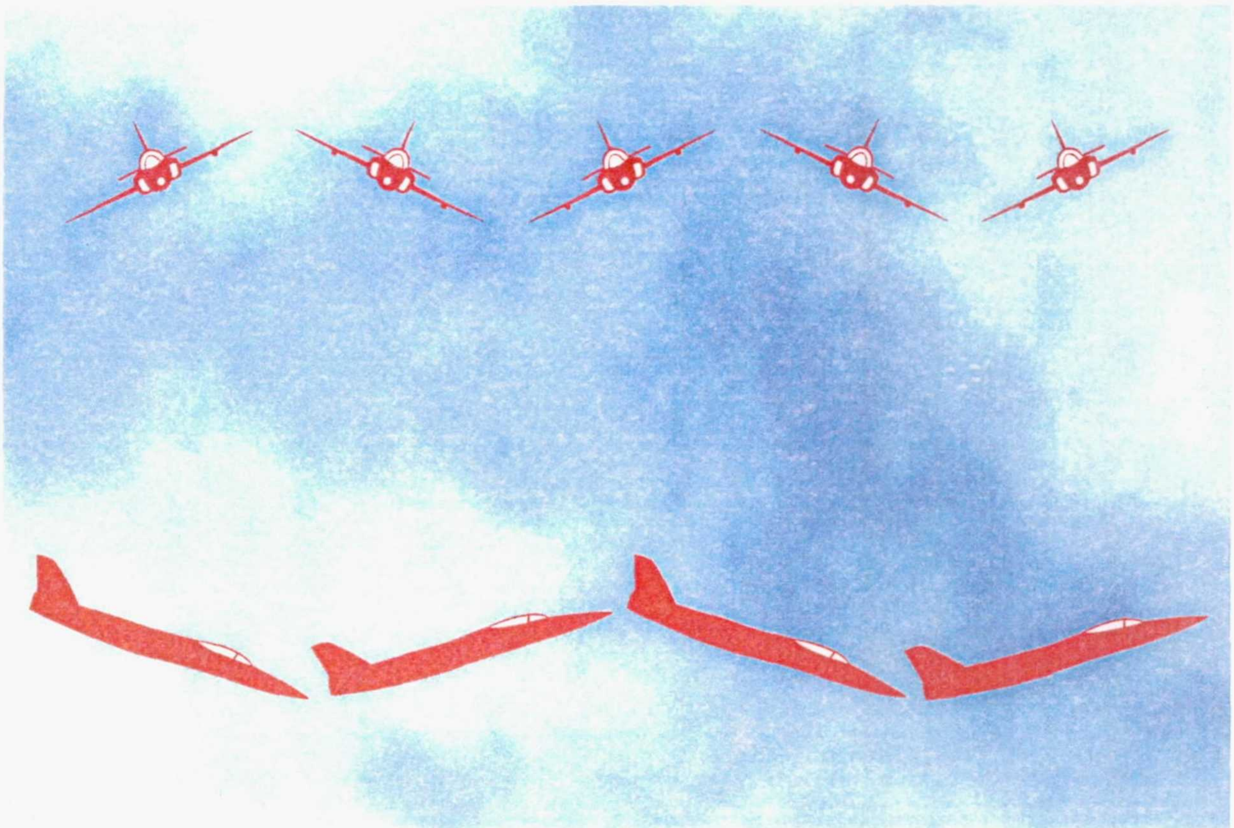
NASA/CP-2001-210389/VOL1

Pilot-Induced Oscillation Research: Status at the End of the Century

Compiled by Mary F. Shafer and Paul Steinmetz
NASA Dryden Flight Research Center
Edwards, California



April 2001

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Foreword

"Pilot-Induced Oscillation Research: The Status at the End of the Century," a workshop held at NASA Dryden Flight Research Center on 6–8 April 1999, may well be the last large international workshop of the twentieth century on pilot-induced oscillation (PIO). With nearly a hundred attendees from ten countries and thirty presentations (plus two that were not presented but are included in the proceedings) the workshop did indeed represent the status of PIO at the end of the century.

These presentations address the most current information available, addressing regulatory issues, flight test, safety, modeling, prediction, simulation, mitigation or prevention, and areas that require further research. All presentations were approved for publication as unclassified documents with no limits on their distribution.

This proceedings include the viewgraphs (some with authors' notes) used for the thirty presentations that were actually given as well as two presentations that were not given because of time limitations. Four technical papers on this subject that offer this information in a more complete form are also included. In addition, copies of the related announcements and the program are incorporated, to better place the workshop in the context in which it was presented.

Mary F. Shafer

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VOLUME 2 – SESSIONS IV – V

VOLUME 3 – SESSION VI AND APPENDICES

Session I

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Modeling the Human Pilot in Single-Axis Linear & Nonlinear Tracking Tasks

Yasser Zeyada, and Ronald A. Hess
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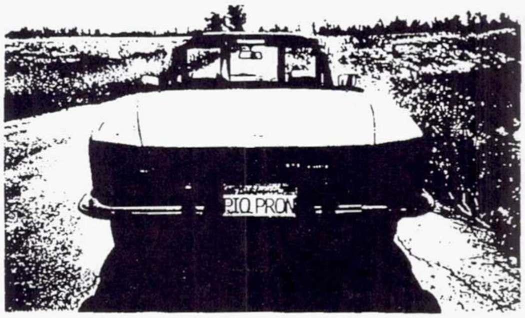
University of California
Davis, CA 95616



Outline

- Introduction
- Analytical Approach
  - Structural Model
  - Linear Analysis (Program PVD)
  - Nonlinear Analysis (Program PVD_{NL})
  - Improved Version of PVD_{NL} with Graphical User Interface
- Analyzing HAVE LIMITS data
- Design Example - Longitudinal Flight Control System For HARV
- Self-Report Card on "Criteria for Criteria"
- Conclusions

Introduction

- Motivation
  - "Research to develop design assessment criteria and analysis tools should focus on Category II and III PIOs….This research should combine experiments with the development of effective mathematical analysis methods capable of rationalizing and emulating the experimental results"
    - » Recommendation 6-3 *Aviation Safety and Pilot Control*, Report of the Committee on the Effects of Aircraft-Pilot Coupling on Flight Safety, NRC, 1997
- Approach
  - Extend linear, closed-loop, HQR/PIO prediction technique to vehicles with significant nonlinearities, e.g., actuator rate saturation
- Assess technique using HAVE LIMITS flight test data

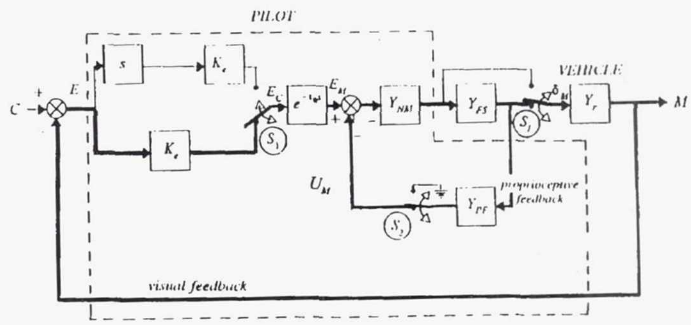
Analytical Approach

Principal Assertions

- Aircraft handling qualities, including PIO events are fundamentally <u>closed-loop phenomena</u>
- A unifying theory for handling qualities and PIO, should, therefore, adopt a <u>closed-loop perspective</u>
- A closed-loop perspective, of necessity, requires a <u>model of the human pilot</u>

Analytical Approach

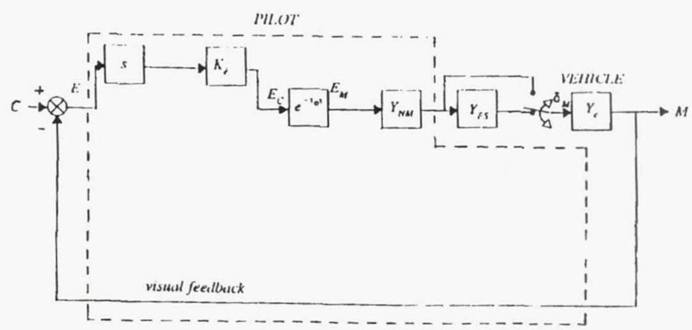
Structural Model of Human Pilot



Analytical Approach

Structural Model of Human Pilot

"Regressive Mode" - Assumed to Occur in Fully-Developed PIO



Analytical Approach

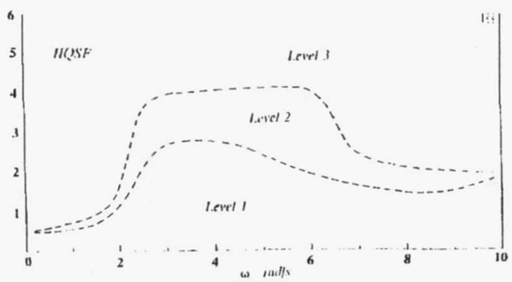
Applying Structural Model to Linear Vehicles

- Methodology developed in
  - Hess, R. A., "Unifying Theory for Aircraft Handling Qualities and Adverse Aircraft-Pilot Coupling," *Journal of Guidance, Control, and Dynamics*, Vol. 20, No. 6, 1997
- Interactive MATLAB-based computer program developed as
  - Zeyada, Y., and Hess, R. A. "PVD Pilot Vehicle Dynamics, An Interactive Computer Program for Modeling the Human Pilot in Single-Axis Linear Tracking Tasks, Dept. of Mechanical and Aeronautical Engineering, UC Davis, 1998.

Analytical Approach

The Handling Qualities Sensitivity Function (HQSF)

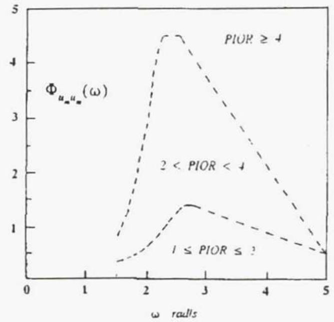
- Given model of vehicle dynamics, PVD allows creation of a Structural Model of the pilot
- The HQSF is defined by $|U_M/C|$, after normalized by gain K_e in model
- Using NT-33A and TIFS flight test data, bounds on $|U_M/C|$ obtained which could delineate handling qualities levels



Analytical Approach

The Power Spectral Density of U_M ($\Phi_{u_m u_m}(\omega)$)

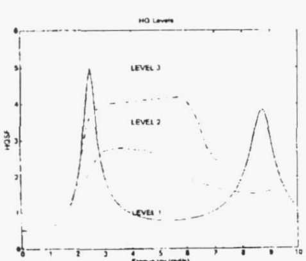
- Given model of vehicle dynamics, PVD allows creation of a Structural Model of the pilot
- The power spectral density of U_M, after normalized by gain K_e^2 in model, is obtained
- Using NT-33A and TIFS flight test data, bounds on $\Phi_{u_m u_m}(\omega)$ obtained which could delineate PIOR "levels"



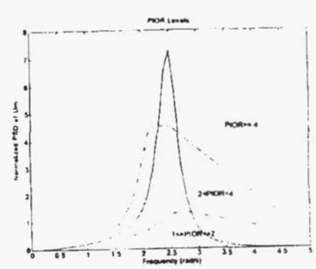
Analytical Approach

Example - A LAHOS Config. with 0.2 s time delay added

Handling Qualities Level



Pilot-Induced Oscillation "Level"



Analytical Approach

Applying Structural Model to Nonlinear Vehicles
("Nuisance" Nonlinearities)

- Methodology developed in
  - Hess, R. A., and Stout, P. W., "Assessing Aircraft Susceptibility to Nonlinear Aircraft-Pilot Coupling/Pilot-Induced Oscillations, *Journal of Guidance, Control and Dynamics, Nov.-Dec. 1998, pp. 957-965*)
- Interactive MATLAB/Simulink-based computer program developed as
  - Zeyada, Y., and Hess, R. A., "PVD_{NL} Pilot/Vehicle Dynamics $_{NonLinear}$ An Interactive Computer Program for Modeling the Human Pilot in Single-Axis Linear and Nonlinear Tracking Tasks, Dept. of Mechanical and Aeronautical Engineering, UC Davis, 1998.

Analytical Approach

- No fundamental changes in theoretical approach....normalized HQSF and $\Phi_{u_m u_m}(\omega)$ still used, but obtained from nonlinear Simulink simulation
- HQSF now obtained as

$$HQSF = \frac{\left|\int_0^T u_m(t)e^{-j(\omega t)}dt\right|_{\omega=\omega_i}}{\left|\int_0^T c(t)e^{-j(\omega t)}dt\right|_{\omega=\omega_i}} \cdot \left|\frac{1}{K_e}\right| \quad i = 1,2,\ldots,50$$

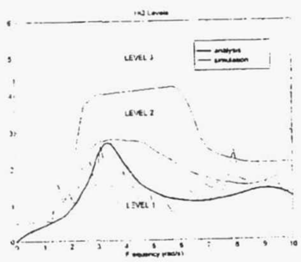
- $\Phi_{u_m u_m}(\omega)$ now obtained as

$$\Phi_{u_m u_m}(\omega) = \left[\frac{4^2}{\omega^4 + 4^2}\right] \cdot HQSF^2$$

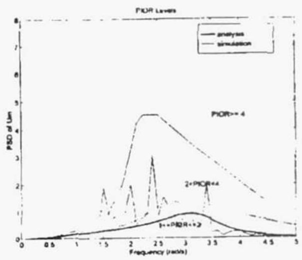
Analytical Approach

Example - A LAHOS Config. with amplitude and rate-limited elevator actuator

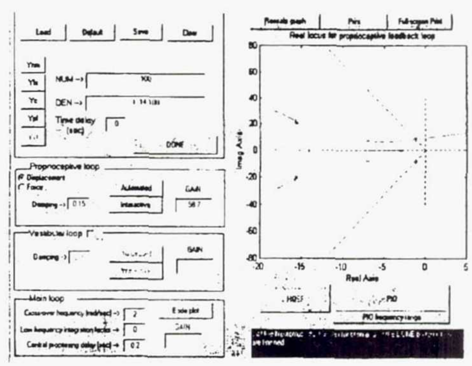
Handling Qualities Level



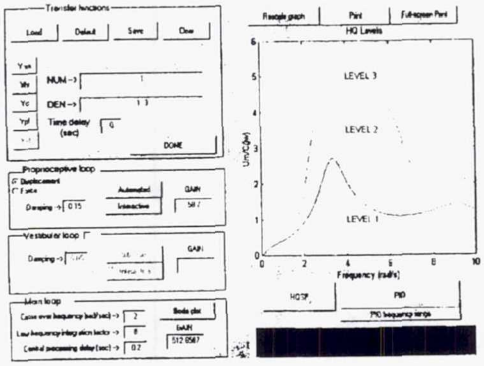
Pilot-Induced Oscillation "Level"



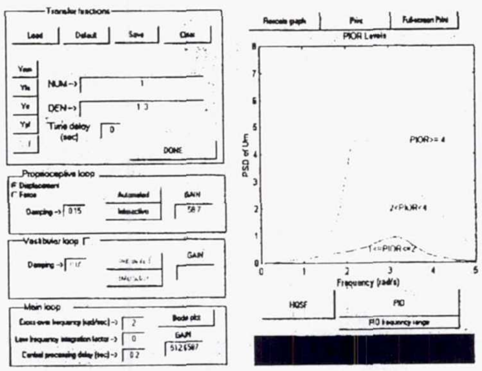
Improved Version of PVD_{NL} with GUI



Improved Version of PVD_{NL} with GUI



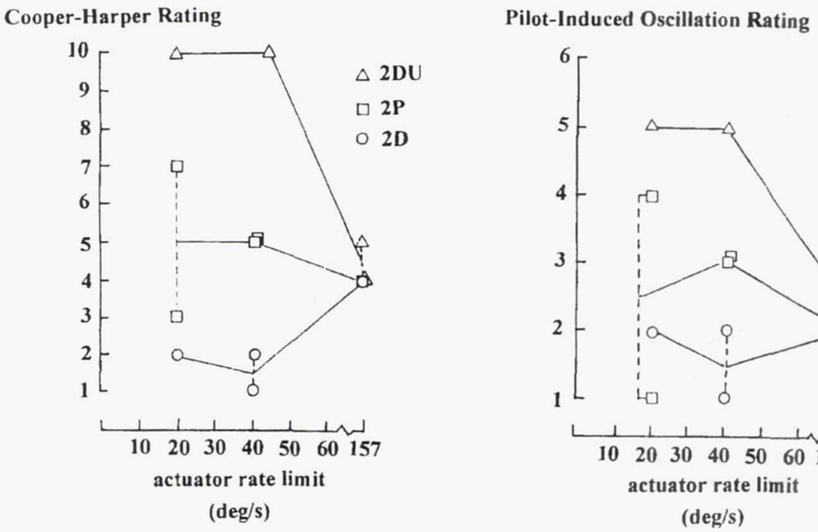
Improved Version of PVD_{NL} with GUI



HAVE LIMITS Flight Tests

- USAF-Sponsored flight tests using (for the last time) the NT-33A variable stability aircraft
- Goal: Evaluation of effects of actuator rate limiting on longitudinal handling qualities and PIO
- Three configurations evaluated:
  - 2D (stable unaugmented airframe
  - 2P (essentially 2D with stick filter)
  - 2DU (unstable unaugmented airframe, similar to 2D when augmented) ✓
- Two HUD pitch-attitude commands utilized
  - sum of sinusoids
  - discrete, step-like ✓

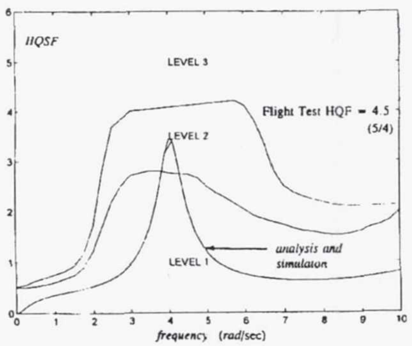
HAVE LIMITS Flight Tests (Pilot 3)



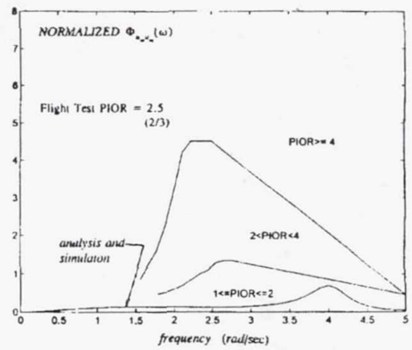
Analyzing HAVE LIMITS data

Configuration 2DU with rate limit = 157 deg/s

Handling Qualities Level



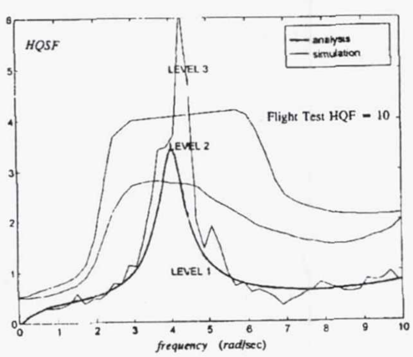
Pilot-Induced Oscillation "Level"



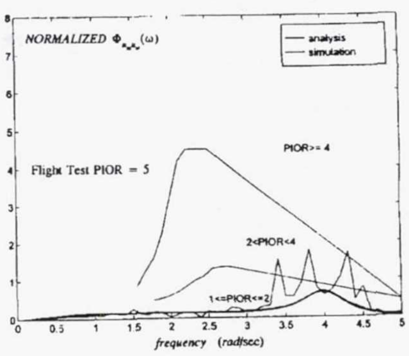
Analyzing HAVE LIMITS data

Configuration 2DU with rate limit = 60 deg/s
(pilot/vehicle system unstable @ 40 deg/s)

Handling Qualities Level



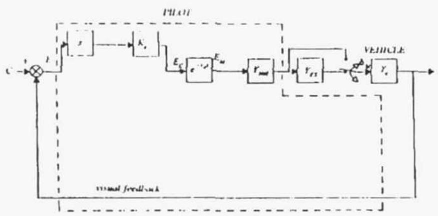
Pilot-Induced Oscillation "Level"



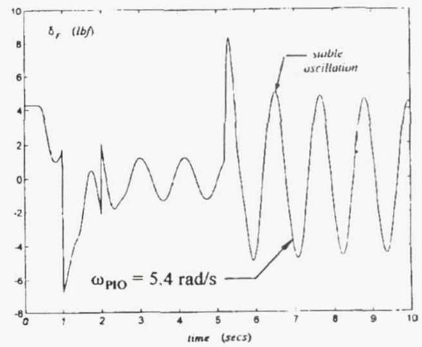
Analyzing HAVE LIMITS data

Configuration 2DU with rate limit = 53 deg/s
(minimum rate limit for pilot/vehicle stability)

Rate-tracking Structural Model

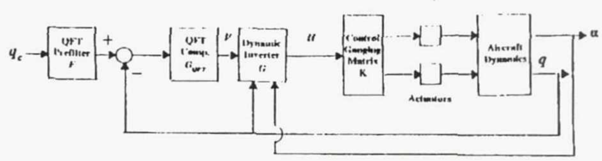


Predicted (fully-developed) PIO



Design Example
Longitudinal Control of HARV

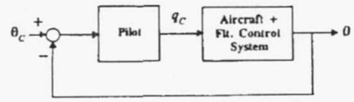
- Control structure



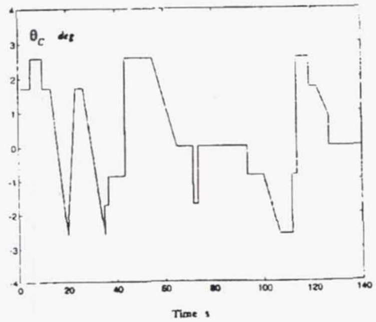
- Reduced-order model
  - only rigid-body vehicle dynamics considered - (dynamics of two actuators ignored)
  - simple two-state reduced-order model results (short-period vehicle model used)

Nonlinear Pilot/Vehicle Analysis

- Actuator rate and amplitude limiting must be considered in final handling qualities evaluation
- Pilot/vehicle system



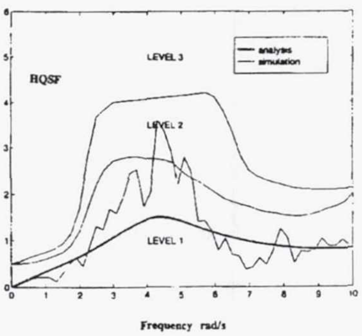
- Pitch command

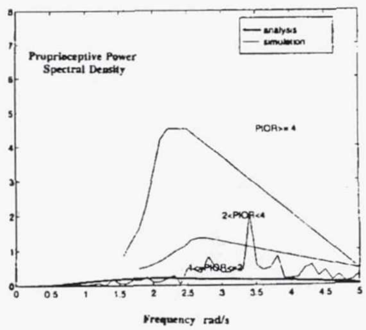


Nonlinear Pilot/Vehicle Analysis

Initial predicted handling qualities and PIO levels
using Structural Pilot Model and program PVD_{NL}

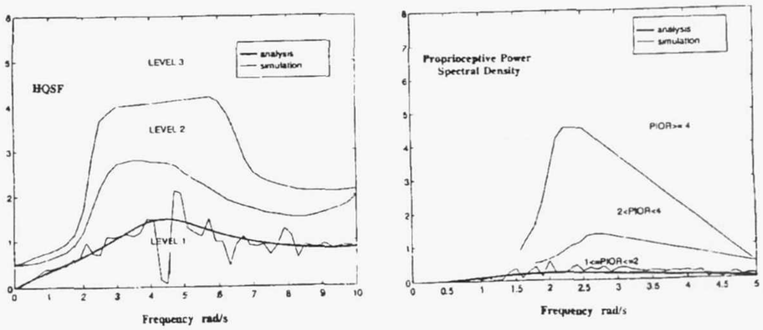
Flight Cond: Mach No. = 0.3, Alt. = 26.000 ft
full ± 20% perturbations on vehicle $\mathbf{A}_r$ and $\mathbf{B}_r$ matrix elements





Nonlinear Pilot/Vehicle Analysis

Predicted handling qualities and PIO levels
after addition of anti-windup logic in $G_{QFT}(s)$



Self -Report Card on
Criteria for Criteria

Definitions taken from NRC PIO report

- ***Validity:*** *Implies that a criterion embodies properties and characteristics that define the environment of interest...criterion must relate to closed-loop, high-gain, aggressive, urgent and precise pilot-control behavior*

  Grade = 7.5/10

- ***Selectivity:*** *Demands that criterion differentiate sharply between "good" and "bad" systems... in context of PIO prediction, must distinguish between configurations that may be susceptible to severe PIOs from those that are not*

  Grade = 7/10

- ***Ready Applicability:*** *requires that criterions be easily and conveniently applied*

  Grade = 6.5/10 (Original PVD_{NL})
  =7.5/10 (PVD_{NL} with GUI)

Conclusions

- Unifying theory for handling qualities and PIO can be offered for both linear and nonlinear (nuisance nonlinearity) systems

- Structural Pilot model, implemented in a computer-aided design program provided predictions of handling qualities levels and PIOR levels which compared well with those from HAVE LIMITS flight tests

- Methodology could be said to receive passing grade in "Criteria for Criteria"

Bandwidth Criteria for Category I and II PIOs

David G. Mitchell
Hoh Aeronautics, Inc.

David H. Klyde
Systems Technology, Inc.

Pilot Induced Oscillation Research Workshop
NASA Dryden Flight Research Center
6 April 1999

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

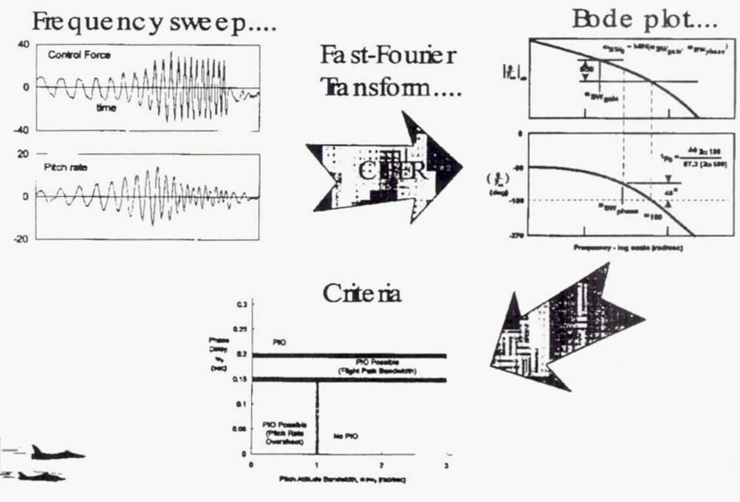
Analytical Criteria

- 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

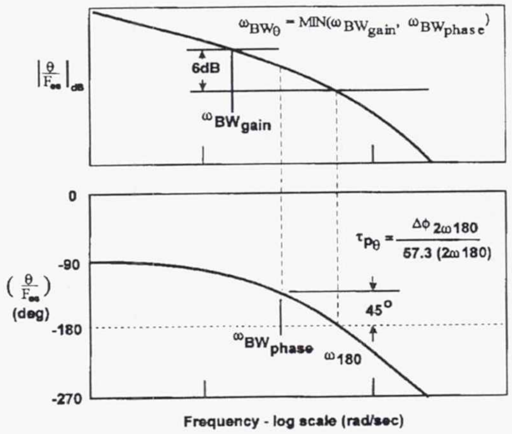
Handling Qualities Criteria

- 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

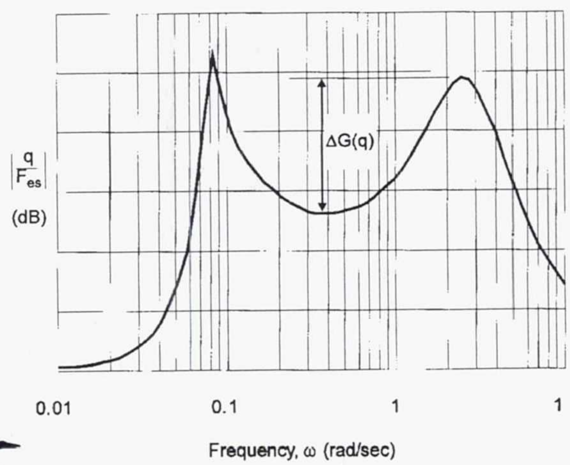
Process for Obtaining Bandwidth Information from Flight



Attitude Bandwidth Parameters

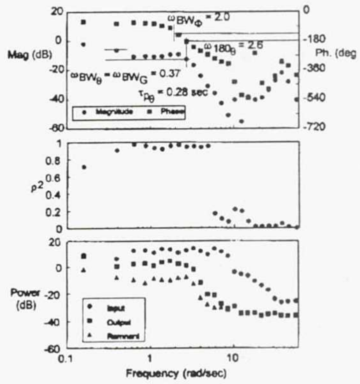


Pitch Rate Overshoot

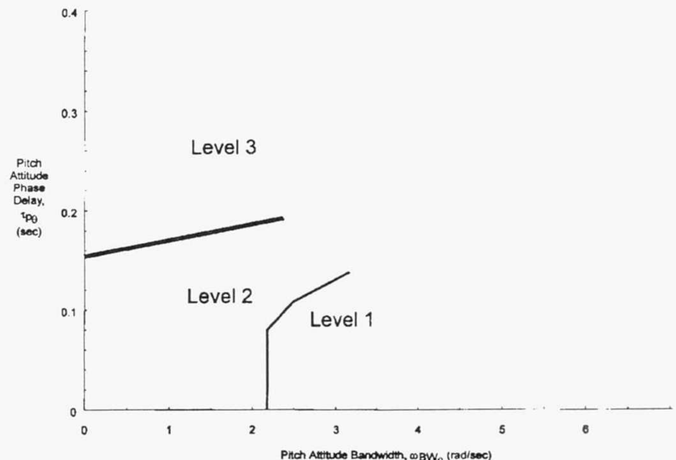


Nonlinearities Can Cause Data Quality to Degrade

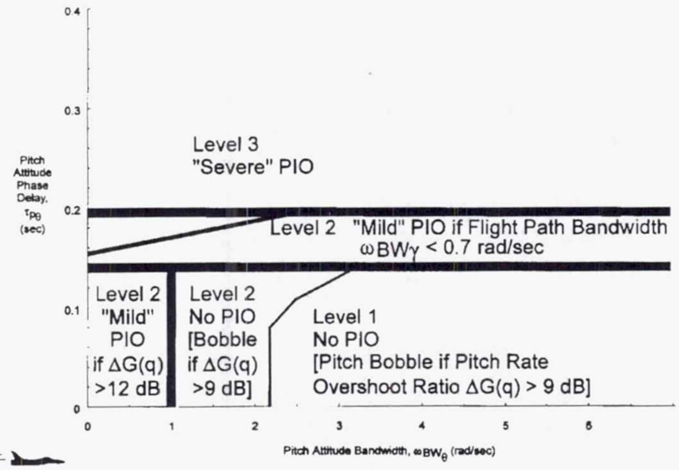
- Example data from in-flight frequency sweep
- Coherence drops as a result of rate limiting
  - ρ^2 is a measure of *linear* correlation between input and output
- Input power high
- Frequency response looks reasonable
- Examined in AIAA-99-0639 (Reno)



Bandwidth Criteria for Handling Qualities (Fighters -- Landing)

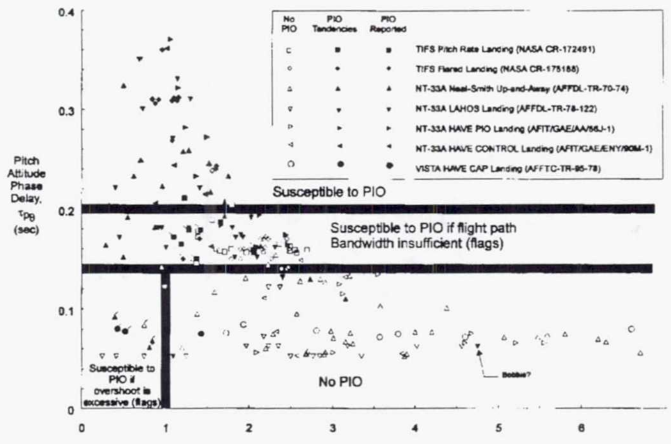


Bandwidth Criteria for PIO (Fighters -- Landing)



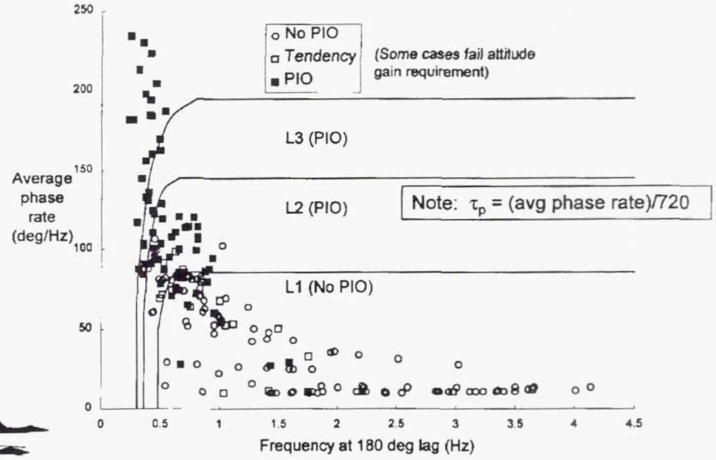
Criteria Applied to Research Data

Successful on 188 of 207 (91%) [78 of 91 PIOs (86%)]



