Successful on 188 of 207 (91%) [78 of 91 PIOs (86%)]

No PIO

Susceptible to PIO

Susceptible to PIO if flight path
Bandwidth insufficient (flaps)
Gibson Criteria (Research Data)
166 of 207 cases (80%) [66 of 91 PIOs (73%)]

![Graph showing data points with labels L1, L2, and L3.]

Note: t_p = (avg phase rate)/720

Neal-Smith Criteria (Research Data)
158 of 207 cases (76%) [75 of 91 PIOs (82%)]

![Graph showing data points with labels L1, L2, and L3.]

BW = 3 rad/sec

Smith-Geddes Criteria (Research Data)
133 of 207 cases (64%) [82 of 91 PIOs (90%)]

Bandwidth Criteria Applied
to Real Airplanes
45 of 49 cases (92%) [20 of 24 PIOs (83%)]

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Application to Rate-Limited Configurations

Example: Frequency sweeps from LAMARS simulation
(20-deg/sec RL, unstable open-loop; 1 of 5 pilots encountered divergent PIOs)

Application to Rate-Limited Configurations

Example: Config. 2D from HAVE LIMITS TPS Project
(RL on stable bare airplane; no PIOs reported for discrete tracking task)
### Application to Rate-Limited Configurations

**Example:** Config. 2DU from HAVE LIMITS TPS Project

(Unstable open-loop; divergent PIOs for RL of 60 deg/sec and below)

<table>
<thead>
<tr>
<th>Phase Delay (sec)</th>
<th>PIO Possible (if flight path Bandwidth is low)</th>
<th>No PIO</th>
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<tr>
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<tr>
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<td>0.25</td>
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**Pitch Attitude Bandwidth, \( \omega_{BW} \) (rad/sec)**

- Max. sweep size: 0g, 0.25g, 0.5g
- PIO Possible (if pitch rate overshoot is excessive)
- Actuator rate limit (deg/sec)
- 0.15 = 0.157 PIO Possible

### Inappropriate Control/Response Sensitivity Contributes to PIO

**Pitch Example:** TIFS Flared Landing Data

- Open - No PIO
- Solid - PIO reported
- Plots separated by each Repetition separated by comma

<table>
<thead>
<tr>
<th>Added Time Delay (sec)</th>
<th>0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
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<tbody>
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</table>
Inappropriate Control/Response Sensitivity Contributes to PIO

Roll Example: LATHOS ($T_R = 0.45$ sec data)

Airplane Bandwidth Criteria for Roll

- Much smaller data base
  - Not as many real experiences
  - Most research experiments did not record PIO ratings
- Limits proposed in WL-TR-94-3162:
Recommendations

• Apply criteria as early in development as possible
• Focus especially on Phase Delay limits
  – No greater than 0.14 sec in pitch or roll
• If feel system dynamics are not known or are known to be very good, limits excluding feel system are
  – No greater than 0.09 sec in pitch or roll
• Use criteria for all amplitudes of control input, up to maximum possible
  – Examine frequency-sweep results if coherence drops