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NASA's Flying Qualities Research Contributions to MIL-STD-1797C

Technical Report No. 26-1

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May 2020

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1.0 Introduction

1.1 Background

The US Department of Defense Interface Standard for Flying Qualities of Military Aircraft, MIL-STD-1797B,[1] contains both quantitative and qualitative requirements that are based on decades of flight and ground-based research and testing. The caretaker of the document, the U.S. Air Force, plans an update in the future.

MIL-STD-1797B is the latest in a long succession of standards and handbooks for flying qualities of piloted aircraft. The first version of the MIL Standard format, intended to replace MIL-F-8785C,[2] was published in an Air Force report as a proposed specification in 1982,[3] using data from a 1969 background document[4] for MIL-F-8785B as a guide. (A later background document for MIL-F-8785C was also released[5] but too late for inclusion in the draft MIL Standard.) The first official standard, MIL-STD-1797(USAF), was released for Air Force use only in 1987.[6] The document has undergone various transformations since then, from a Standard to a Handbook (for guidance only) to a supporting document for Joint Services Specification Guide 2001B,[7] and back to the current Standard.

In 1998 the US Air Force, the supporting agency for all flying qualities research and spec development in the US Department of Defense (DoD), made the decision that the future was in unmanned aircraft and in space, and the dismantling of the Flight Dynamics Branch at Wright-Patterson AFB was begun. As support for flying and handling qualities research at the Air Force has waned over the past twenty years, so has support for incorporation of entirely new sources of research into the revisions to the Standard.[i] This is true for all branches of the US Government, but it is perhaps more pointedly true for work performed or sponsored by NASA. In truth, if all contributions to airplane flying and handling qualities since 1998 were sorted by US agency, NASA and the Navy would almost certainly outperform the Air Force. If the list were expanded to include rotorcraft and V/STOLs, the Army would join NASA and Navy ahead of Air Force.

1.2 Phase I Findings

This report represents the second phase of a multi-phase effort to document NASA's contributions to the military handling qualities specification. The first phase was a literature review to identify those topics that promised the greatest return on investment. The findings for that phase are summarized in a report released in 2018.[8]

As plans for the follow-on technical phase of work were developing, it was learned that a draft version of MIL-STD-1797C was in process, and only high-priority, short-time technical topics were to be considered if they were to be completed in time to be folded into 1797C. The team that assembled the phase I report (Mitchell from Mitchell Aerospace Research, Klyde from Systems Technology, Inc., and Hoffler and Jackson from Adaptive Aerospace Group, Inc.) proposed that

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[i] As a principal contributor to the 1982 draft MIL Standard, one author of this report (DM) recalls receiving specific instructions from the Air Force: do not attempt to bring in new data, but simply convert the old flying qualities specification to the new Standard format, using only the data originally published in the 1969 background document as the supporting material. The authors of the draft Standard struggled with this edict and had no choice but to violate it at times, but even then, there was never a dedicated effort to bring more recent (between 1969 and 1981) research results into the Standard.

the following four topics were the best candidates: High-Alpha Technology, High-Speed Research (including transport aircraft handling qualities), Pilot-Induced and -Assisted Oscillations, and Inceptor Characteristics.

In April 2019, a contract was issued from Analytical Mechanics Associates, Inc. to Mitchell Aerospace Research to conduct the Phase II work. This report presents the outcome of this second phase of work.

1.3 Organization of This Report

This final report is a compilation of efforts from the research team. Topics investigated can be classified into one of three general areas: 1) directly supporting modifications to MIL-STD-1797C; 2) amplifying information for existing requirements without supporting modification; or 3) not yet ready for inclusion but worthy of future investigation. Section II summarizes the recommended modifications to MIL-STD-1797C. Section III introduces amplifying background information, much of which is contained in the Appendices; and Section IV discusses the areas for possible follow-on work, including the justification for cooperative investigations by units of the US Department of Defense in conjunction with NASA.

2.0 Recommended Modifications for MIL-STD-1797C

2.1 Summary

This section documents proposed changes to requirements, background information, lessons learned, and other areas of the current version of the current flying qualities specification, MIL-STD-1797B.

2.2 Additions and Modifications to Verification Under 5.1.1.1 Allowable Levels for Air Vehicle Normal States

MIL-STD-1797B contains a single paragraph (pages 135-136) referencing the Standard Evaluation Maneuver Set (STEMS), developed by McDonnell Douglas. STEMS were first investigated only in a ground-based simulation. In the late 1990’s the US Air Force worked with NASA to conduct flight research into the high-alpha, post-stall maneuvering STEMS, using the F/A-18 High Alpha Research Vehicle (HARV). Five of the STEMS were determined to be sufficiently well-designed to justify their inclusion in a future version of 1797. Following documents changes to 1797B to incorporate those maneuvers.[ii]

[ii] The STEMS maneuvers have been inserted into a draft version of MIL-STD-1797C. This occurred after the start of work on the material included here and was as a direct result of this work. The specific format in the draft 1797C is different, but the material printed here was written to follow the format used in 1797B.