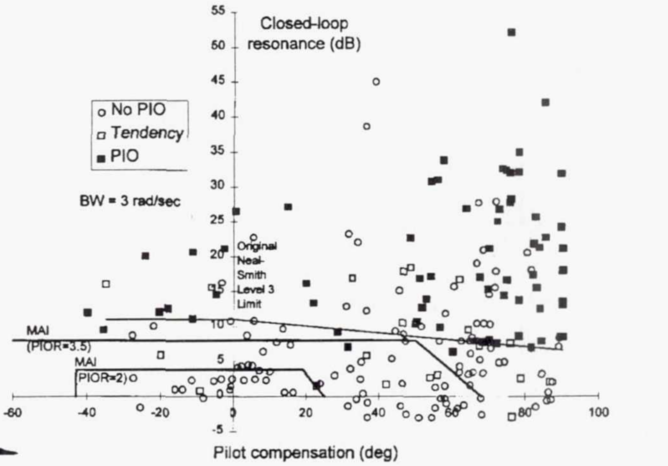
Gibson Criteria (Research Data)

166 of 207 cases (80%) [66 of 91 PIOs (73%)]



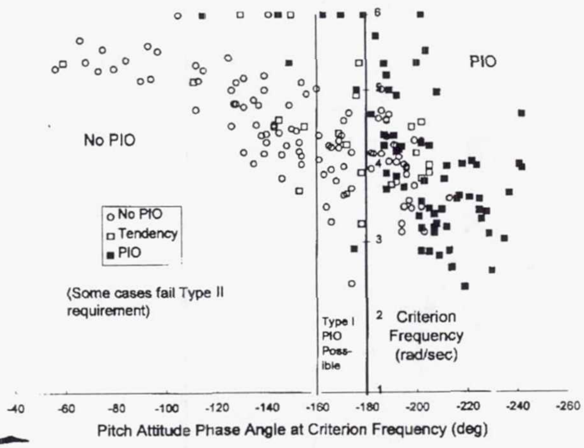
Neal-Smith Criteria (Research Data)

158 of 207 cases (76%) [75 of 91 PIOs (82%)]



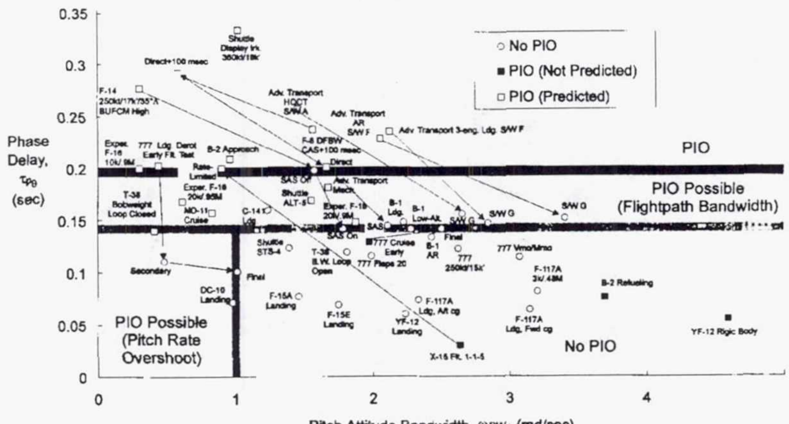
Smith-Geddes Criteria (Research Data)

133 of 207 cases (64%) [82 of 91 PIOs (90%)]



Bandwidth Criteria Applied to Real Airplanes

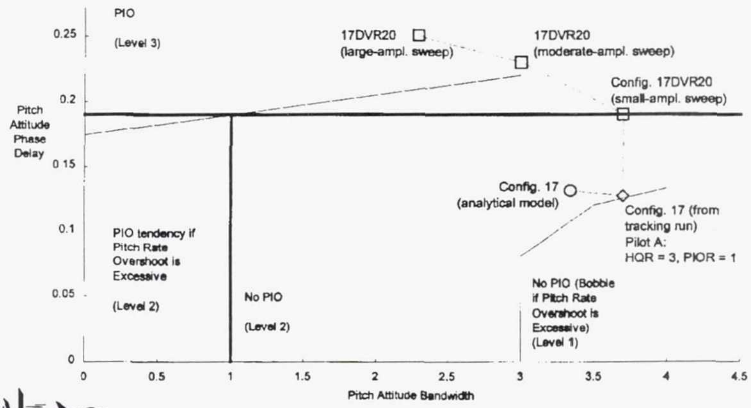
45 of 49 cases (92%) [20 of 24 PIOs (83%)]



Application to Rate-Limited Configurations

Example: Frequency sweeps from LAMARS simulation

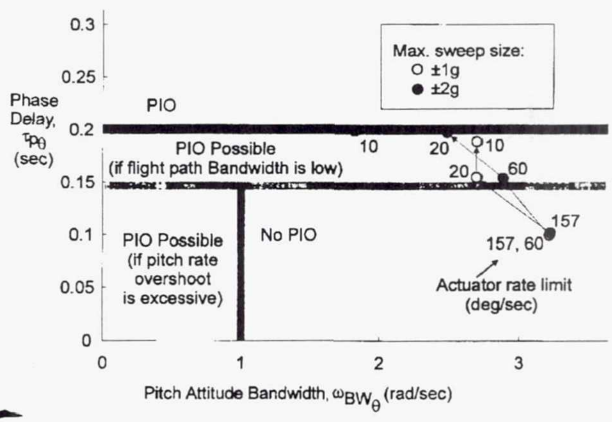
(20-deg/sec RL, unstable open-loop; 1 of 5 pilots encountered divergent PIOs)



Application to Rate-Limited Configurations

Example: Config. 2D from HAVE LIMITS TPS Project

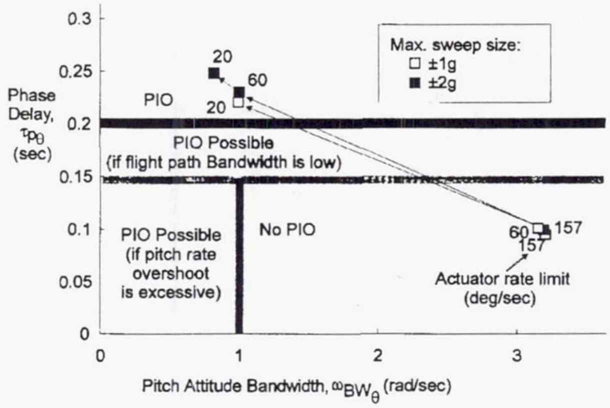
(RL on stable bare airplane; no PIOs reported for discrete tracking task)



Application to Rate-Limited Configurations

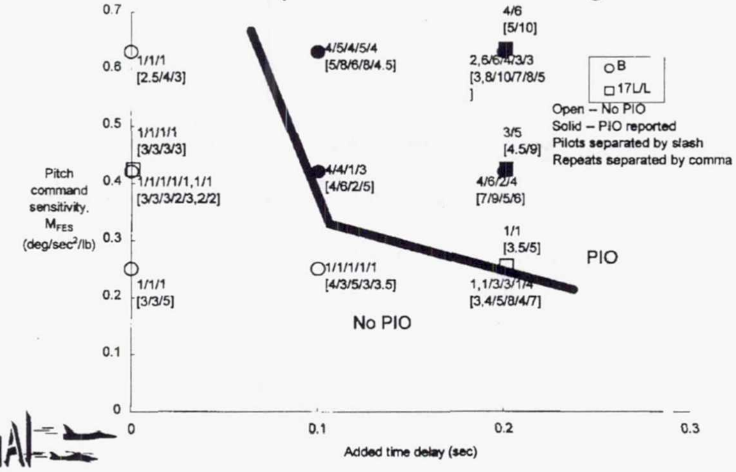
Example: Config. 2DU from HAVE LIMITS TPS Project

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



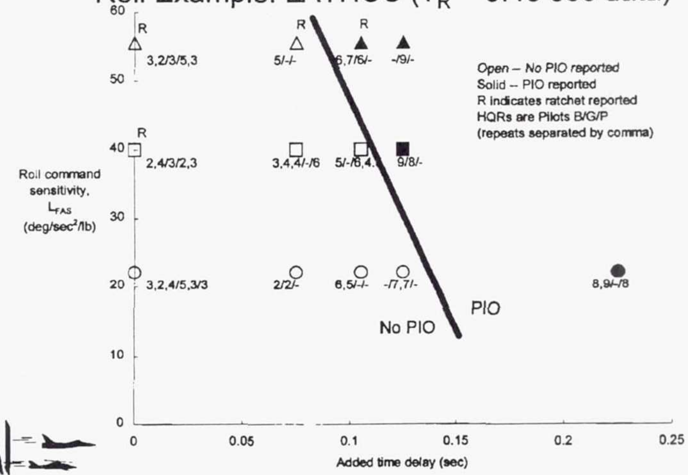
Inappropriate Control/Response Sensitivity Contributes to PIO

Pitch Example: TIFS Flared Landing Data



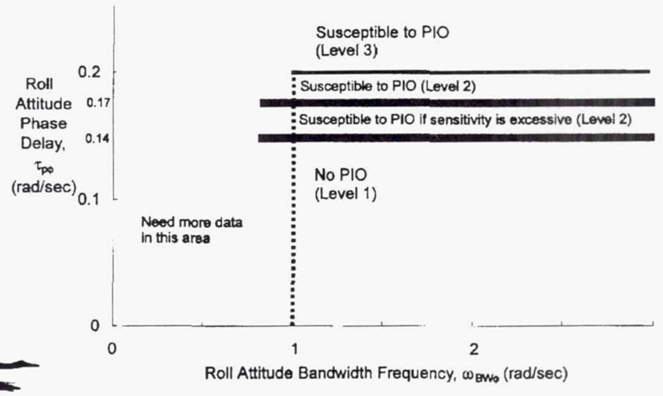
Inappropriate Control/Response Sensitivity Contributes to PIO

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

PHANTOM WORKS

Stability, Control & Flying Qualities

Criteria for Category I PIOs of Transports Based on Equivalent Systems and Bandwidth

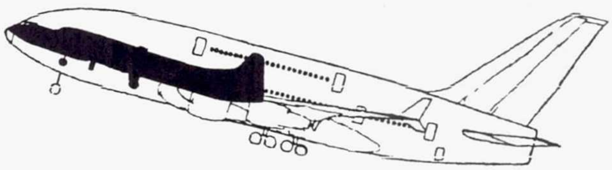
Ken F. Rossitto and Edmund J. Field

Boeing, Long Beach

PIO Workshop

NASA Dryden

April 6-8, 1999



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NASA Dryden PIO Workshop / 6-8 Apr-99 / EJF / 1

Between 1992 and 1994 The Boeing Company, Long Beach, performed a series of flying qualities experiments concerning transport aircraft. The experiments were performed in cooperation with the USAF (focal point Dave Leggett) and NASA Langley (focal point Bruce Jackson). Both government partners provided evaluation pilots, the USAF also contributed funding for flight evaluations.

The purpose of the experiments was to generate a longitudinal flying qualities database that could be used for criteria development. The flying qualities results of these experiments will be presented in a paper at the AIAA Atmospheric Flight Mechanics conference this August in Portland, Oregon[1].

The results of the experiments have also been analyzed to identify PIO tendencies in the aircraft configurations evaluated. Results from these analyses will be presented here.

After reviewing the background to the experiments and the approach taken, the evaluation task will be discussed. The results, as they apply to flying qualities criteria, will then be presented. Finally, PIO prediction criteria based on the results will be presented.

1. Field, Edmund J., and Rossitto, Ken R., "Approach and Landing Longitudinal Flying Qualities for Large Transports Based on In-Flight Results", AIAA-99-4095, presented at the AIAA Atmospheric Flight Mechanics conference, Portland, Oregon, August 1999 .

PHANTOM WORKS

Stability, Control & Flying Qualities

Criteria for Category I PIOs of Transports Based on Equivalent Systems and Bandwidth

Background

- Requirements for transports not well defined and supported.
- Active control technology make existing flying qualities criteria obsolete.

Approach

- Develop/validate flying qualities and PIO prediction criteria and design requirements through a series of generic in-flight simulation experiments.

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Background

Flying qualities requirements for transport aircraft are not well defined and supported:

• FARs and JARs are very limited

•Military specifications are more fighter oriented

•Limited database on 1 million pound airplanes.

Additionally, active control technology makes existing flying qualities criteria, where they exist, obsolete.

Approach

To develop / validate criteria and design requirements through a series of generic in-flight simulation experiments. Need:

•Preferred response type

•Pitch axis dynamics

•Pitch axis time delays

PHANTOM WORKS

Stability, Control & Flying Qualities

Criteria for Category I PIOs of Transports Based on Equivalent Systems and Bandwidth

USAF / Calspan Total In-Flight Simulator (TIFS)

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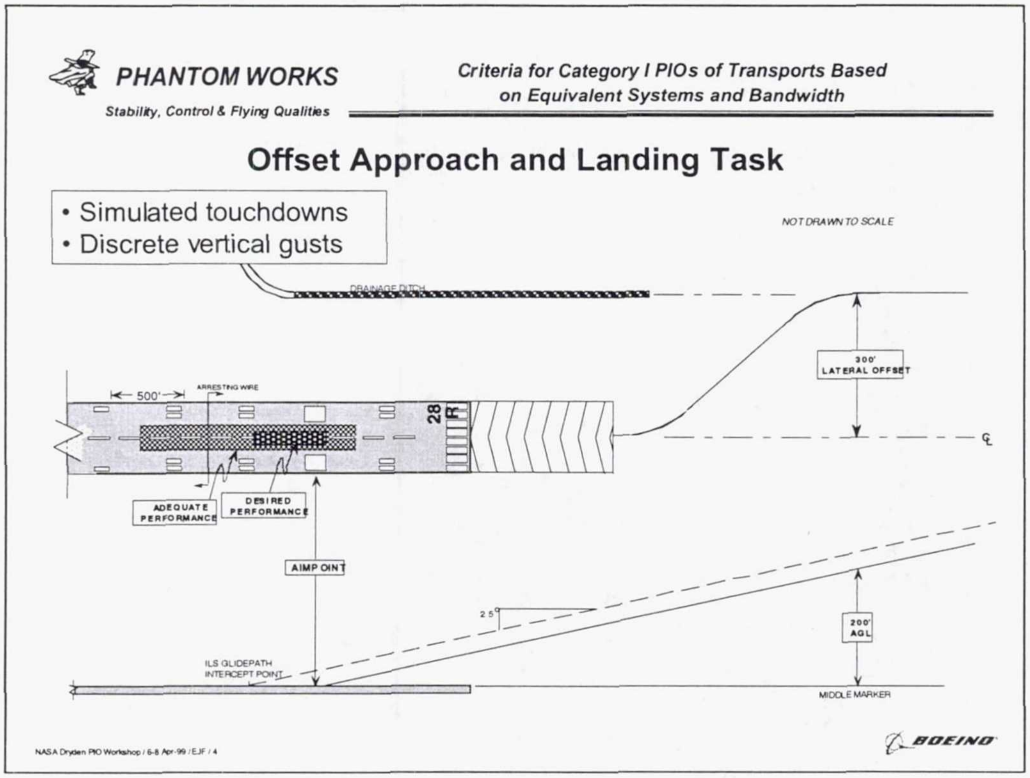
The facility used for the experiment was the USAF Total In-Flight Simulator (TIFS), operated by Calspan, Buffalo, NY.

Most approaches were flown into Niagara Airport, though some were flown at Buffalo.



The evaluation task used for the experiment was an offset approach and landing. The lateral offset of 300 feet was corrected at around 200 feet AGL and required an additional pitch axis "duck under" to land on the aim point.

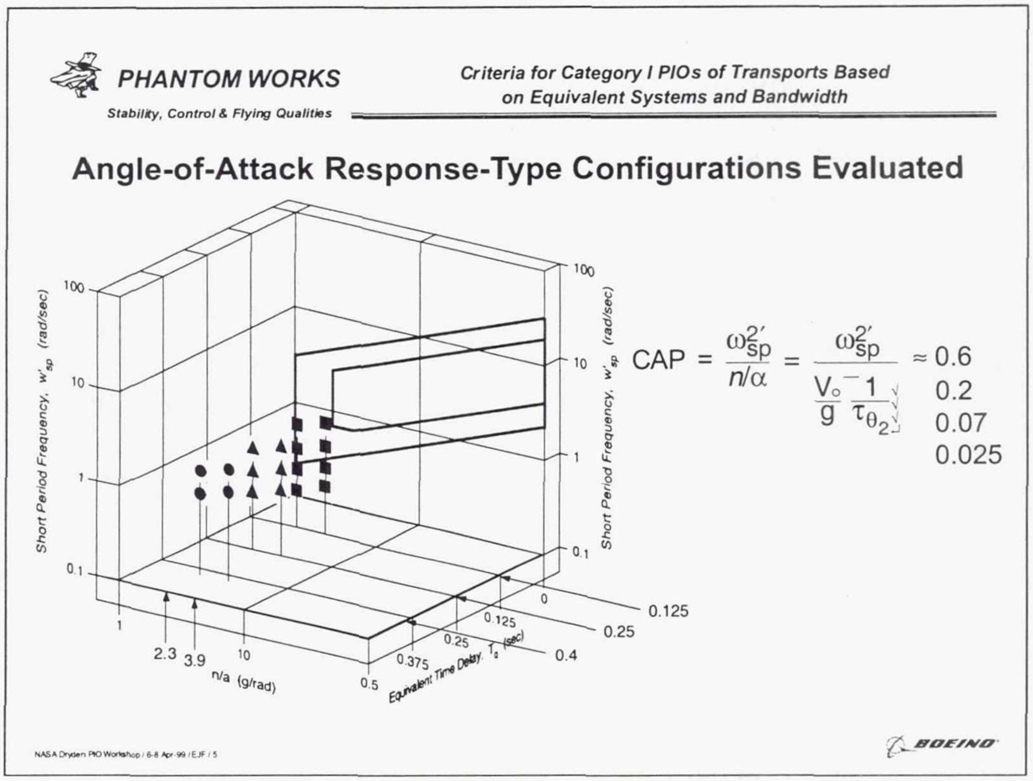
Desired performance criteria were:

> Touchdown between 1000 and 1500 feet past threshold
>
> Touchdown within 10 feet of centerline
>
> Touchdown sink rate between 0 and 4 feet/second
>
> No PIO

Adequate performance criteria were:

> Touchdown between 750 and 2250 feet past threshold
>
> Touchdown within 27 feet of centerline
>
> Touchdown sink rate between 4 and 7 feet/second

All data reported here resulted from simulated landings performed to match the pilot's correct "eye-height" at the landing point in the simulated aircraft.

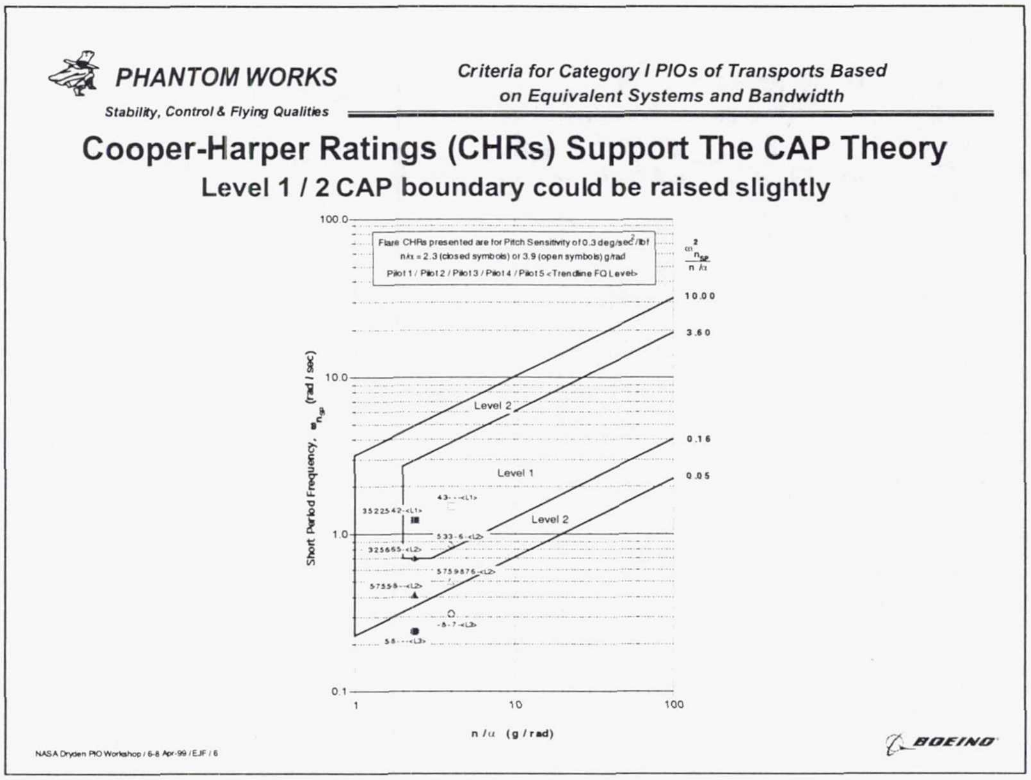


The flying qualities experiment evaluated a range of different dynamics for a one million pound transport aircraft. The bulk of the data collected was for an angle-of-attack (or conventional) response-type. Only that data will be presented here.

Experiment variables were:

n/α:	2.3 and 3.9
CAP:	0.025, 0.07, 0.2 and 0.6
Time delay:	125, 250 and 400 msec

Additionally, two pitch sensitivities were evaluated. The majority of the evaluations were with a pitch sensitivity of 0.3 deg/s^2/lb, and only that data is presented. A pitch sensitivity of 0.45 deg/s^2/lb was also evaluated for selected configurations.



The results for the configurations with zero added time delay (125 msec baseline configurations) are plotted on the existing Military specification CAP boundaries. Cooper-Harper ratings for each pilot are presented together with a "Trendline FQ Level". This trendline flying qualities level was determined from the individual ratings, the median rating and pilot comments. Additionally, experimental issues, such as quality of model following in the TIFS, were assessed. These trendline flying qualities levels have been fixed and are now used for development of flying qualities criteria.

The trendline flying qualities levels support the theory behind the CAP criterion. Additionally they support the raising of the Level 1/2 boundary.

For more details and discussion of these results refer to the AIAA paper mentioned above.

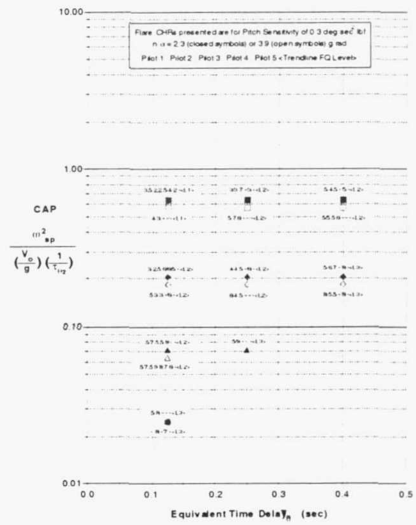
PHANTOM WORKS

Stability, Control & Flying Qualities

Criteria for Category I PIOs of Transports Based on Equivalent Systems and Bandwidth

Cooper-Harper Ratings Show Correlation Between CAP & Time Delay

The results show a multi-parameter correlation between CAP and Time Delay



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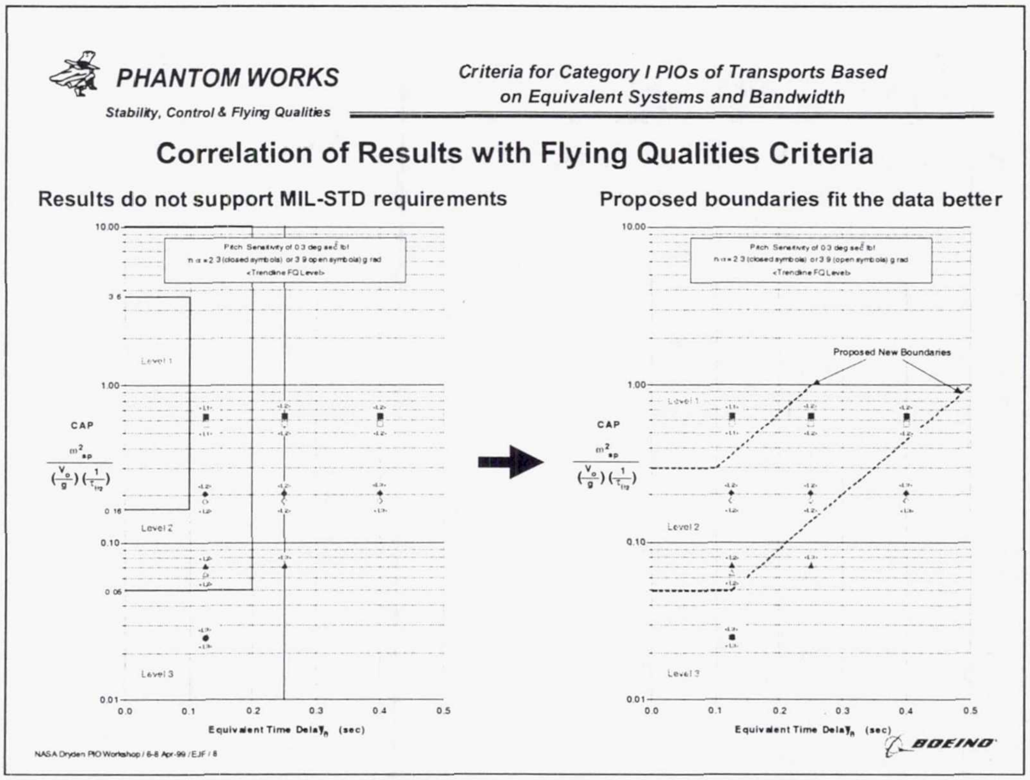
With the time delay configurations added CAP is plotted against Time Delay. Note that the two values of n/α yield slightly different values of CAP, except for the lowest value of CAP (represented by the circle) which both share the same value.

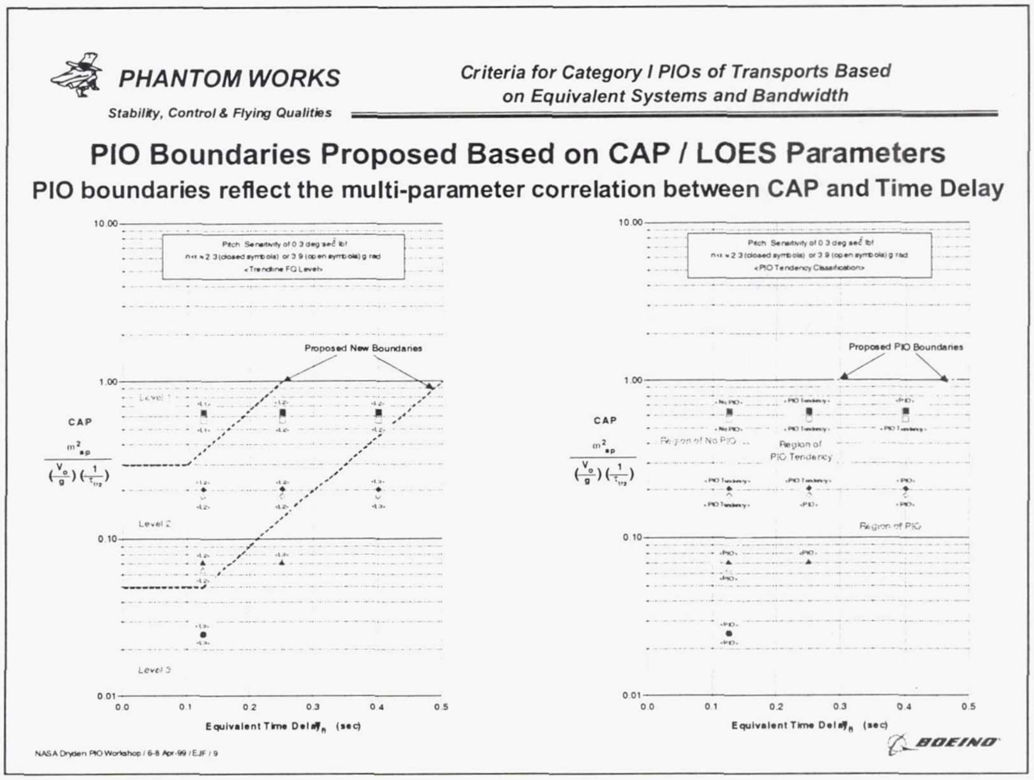
It is clear from this plot that there is a multi-parameter link between CAP and Time Delay in the pilots' perception of flying qualities.



When the MIL-STD 1797 flying qualities level limit boundaries are added to the plot of CAP versus time delay (left hand plot) it is clear that these requirements neither match the data nor allow for the observed multi-parameter correlation between CAP and time delay.

New flying qualities boundaries have been developed and are proposed (right hand plot). These boundaries reflect the multi-parameter correlation between CAP and time delay that were identified from pilot ratings and comments. These trends have also been observed the results of other ground-based simulation experiments.

Note: For clarity only the "Trendline Flying Qualities Level" is presented on all charts from here.



Analysis of the PIO ratings and pilot comments from the experiments led to the awarding of a "PIO Tendency Classification" to each configuration. This was achieved in the same way as the earlier "Trendline Flying Qualities Level". Each configuration was awarded a classification of "No PIO", "PIO Tendency" or "PIO".

Boundaries delineating the regions of these classifications reflect the same multi-parameter correlation between CAP and time delay as was observed in the flying qualities analysis. The limit of "No PIO" boundary appears to be slightly more relaxed than the Level 1 limit boundary. This is based upon the configurations for a CAP of 0.6 and time delay of 250 msec. These configurations exhibited only marginal PIO tendency, but sufficient to exclude them from classification of "No PIO". Hence the boundary was drawn close to these configurations.

However, the "PIO" limit boundary appears more stringent than the Level 2 limit boundary.

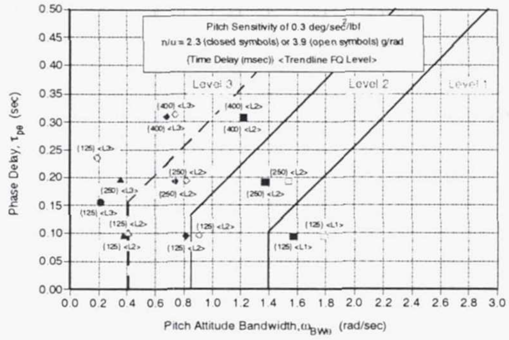
PHANTOM WORKS

Stability, Control & Flying Qualities

Criteria for Category I PIOs of Transports Based on Equivalent Systems and Bandwidth

Cooper-Harper Ratings Support The Bandwidth Theory

Level 2 / 3 boundaries could be relaxed significantly



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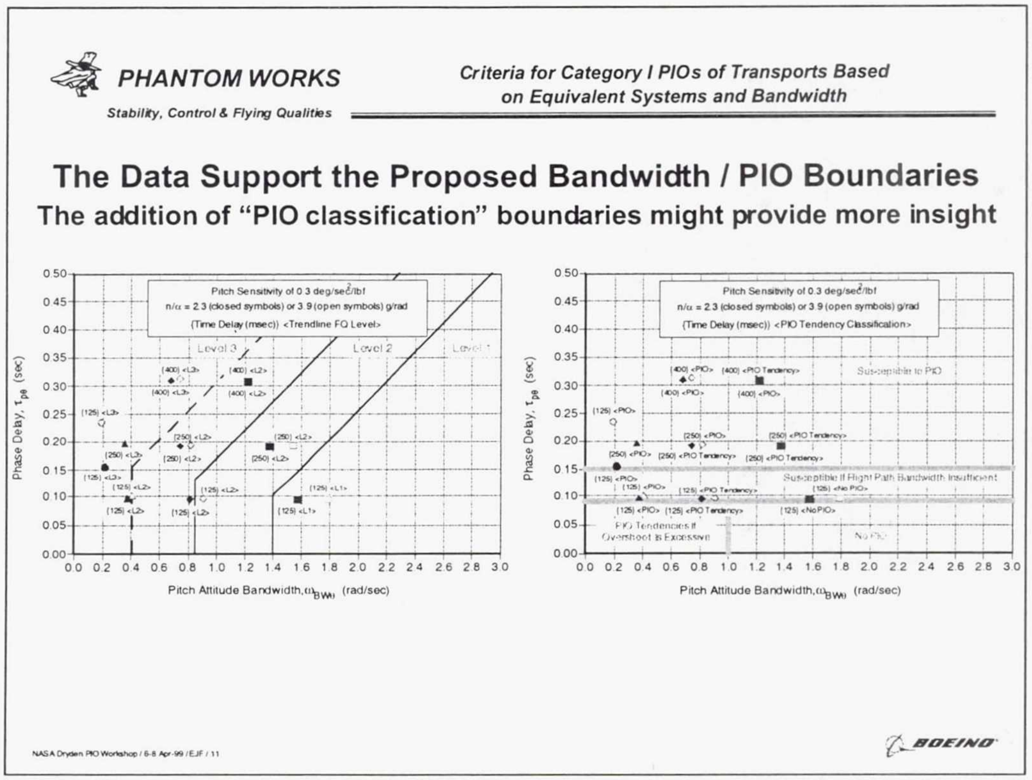
When the results of the flying qualities experiment are plotted on the Bandwidth Criterion, it is clear they support the theory of the criterion. However, they also support the significant relaxation of the Level 2/3 boundary.



When the PIO tendency classifications are plotted on the Bandwidth requirement they support the boundaries delineating the different PIO susceptibility regions. This may not be immediately obvious, but the following discussion will show this.

The two configurations that were classified "No PIO" fall just above the lower limit of the "Susceptible if Flight Path Bandwidth Insufficient" zone. For these configurations the flight path bandwidth was sufficient, and so they correlate with the criterion.

The configurations with lower bandwidth (the diamonds and triangles) but nominal 125 msec of time delay all had flight path bandwidths below the Level 1 limit, and hence are predicted susceptible to PIO. Note that the pitch sensitivity of the configurations represented by the triangles may have been high for their pitch dynamics, possibly the cause of the increased PIO susceptibility of these configurations.

All configurations with τ_P greater than 0.15 sec are predicted "Susceptible to PIO", and these tendencies were observed during the evaluations.

However, the criterion does not account for degrees of PIO susceptibility, as does the proposed criterion based on CAP parameters. This could be addressed by the inclusion of a diagonal line in the "Susceptible to PIO" region, approximately equidistant from the existing and proposed upper Level 2 limit on the flying qualities requirement (the plot on the left).

Conclusions

- Level 1 / 2 CAP boundary could be raised to 0.3
- There is a multi-parameter correlation between CAP and time delay
- This same correlation is reflected in PIO tendencies
- PIO boundaries were proposed based upon LOES parameters
- Level 2 / 3 pitch Bandwidth boundary could be relaxed
- The data supports the proposed Bandwidth / PIO criterion

Video of TIFS Landing

- Ground View
- Pilot View
- Configuration:
  - Angle-of-attack response-type
  - n/α = 3.9 g/rad
  - ω'_{sp} = 0.3 rad/sec
  - T_θ = 0.125 sec

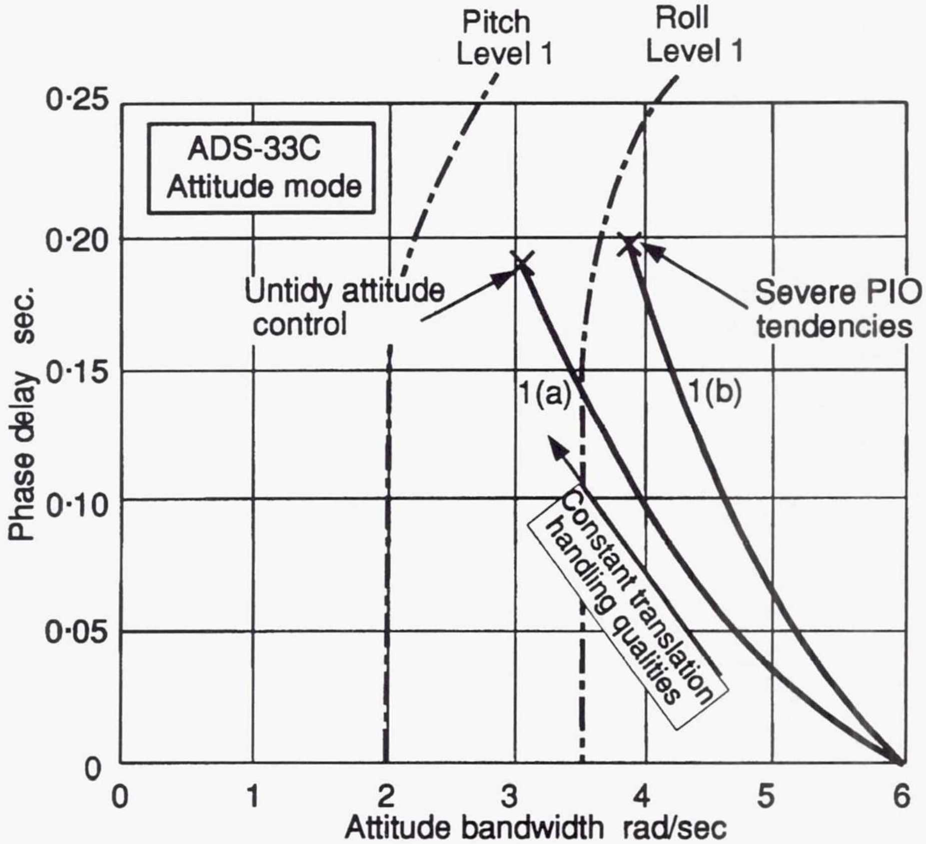
Designing to Prevent PIO

John C. Gibson
Consultant,
British Aerospace

Safety-related PIO

is like the Sword of Damocles, that may:

- break the hair and fall on you if you ignore it,
- but it can also act as a constant reminder if you act to chain it safely to the ceiling.
- Which one it is depends on you, the designer



1(a) has critical damping and low PIO gain, with translation control qualities that remain constant as bandwidth reduces and phase delay increases, while the attitude control becomes untidy.

1(b) has Level 1 damping (0·5), phase delay and bandwidth to ADS-33C, but degrades to dangerous PIO due to high PIO gain and motion coupling as phase delay increases.

Figure 1 Generic ASTOVL research:
Lateral translation handling in roll attitude mode

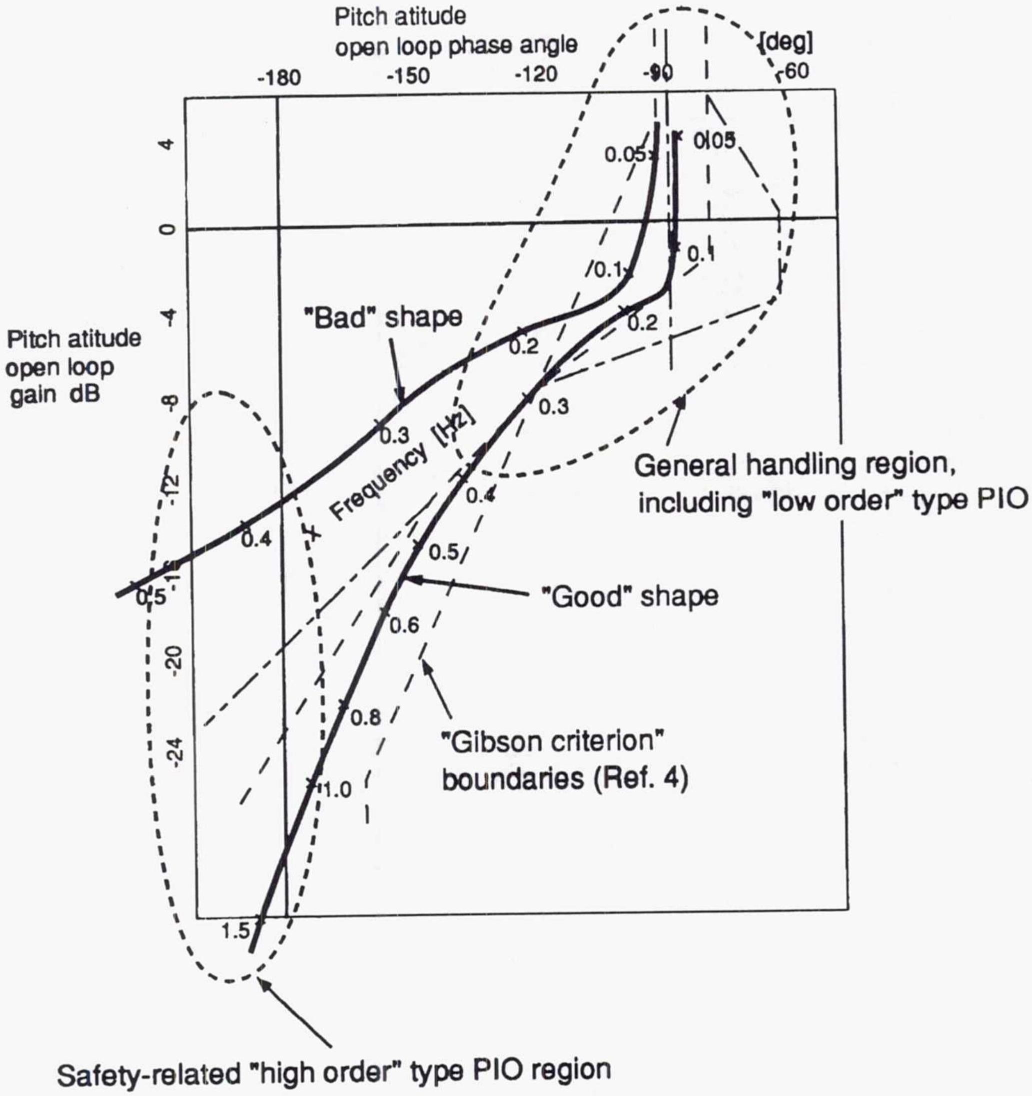
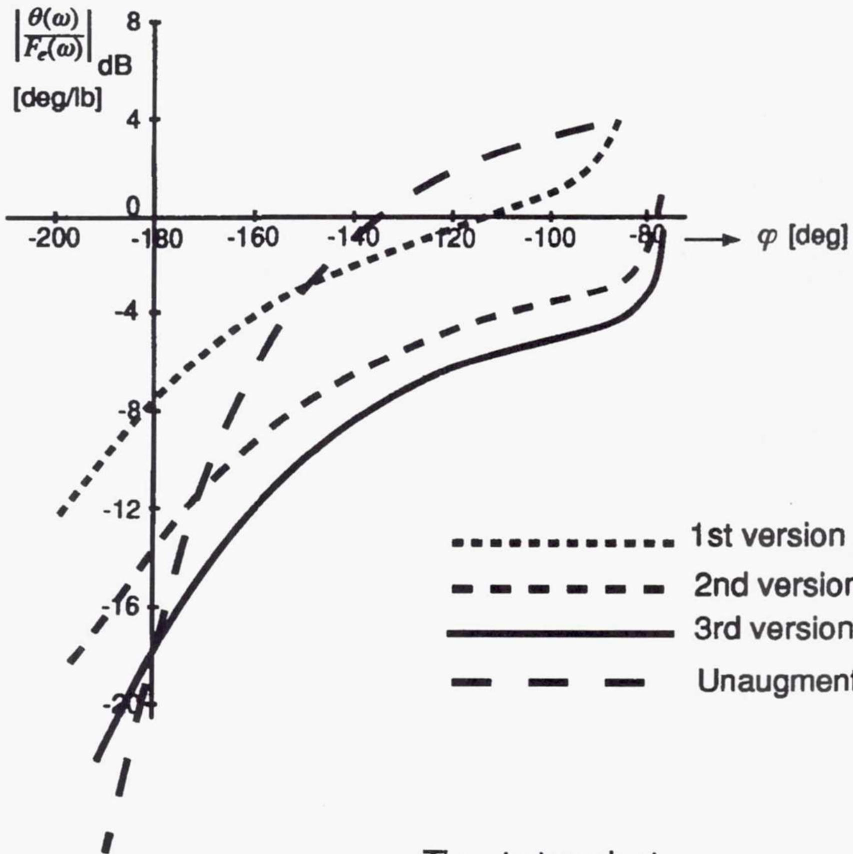


Figure 2 Frequency response qualities illustrated by non-parametric shape



Time to transient acceleration peak

PIO frequency

Bandwidth

Version	$\omega_{(-120)}$ Hz	$\omega_{(-180)}$ Hz	$t_{\ddot{q}}$ sec	Pre-filter characteristics
1st	0·245	0·43	0·35	(1 + 0·157s)/(1 + 0·47s)
2nd	0·245	0·455	0·3	(1 + 0·133s)/(1 + 0·454s)(1 + 0·0625s)
3rd	0·26	0·535	0·22	(1·0)
Unaug.	0·145	0·44	0·12	(1·0)

Figure 3 Tornado pitch attitude responses at landing: solution to PIO by development of the command pre-filter.

The unaugmented and third version pre-filtered dynamics are PIO-free.

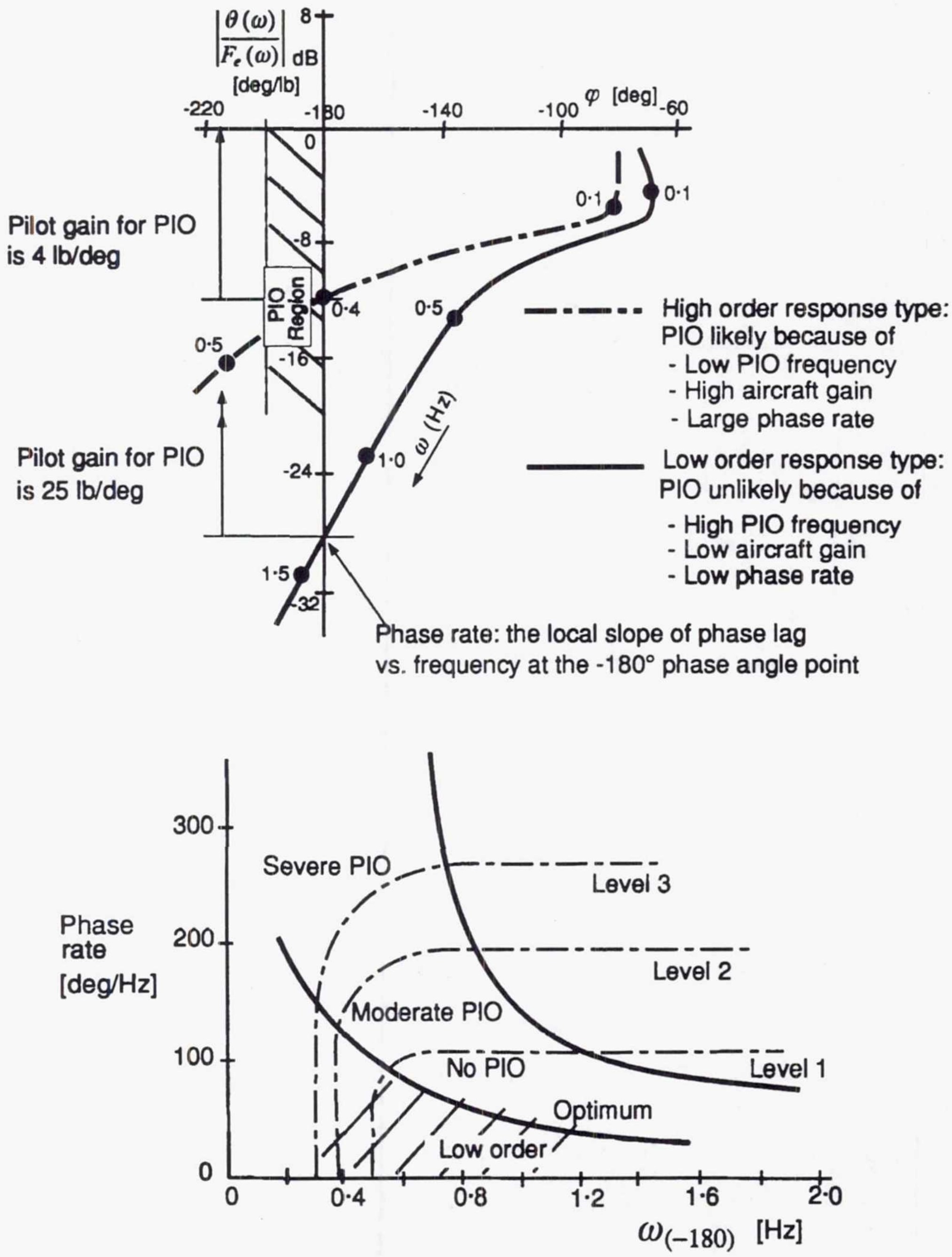
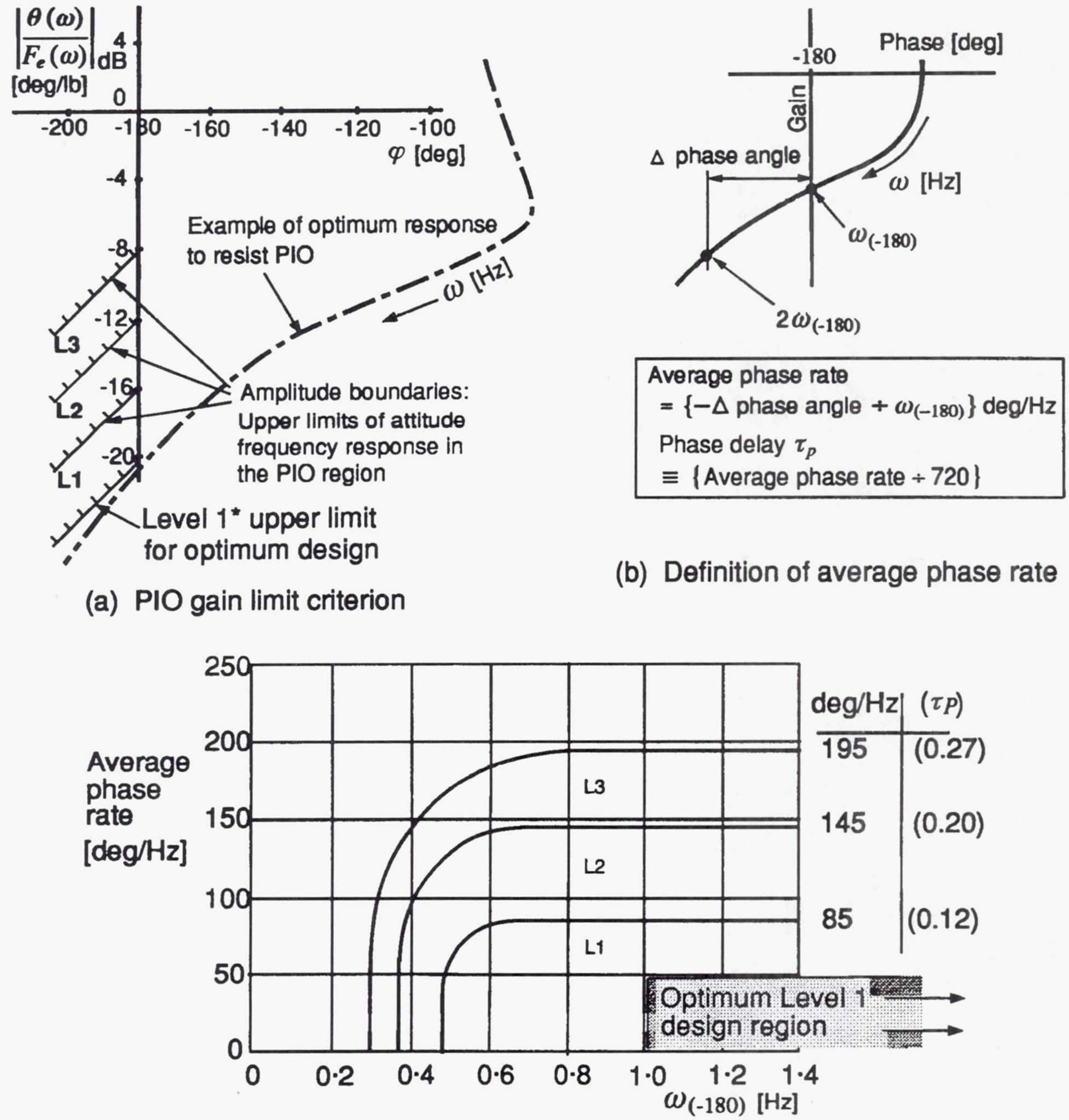


Figure 4 PIO tendency indicators and design guidelines derived from LAHOS etc.



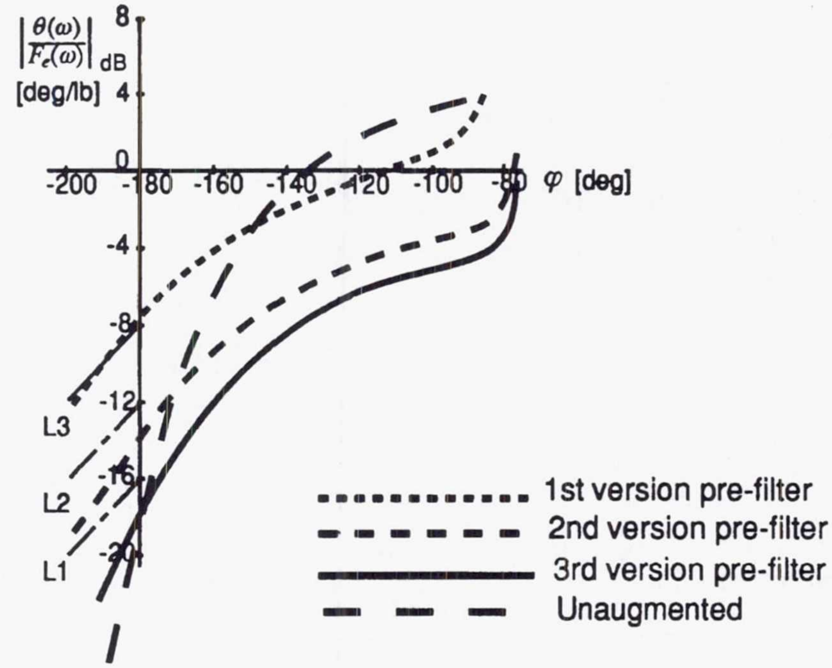
(a) PIO gain limit criterion

(b) Definition of average phase rate

(c) Phase rate and frequency criterion

Figure 5 Final development of PIO criteria (1993)

1. Level 1, 2 and 3 boundaries represent historical data.
2. Undesirable residual high order characteristics exist within the Level 1 region near the low frequency boundary limit.
3. Best design practice for freedom from linear high order PIO requires the more stringent Level 1* gain, phase rate and frequency limits.



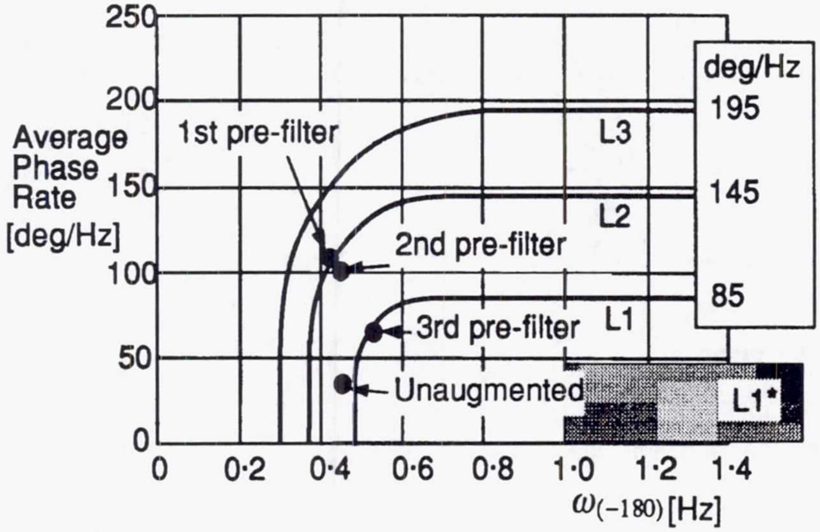


Figure 6 Tornado viewed in retrospect against author's later criteria

Note: although the 3rd pre-filter just satisfies the criterion and has prevented PIO for 20 years, it would not have been accepted as a new design by subsequent criteria.

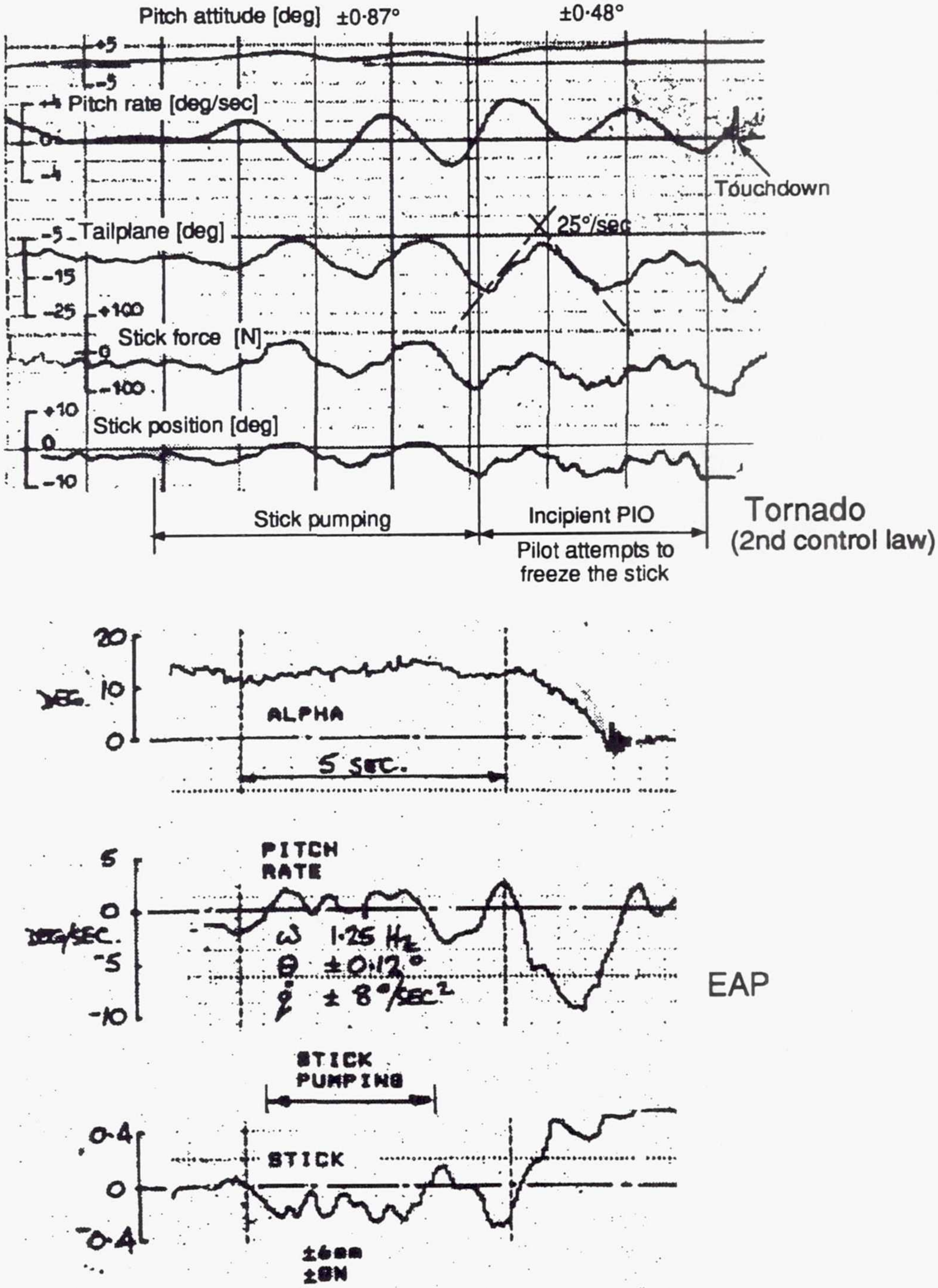


Figure 7 Effect of design process on stick pumping and associated PIO resistance

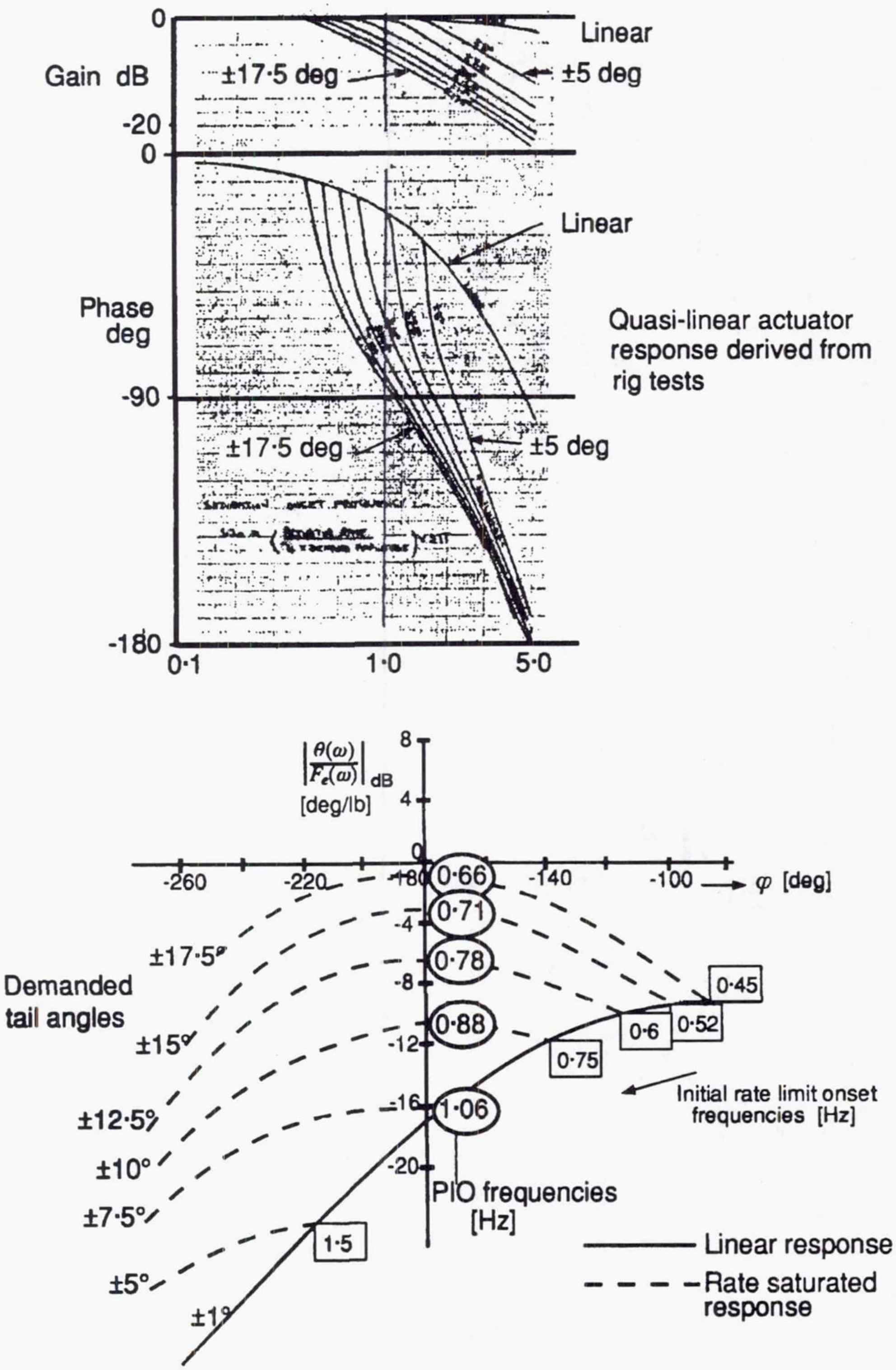
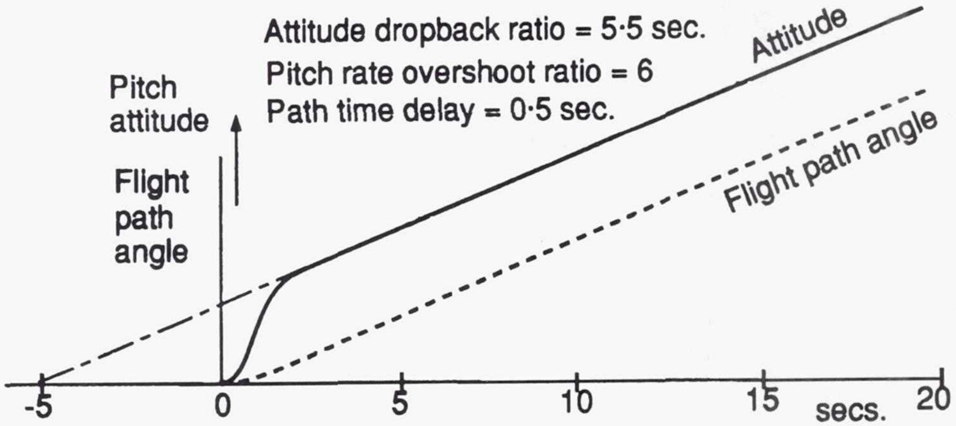
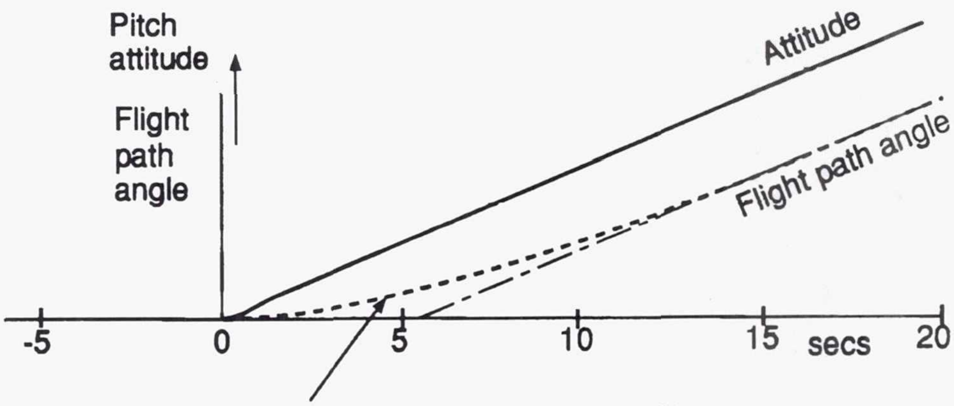