Add to Table VII (pp. 131-132):

Post-Stall Air-to-Air Longitudinal Gross Acquisition	Desired Performance Aggressively acquire target within 80 mils Acquire the target with no more than one longitudinal overshoot
	Adequate Performance Aggressively acquire target within 80 mils Acquire the target with no more than two longitudinal overshoots
Post-Stall Air-to-Air Lateral Gross Acquisition	Desired Performance Aggressively acquire target within 80 mils Acquire the target with no more than one lateral overshoot
	Adequate Performance Aggressively acquire target within 80 mils Acquire the target with no more than two lateral overshoots
Post-Stall Roll Reversal	Desired Performance Aggressively acquire target within 80 mils Acquire the target with no more than one lateral overshoot
	Adequate Performance Aggressively acquire target within 80 mils Acquire the target with no more than two lateral overshoots
Post-Stall Pitch Attitude Capture and Hold	Desired Performance Aggressively acquire target within 80 mils Acquire the target with no more than one longitudinal overshoot
	Adequate Performance Aggressively acquire target within 80 mils Acquire the target with no more than two longitudinal overshoots
Post-Stall Air-to-Air Fine Tracking	Desired Performance Maintain pipper within ±5 mils of aimpoint for 50% of the task Maintain pipper within ±25 mils of aimpoint for the remainder of the task
	Adequate Performance Maintain pipper within ±5 mils of aimpoint for 10% of the task Maintain pipper within ±25 mils of aimpoint for the remainder of the task

Remove and replace the last paragraph on p. 135 (continues on p. 136) as follows:

Another source of closed-loop evaluation tasks is the Standard Evaluation Maneuver Set (STEMS). The initial development work is documented in WL-TR-93-3081, WL-TR-93-3082, and WL-TR-93-3083. The main products of this project were: 1) a process to develop handling qualities evaluation maneuvers, 2) an initial set of 20 evaluation maneuvers tested in ground simulation, and 3) guidelines to help users select appropriate maneuvers. The maneuvers developed were primarily aimed at evaluation of agility and high-AOA flying qualities though some conventional flying qualities evaluation maneuvers were included. AIAA-93-3645 provides a summary of the initial STEMS project.

Flight evaluations of the post-stall STEMS were conducted on the NASA High Alpha Research Vehicle (HARV). Seventeen STEMS were assessed by two NASA test pilots using a questionnaire that rated various factors for the maneuvers. Based on those assessments, five of the STEMS were considered sufficiently mature for handling qualities evaluations based on definition, target set-up, difficulty, repeatability, and similarity to operational tasks. The five STEMS are defined in detail in WL-TR-97-3100 and the recommended performance limits are included in table VII.

Add new references:

NASA/CP-1998-207676/PT2	High-Angle-of-Attack Technology: Accomplishments, Lessons Learned, and Future Directions, June 1998
	"In-Flight Evaluation of the Standard Evaluation Maneuver Set (STEMS) with the NASA F/A-18 HARV," Klyde, D. H., K. D. Citurs, N. Fawer, and D. G. Mitchell
WL-TR-97-3100	Handling Quality Demonstration Maneuvers for Fixed-Wing Aircraft, Vol II: Maneuver Catalog; Klyde, D. H., and D. G. Mitchell; October 1997

2.3 Modifications to 5.2.3.1.1 Roll Mode and 5.2.3.5 Roll Control Effectiveness (for Transport Aircraft)

Lateral-directional flying qualities are usually defined in terms of the basic lower-order modal characteristics of the free response, with some additional limits on time-domain measures of forced responses. MIL-STD-1797B contains only modal requirements, though dynamic requirements based on non-modal parameters (such as roll attitude Bandwidth) were proposed, at least for fighters,[9] before 1797B was released.

None of the specification requirements is adequately supported by flight data, and this is especially true for the transport (Class III aircraft) requirements. The supporting material for the roll damping limits in MIL-STD-1797B, for example, shows a considerable amount of ground simulation data for fighter-type aircraft, but all of it was before the development of the now-universal Cooper-Harper HQR scale and the rigorous task development process that goes with it.[10] This means all of the supporting data are not to be given too much weight – and none of those data are for transports.