Figure 8 Significant non-linear actuation effects on PIO characteristics



Nominal YF-12 time response
at Mach 3 cruise



Short period roughly approximated by:

$\omega_{sp} = 0{\cdot}5$ rad/sec

$\zeta_{sp} = 1{\cdot}3$

Path delay = 5·2 sec.

$$\text{YF-12 with pre-filter} = \frac{1 + 0{\cdot}8s}{1 + 5{\cdot}5s}$$

Figure 9 Sluggish PIO-prone flight path response caused by inappropriate pitch attitude optimisation

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Session II

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Replicating HAVE PIO on the NASA Ames VMS

Jeffery Schroeder
NASA Ames Research Center

Outline

- Introduction
- Experiment description
- Results
- Known simulation/flight disparities
- Conclusions

Introduction

- Ground-based simulation has not had much success in predicting PIOs
- National Research Council recommended high priority be given to validating simulation
- Previous flight-test study (HAVE PIO) offers a set of pitch data for validation

Introduction

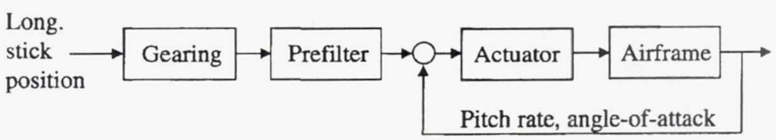
- Wright Laboratory replicated in-flight study using two fixed-base simulators
- Purpose of this study:
  - Determine if the amount of platform motion affects ability to replicate in-flight results

Experiment description

- Math model
- Task
- Visual system
- Motion configurations
- Safety pilot and miscellany

Experiment description

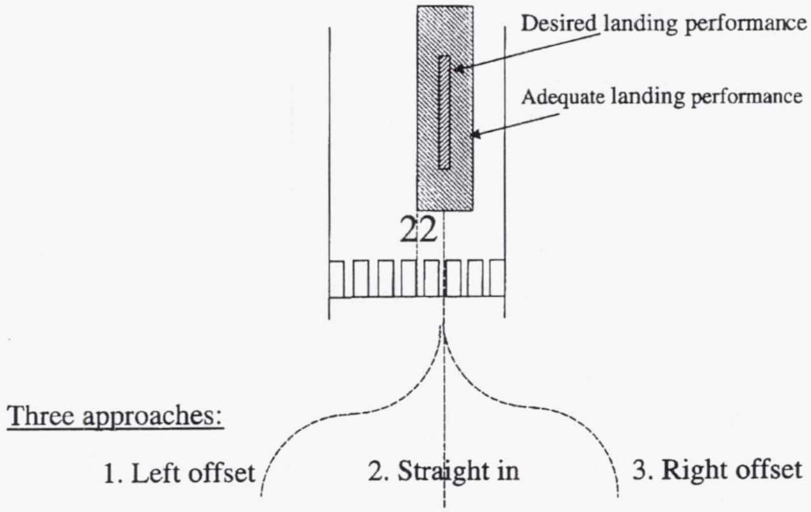
Math model



- NT-33 airframe simulated w/ stability derivs.
- 18 sets of pitch dynamics

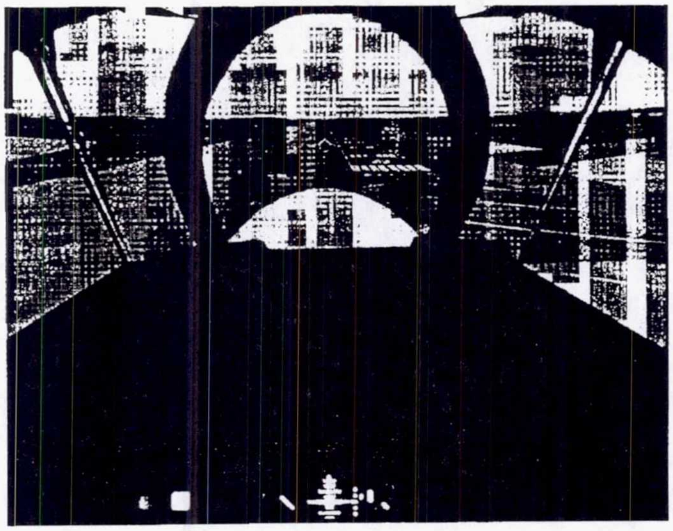
Experiment description

Task



Experiment description

Image system

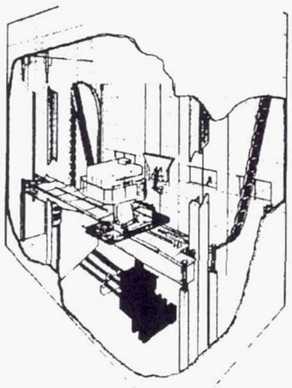


Experiment description

Motion configurations

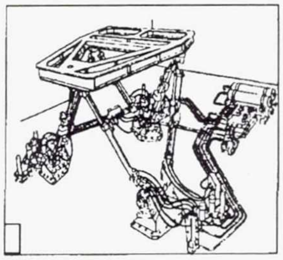
• Vertical Motion Simulator used to simulate all motion configurations

Vertical Motion Simulator displacements



Classical motion drive logic

Typical hexapod displacements (5 ft stroke)



Coordinated adaptive motion drive logic

No motion

Experiment description

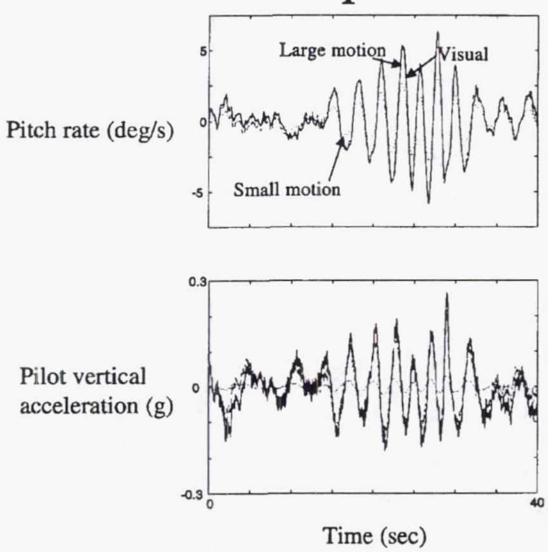
Safety pilot and miscellany

- Automated safety pilot assumed command if situation deemed hazardous
  – Nosegear sink rate > 8 ft/sec when below 12 ft
- Stick ergonomics and force-feel closely matched aircraft
- Five test pilots (3 NASA, 1 FAA, 1 Boeing) flew all combinations of motion and aircraft configurations (randomized)

Results

- Example PIO
- Handling qualities ratings
- Pilot confidence ratings
- PIO ratings
- Touchdown velocities

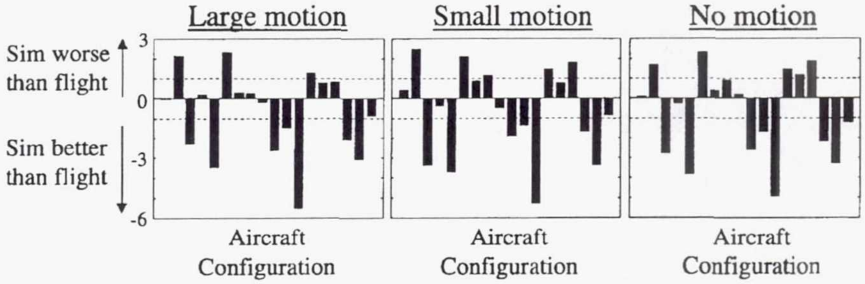
Example PIO



Large motion satisfactorily simulates pilot normal acceleration

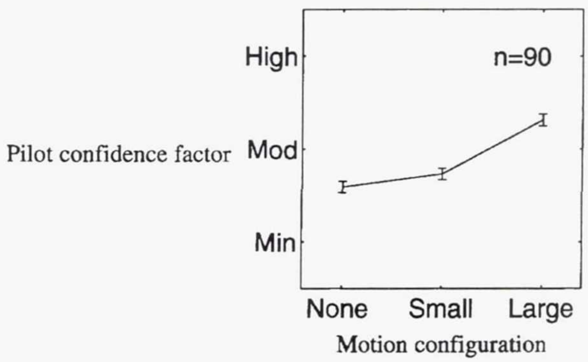
Handling qualities ratings

Simulation versus flight



Large motion had more ratings within +/- 1 of flight rating

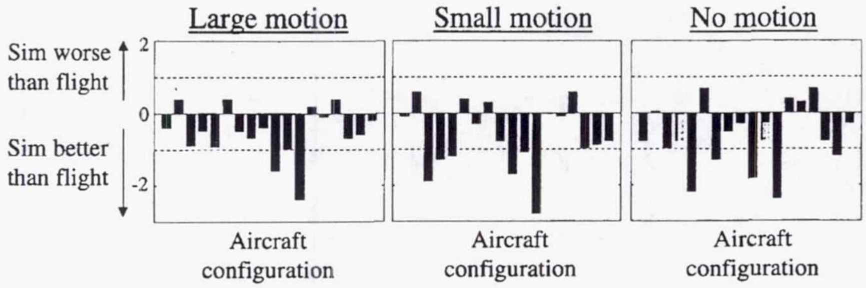
Pilot confidence factors



More confidence in rating with more motion

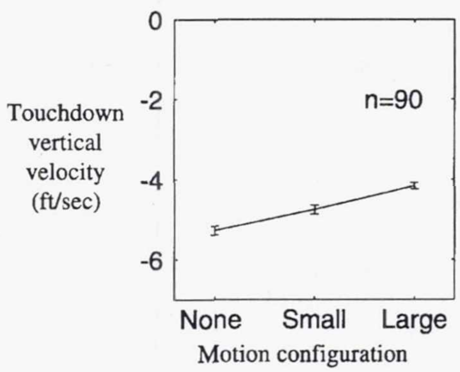
PIO ratings

Simulation versus flight



Large motion had more ratings within +/- 1 of flight rating

Touchdown velocities



Large motion allowed better touchdown sink rate control

Known simulation/flight disparities

Likely top 5

- Stress-induced environment
- Visual content
- Different evaluation pilots
- Simple automatic versus real safety pilot
- Field-of-view

Conclusions

- With large motion:
  - handling qualities ratings correlated best with flight
  - higher pilot confidence ratings achieved
  - PIO ratings correlated best with flight
  - lower touchdown velocities resulted
- Only large motion provided high fidelity vertical motion cues
- List of disparities between simulation and flight suggests future work

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Replicating HAVE PIO on Air Force Simulators

Ba T. Nguyen, Air Force Research Laboratory

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BOEING

PREDICTION OF LONGITUDINAL PILOT-INDUCED OSCILLATIONS USING A LOW ORDER EQUIVALENT SYSTEM APPROACH.

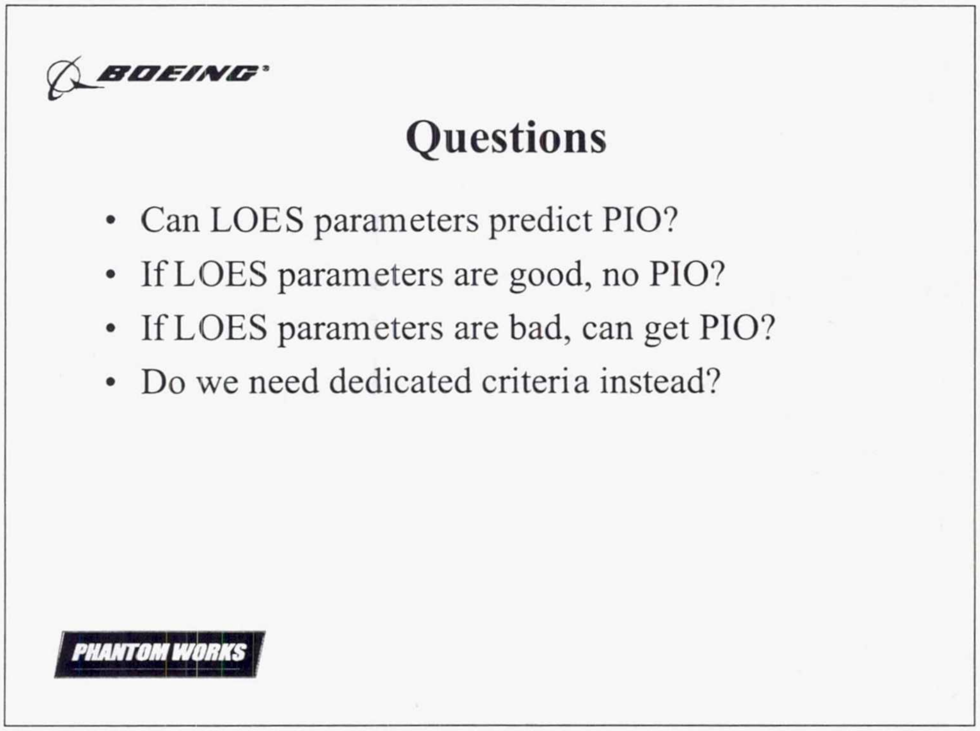
John Hodgkinson and Paul T. Glessner
The Boeing Company, Phantom Works, Advanced Transports and Tankers
Long Beach, California

David G. Mitchell
Hoh Aeronautics, Inc.
Lomita, California

PHANTOM WORKS

Abstract

A study was undertaken to determine whether longitudinal low order equivalent system parameters could be used to predict pilot-induced oscillations (PIOs), also known as adverse aircraft-pilot coupling (APC), for high order aircraft pitch dynamics. The study was confined to linear dynamic models, and therefore to Category I PIOs. Variable stability aircraft results were used from three data sources simulating fighter up-and-away maneuvering, fighter touchdown, and large transport touchdown. The equivalent system parameters (alone or in combination) from the current US Military Standard correlated well with incipient or developed PIOs. Excessive equivalent time delay was by far the most frequent cause of PIO, and a few cases were explained by low short period damping, low short period frequency and low maneuvering stick force gradient. A high-gain asymptote parameter offered some additional insight into pilot loop closures with large delays.



PIO Prediction using equivalent system criteria

In addition, we would ideally like to answer the questions:

.If the equivalent system parameters were good compared with the equivalent system criteria, did the pilots find no PIO tendency?

.When the pilots experienced a PIO, did one or more equivalent system parameters predict a PIO?

.Also, if it is difficult to obtain a match for a configuration, can this also suggest PIO susceptibility?

We were able to answer all these questions to varying degrees.

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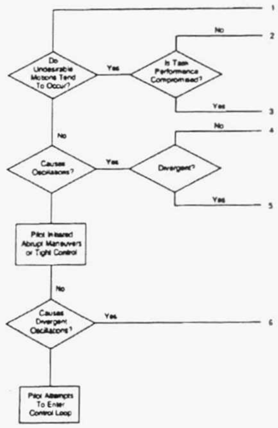
PIO Rating (PIOR) Scale

DESCRIPTION	RATING
No tendency for pilot to induce undesirable oscillations.	1
Undesirable motions tend to occur when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated by pilot technique.	2
Undesirable motions easily induced when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated but only at sacrifice to task performance or through considerable pilot attention and effort.	3
Oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must reduce gain or abandon task to recover.	4
Divergent oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must open loop by releasing or freezing the stick.	5
Disturbance of normal pilot control may cause divergent oscillation. Pilot must open control loop by releasing or freezing the stick.	6



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PIO ratings awarded by the pilots aided this study.

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Three data sources

- Neal-Smith
- LAHOS
- GLT

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Correlation database

Three data sources were utilized. All were from in-flight simulations. Reference 6, Neal and Smith's study, examined up-and-away dynamics of fighter aircraft. Reference 10, the so-called LAHOS study, considered fighter dynamics in the landing approach. The Generic Large Transport (GLT) study of Reference 11 was for landing and touchdown dynamics of very large (approximately 1-million-pound) transports. In these data bases, the pilot ratings and comments were used to separate the configurations into those without PIO tendencies, those with incipient PIOs, and those with actual PIOs.

(for Reference definition, see the last two charts, or AIAA Paper 99-4008,'Prediction of Longitudinal Pilot-Induced Oscillations using a Low Order Equivalent System Approach', John Hodgkinson and Paul T. Glessner, The Boeing Company, Phantom Works, Advanced Transports and Tankers, Long Beach, California, and David G. Mitchell, Hoh Aeronautics, Inc., Lomita, California).

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LOES form for pitch rate control

$$K_\theta \frac{(s+L_\alpha)e^{-\tau s}}{[s^2+2\varsigma_{sp}\omega_{n_{sp}}s+\omega_{n_{sp}}{}^2]}$$

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The accepted method for determining the longitudinal short period equivalent system is to match the pitch and normal load factor dynamics (at the instantaneous center of rotation) simultaneously. Similar parameters are obtained by matching the pitch rate dynamics alone with the transfer function shown in the chart, with fixed at the value for the aircraft. The transfer function numerator includes a gain; the dimensional lift curve slope of the aircraft; and a time delay. The denominator includes the short period damping and undamped natural frequency. For these pitch dynamics, good and bad values of the parameters are all defined directly or in combination by the current specification, Reference 1.

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Candidate equivalent parameters

- Time delay
- Short period frequency
- Dimensional lift curve slope
- Short period damping
- Stick force per g
- High Gain Asymptote Parameter (HGAP)

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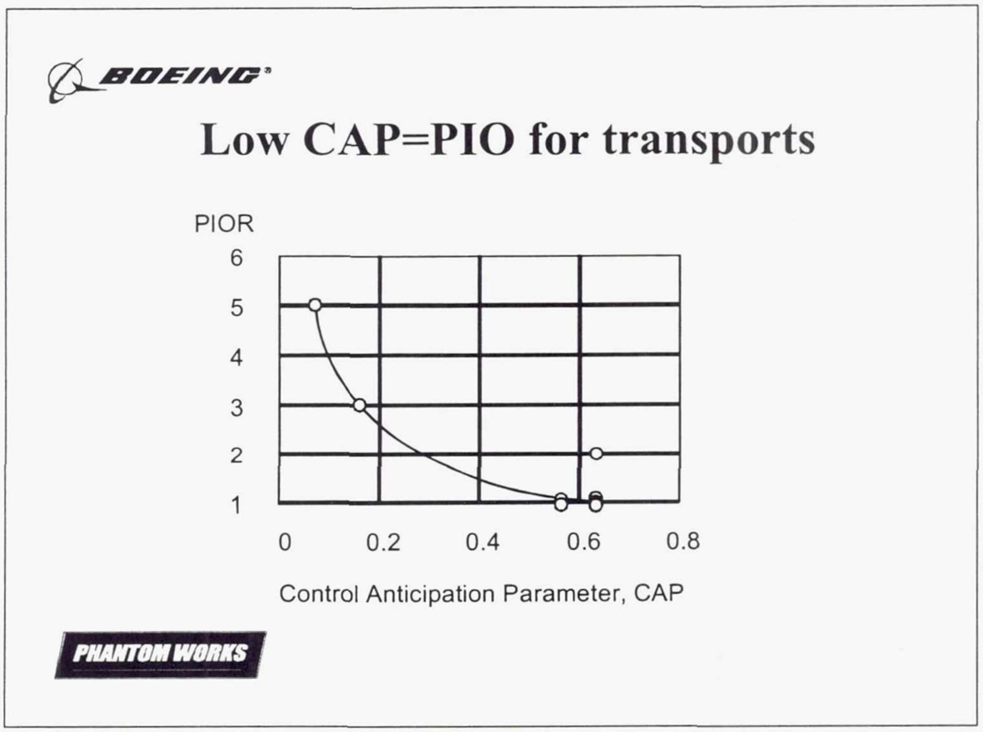
Early equivalent systems researchers quickly found that the high frequency phase lag, or rolloff, of some high order responses was greater than that which the low order forms could accommodate. Therefore a time delay term was added to the low order forms. The delay itself eventually became a criterion for handling qualities specification (see Reference 1). The High Gain Asymptote Parameter suggests that a tight pitch loop closure by the pilot could cause unstable pitch oscillations. (Ashkenas et al Reference 9). Low values of short period frequency produce sluggish dynamics and a low Control Anticipation Parameter (CAP). Low values of short period damping produce open-loop oscillations. Combined low stick force per g and low damping produces dynamic sensitivity. High steady-state sensitivity of response to stick command can produce PIO, as can combinations of rapid short period frequency with significant pitch delay. Too-abrupt (too-high) short period frequency can cause PIO. Fundamentally conventional aircraft with high mismatch, i.e., whose dynamics cannot be matched with a conventional transfer function, are unlikely to have good handling qualities. However, first, configurations with high mismatches tend to have extreme and unsatisfactory equivalent parameters, and second, if an inappropriate equivalent system form is used for an unconventional response-type (like an attitude command system), then the resulting high mismatch is just a consequence of misuse of the method.

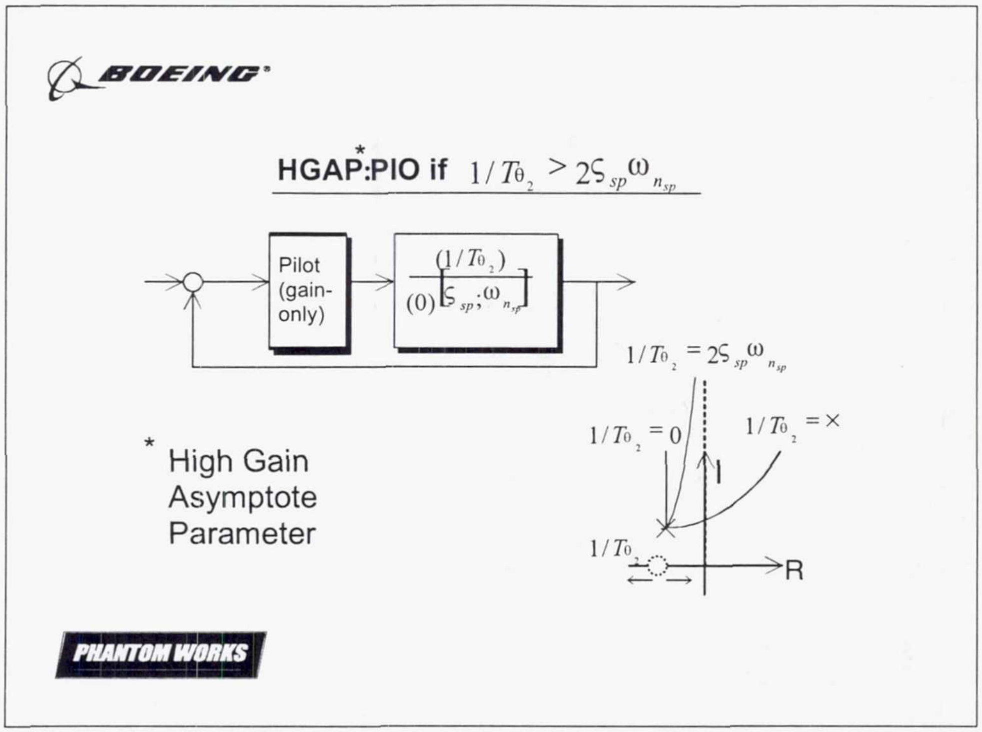


Control Anticipation parameter (CAP)

Sluggish short period frequency would be expected to correlate with PIO tendency. When all the CAP data from the experiments were plotted without regard to other parameters, a tendency to support this expectation emerged, as seen in this Table:

CAP Data Source	Apparent tendency for PIO if CAP is less than:
Neal-Smith	0.2
LAHOS	0.18
GLT	0.18

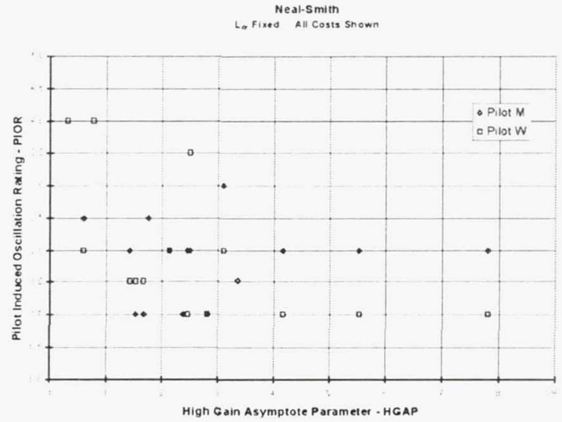
However, further examination of the data shows considerable influence of other parameters. For example, the low-CAP configurations in the Neal-Smith data generally had high equivalent delays. This is a natural consequence of how Neal and Smith added lags to fundamentally conventional dynamics to create their sluggish configurations. Lags not only add equivalent time delay at higher frequencies, but also depress the short period equivalent frequency in the mid-frequency range. When the effects of other parameters are separated from the data, we were left with only the GLT data giving a significant indication of PIO tendency due to low CAP values, as seen in the chart.



High Gain Asymptote Parameter (HGAP)

The early equivalent systems analysis of the Neal-Smith data did show a high correlation of the high gain asymptote parameter with poor ratings (Reference 2) but equivalent time delay, i.e., high frequency phase lag, dominated the PIO-prone cases. Low values of HGAP would be expected to correlate with PIO tendency. In the original theory, it was pointed out that an adverse constellation of roots for the pitch rate transfer function was unlikely for conventional aircraft, and that additional phase lags (i.e., equivalent delays) would be needed to cause PIO. Use of the 'free L-alpha' data promised to be a way of incorporating some lag into the basic root array by shifting the lead due to to artificially high frequencies. That technique also created negative values of HGAP, correlating with PIO. However, since freeing in the matching process is quite artificial, and the resulting delay values are not comparable with most studies, we do not present these data here.

Low HGAP=PIO for Neal-Smith



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Plotting the HGAP (with fixed L-alpha) against PIO rating for the Neal-Smith data does show a general trend of worsening rating with smaller HGAP but for the other data bases the data did not show a clear correlation.

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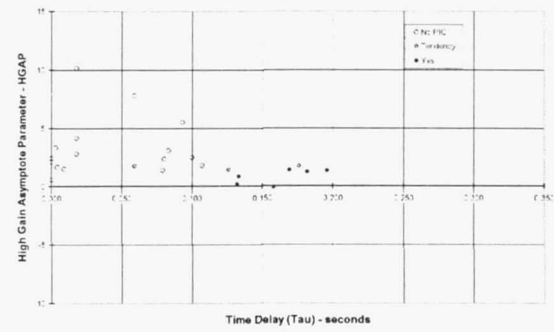
HGAP and equivalent delay... can HGAP help bad delays?



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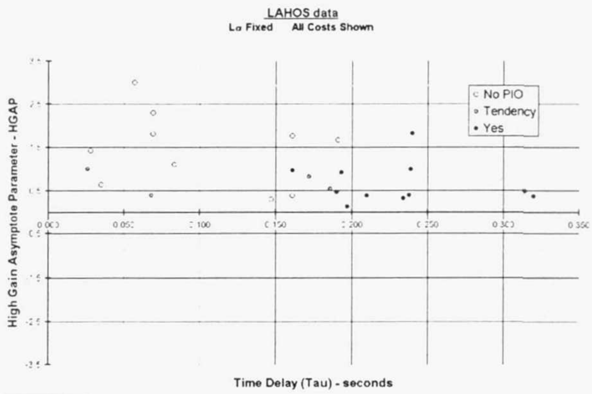
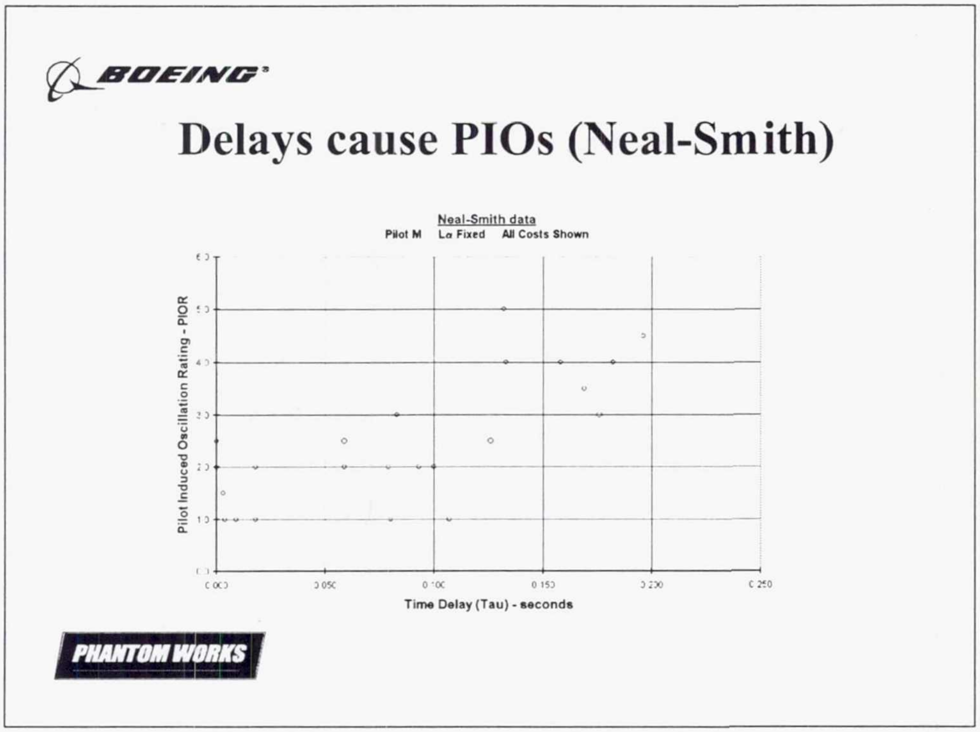
Plotting HGAP versus time delay for fixed shows that Neal and Smith's configurations with high time delay in general also had low (theoretically bad) values of HGAP. There is a weak suggestion in the right eight data points in this Figure that the PIO tendency of configurations with high delays might be ameliorated by increasing HGAP.

Can HGAP help bad delays in LAHOS too?



The LAHOS data also contain this weak suggestion in the region where time delay is between 0.15 and 0.2. The data are not conclusive enough to suggest an actual requirement involving HGAP. Further systematic data involving HGAP variations are needed.



Equivalent time delay

Correlation of this parameter with PIO susceptibility has previously been noted by researchers including Neal and Smith (Reference 6) and Hodgkinson et al (Reference 2). Our re-examination of the Neal-Smith data did confirm the progressive increase in PIO susceptibility with increased delay. The other data bases allowed only an indication of when tendencies towards PIO could be expected. The following Table summarizes the delay values:

Equivalent Delay

Data Source	Tendency for PIO if delay exceeds:	Definite PIO if delay exceeds:
Neal-Smith	0.12	0.18
LAHOS	0.16	-
GLT	0.25	-

Conclusions

- LOES parameters predict PIOs reliably
- Data bases mostly delay-dominated
- Low CAP for transports causes PIO
- Low Fs/n caused one PIO in Neal-Smith
- HGAP- intriguing interaction with delay?

Conclusions

Short-period equivalent system parameters offer many clues to longitudinal PIO susceptibility. In the data examined, excessive equivalent time delay was the chief culprit. For example, in the Neal-Smith data, every configuration with a delay exceeding 0.116 seconds had a tendency to PIO. Other parameters correlating with PIO tendency included low equivalent damping ratio and low stick force per 'g' for the fighter configurations, and low equivalent frequency for the transport.

These results suggest that meeting the military equivalent system requirements would help to avoid PIOs.

The linear parameters used in most of the alternative PIO criteria and in the equivalent system parameters in this paper evidently address only a part of the PIO problem. Future work needs to address the roles of non-linearities and of structural dynamics.

Finally, the High Gain Asymptote Parameter (HGAP), based on linear equivalent system parameters, shows some correlation with PIOs, and there is some evidence that configurations with marginal equivalent delays may benefit from larger values of HGAP.

The work in this paper was supported by Hoh Aeronautics, Inc. under their Air Force Research Laboratory contract on PIOs, and by the Boeing Company.

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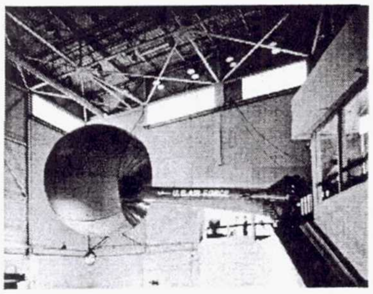
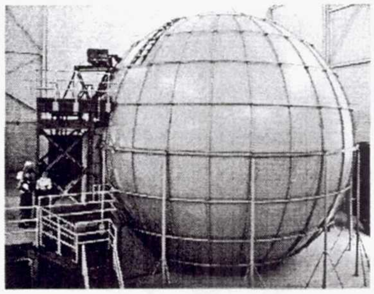

Recommendations to Improve Future PIO Simulations

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Why Important?

- Manned simulation is being relied upon ever more
- Virtual Combat Simulations
  - Used to design and set aircraft system requirements
  - Determine force mixes
- Simulation during aircraft development
  - Assess vehicle and train pilots before flight
  - Considered alternative to flight test!
- Classic use of simulation (control design tool)
  - Assess aircraft handling qualities
  - Iterate flight control design with pilot-in-loop
- Modeling and Simulation is perceived as a means to reduce costs!!

PIO Simulation Dilemma

- Historically PIOs not readily uncovered during simulation experiments
- Often found in flight test and then repeated in simulator
- Several types of PIO initiated for different reasons
  - Category I: PIOs by linear phenomena, phase loss,
    - Empirical Criteria Exist
    - Correlates to bad handling qualities
  - Category II: PIOs caused by non-linear phenomena, rate limiting position limiting, gradient breaks
    - Criteria under development
  - Category III: PIOs caused by mode switching
- PIOs generally occur when pilot is <u>high gain</u> and working hard at a <u>precision</u> task.

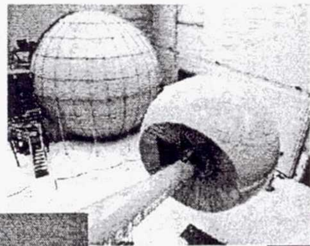
PIO Simulation Background

- AFRL/VA PIO Simulation Objectives:
  - Attempt to determine reasons why ground based simulations do not readily uncover PIOs during development
  - Use a known flight-test *truth* model to conduct comparisons to ground based implementation
  - Attempt to develop a methodology to uncover potential PIOs in aircraft more reliably via simulation
- Two truth models:
  - HAVE PIO: USAFTPS-TR-85B-S4
  - HAVE LIMITS: AFFTC-TR-97-12
- Want simulations to correlate better with flight test
  - What do we mean by correlate?

Simulation Facilities Used

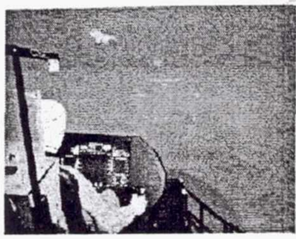
Mission Simulator 1 (MS-1)

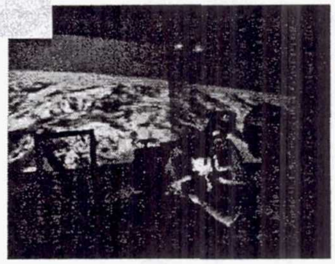
- Fixed Base, 40Ft Dome
- McFadden Feel System
- Wrap around visuals
- HUD projected



Large Amplitude Multi-Mode Aerospace Research Simulator (LAMARS)

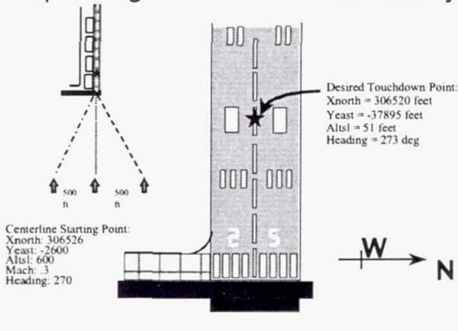
- 5-DOF Simulator
- McFadden Feel System
- 20ft Diameter Sphere on end of 30 ft beam
- Wrap around visuals





HAVE PIO Phase 1Tests

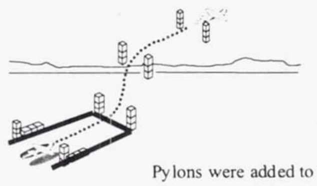
- HAVE PIO Phase 1 Tests
  - Eighteen different configurations
  - Linear sources of PIO
  - LAMARS (w/wo motion) and MS-1
  - Power approach task only
  - Priority on replicating NT-33 tests as accurately as possible



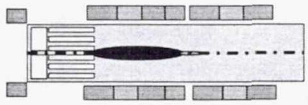
HAVE PIO Phase 2 Test

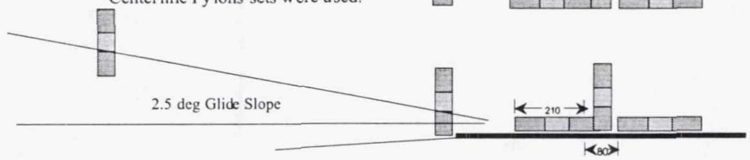
HAVE PIO Phase 2 Tests

- MS-1
- Power approach only
- Assessed simulation tweaks
  - Stick Gain
  - Time delay
  - Winds/Turb/Gusts
  - Pylons



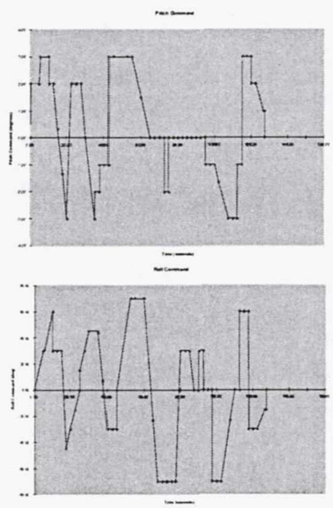
Pylons were added to the landing task to force pilots to fly a particular path and to hi-light the touchdown point. Left, Right, and Centerline Pylons sets were used.

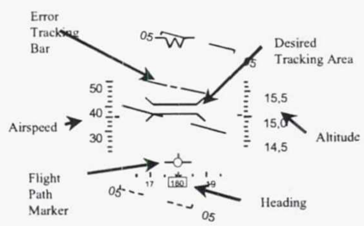




HAVE LIMITS Tests

- HAVE LIMITS Tests
  - LAMARS with motion (retune)
  - SOS and Calspan Discrete task
  - Attempt to correlate with NT-33 Test
  - Core of an expanded database
  - Changed HUD Symbology from NT-33





Results

- HAVE PIO
  - Able to generate Category I PIOs in simulation
  - Desired correlation between flight and simulator per configuration not achieved
  - Data trend: good was good, but bad was not as bad
- HAVE LIMITS
  - Initial tests uncovered problems with model replication between what occurred in-flight and what was integrated on simulator
  - Category II PIOs replicated in simulation
- *Wanted direct correlation with flight test for each configuration or predictable variation across Cooper-Harper and PIO Rating Scales*

Reason for Differences

- Fundamental difference between handling qualities evaluations and PIO experiment
  - Evaluating a configuration versus searching for defects
- Pilot variability even a larger factor in PIO experiments
  - Large variations not unusual
  - 3 Pilots do not a make a sufficient sample space
  - Pilot technique
- Briefing Techniques
  - This has an effect: Reviewing PIO charts, definitions
- Task Definitions
  - Already difficult to match reality
- It's a simulation!!!!!!!!

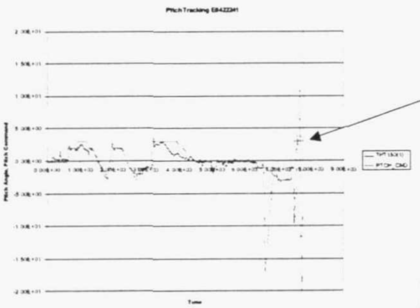
PIO Testing

- Hypothesis: Fundamentally different from standard handling qualities testing
- During HQ testing pilots are rating the configuration as is, not actively looking for deficiency
  - If we run into PIO great, if not, no PIO
  - This does not imply configuration is not PIO proof
- PIO requires an active search
- Test matrix and task development require much more attention and care
- Need real-time measure of pilot effectiveness during task to keep honest (RMS , Touchdown dispersions)

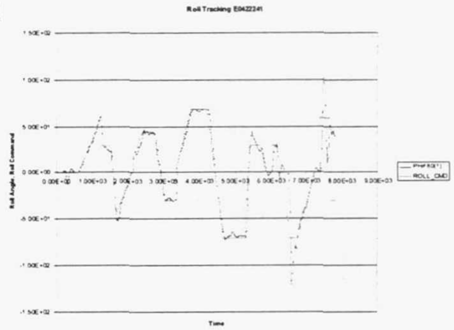
Task Generation

- PIO Testing requires closed loop high gain tasks that stress pilot/vehicle system
- Approach Task Too Open Loop
  - Suggest use of pylons, ILS needles
  - Measure pilot performance along path
  - If pilot doesn't land is that a CH 10???!!!
- Discrete Tracking Task
  - Works well in simulator
  - Pilots game system so variations must be used to avoid learning
  - Requires Tuning, we found pilots could trip into PIOs especially in one region!
- Remember: It's a simulation

Tracking Task



Gotcha Region



Pilot had rated this pitch configuration (2DUR30) in earlier runs as a CH-2 PIOR-1. During this run a rate limited roll was added to increase workload.

Pilots

- Natural variability puts pressure on other parts of PIO test
  - Need more than 3 pilots, but not just for statistics
  - High/Low Gain, Golden Arm, The guy who hates simulators
- Shouldn't fly more than an hour !
  - Fatigued pilots good for PIO generation but bad evaluators
  - Fresh pilots make good evaluators but poor PIO generators
  - When pilots refer more and more to previous runs, break!!!
- Need to keep aggressive by any means necessary
  - RMS feedback worked well, but when do we give to pilot?
- Need to reset pilots often
  - Good->Bad, follow really bad config with a good config

Pilot Briefing

- Critical to success of any test.
  - Not all Test Pilots have seen a PIO
- Define PIO
  - What is a bobble? What is an oscillation? Overshoot?
  - Does backing out of loop imply PIO and what to do?
- Define tolerable/intolerable workloads and define adequate and desired.
  - Some pilots definitely have a distinct definition of these.
- Pilot ratings in a simulator
  - Level 1 ratings reserved, psychological block
  - Some pilots won't even give a CH-10!!!!
  - Pilot can crash in a plane but not in a simulator

Simulation Motion

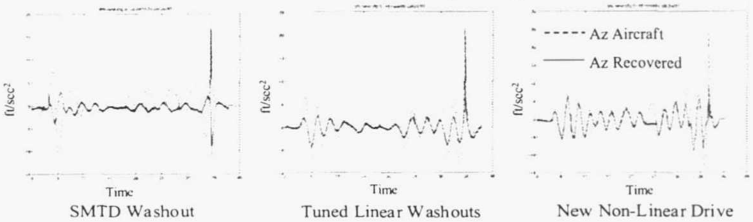
- Motion versus no-motion
  - Well tuned motion helps
  - Extra cueing to pilot, especially of AZ phasing
  - Give hint to pilot if something is not right
- Lack of motion puts pilot reliance on visual cueing
  - Hard to discern rates of descent
  - Visual detail limitations
  - During air-to-air tracking scenery isn't important anyway
- Hard to determine value due to interpilot/intrapilot variability
  - Can't really determine worth via Cooper Harper Ratings
  - Pilot comments have been extremely positive
- If good motion doesn't help does bad motion really hinder?

Motion Work

Objective: Maximize Acceleration Recovery

Use the most motion travel w/o hitting limits

Minimize False cues with proper phasing



Non-Linear: Uses Fuzzy Logic Approach

Uses Predetermined Braking and Return Profiles

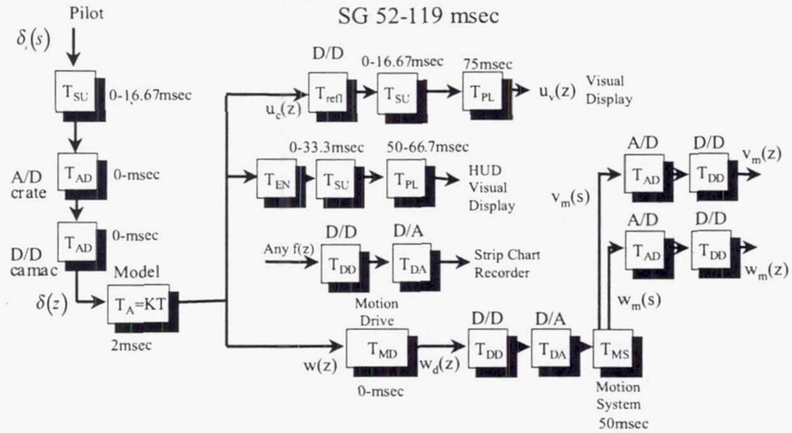
Uses Human Thresholds and Indifference Levels

Wrap Up

- Simulation ≠ Replication!!!!!
  - Attempting to replicate flight test results dubious effort
- PIO simulations require extra effort in other areas
  - *Not asking do you like this or not?*
  - Asking, did you find a problem
- The more pilots the better
- Test setup and pilot brief can do more to trash results than simulation artifacts
- Task design critical. Can only do so much to simulator
- Motion use recommended, but must be properly tuned to be of benefit

Analytical Time Delay Measurements

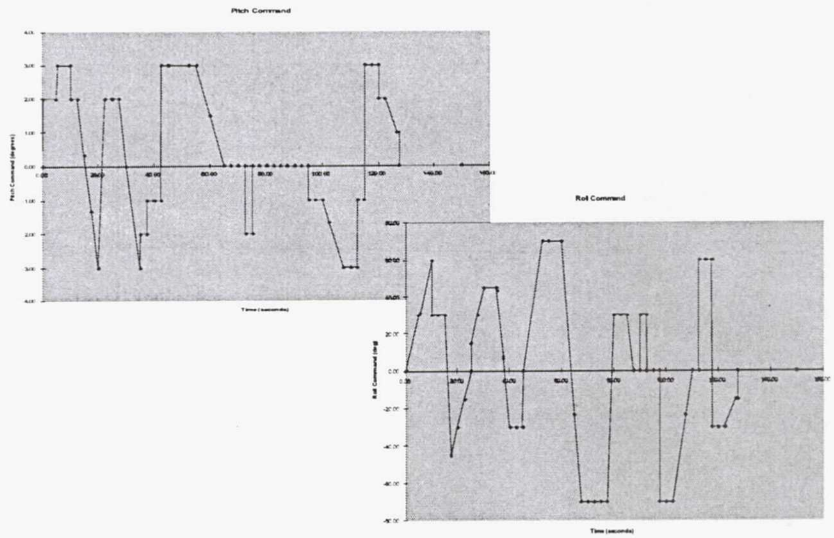
Total: C4 77-110msec
SG 52-119 msec



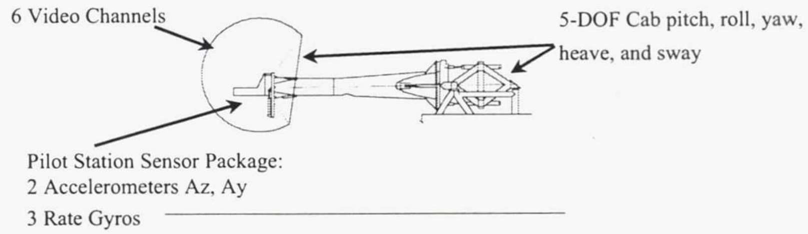
Measured Time Delays

- Two types of delay measurements in simulators
  - Time Domain: time to wiggle to time to response
  - Frequency Domain: Sum-of-Sines phase delay
  - LAMARS freq domain tests accomplished on motion while both freq and time measurements were done on visual
  - MS-1 only time domain tests were done on visual
- LAMARS Measured Visual System Delays
  - Compuscene transport delay: TD=88msec
  - Compuscene End-to-End: TD=108-124msec FD=72msec
  - HUD End-to-End: TD=69-153msec
- MS-1 Measured Visual System Delays Time Domain
  - Compuscene transport delay: TD=75msec
  - Compuscene End-to-End: TD=94-111msec
  - HUD End-to-End: TD=69-153msec

Tracking Task



Motion Work



- Conducted parameter identification of all servo-axes.
- Developed new beam compensation terms.
- Retuned linear washout terms.
  - Used new terms during HAVE LIMIT testing
- Non-linear washout scheme developed for AZ cueing
  - Implemented tested using Capt. Chapa as test subject
  - Initial feedback good both subjective and analytical

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Session III

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FAA'S HISTORY WITH APC

Guy C. Thiel, FAA

FAA'S HISTORY WITH APC

- BACKGROUND
- INITITAL DEVELOPMENT OF CRITERIA
- FINAL CRITERIA & RATINGS SCALE

BACKGROUND

- **1993** - Special Certification Review
  - High Altitude Turbulence Upsets
- **1994** - Initial Draft Criteria - FBW Program
- **1995** - First Meeting of NRC Committee
- **1996** - New AC 25-7 with APC included
- **1997** - Final Release of AC with Comments

BACKGROUND

- MD-11 INCIDENTS
- FLYING QUALITY RULES

  ONLY CLOSED LOOP

  NO HIGH ALTITUDE TASKS

INCIDENTS

- MD-11 HIGH ALTITUDE UPSETS
- OTHER INCIDENTS
- CAUSES

    Basic Handling Qualities ??

    Lack of Training

    Unusual Atmospheric Conditions

FLYING QUALITY RULES

- Normally Open Loop Tests
- Tasks are not Used in Certification
- High Altitude Flying - Autopilot

CRITERIA

- REGULATORY BASIS - FAR 25.1143

- A) The Aircraft must be safely controllable and maneuverable throughout the flight envelope.

- B) Must be possible to make smooth transitions from one flight condition to other flight conditions without

  1) exceptonal pilot skill, alertness, or strength

  2) exceeding airplane limiting load factor

CRITERIA

- Link FAR 25.143

- Handling Qualities Rating Scales FBW Aircraft

- FAA Rating Criteria

- Develop APC/PIO Rating Scale

IMPLEMENT CRITERIA

- Use Advisory Circular Method
    - A) New Rules - 5 to 7 Yrs.
    - B) Add to Flight Test Guide (25-7)
    - C) Para. for FAR 25.143
- Add Required Maneuvers
- Tie APC Ratings to HQR Section

IMPLEMENT CRITERIA

- Issued Draft of AC 25 - 7 in Early 1996
- Basis for Certification
- Aircraft Tested - MD-11, B-777, IL-96T, A330-200, Citation X, G-5, Global Express

NEW CRITERIA

- Published AC 25 - 7 (Original Criteria)
- Train FAA Test Pilots
- Modify Original AC 25-7 Material

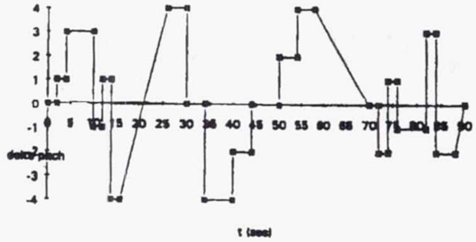
TRAIN TEST PILOTS

- Select First Group for Calspan Training
- Interim use of Intitial Group
- Plan for Remaining Pilots

MODIFY APC CRITERIA

- Because of Results from Past Programs
- Add Operational Maneuvers
- Require Tracking Device
- Modify APC/PIO Rating Scale

FIGURE 20-1. SAMPLE PITCH TRACKING TASK



Flight Working Paper # 599-2

FIGURE 20-12

APC RATING CRITERIA AND COMPARISON TO MIL STANDARD

FAA HQ RATING	APC CHARACTERISTICS DESCRIPTION	MIL 1797A STANDARD PIO RATING SCALE
SAT	NO TENDENCY FOR PILOT TO INDUCE UNDESIRABLE MOTION.	1
	UNDESIRABLE MOTIONS (OVERSHOOTS) *TEND TO OCCUR* WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. THESE MOTIONS CAN BE PREVENTED OR ELIMINATED BY PILOT TECHNIQUE. *(NO MORE THAN MINIMAL PILOT COMPENSATION REQUIRED)*	2
ADQ	UNDESIRABLE MOTIONS (UNPREDICTABILITY OR OVER CONTROL) *EASILY INDUCED* WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. THESE MOTIONS CAN BE PREVENTED OR ELIMINATED BUT ONLY AT SACRIFICE TO TASK PERFORMANCE OR THROUGH *CONSIDERABLE* PILOT ATTENTION AND EFFORT. *(NO MORE THAN EXTENSIVE PILOT COMPENSATION REQUIRED)*	3
CON	*OSCILLATIONS TEND TO DEVELOP* WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. ADEQUATE PERFORMANCE IS NOT ATTAINABLE AND PILOT MUST REDUCE GAIN TO RECOVER. (PILOT CAN RECOVER BY MERELY REDUCING GAIN)	4
UNSAT	*DIVERGENT OSCILLATIONS* TEND TO DEVELOP WHEN PILOT INITIATES *ABRUPT MANEUVERS* OR ATTEMPTS TIGHT CONTROL. PILOT MUST OPEN LOOP BY RELEASING OR FREEZING THE CONTROLLER.	5
	DISTURBANCE OR *NORMAL PILOT CONTROL* MAY CAUSE DIVERGENT OSCILLATION. PILOT MUST OPEN CONTROL LOOP BY RELEASING OR FREEZING THE CONTROLLER.	6

Ratings contained in Appendix 7

__SAT = Satisfactory
__ADQ = Adequate
__CON = Controllable
UNSAT = Unsatisfactory or Failed, corrective action must be taken.

Mel Rogers, ANM-111
(425) 227-1405
APC_FTG2.DOC

Minimum Rating, Pass/Fail Criteria Presented in Appendix 7

Flight Envelope **	NFE	OFE	LFE	NFE	OFE	LFE	NFE	OFE	LFE
Atmospheric Disturbance	Calm or Light			Moderate			Severe		
Normal to Probable Failure $< 10^{-5}$	Sat	Sat	Adq	Adq	Con	Con	Con	Con	Con
Improbable Failure 10^{-5} to 10^{-9}	Adq	Adq	Con	Con	Con	N/A	Con	N/A	N/A

Sat = Satisfactory
Adq = Adequate
Con = Controllable
N/A =Not Applicable, No Requirement

** = see Figure 6 of Appendix 7 for details of the flight envelope descriptions

NFE = Normal Flight Envelope, is associated with routine operation and/or prescribed conditions for all engine and one engine inoperative.

OFE = Operational Flight Envelope, is associated with warning onset outside the normal flight envelope.

LFE = Limit Flight Envelope, is associated with the airplane design limits or electronic flight control system protection limits.

Atmospheric Disturbance Level:

Light: Turbulence momentarily causes slight, erratic changes in altitude and/or attitude (pitch , roll and yaw). Crosswinds up to 10 knots.

Moderate:- Turbulence has greater intensity and changes in altitude and/or attitude and flight path and usually causes variations in indicated airspeed. Crosswinds up to 25 knots.

Severe:- Turbulence can cause large, abrupt deviations in altitude and/or attitude and flight path as well as large variations in indicated airspeeds. Crosswinds can be substantially larger than the minimum required crosswinds to be demonstrated.

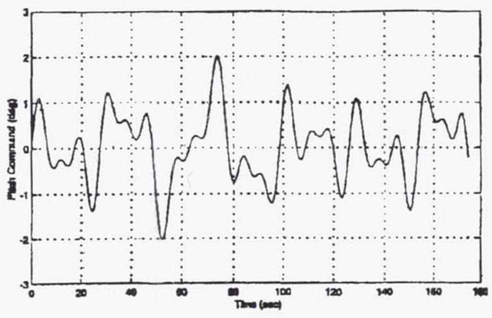
FIGURE 20-2. A-PC RATING CRITERIA AND COMPARISON TO MIL STANDARD

FAA HQ RATING	A-PC CHARACTERISTICS DESCRIPTION
SAT	NO TENDENCY FOR PILOT TO INDUCE UNDESIRABLE MOTION.
	UNDESIRABLE MOTIONS (OVERSHOOTS) TEND TO OCCUR WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. THESE MOTIONS CAN BE PREVENTED OR ELIMINATED BY PILOT TECHNIQUE. (NO MORE THAN MINIMAL PILOT COMPENSATION REQUIRED)
ADQ	UNDESIRABLE MOTIONS (UNPREDICTABILITY OR OVER CONTROL) EASILY INDUCED WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. THESE MOTIONS CAN BE PREVENTED OR ELIMINATED BUT ONLY AT SACRIFICE TO TASK PERFORMANCE OR THROUGH CONSIDERABLE PILOT ATTENTION AND EFFORT. (NO MORE THAN EXTENSIVE PILOT COMPENSATION REQUIRED)
CON	OSCILLATIONS TEND TO DEVELOP WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. ADEQUATE PERFORMANCE IS NOT ATTAINABLE AND PILOT MUST REDUCE GAIN TO RECOVER. (PILOT CAN RECOVER BY MERELY REDUCING GAIN)
UNSAT	DIVERGENT OSCILLATIONS TEND TO DEVELOP WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. PILOT MUST OPEN LOOP BY RELEASING OR FREEZING THE CONTROLLER.
	DISTURBANCE OR NORMAL PILOT CONTROL MAY CAUSE DIVERGENT OSCILLATION. PILOT MUST OPEN CONTROL LOOP BY RELEASING OR FREEZING THE CONTROLLER.

SAT = Satisfactory
ADQ = Adequate
CON = Controllable
UNSAT = Unsatisfactory or Failed

CALSPAN
An Operation of Veridian

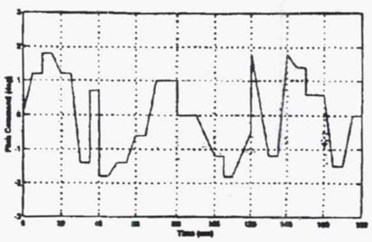
Tools for the Evaluation Pilots

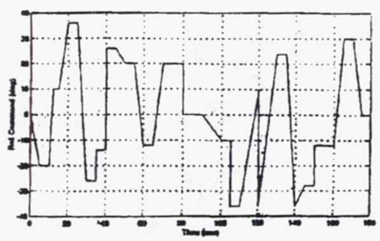


Sum of Sines Tracking Task
(similar in roll)

CALSPAN
An Operation of Veridian

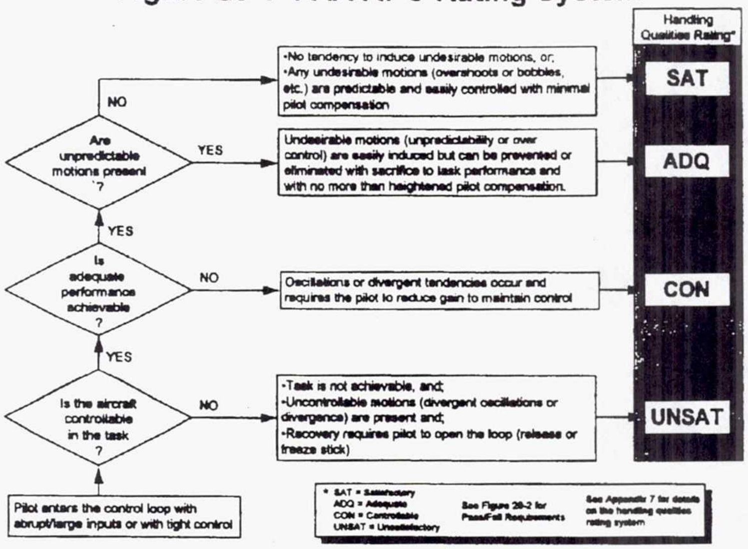
Tools for the Evaluation Pilots

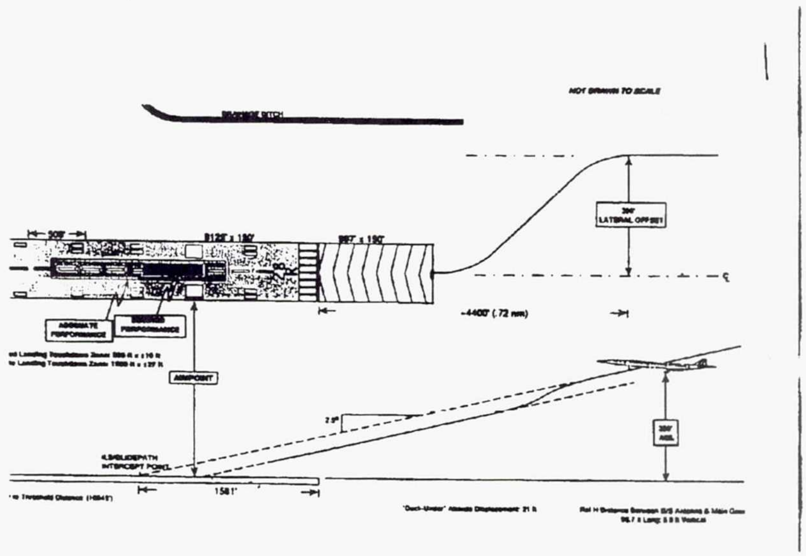




Discrete Tracking Task

Figure 20-1 FAA APC Rating System





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APC/PIO Workshop

NASA Dryden Flight Research Centre
Edwards, California
6-8 April 1999

Graham Weightman, JAA (UK CAA)

APC/PIO Workshop
Dryden Flight Research Centre, 6-8 April 1999

- Initial discussions with FAA in the JAA Flight Study Group (FSG) on proposed APC text for draft revision to FAA Flight Test Guide (AC 25-7X) beginning early in 1996
- JAA submitted comments on AC 25-7X (September 1996)
- Further discussions on APC in FSG (reference Flight Working Paper 599 prepared by FAA)
- JAA has reserved the APC text for the first issue of the JAA Flight Test Guide (based on AC 25-7A and to be published for comment shortly) pending further work

APC/PIO Workshop
Dryden Flight Research Centre, 6-8 April 1999

- FSG established an ad-hoc Sub-Group to work with FAA on harmonised guidance material for APC
- FAA (Mel Rogers) invited to chair Sub-Group
- First "kick-off" meeting in Braunschweig, Germany in January 1999. CAA, LBA, DGAC/CEV, FAA, Aérospatiale, Airbus and Boeing/AIA present
- Intention to work largely by E-mail
- Target: Draft revision of FWP 599 by June 1999

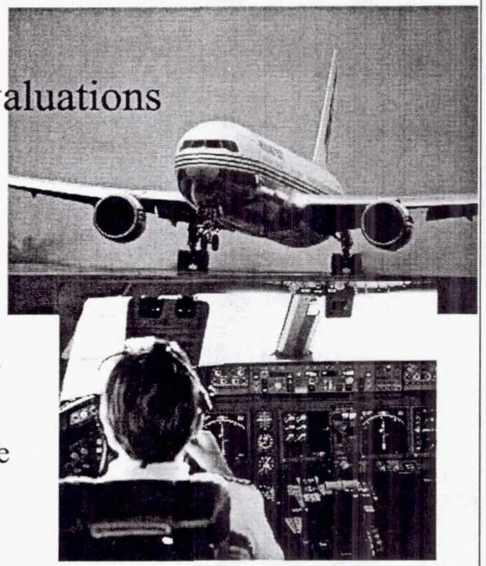

PIO Flight Test Experience at
Boeing (Puget Sound)
--and the need for more research
B. P. Lee
Airplane Handling Qualities
Boeing Commercial Airplane Group
Seattle, WA
April, 1999

Introduction and Disclaimer

- This presentation represents a snapshot in time with regard to Boeing's flight test experience with Pilot-Induced Oscillations.
- The information contained herein is presented in the hope that in sharing technical information, safety can be enhanced through cooperative focus of research, and reduced duplication of efforts.

Agenda

- Boeing Flight Test Evaluations
  - Aircraft Scope
  - Data Collected
  - Maneuvers Used
- Need for further work
  - Controller Characteristics
  - Nonlinearities in Response
  - Pilot Aggressiveness



This presentation consists of two parts.

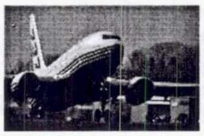
The first is intended to let the technical community know about Boeing (Commercial) flight test activity with respect to PIO. The scope of aircraft models tested, the kinds of data collected, and experience regarding various specific evaluation maneuvers will be discussed.

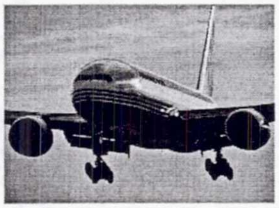
The second part of the presentation contains suggestions for focus areas in which the current state of analytical techniques is not adequate to address many very real situations which arise in the testing of large commercial jet transport aircraft.

PIO Testing History at Boeing

- Specific Evaluations carried out since 1995
  - 777-200 737-700
  - 777-300 737-800
  - 757-200 757-300

- Plan to include other models at "windows of opportunity"





Boeing Commercial Airplanes takes Pilot Induced Oscillations very seriously and endeavors to understand the phenomenon to insure that its products do not exhibit these adverse characteristics. Since 1995, Boeing has undertaken to evaluate a number of airplane models, and have a plan in place to evaluate others as opportunities present themselves.

As can be imagined, fully instrumented airplanes are not always easy to come by, so data is acquired whenever it is available.

Intent of Generic Test Program

- Evaluate Each Boeing Airplane Model
- Collect Data
  - End-to-End Open Loop Dynamic Response
  - Control System Response
  - Qualitative Evaluation During High Gain Tasks
  - Quantitative Evaluation During High Gain Tasks
- Document Lessons in Design Requirements

At the outset, Boeing conceived a generic test program which had the intent to conduct specific evaluations for PIO tendencies on each Boeing airplane model.

These evaluations were multi-faceted and intended to acquire four different types of data. These included:

•end-to-end open loop dynamic response

•conrol system response data

•qualitative evaluation during high gain tasks

•quantitative evaluation during high gain tasks

In addition to collecting the data, the results of the testing and subsequent analysis would be documented as lessons learned in internal design requirements.

Maneuvers Flown

Maneuver

- Frequency Sweeps
- Control Doublets
- Control Releases
- Close Formation
- Constant Altitude flybys
- Lateral S-Turns
- Vertical S-Maneuvers
- Offset Landings

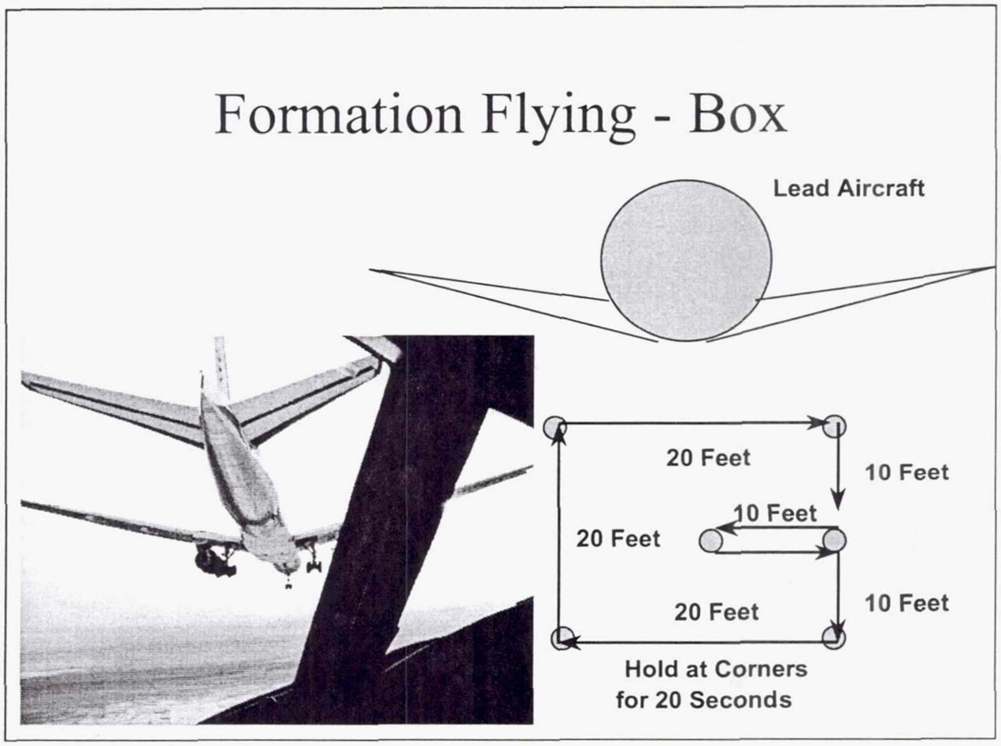
Flight Condition / Configuration

- High Altitude Cruise
- Low Altitude Cruise
- Approach
- Landing

The primary maneuvers in the generic plan are shown on the chart.

Open loop airplane and control system response data and the qualitative close tracking task (formation flying) is collected at high and low altitude cruise, approach, and landing conditions. The runway work is done only in the landing configuration.

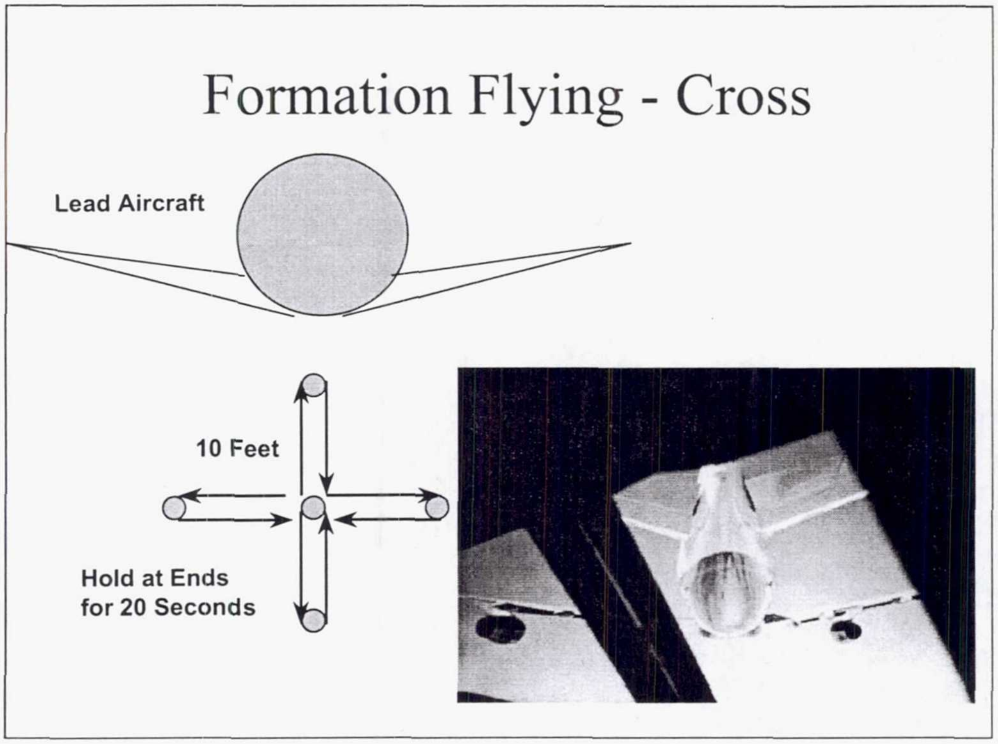
Open loop response data collection, consisting of frequency sweeps, control doublets, and control releases are self explanatory, and not described further.



A number of specific maneuvers have been used as close tracking tasks in up and away flight. One of the most effective has been close formation flying. A particular difficulty in implementation of this technique is that it is mostly qualitative in nature. Accurate measures of pilot-in-the-loop performance and and ways to adequately feed it back to the pilot have not been identified. Although discussions of over-the-shoulder cameras, heads-up displays, and differential GPS installations have taken place, none have as yet been implemented.

One maneuver used as a piloting task is the formation box maneuver, shown here. Once the pilot is established in a close refueling position (thought of as the center of the box), the pilot is asked to rapidly and aggressively acquire a new position 10 feet to the right. This new position is to be held as closely as possible for 20 seconds at which time the pilot is asked to acquire a new position 20 feet below the last. This is similarly held for 20 seconds. The maneuver proceeds around the "box". This maneuver combines a gross acquisition task with close tracking in a very high gain environment, and combines both longitudinal and lateral-directional axes.

The inset shows flying this maneuver with a 777-300 flying against another 777-300.

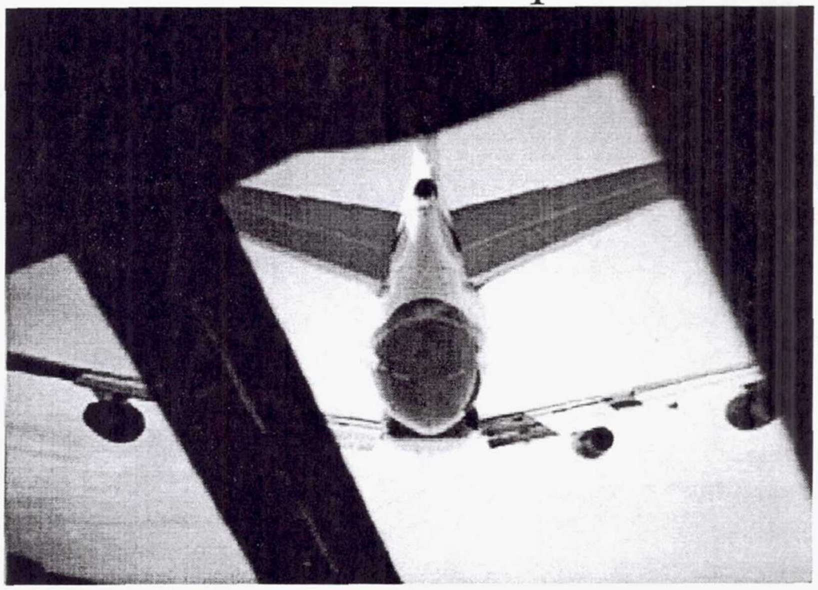


A second maneuver used is the formation cross maneuver. Execution of this maneuver is similar to that for the box.

One element which makes these maneuvers interesting in flight is that the trail airplane is flying in a curved flowfield. What this means is that to hold at the lateral ends of the cross requires flying in sideslip, which adds to pilot workload.

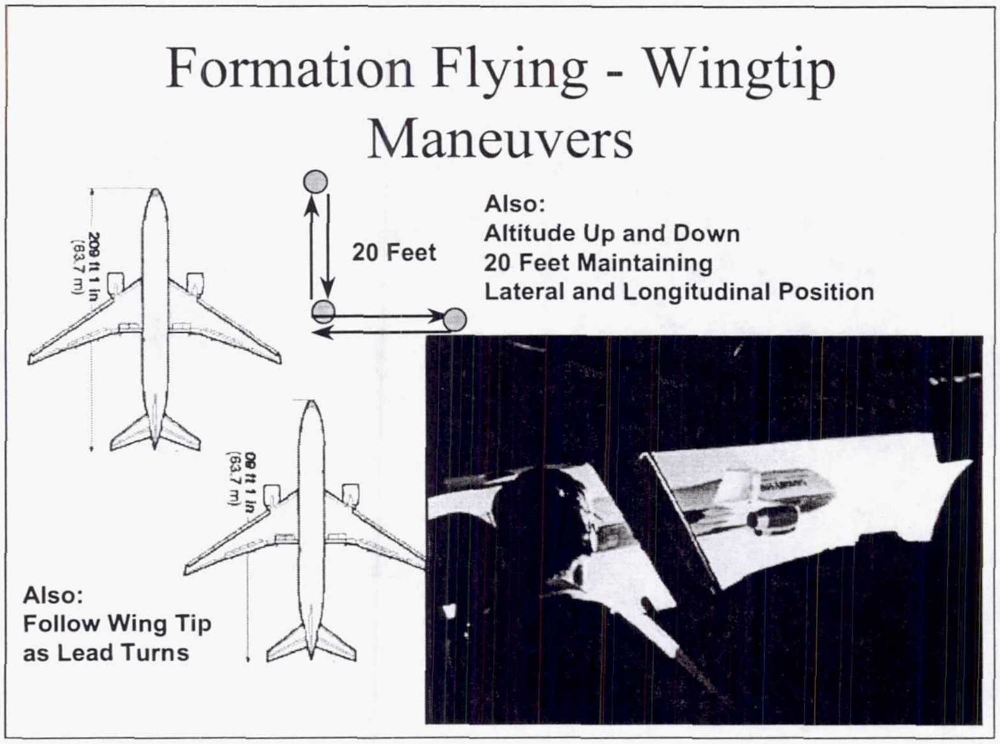
The inset shows this maneuver being flown in a 777-200 against a 747-400.

Trail Position- Flaps Down



When transitioning to the approach and landing configurations, the lead aircraft also transitions in order to match flight speeds. Shown here, the trail pilot is looking rather directly at the upper surfaces of the very large triple slotted flaps of the leading 747.

Now while the vertical tail of the trail airplane is certainly immersed in the wake of the lead airplane in all conditions--and the buffet is noticable--the wake grows considerably for these flap down conditions. This increased the workload for the 777 airplanes, but the attendant buffeting was simply unacceptable for the shorter, lighter 737 airplanes. The task was not possible given the severity of the buffeting for that (737) airplane. So the entire task was moved to the wingtip of the lead airplane.



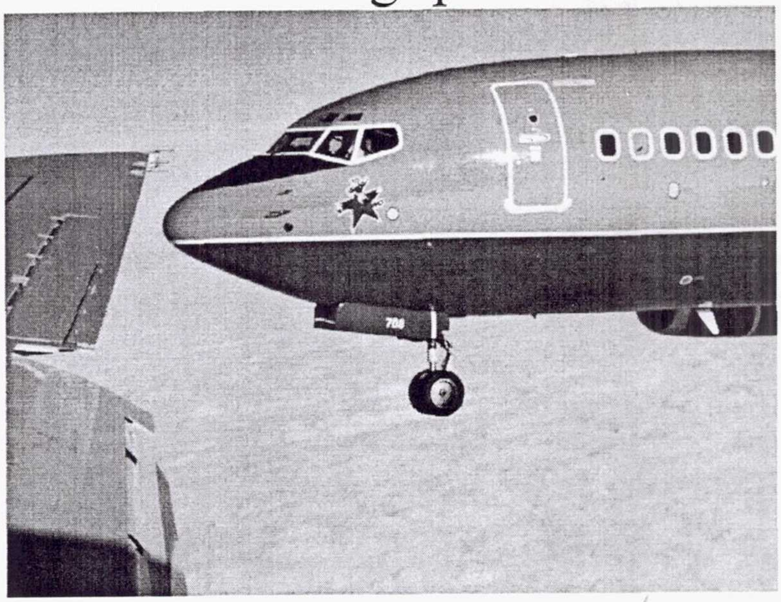
While the wingtip formation maneuvers were planned for all airplanes anyway, it was discovered that this was the only practical position to evaluate the flaps down conditions for the 737.

The wingtip maneuvers are shown here, including transitions fore and aft, in and out, and up and down. In addition the trail airplane was asked to follow the lead through turning maneuvers, keeping station on the wing tip.

These maneuvers proved to be very demanding. Compared to the refueling position, the wingtip position provided a much smaller target (the wing tip itself), which the pilot could see with better precision, and the target was much more active. Especially as the leader turned, the wingtip moved around significantly, generating a very demanding tracking task.

The inset shows a 777-200 flying against the 747-400 in the wingtip position. The evaluation pilot is focused very intently on what the lead aircraft is doing. The situation is just as dramatic when viewed from the lead aircraft.

Close Wingtip Position



This is a 737-700 being flown against a 737-800. The distances are short, and pilot gain is very high.

Formation Flying Summary

- Single Highest Gain Task
- Maneuvers Combine Acquisition with Tracking
- Learned Task Requiring Experience
- Wingtip Tracking Probably Most Effective
- Difficult to Measure Performance (and Feed Back to Pilots)
  - DGPS in the Future?
- Difficult to Enforce Performance Requirements
- Difficult to Get Consistent Level of Aggressiveness

To summarize Boeing experience with close formation flying as a maneuver to explore APC tendencies, it can be said that it provides a very high gain task which combines gross acquisition with tight tracking.

At the same time, it is very difficult to measure the pilot/vehicle performance and feed that back to the pilot in a meaningful, quantitative way. In addition, and perhaps because of the lack of performance information, it is very difficult to achieve consistency in aggressiveness across several evaluation pilots.

Constant Altitude Flyby

- Intended to “Extend” the Flare for Analysis
- Involves both Acquisition and Tracking
  - Fly ILS to 50 Feet
  - Flare and Maintain 50 +/- 10 Feet for Length of Runway
  - Maintain Centerline
  - PNF Calls Radar Altitude

Another set of maneuvers used to explore APC tendencies has involved flying close to the runway. Originally, the flyby task was conceived to provide insight into the pilot/vehicle combination in the flare. Upon examination, if done properly, a flare maneuver takes only a few seconds. On large transports with natural frequencies on the same order, it is difficult to gain much understanding about the interaction. So this maneuver was conceived to provide an extended time period for data gathering. The maneuver involves acquisition and tracking in a high precision environment.

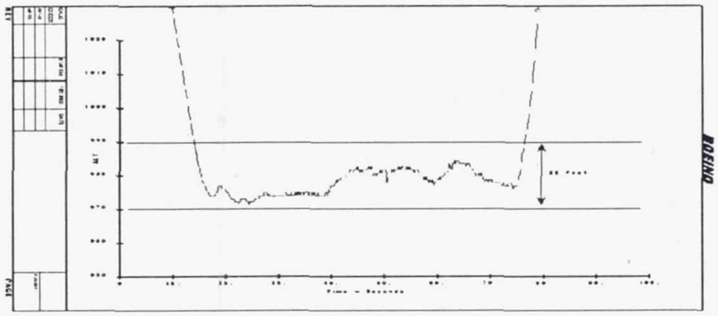
The pilot is asked to flare and maintain 50 +/- 10 feet for the length of the runway. Typically, the pilot will close a loop around radar altitude, with the pilot not flying calling radar altitude continuously. During the maneuver, the pilot is asked to maintain the runway centerline.

It was discovered that the most difficult part of the task was making the power adjustment in the round-out. Too little power and airspeed would bleed away in the level segment; too much, and the airplane would accelerate or climb.

Pilots descried the task as challenging but not impossible.

Flight Performance

- Pilots Characterized Task as "Demanding, but not Impossible"
- Power Setting in Flare Requires Precision



An example time history shows that the desired performance level could be met. It is interesting to note that at the particular runway used for this test, there is a "hump" in the runway at about the midpoint. That is to say that the runway elevation is higher in the middle than on either end. With the pilot closing on radar altitude, the maneuver proceeds nicely until that point, at which time a power adjustment is required as the runway "falls away" from the airplane. This "feature" in the local topography provided a convenient increase in workload for the pilot flying the task.

Comments on Use of Simulation

- Most Valuable for Pilot Familiarization and Practice of Maneuvers
- Easy to Measure Pilot Performance
- Lack of Cues Makes PrecisionTasks More Demanding
  - Depth Perception
  - Visual Acuity/Scene Content
  - Motion
- Lack of Urgency Allows Higher Pilot Gain
- PIO Results are Largely Inconclusive

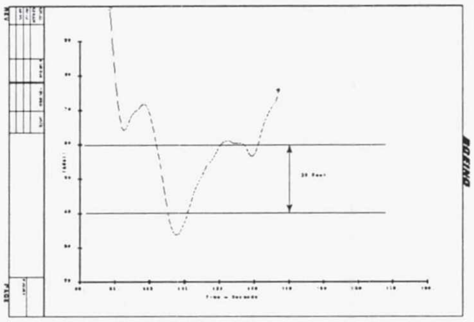
At this point, a small diversion into the subject of the use of simulation is in order. Boeing uses engineering simulation, with pilots in the loop, both fixed and moving base for this kind of testing. As a result of this experience, these sessions are seen as more valuable for pilot familiarization with the task than for collecting data regarding APC tendencies of a particular configuration.

While it is easy to measure and feed back pilot/vehicle performance in the simulation, there are a number of deficiencies as well. On-ground simulation is simply not the same as flight. A number of pilot cues, which may or may not be important for a given APC evaluation are lacking or of insufficient quality. In addition, the pilot knows it is a simulation, and so there is a general lack of urgency. Pilots have been seen to make control movements in simulation which they simply would not do in flight with a large transport.

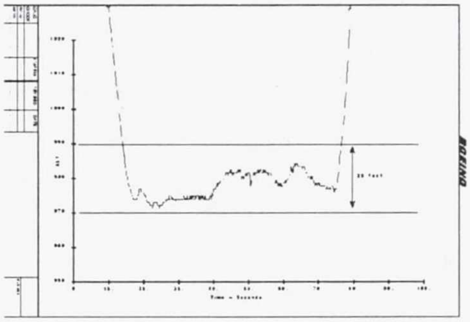
Based on this experience, PIO results from simulation alone are considered largely inconclusive.

Simulation / Flight Performance

Simulation



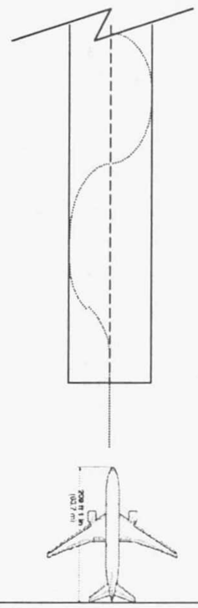
Flight



One example is shown in this comparison. On the right is the in-flight result from the straight fly-by maneuver shown previously. On the left is a time history taken in a fixed base simulator. For whatever reason, the pilot is simply not able to fly the required task in the simulator.

Use of simulation can certainly flag the potential for untoward tendencies, but the effects of myriad cueing issues are yet unanswered. As a result, ground-based simulation is not yet seen as a viable substitute for flight testing. However, it is quite valuable in getting pilots familiar with the maneuvers involved and useful as a tool to explore maneuver set up, etc.

Lateral S-Turns



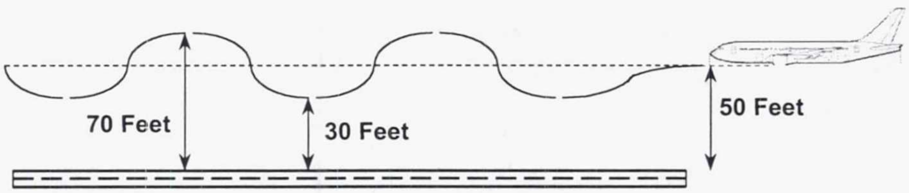
- Intended to Increase Workload by Adding Axis
  - Fly ILS to 50 Feet
  - Acquire as Rapidly as Possible one Runway Edge Line
  - Acquire as Rapidly as Possible the Opposite Edge Line
  - Repeat for Length of Runway
  - Maintain 50 +/- 10 Feet
  - PNF Calls Radar Altitude

In an attempt to increase the workload encountered on the fly-by maneuver, an additional task was superimposed. The lateral S-Turn maneuver asks the pilot to proceed as in the flyby, except once established at 50 feet, the pilot should, as rapidly as possible acquire alternate runway edge lines and continue for the length of the runway.

This is a very impressive maneuver for an airplane with a 200 foot wingspan at 50 feet above the runway.

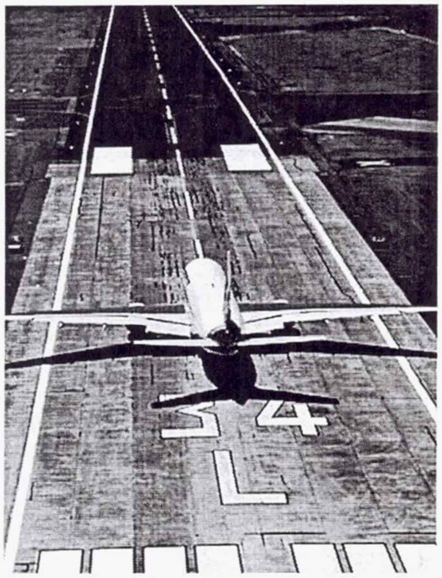
Vertical S-Maneuvers

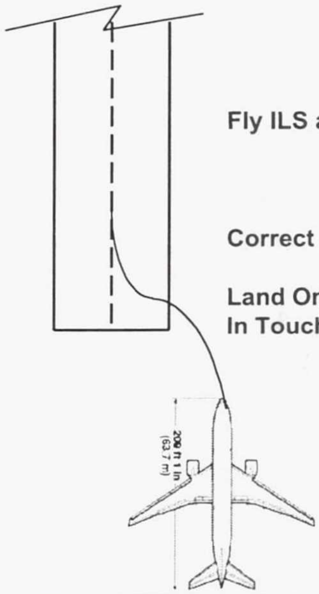
- Further Increases Urgency
  - Fly ILS to 50 Feet and Capture 50 +/- 10 Feet
  - Acquire as Rapidly as Possible 30 +/- 10 Feet
  - Acquire as Rapidly as Possible 70 +/- 10 Feet
  - Repeat for Length of Runway
  - Maintain Centerline
  - PNF Calls Radar Altitude



An additional increase in urgency was achieved when the pilots were asked to perform a vertical S-maneuver. Again leveling at 50 feet, the pilot is asked to rapidly and aggressively acquire 30 feet and 70 feet alternately. While this is a single axis task, urgency is very high in a large airplane maneuvering vertically close to the ground.

Offset Precision Landing





Fly ILS at
2 Dots Offset
2 Dots High

Correct at 250 AGL

Land On Centerline
In Touchdown Zone

The offset precision landing is a maneuver used by most testing organizations to investigate PIO tendencies, and Boeing has used it as well. The familiar set-up for this maneuver is to align on the drainage ditch beside the runway at Buffalo, NY, as used by Veridian/Calspan. Most airports do not have this convenient landmark, however, so Boeing has adopted a multi-axis task which involves flying the ILS intentionally offset. The offset chosen is 2 dots laterally and 2 dots high. At 250 AGL, the pilot is asked to correct to the centerline and land in the touchdown zone. This is a very challenging maneuver at low altitude.

Flyby / Landing Evaluation Summary

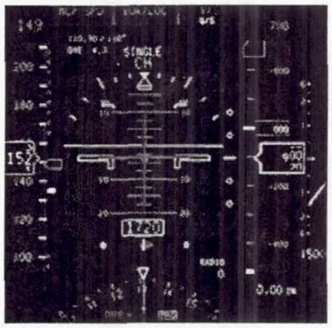
- Combines Acquisition with Tracking
- Very Demanding Piloting Tasks
- Urgency is High Near the Ground
- Performance is Measurable / Readable
- Regarded by Some as High Risk

For the low altitude tasks, Boeing has chosen maneuvers which combine acquisition with tight tracking in very demanding tasks. Being close to the ground increases the pilot's urgency and thus pilot gain. Because the target (the runway) is fixed in space, it is relatively easy to measure quantitative pilot/vehicle performance.

A consideration worthy of note is the proximity to the ground with a very large airplane is regarded (properly) by some as high risk. The risk of encountering undesirable characteristics in such a situation must always be weighed in the test planning process.

Other Maneuvers in the Toolbox

- Flight Director Tracking
  - Sum-of-Sines
  - Steps-and-Ramps
  - Log Frequency Sweeps
  - Added Discrete Disturbances
- Bank Angle Captures
- Heading Angle Captures
- Lateral Pilot Handoff
- Full Rudder Sideslip in Ground Effect
- Constant Track Rudder Step



While the "generic" maneuver set is defined as above, a number of other maneuvers have been used for specialized applications.

Flight Director tracking has been used in some cases, with a number of different input functions. In all cases, the pilot is shown only the error between commanded attitude and actual attitude, forcing a compensatory tracking scheme. Log frequency sweeps provided both insight and broad frequency coverage for future analysis. The ability to insert discrete disturbances into the flight director signal also provided additional insight.

Bank angle and heading angle captures are standard evaluation maneuvers. The lateral pilot handoff involves one pilot initiating a rolling maneuver, relinquishing command of the airplane to the other pilot while at the same time calling out a bank angle to capture. This is essentially a bank angle capture initiated from a non-zero roll rate.

Full rudder sideslips in ground effect are an attempt to investigate a landing de-crab maneuver in much the same way that the fly-by allowed investigation of the landing flare.

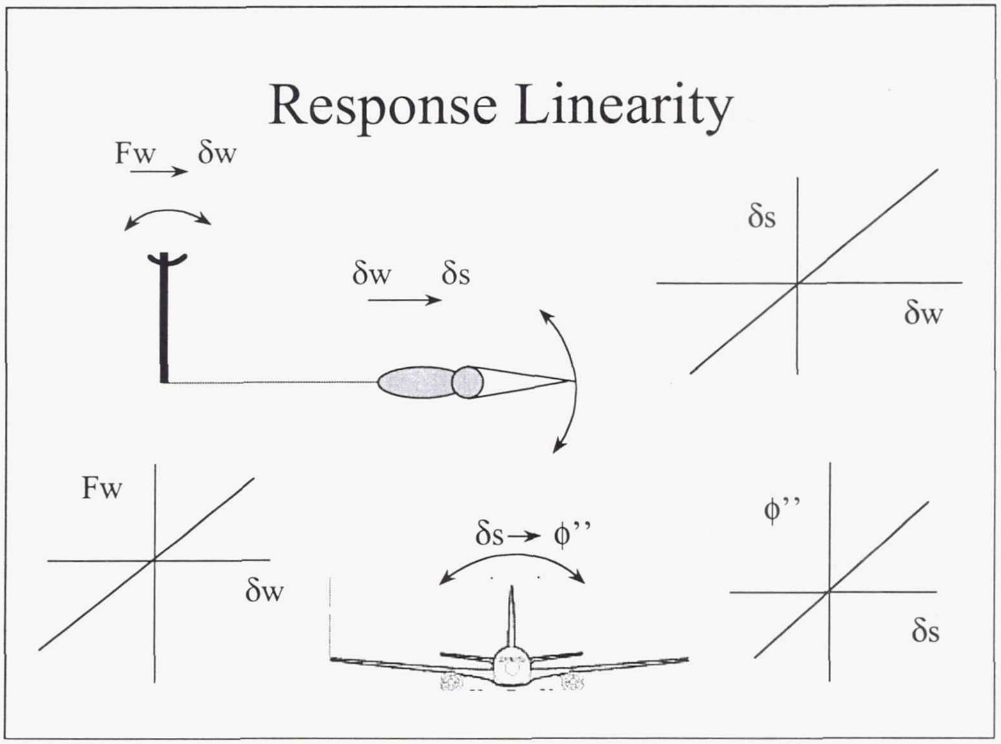
The constant track rudder step is an up-and-away maneuver in which the pilot inserts a rudder step and flys track (on the nav display) with wheel. This maneuver turned out to be very difficult to fly. While it is essentially a transition from crab to slip as in a crosswind landing, it proved unnatural to perform up and away on instruments.

Flight Test Evaluation Summary

- Boeing has Extensive Experience Flight Testing for PIO
  - Several Hundred Hours of Testing
  - Six Different Models
  - Large Number of Manuevers / Techniques
- No Single Maneuver / Technique has Proven to be Effective for Exposing PIO Tendencies
- Most Effective Testing Strategy Appears to be Careful Diligence During Normal Test Flying
- Prudent Handling Qualities Design Appears to be Effective for Prevention
- Evaluation Process Continues to Evolve

Through several hundred hours of flight testing to evaluate PIO tendencies over a large number of airplane models and involving a large number of specific maneuvers, no single maneuver or technique has proven to be effective for exposing potential PIO tendencies. The conclusion from this is that the most effective design strategy appears to be prudent attention to fundamental handling qualities design while the most effective testing strategy appears to be careful diligence during normal test flying. The testing which is done for development and certification of a transport airplane provides significant opportunities to be at remote corners of the flight envelope and investigate airplane characteristics.

Even so, the evaluation process continues to evolve and more new information is learned with each additional test program.



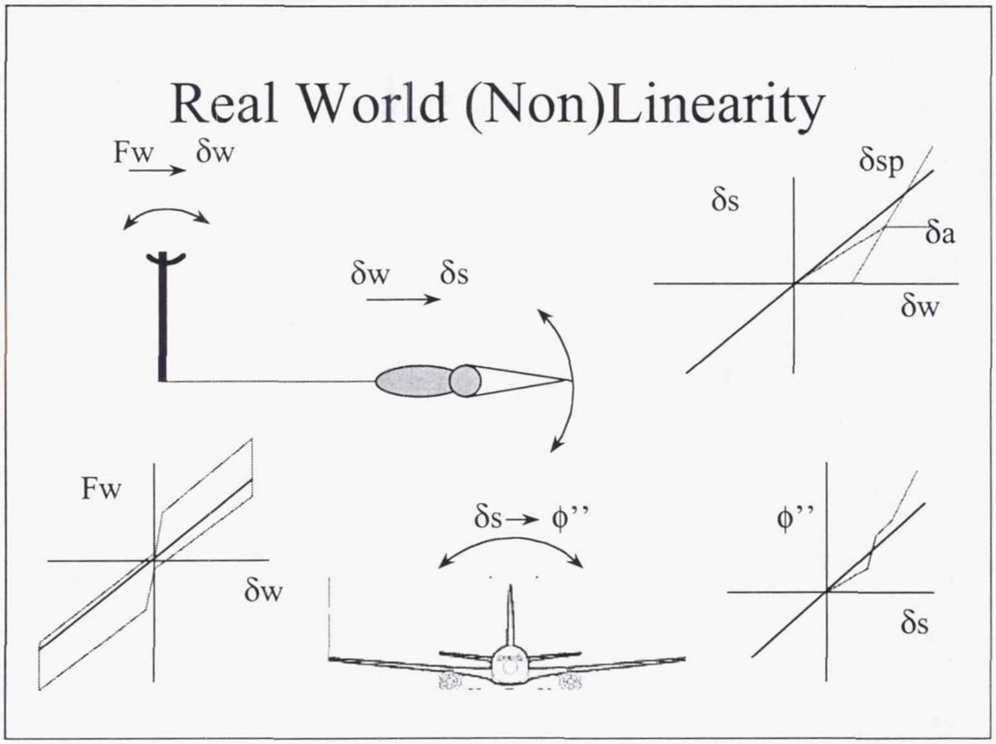
Moving from generic testing to identifying challenges for future work, this chart depicts a number of steps between the pilot's application of force to an inceptor and the airplane response.

In the upper left is a (crude) depiction of a column/yoke. As the pilot applies a force (Fw) to the wheel, the wheel would be expected to move. Moreover, as the sketch below it shows, it is normally assumed that there is some linear relationship between applied force and wheel deflection (δw).

For mechanical or displacement command systems, that displacement of the wheel should result in a corresponding displacement of an aerodynamic surface (δs), as depicted in the center sketch. Again, it is typically assumed that there is a linear relationship between controller displacement and surface displacement, as in the sketch in the upper right corner.

Finally, a surface displacement (δs) is expected to result in an acceleration of the airplane, in this case, a roll acceleration (ϕ''). In most cases there is a goal to achieve a linear relationship between these two as well, as shown in the lower right sketch.

These assumptions of linearity form the basis for the use of frequency domain analysis to study airplane dynamics and PIO.



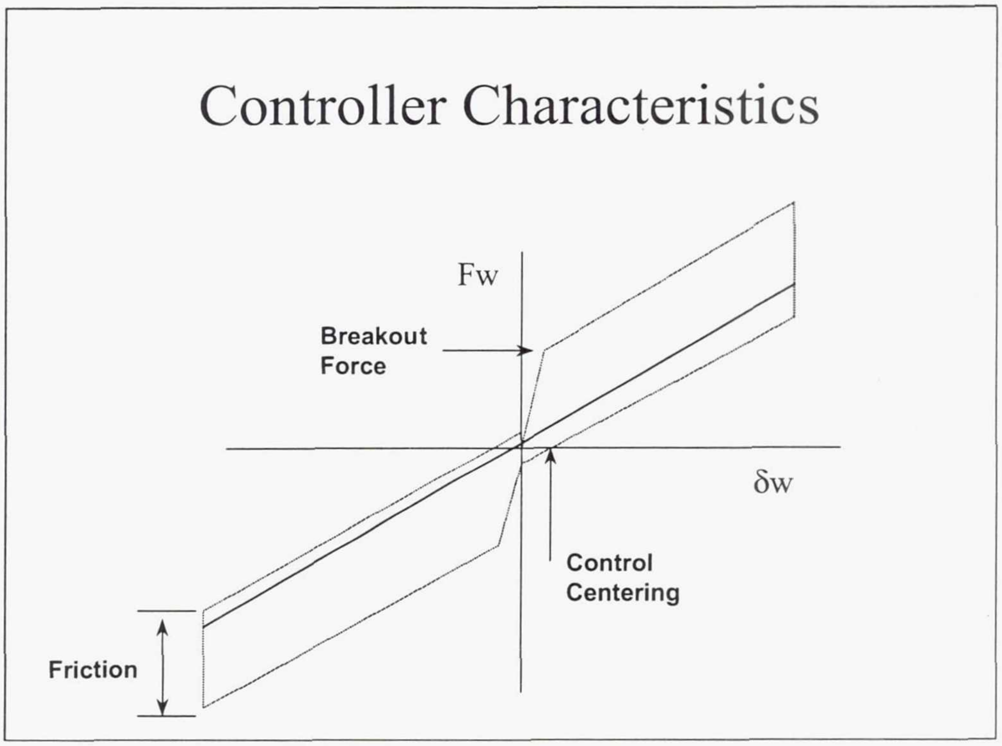
Unfortunately, the real world does not always conform to these assumptions.

In the presence of system friction, the control force to controller displacement relationship exhibits discontinuities and hysteresis. (lower left).

Modern transport airplanes typically use a combination of aileron and spoiler surfaces for roll control, each of which may be scheduled on different deflection curves, have different rate capabilities, etc. (upper right)

Finally, though a linear roll rate capability is desired, it is rarely achieved in practice.

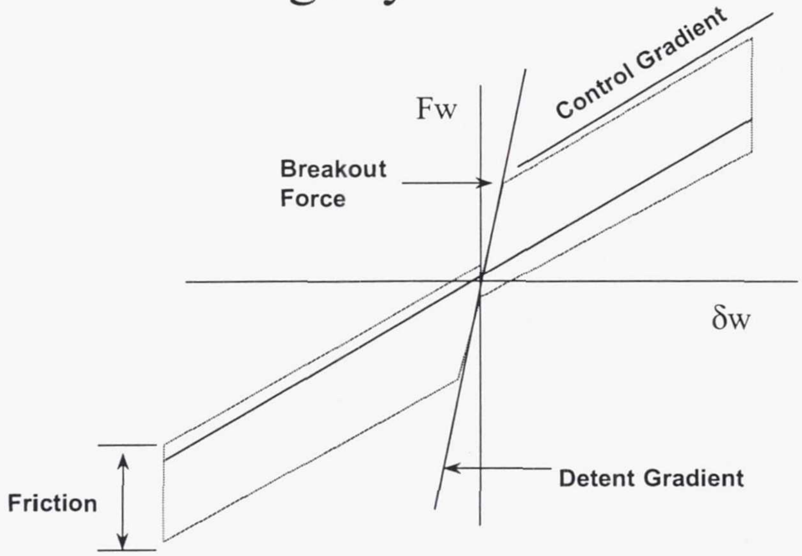
Each of these sources of nonlinearity causes difficulty in application of the typical analysis methods for PIO which are found in the literature. To focus on the need for methods to accommodate these characteristics, each is discussed in detail in what follows.



Starting at the pilot's fingertips, while most agree that linear force/displacement characteristics are desirable, all control systems have friction. In particular, large transport aircraft with mechanical control systems can have friction levels which are not trivial.

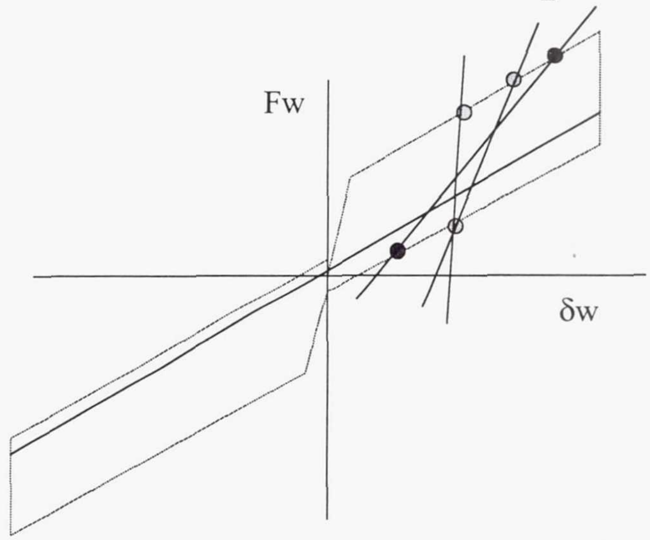
One thing that friction brings is hysteresis. In order to achieve some degree of control centering,, a breakout force is typically added. This breakout essentially offsets the force/displacement curves around zero, allowing the wheel to return to the center position when no force is applied.

Friction Generates Gradient Ambiguity Around Detent



The presence of this breakout produces a force/displacement discontinuity. The presence of a slope change can have detrimental effects on pilot predictability. The pilot loses his sense of how much force to apply to get a desired displacement. Moreover, the slope discontinuity is right in the center of the control operating range, where the pilot works the most. This can make small displacements, e.g. those required for tight tracking around neutral wheel, difficult for the pilot.

Gradient Ambiguity Away From Detent is Function of Amplitude

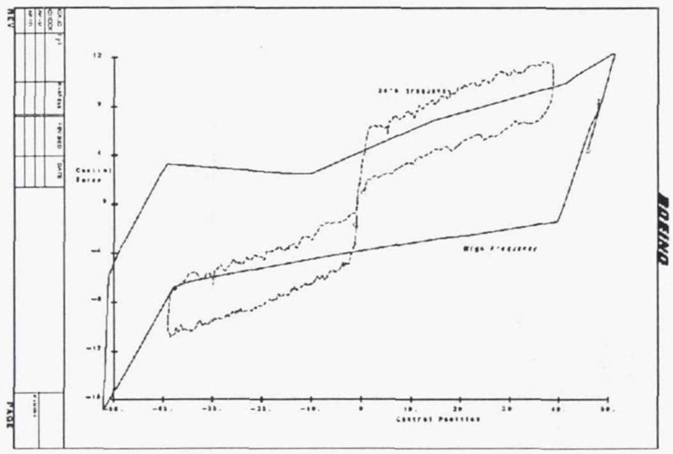


Away from the detent, the presence of friction and the associated hysteresis causes a similar gradient ambiguity. Moreover, the degree of ambiguity is a function of the size of the input for a given friction level.

This is significant for example in a decrab maneuver for a crosswind landing. The gradient of the force required to move the wheel a given amount in each direction around a (non-zero) trim point depends on how big the input needs to be.

Again, predictability from the pilot's point of view is compromised.

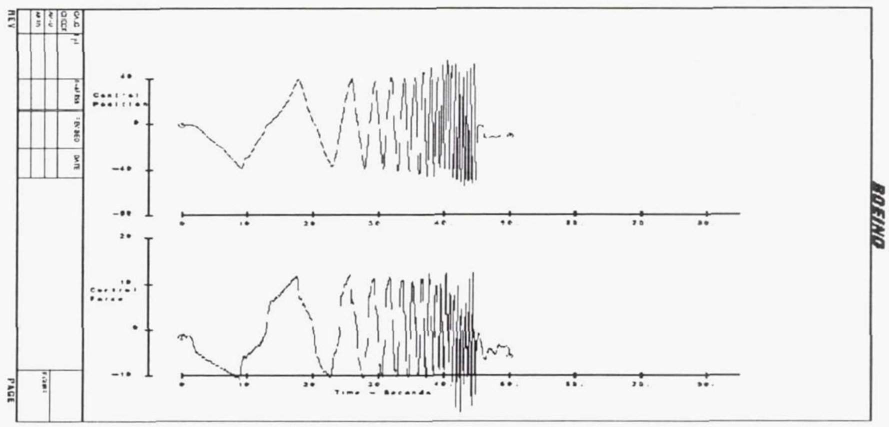
Dynamic Inertial Effects on Controller Characteristics



The static force/displacement characteristics of the controller are only part of the story. Since the control system itself has mass (and large transports can exhibit significant mass characteristics), the force/displacement characteristics vary as a function of the frequency or speed at which the control is moved.

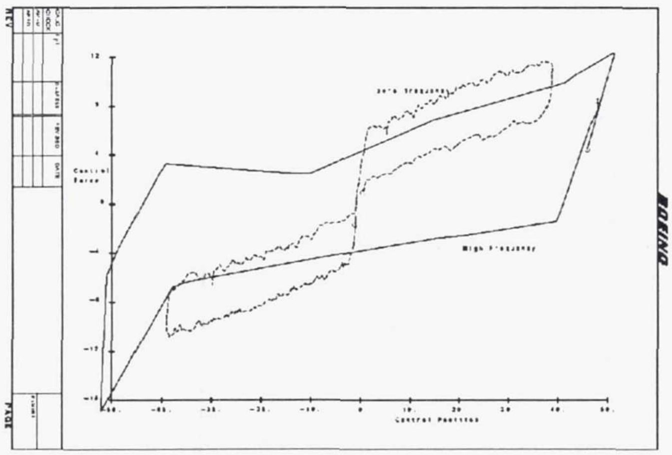
What is shown is force vs displacement at near zero frequency and another sweep at significantly higher frequency. It is clear that the two curves are significantly different. The center detent is not even evident in the high frequency case, the slope of the return (long lower path going from right to left) at high frequency is not similar to the near zero frequency case, and there are some non-linear characteristics near the ends of the travel.

Dynamic Inertial Effects Depend Also on Path (History)



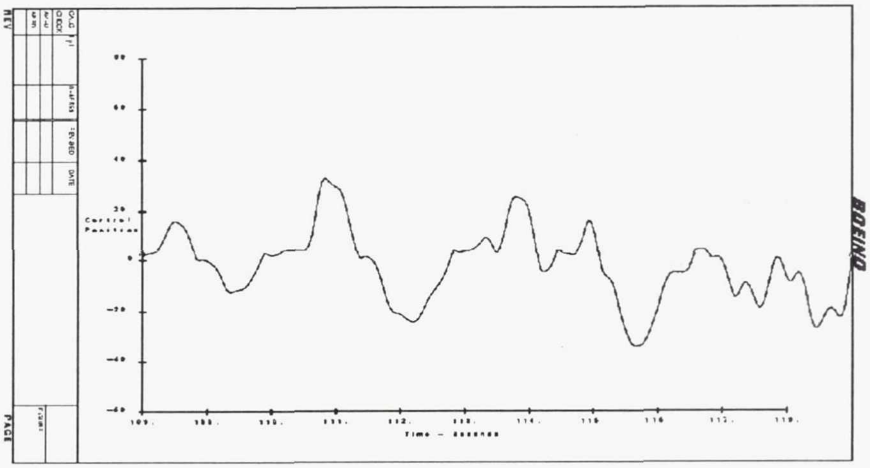
Now, the high frequency sweep on the previous chart was taken from the middle of a log frequency sweep. Had a single high frequency sweep been undertaken from a standing start, the force/displacement curve would have looked different yet. All of this is because the control system itself has mass and inertia.

Dynamic Inertial Effects on Controller Characteristics



The end result is again a question of predictability. At any given time in the flying of an airplane, the pilot needs to have some idea of how much force to apply to the controller to get to move to where he wants it to go. These dynamic characteristics cloud the issue and contribute to ambiguity.

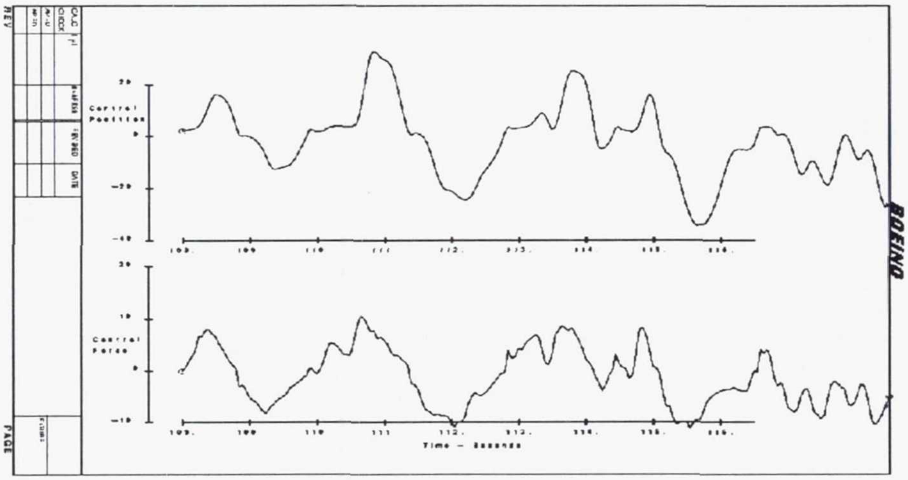
Control Activity on Final Approach



What this has to do with real flying of airplanes is shown here. This is a time history of wheel position for a normal approach to landing. Wind was light, turbulence was not a factor.

What is unique about this is the pulse-like character of the wheel inputs. At the left hand side note the quick pulse as the wheel moves more than 15 degrees, then is taken back to zero in about a half second. This is followed by an equal pulse in the other direction. After a period of quiescence, the sequence is repeated at roughly twice the amplitude, still with very short duration.

Pilot / Controller Interaction

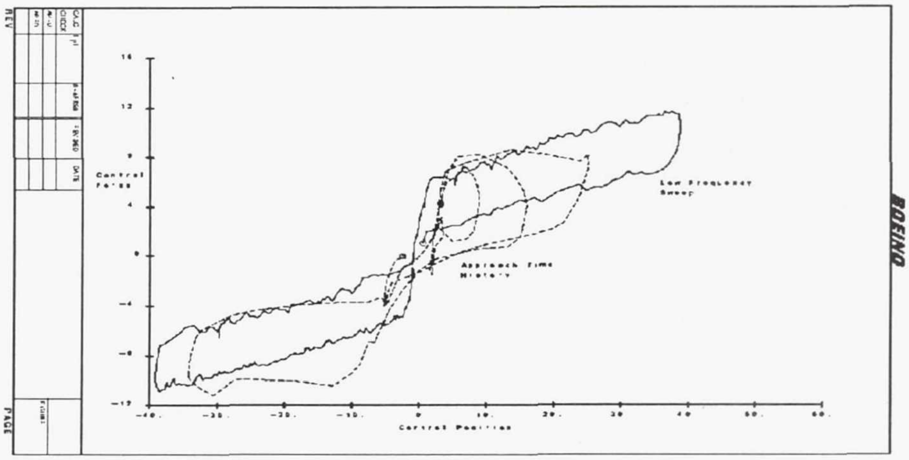


Just why this is happening can be further understood by examining the corresponding pilot force inputs.

Note that between the first and second position doublets, where the wheel is approximately zero, the force is not. In fact the pilot tried to move the wheel. There is a brief 5 pound input in which the wheel did not move. This is followed by a larger, nearly 10 pound input which generated the larger wheel deflection (upward on this plot) which the pilot immediately removed, and corrected in the other direction.

In this case, the wheel feels "sticky" to the pilot and small, smooth inputs are difficult. This degrades precision of control.

Effective Controller Characteristics



A phase-plane representation of the same sequence is overlaid on the near-zero frequency force/displacement plot for the same configuration. This illustrates the lack of predictability which is generated by inertial characteristics of the control system itself.

The result is that at any point in this dynamic maneuver, the pilot is unable to predict how much force to apply to generate what wheel position.

These kinds of controller effects are not adequately dealt with in the literature, and represent an area which is ripe for investigation.

Determine “Best” Controller Characteristics Set

- Given Minimum:
  - System Inertial Characteristics
  - System Damping
  - System Friction
- With Constraints on Maximum:
  - Force at Stop
  - Power to Drive System (Pilot Qualitative Input)
- Find Desirable Combinations of Breakout, Gradient, and Damping

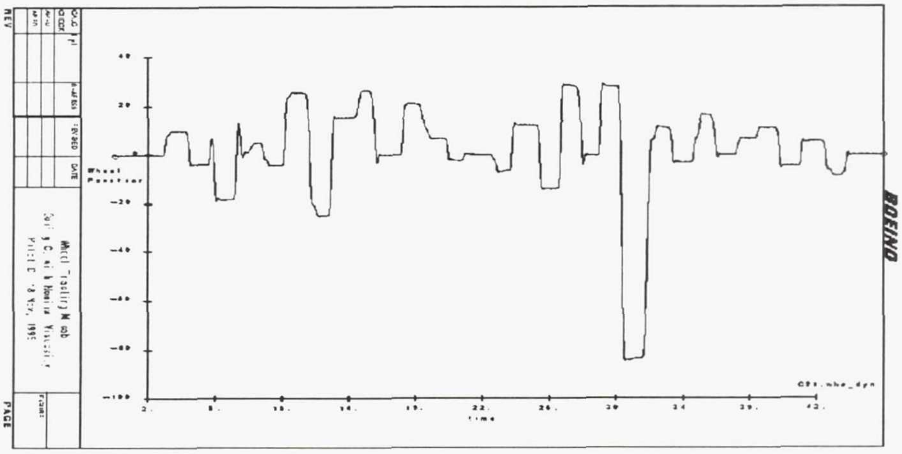
These were dealt with at Boeing in the following way.

It is understood that the control system has a minimum inertia, damping, and friction. Any modifications cannot change those, although additions to each would be possible.

In addition, there are constraints on maximum force at the wheel stop (regulatory) and on the power to drive the system (e.g. if friction or damping get too high, pilots will be easily fatigued by simply moving the wheel around).

The challenge was to find desirable combinations of these parameters to improve the pilots ability to make smooth, predictable control inputs.

Human Centered Design
The Experiment

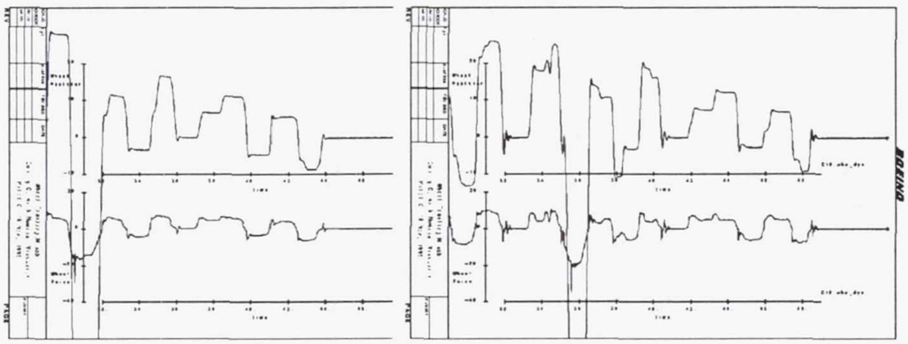


An experiment was designed for a high fidelity simulation in which the control loader characteristics could be changed to reflect the changes in the parameters. This is a time history of the wheel deflections commanded in the study. The pilots were asked to position the wheel according to this scheme.

This did not involve "flying" an airplane model at this point. It was simply a one-dimensional task to see if some combinations of friction, damping, and inertia were better than others for the pilots' ability to precisely position the wheel.

In looking at some results, the time period just after the full left wheel input will be examined.

Human Centered Design
Some Results



Some sample results are given here. In the time history plots, wheel position is on the top, wheel force is on the bottom.

For the configuration on the left, it is clear that the pilot was able to achieve the desired wheel positions accurately and quickly with little overshoot. Good damping is seen on the lower force trace, wherein the pilot used a small but well damped oscillatory force input in order to get a good square shaped response.

For the configuration on the right, it is just as clear that the pilot is having difficulty achieving the desired wheel positions. The force oscillatory at the corner points is not as well damped as before, and larger in magnitude.

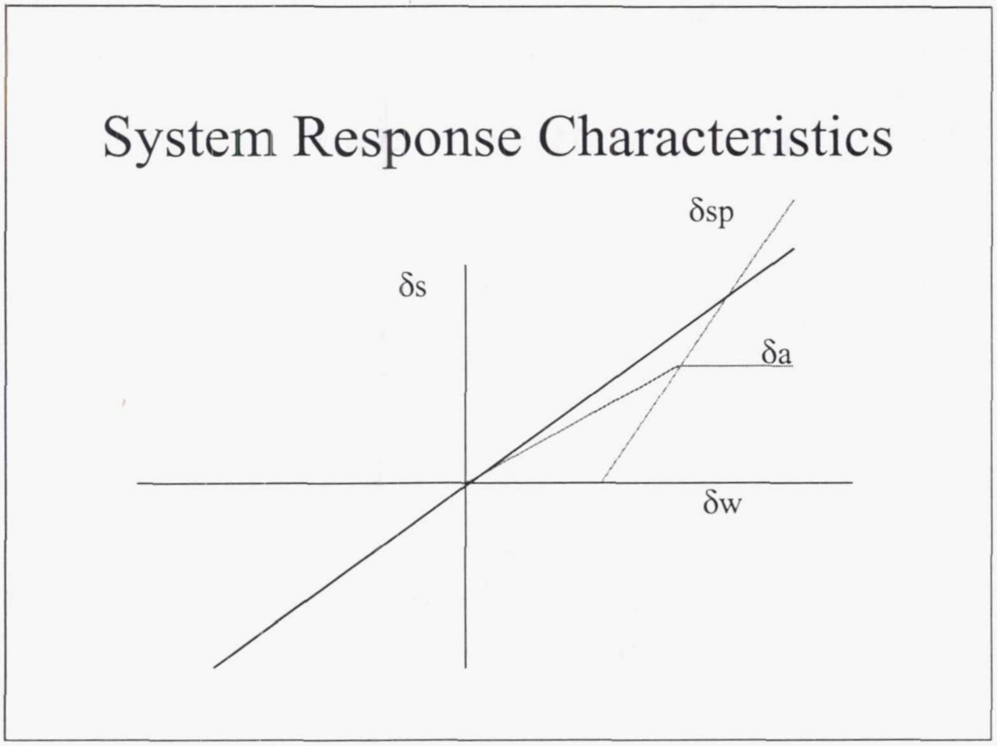
Application of Results

- "Best" Configurations (and one "Bad" one) Flown in Simulation for Pilot Opinion
- Best of Those Configurations Flown in Flight Test
- ...Results Indicate Improved Pilot Opinion, Improved Precision (Pilot Performance), and Less Structural Excitation

With the results from the single axis wheel positioning task, the "best" configurations were flown along with an airplane model, still in simulation, asking the pilot to perform operational tasks. This was also done with one configuration deemed "bad" by the single axis task, just to insure that the first results were not misleading.

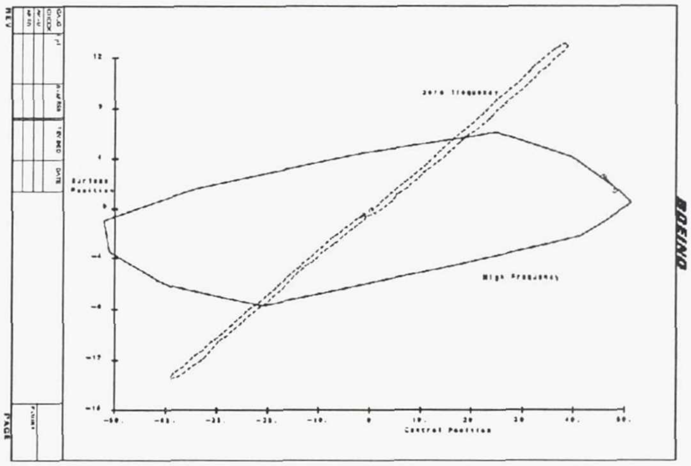
The best combinations of friction, damping, and inertia from simulation were flown in flight test (airplane systems were modified to match the characteristics determined in simulation).

The results of the flight testing indicated that pilots did indeed both prefer the new feel configuration and found that it afforded them a higher level of precision in their maneuver performance. An unexpected benefit was the realization that with the new configuration maneuvers could be flown with less structural excitation.



As was mentioned earlier, on modern jet transport aircraft, the roll control surfaces are often scheduled separately as a function of controller deflection. Ailerons and spoilers are often actuated on different schedules and with different rate capability actuators.

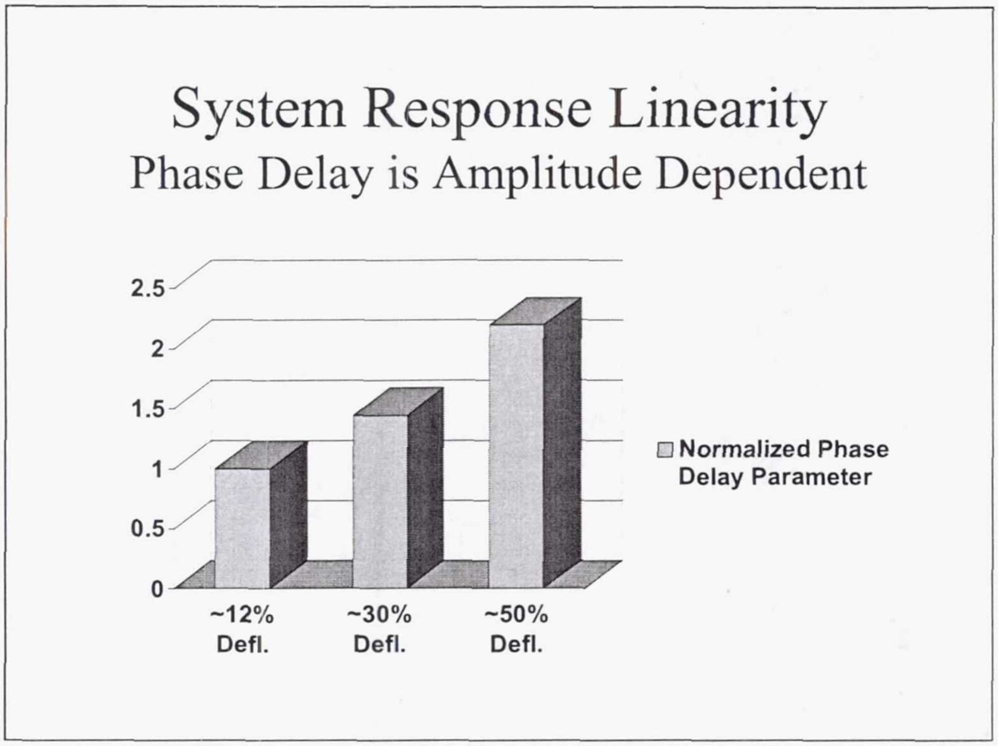
Effect of Frequency on System Performance



The presence of rate limits in any element of the system generates ambiguity with respect to surface position which is a function of the frequency of the controller motion.

Shown here is controller position vs surface position. For the near-zero frequency case, the relationship is indeed close to linear. However, at larger frequencies, particularly past that required to saturate actuator rate limits, the relationship becomes more ambiguous.

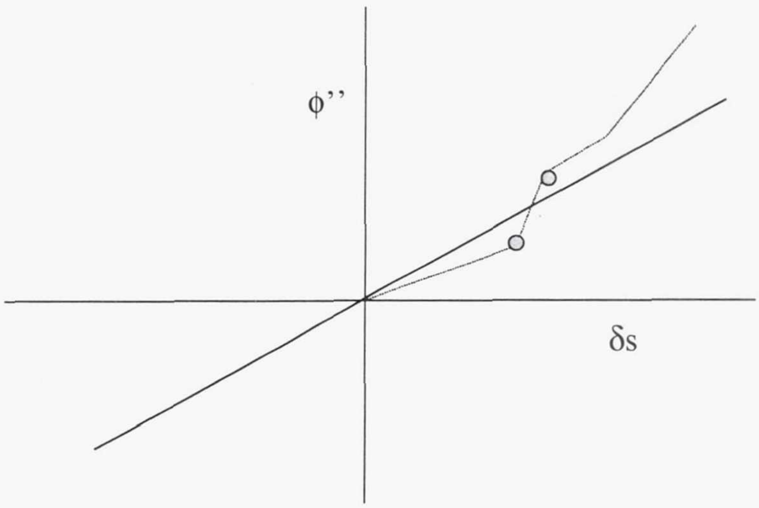
To the pilot, this means that at any point in time, the surface position may not correspond to the controller position.



For cyclic motion of the controller, the rate limits are reached at different frequencies for different amplitudes of motion. This will show up as a non-constant phase delay parameter as a function of controller deflection.

Shown here are results of frequency sweeps done at three different amplitudes, indicating that at larger deflections, the apparent phase delay can become significantly larger than at lower deflections. This can come as a surprise to the pilot who had predictable characteristics with smaller deflections.

Aerodynamic Response Linearity Generates Gradient Ambiguity



The final element in the nonlinear control response story is the aerodynamic response to surface deflection. While it is desirable to achieve a linear response to surface deflection, such is simply not always the case.

For the same reasons that the control force characteristics produce ambiguity, discontinuities in aerodynamic response do as well. For example, consider a pilot holding a sideslip requiring a surface deflection between the two yellow points. Correction for gusts which may force a deflection which crosses one or both points, will result in the pilot geting less response than was commanded based on the first seen gradient. This lack of predictability can result in loss of precision and frustration on the part of the pilot.

The Result Is Really Difficult to Analyze

- Modern Airplanes Have Many Nonlinear Elements
- Pilots are Quite Adaptable Controllers
- Current Theory is Inadequate for these Cases

The end result of all of these nonlinear elements is of course that the real airplane is really difficult to analyze with current methods.

Complicating the situation is the fact that pilots, and in particular test pilots, are remarkably adaptable controllers. They may compensate for these elements without being aware that they are, and they may not be able to communicate to the engineer the full consequences of the situation.

Finally, the state of the art in analytical techniques is not felt to be to the point at which these elements can be addressed adequately, and in particular with regard to PIO tendencies.

Pilot / Management Perceptions

There's a Fine Line Between:

Looking for a PIO

Proving That There's Not One There

Ultimately, the pilot is on the spot to pass judgment on PIO tendencies.

Often, the pilot (and sometimes managers who listen to them) will believe that the engineer wants the pilot to induce a PIO. In fact, the engineer usually wants to demonstrate that the pilot will not induce a PIO. The difference between these two situations is often very fine.

In any case, encountering such an event is usually seen as an honest-to-goodness out of control situation, which is generally considered not a good thing. Arriving at an agreed upon set of conditions which will both adequately explore the pilot/vehicle combination and retain adequate safety margins is a very important step in the process.

The Pilot is Part of the Equation

- Pilot "Gain" is Important in Closed Loop Performance and Stability
- Pilot "Gain" is not Easily Controlled
- Standardized Evaluation Tasks will Require a Consistent Level of Pilot Agressiveness

A very important part of the pilot/vehicle combination is of course the pilot himself. An important part of the stability of the combination is the pilot "gain". Unfortunately, most pilots don't change their gain at will. A few can increase their gain when asked, but it is rare that a pilot, once in a "high gain" situation can choose to reduce it.

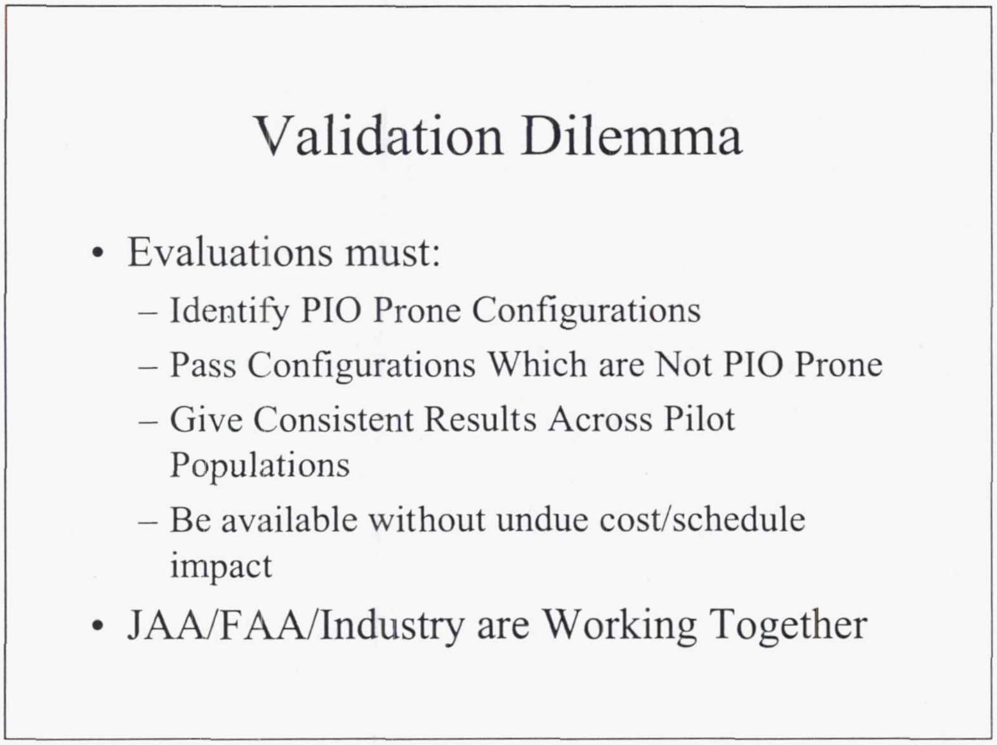
If a standardized evaluation is to take place, there must be a way to normalize pilot aggressiveness across pilots and across individual evaluations. This is essential precisely because of the extreme dependence of the result (PIO or no PIO) on pilot gain.

Techniques to Boost Aggressiveness

- Maneuver Performance Requirements
  - Extreme Precision in Performance
  - Mandatory Control Positions (on stops)
- Urgent Flight Situation
  - Close to the Ground
  - Close to Another Airplane
- Consistency is Difficult to Achieve

Given what was said above about aggressiveness, it should be noted that there are known ways of increasing an individual pilot's gain in a given situation. These include maneuver performance control and control of the urgency of the flight situation.

What remains uncertain, though is a way to achieve consistency. Without that, consistent evaluations will be difficult to achieve.



What can be said about techniques for validating that a configuration is free of PIO tendencies is what an evaluation criterion must do.

Accurate identification of PIO prone configurations is obviously an important characteristic of any evaluation technique.

Equally important is the ability to pass configurations which are not PIO prone. False positives can result in wasted time and energy in identifying unnecessary solutions.

Any proposed evaluation technique must give consistent results across pilot populations so that the results do not depend on which pilot does the evaluation.

Finally, any evaluation technique should be available without undue cost or schedule impact.

The dilemma is of course that there is no evidence that an evaluation metric is available which meets these criteria.

The good news is that the world's regulatory authorities for transport aircraft are actively working together to monitor the situation and act if appropriate.

Summary

- Boeing's Experience in Testing for PIO is Extensive
  - Generic Testing Program is in Place
  - Database is Being Built / Lessons are Recorded
  - Toolbox is Growing
  - Effective Validation Maneuvers are Elusive
- Many Analysis Details are Available for Consideration
- Most Effective Prevention Strategy is Prudent Handling Qualities Design Practice
- Pilots Are a Key Ingredient: They Must be Involved
- Most Effective Testing Stragegy Appears to be Careful Diligence in Normal Test Flying
- The Process Continues to Evolve

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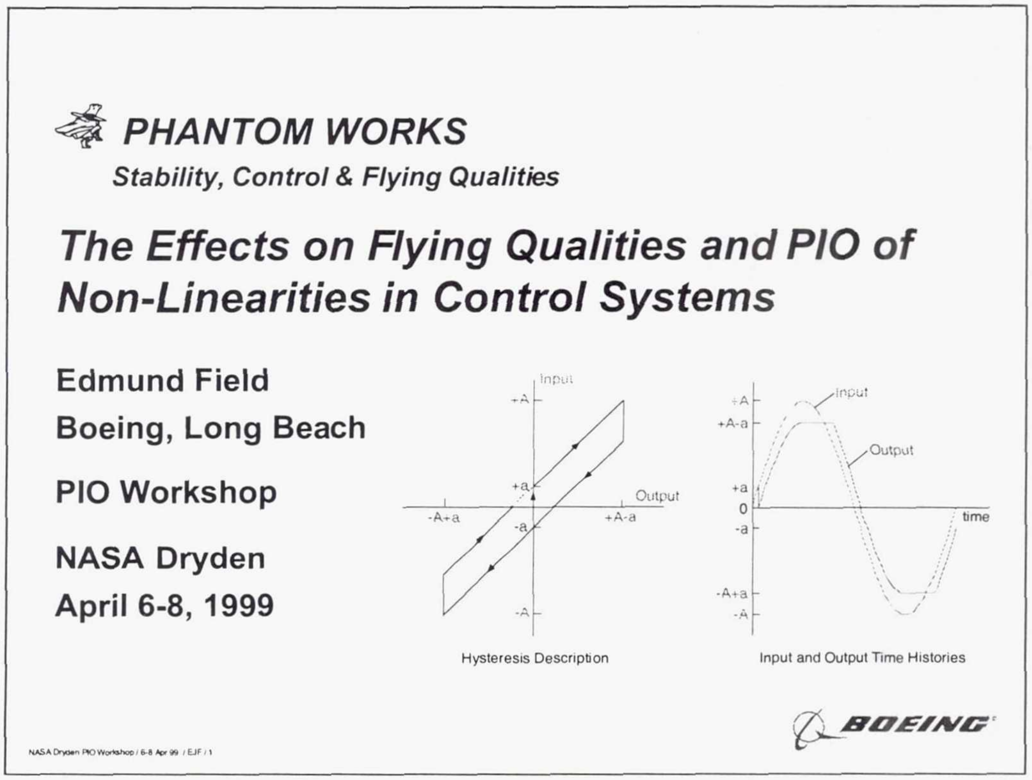


Factors that cause Category I PIOs have received much attention over many years, resulting in the development of many PIO prediction criteria.

More recently attention has turned to Category II PIOs, those that include non-linear effects such as rate limiting. Other sources of non-linearity also exist in an aircraft's control system, however, these have received less attention.

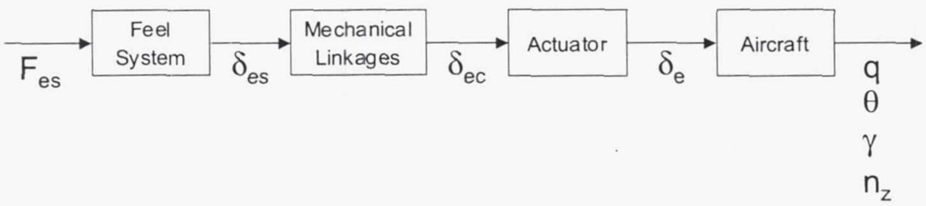
This presentation discusses some recent experience with non-linear elements in control systems, and their implications for flying qualities and PIO susceptibility.

PHANTOM WORKS
Stability, Control & Flying Qualities

The Effects on Flying Qualities & PIO of Non-Linearities in Control Systems

Background

Most Flying Qualities and PIO criteria assume linear models for all elements in the total control / aircraft system



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Most flying qualities and PIO prediction criteria assume linear models for all elements in the total control / aircraft system. That includes linear models of the feel system, the mechanical linkages, the actuators and the aircraft dynamics.

Category I PIO criteria concern only linear causes of PIO.

Category II PIO assume non-linearities due to rate limiting only, all other elements in the total control / aircraft system are assumed linear.

While this may be reasonable for a first approximation, in reality all these elements include some non-linearities. The total contribution of all these non-linearities may become appreciable and so have important implications for an aircraft's flying qualities and PIO susceptibility.

For example, hysteresis in the feel system is a well known phenomenon, and yet its effect on an aircraft's flying qualities are neglected when performing linear analyses. To some extent its effects can be neglected if the analyses use control inceptor position (as opposed to force) as the input. However, the effects of the hysteresis should be taken into account elsewhere. Current criteria for this are lacking.

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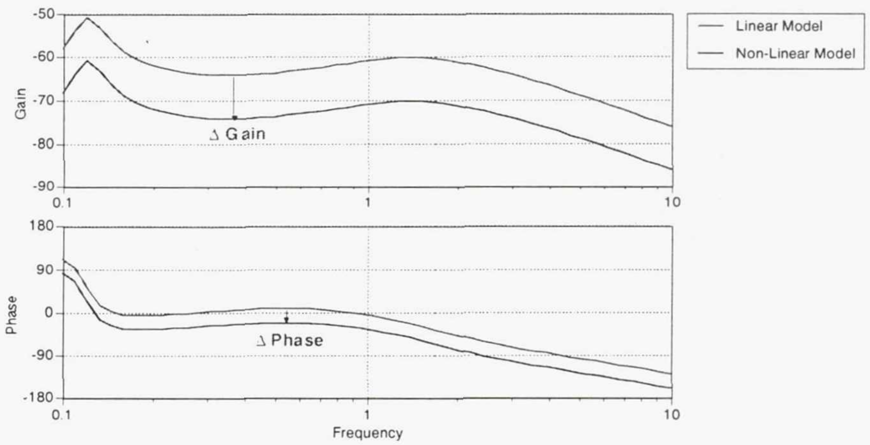
Stability, Control & Flying Qualities

The Effects on Flying Qualities & PIO of Non-Linearities in Control Systems

Analysis of Pitch Frequency Sweeps Identified Phase Loss at all Frequencies

This phase loss may have been caused by non-linearities in the control system



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When analyzing data obtained from pilot generated pitch axis frequency sweeps a phase loss was identified at all frequencies in the Bodes of stick force to aircraft response. It was suggested by Mr. Dave Mitchell that this phase loss may have been caused by non-linearities in the control system, specifically hysteresis.

Categories of Non-Linearities

Input/Output Relationship	Simple	Complex	
Phase Angle	Zero	Non-Zero	
Amplitude Dependent?	Yes	Yes	
Frequency Dependent?	No	No	Yes
Examples:	Friction Threshold Saturation	Hysteresis Toggle Elementary Backlash	Backlash with Coulomb Friction

There are several categories of non-linearity that may be present in an aircraft's control system These may be represented by either simple or complex describing functions[1].

Simple non-linearities exhibit gain attenuation, but no phase attenuation. The gain attenuation is independent of the frequency of the input, but dependent upon the magnitude of the input amplitude. Examples include friction, threshold and saturation.

Complex non-linearities exhibit both gain and phase attenuation. The magnitude of the gain attenuation is dependent upon the magnitude of the input amplitude, and may or may not be dependent upon the frequency of the input. Examples of frequency independent complex non-linearities include hysteresis, toggle and elementary backlash. Frequency dependent non-linearities include backlash with Coulomb friction.

Various of these non-linearities may be present in an aircraft's control system. When added together, from the pilot applying a force to the control inceptor to the aircraft responding, there may be appreciable gain and phase attenuation at all frequencies.

1 Graham, Dunstan, and McRuer, Duane, "Analysis of Nonlinear Control Systems", John Wiley and Sons, 1961

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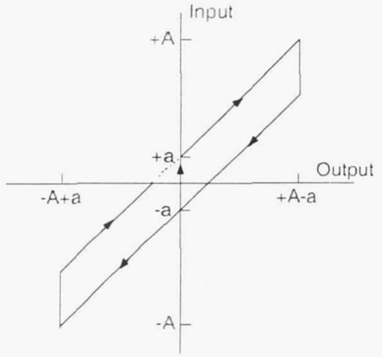
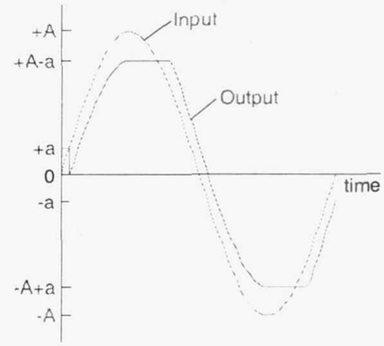
Stability, Control & Flying Qualities

The Effects on Flying Qualities & PIO of Non-Linearities in Control Systems

Hysteresis - An Example Control System Non-Linearity



Hysteresis Description



Input and Output Time Histories

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Hysteresis is a well known non-linearity which is present in aircraft feel systems. The effects of hysteresis will be discussed as a representative example of control system non-linearities.

Hysteresis is a complex non-linearity which produces gain and phase attenuation independent of the frequency of the input.

In the following discussion the characteristics of hysteresis will be described by the magnitude of the non-linearity 'a' and the magnitude of the input signal 'A'.

The effect of the non-linearity in the time domain is evident in the figure. The magnitude of the output is limited to 'A-a', and the output is lagged behind the input, as well as the shape being modified.

The magnitude limiting causes the gain attenuation and the lag provides the phase attenuation that is evident in the Bode plots.

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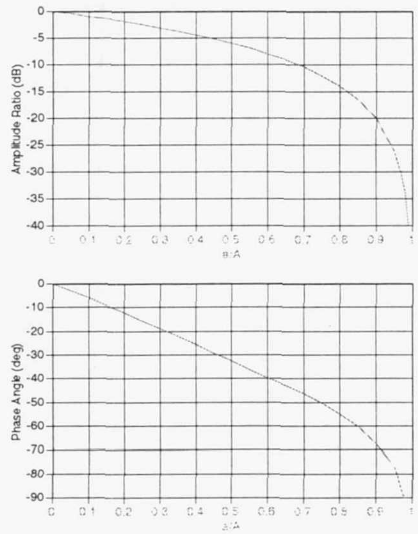
Stability, Control & Flying Qualities

The Effects on Flying Qualities & PIO of Non-Linearities in Control Systems

Sinusoidal Describing Function for Hysteresis



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The sinusoidal describing function for hysteresis is shown graphically. The magnitude of the gain and phase attenuation provided by the hysteresis is simply a function of the ratio of the magnitudes of the non-linearity to the input, 'a/A'.

When 'a/A' is zero (i.e. zero deadband) there is no gain or phase attenuation. As 'a/A' increases both gain and phase loss increase as the effect of part of the applied force is now lost in the deadband zone (-a to +a). As 'a/A' increases towards 1 (all applied force is in the deadband region) the gain and phase attenuation approaches infinity, there is no output to the corresponding input.

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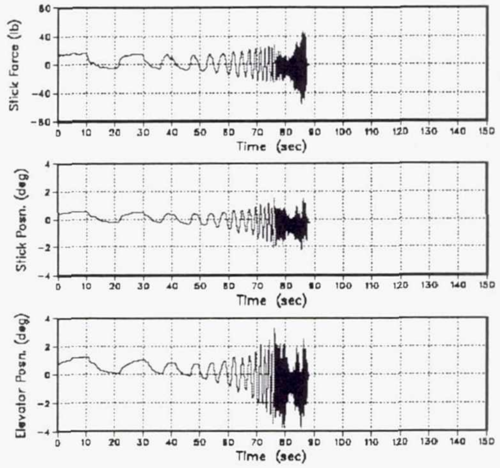
Stability, Control & Flying Qualities

The Effects on Flying Qualities & PIO of Non-Linearities in Control Systems

Time Histories from Typical Piloted Sweep

Input Magnitude (A) Increases as Frequency Increases



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Although hysteresis is a frequency independent non-linearity, the attenuation it introduces may vary with frequency indirectly.

The figure shows time histories taken from a typical piloted frequency sweep. It can be seen from the figure that as the frequency of the pilot inputs increases the magnitude of the inputs ('A') also changes. Generally, as the frequency increases so does the magnitude, although this is not universally true.

The implications for the analysis of frequency sweep data is that the attenuation introduced by any non-linearities may be affected by the frequency/magnitude relationship of the input.

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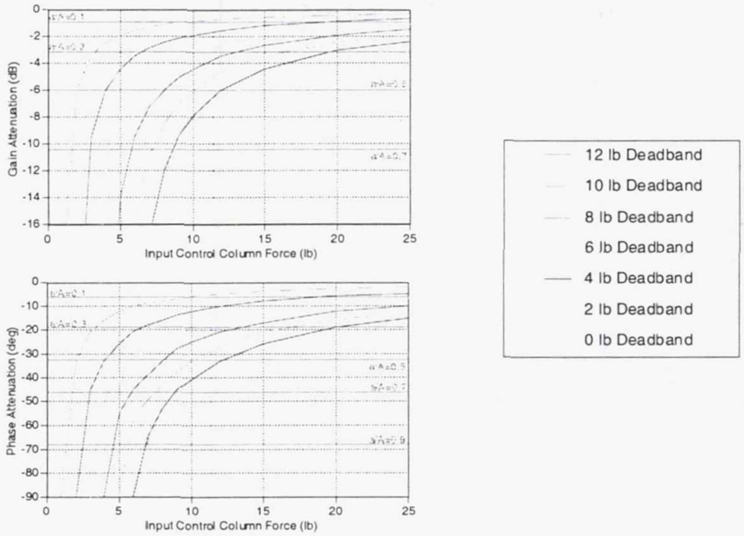
Gain & Phase Attenuation Relationship to Deadband Magnitude



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The gain and phase attenuation provided by hysteresis is a function of the magnitudes of the non-linearity ‘a’ and the input sinusoid ‘A’. During a frequency sweep, such as that shown on the previous slide, ‘a’ remains constant, but ‘A’ varies, possibly with frequency. The figures show the variation in gain and phase attenuation with input magnitude ‘A’ for 7 different values of non-linearity ‘a’. Also included are lines of constant ‘a/A’, taken from the slide before the previous .

For a constant deadband ‘a’, as ‘A’ increases ‘a/A’ will reduce. This can be seen by following a line of constant deadband, for instance the solid bold line for a deadband of 8 lb (a = 4 lb either side of trim, to give a total deadband of 8 lb). For low force inputs ‘a/A’ is high, about 0.9 at 4.5 lb. As the magnitude of the inputs increase ‘a/A’ reduces, so that at 6 lb input ‘a/A’ is 0.7, at 8 lb ‘a/A’ is 0.5 and at 13 lb ‘a/A’ is 0.3. As the force increases and ‘a/A’ decreases the curves of constant deadband flatten. The change in gain and phase attenuation with increasing applied force becomes minimal. Physically, this is because the effect of the deadband becomes reduced as the available applied force ‘A-a’ becomes much larger than ‘a’.

The implications for piloted frequency sweep generated data are that the gain and phase attenuation introduced by the non-linearities will be dependent upon the magnitudes of the input, and to some extent will vary with frequency. This makes the prediction of the effects of the non-linearities more difficult.

Implications for Flying Qualities and PIO Susceptibility

- The phase and gain attenuation introduced by non-linearities in the control system will have implications for the flying qualities and PIO susceptibility of the aircraft
- The gain and phase attenuation will be greatest for small control inputs, such as during fine tracking tasks
- Non-linearities in aircraft control systems should be minimized to reduce these effects
- Caution must be taken when applying flying qualities analyses

The phase and gain attenuation introduced by non-linearities in the control system will have implications for the flying qualities and PIO susceptibility of the aircraft.

The greatest attenuation will be observed when making small control inputs, such as during fine tracking tasks. Susceptibility to PIO will be greatest for these tasks.

Where possible, the non-linearities in aircraft control systems should be minimized to reduce the attenuation effects they introduce.

When performing flying qualities analyze it is important to appreciate the effects that control systems non-linearities have on an aircraft's flying qualities and PIO susceptibility. Linear analyses that exclude these non-linearities are prone to error, and are likely to predict better flying qualities and lower PIO susceptibility than the real aircraft will exhibit.

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The Effects on Flying Qualities & PIO of Non-Linearities in Control Systems

Implications for Flying Qualities Analyses

Aircraft Models:

- Usually linear models are used. They do not include phase attenuation characteristics of non-linearities

Flight Data:

- Complete non-linear aircraft. Data does include phase attenuation characteristics of non-linearities
- The effects of the non-linearities dependent upon the magnitude of the control inputs

Inceptor Force or Position?:

- Control inceptor force or position can be used as input. Using position avoids the effect of the inceptor hysteresis, a major contributor to the phase attenuation
- Elements between the feel system and actuator will be present in both force and position analyses

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Control system non-linearities introduce several implications for performing flying qualities analyses. It is important that appropriate analyses are performed and that criteria are applied consistently.

When analyzing aircraft models usually only the linear dynamics are considered, and the non-linearities are neglected. Data obtained in-flight represent the total non-linear aircraft. Care must be taken when comparing results from analyses of the linear model and flight derived data. Additionally, data obtained in-flight will be dependent upon the magnitude of the input.

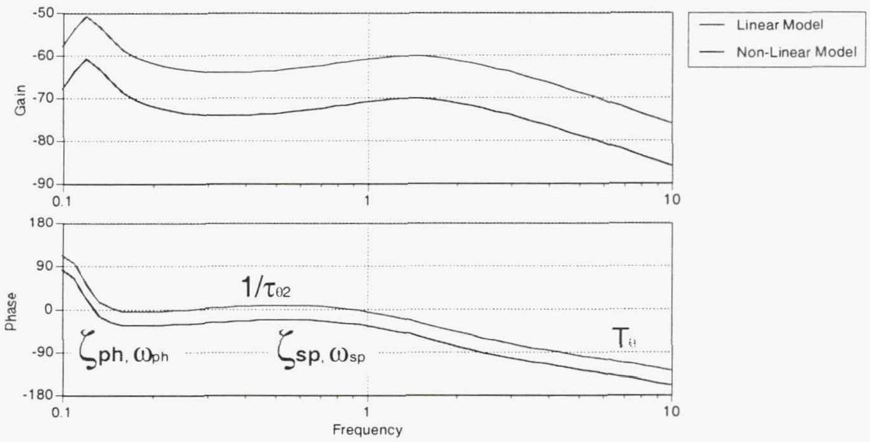
The choice of whether to use stick force or stick position as the input for such analyses will affect the results, since the feel system includes non-linear effects such as hysteresis. Using stick position will limit the included non-linearities.

The implications of analyzing data from the non-linear model (or flight derived data) will be demonstrated against two popular flying qualities analyses:

- Low Order Equivalent Systems
- Bandwidth Criterion

Low Order Equivalent Systems (LOES)

To achieve a good match the LOES dynamics may be altered to account for the phase loss. In the Pitch axis, particularly ζ_{ph}, ζ_{sp}, T_θ and perhaps ω_{ph}, ω_{sp}, $1/T_{\theta 2}$



For a constant gain attenuation at all frequencies the only impact on the LOES fit will be a lower gain factor. If the gain attenuation is not constant across all frequencies then the poles and zeros may be affected, possibly resulting in changes to the equivalent short period frequency and damping. Any phase attenuation, regardless of whether frequency dependent or independent, will result in different LOES matches between the linear and non-linear models.

A constant phase loss across all frequencies will likely be matched by an increase in the equivalent damping ratios of the oscillatory modes (ζ_{sp} and ζ_{ph}), spreading the phase reduction across a wider (and so lower) frequency range. If this alone is unable to provide sufficient phase loss it may also be necessary to reduce the equivalent frequency of the oscillatory modes (ω_{sp} and ω_{ph}). Additionally the numerator term $1/T_{\theta 2}$ may also move, partly to offset the movement of the poles. The equivalent time delay term, T_θ, will be adjusted to account for any high frequency offset that is either residual from or caused by the movement of the poles and zeros. Note also that T_θ will also be affected if there is any frequency dependent gain attenuation that causes movement of the poles and zeros.

ω_{sp} and $1/T_{\theta 2}$, are both factors in CAP. A PIO prediction criterion based upon CAP and T_θ has been proposed. Clearly, any inaccuracies in the prediction of these parameters will affect the prediction of an aircraft's susceptibility to PIO. The likely effect of hysteresis is to increase an aircraft's PIO susceptibility.

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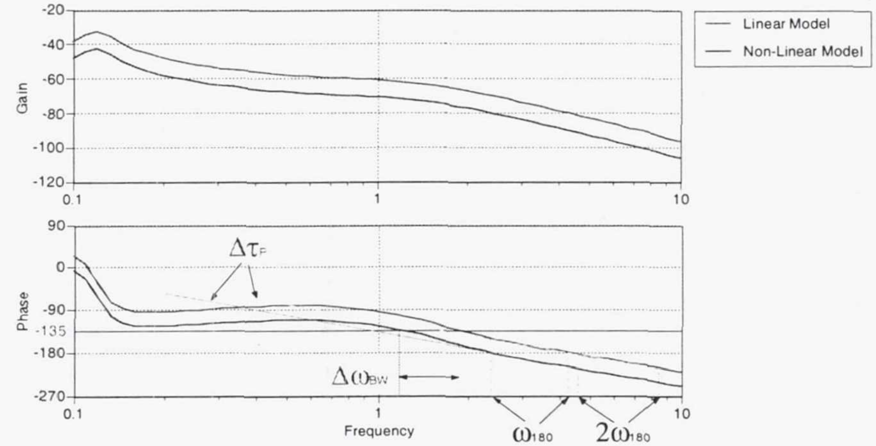
Bandwidth Criterion

To account for the phase loss the Bandwidth frequencies (both attitude and flight path) will be reduced. τ_p may be affected, depending upon the type of non-linearity.



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As with LOES, a constant gain attenuation at all frequencies will not affect the Bandwidth criterion parameters. Even if the gain attenuation is frequency dependent it is unlikely to affect the Bandwidth criterion parameters since most aircraft are phase Bandwidth limited, and whatever causes the gain response to attenuate is likely to have a greater effect on the phase response.

Any downward shift of the phase response will have a direct effect on the Bandwidth frequency, reducing it by $\Delta\omega_{BW}$. Since τ_P is proportional to the slope of the phase curve between ω_{180} and $2\omega_{180}$ it will be affected slightly by a downward shift in the phase response, as can be seen in the figure. However, τ_P may be affected even more if the slope of the phase response is dramatically different between the ω_{180} and $2\omega_{180}$ frequencies of the linear and non-linear models.

ω_{BW} and τ_P are variables in a proposed PIO prediction criterion. Clearly their accurate definition is important if the PIO prediction criterion is to be valid. As with LOES, the omission of non-linearities from the analysis is likely to predict the aircraft less PIO susceptible than it really is.

Conclusions

- Non-Linearities in control systems can introduce gain and phase attenuation
- Depending upon the type of non-linearity, the attenuation may be frequency and / or input magnitude dependent
- FQ analyses performed with and without the non-linearities will yield different results
- This may account for inconsistent predictions from flying qualities analyses of linear and non-linear models and flight data, and when including and excluding the feel system

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Recommendations

- Non-Linearities in control systems must always be considered when addressing an aircraft's flying qualities
- This might be achieved through the development of a criterion accounting for all non-linearities in a control system. This metric might be additive to existing criteria

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Mitigating the APC Threat - a work in progress

Ralph A'Harrah

APC Workshop
DFRC
6-8 April 1999

My Perspective

- **What I would do** if I was responsible for
  - Research
  - Design & Development
  - Flight Test
  - Certification
  - Airline Safety
  - Accident Investigation

... relative to mitigating the APC threat

2

Mitigating the APC Threat - AT

Cat. II APC Research

- **Task Identification**
  - e.g., a large ("over driving") correction to an upset, followed by closed-loop control to get back on original flight path
- **Subject Identification**
  - e.g., APC evaluation results from naïve "line" pilots compared with experienced test pilots
- **Vehicle Identification**
  - Variable stability aircraft, or ground based flight simulator, or actual aircraft

continues

2

Mitigating the APC Threat - AT

Cat. II APC Research, continued

- Design and demonstrate a control system that is free from Cat. II APC characteristics for a wide range of surface rate limits (e.g., from 1% to 100% of the maximum achievable surface rate)

3

Mitigating the APC Threat - AT

Design & Development

- **Incorporate favorite PIO criteria into Mark Tischler's Conduit* Program to address Cat. I**
- **Minimize the actuator energy metric (cost function) in Conduit (Control Designer's Unified Interface)**
  - to reduce probability of "over driving" beyond rate limits, a Cat. II condition
  - to increase actuator life
- **Utilize tactile control feedback[1] on primary controls to warn of approach to rate and/or position limiting, with active stops to preclude "over driving"**

continues

[1]analogous to NRC's collective limit cueing, AvWk, p.53, 22Feb99

3

Mitigating the APC Threat - AT

Design & Development, continued

- Backup tactile control feedback on primary controls design with adaptive filtering[1,2] to compensate for time delay caused by "over driving"
- Isolate pilot controlled surfaces and actuators from non-pilot controlled surfaces and actuators
  - Reduce erosion of pilot control response and authority from non-piloted intrusion

[1]Hanke, Dietrich, Phase compensation: a means of preventing APC caused by rate limiting, Forschungbericht 98-15

[2]Runqudqwist, Lars, Phase compensation of rate limiters in JAS-39 Grippen, AIAA Paper 96-3368

4

Mitigating the APC Threat -

Ground/Flight Test

- From ground calibration tests, determine the cockpit controls to surface response time delay and hysteresis characteristics for inputs up to the maximum input rate & deflection capability of the pilot
- If values exceed expectations /guidance /specifications, evaluate options for improvement
- Alternately, evaluate on variable stability aircraft while performing off-set landing, large upset correction, etc., Cat. 2 APC maneuvers to define criticality of the problem

Note: The issue here is the consistent ability of line pilots to accommodate the change in time delay and hysteresis characteristics that may be experienced as part of a "hair raising" experience such as a large upset, or an *eminent inflight*

4

Mitigating the APC Threat -

Certification

- Continue APC exposure/training of certification pilots, using a variable stability aircraft
- Emphasize the determination of evaluation tasks for Cat. II APC that are both safe and effective
- Evaluate in flight APC Cat. I characteristics using existing FAA APC testing bench mark tasks
- Would not attempt Cat. II in-flight evaluation until ~~safe~~ and effective test technique is identified

continues

5

Mitigating the APC Threat -

Certification, continued

- From ground calibration tests, determine the cockpit controls to surface response time delay and hysteresis characteristics for inputs up to the maximum input rate & deflection capability of the pilot

continues

5

Mitigating the APC Threat -

Certification, continued

- If time delay or hysteresis values exceed expectations /guidance /specifications, evaluate on variable stability aircraft while performing off-set landing, large upset correction, etc., Cat. 2 APC maneuvers

Note: The issue here is the consistent ability of line pilots to accommodate ~~the change~~ in time delay and hysteresis characteristics that may be experienced as part of a "hair raising" experience

6

Mitigating the APC Threat -

Airline Safety

- For the cockpit primary control inputs and the resulting control surface outputs, record at data rates of 20 Hz or greater on the QAR
- Initial APC Precursor
  - Monitor QAR data for the time lapse between reversal of the cockpit control rate and the associated reversal of the surface rate as APC precursor
    - Flag occurrences with $t_D > 100$ msec.
    - Flag & record values of t_D when $t_D > 150$ msec.
- Involve APC specialist for consistent flags, or values of $t_D > 150$ msec.

continues

6

Mitigating the APC Threat -

Airline Safety

- Growth APC Precursor
  - Utilize 20 Hz. or greater data rates on primary controls, primary control surfaces, aircraft accelerations, and warning, such as "stall" and "over-speed"
  - Utilize QAR data to support Conduit as a monitor
    - Flag occurrences violating Level 1 criteria.
    - Flag & record values of t_D when $t_D > 150$ msec., and Level 2 criteria.
    - Involve APC specialist for consistent flags, or values of $t_D > 150$ msec

7

Mitigating the APC Threat -

Accident Investigation

- For the primary cockpit flight controls, the associated control surfaces, and aircraft accelerations felt by the pilots, require that crash recorders utilize data rates of 20 Hz or greater
  - when the flight crew is actively involved with primary flight controls
  - when an emergency has been declared

continues

7

Mitigating the APC Threat -

Accident Investigation, continued

- In an investigation exhibiting significant crew control activity, examine the time lapse between cockpit control inputs, the associated control surface responses, and accelerations (or other response metrics, such as warnings) to which the pilot may be responding
- If the time lapse exceeds 100-150 msec., include a team of APC specialists as part of the investigative team

8

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The workshop "Pilot-Induced Oscillation Research: The Status at the End of the Century," was held at NASA Dryden Flight Research Center on 6–8 April 1999. The presentations at this conference addressed the most current information available, addressing regulatory issues, flight test, safety, modeling, prediction, simulation, mitigation or prevention, and areas that require further research. All presentations were approved for publication as unclassified documents with no limits on their distribution. This proceedings includes the viewgraphs (some with author's notes) used for thirty presentations that were actually given and two presentations that were not given because of time limitations. Four technical papers on this subject are also included.

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