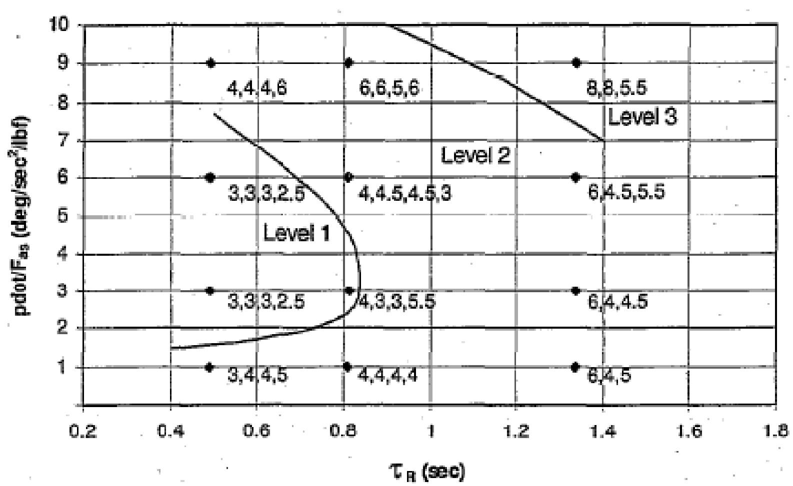
In the early 1980s, Lockheed conducted a study of flying qualities characteristics of Class III aircraft and made numerous recommendations to modify the specification limits.[11] Substantiating data in this study, however, consisted of a combination of the following: 1) a summary of the dynamics of existing aircraft such as the C-5A, C-141, and L-1011; 2) a review of other data to show shortcomings when applied to transports; 3) results of IRAD simulation studies from unpublished reports, with no documentation of task details or evaluation methods; and 4) summaries of HQRs assigned by operational C-5A pilots, unfamiliar with the Cooper-Harper scale, based on a questionnaire and their judgment based on normal flying. This study made such recommendations as increasing roll damping from the military limit of 1.4 seconds to at least 2.3 seconds for Level 1, with a preference to increase it to as much as 4 seconds in cruise.

NASA sponsored an extensive research program in the 1990s to investigate flight control and handling qualities issues for a future Hypersonic Cruise Transport (HSCT). The Hypersonic Cruise

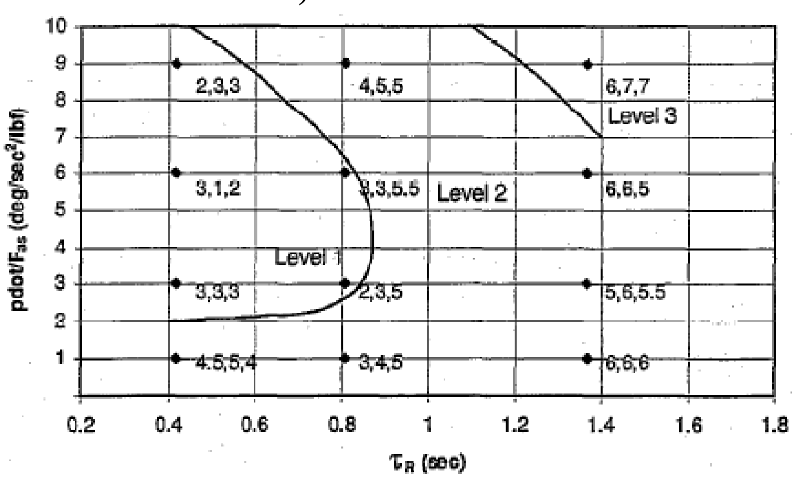
Research (HSR) program included ground-based and in-flight simulations to investigate response requirements for lateral-directional control.

Recommendation for 5.2.3.1.1: decrease Level 1 roll mode time constant limit for transport aircraft from 1.4 seconds for Level 1 to 1.0 second; and decrease Level 2 limit from 3.0 seconds to 2.0 seconds. Modify the following discussion to be incorporated into Requirement Lessons Learned.

One of the simulations conducted as a part of the HSR program investigated roll damping and cockpit roll control sensitivity for a highly-augmented HSR transport model in non-terminal and terminal operations. The study, published in AIAA Paper No. 99-4094, was conducted on the NASA Ames Vertical Motion Simulator (VMS) using a subject aircraft that represented a large, modern, supersonic civil transport with a center control stick. As part of this study, it was found that the current roll time constant requirement of 1.4 seconds for Level 1 for Class III aircraft is too relaxed. This is evidenced in the summary for the results, shown in Figure 1. The results suggest that a roll time constant as short as 0.8 seconds is required for Level 1 for the Terminal and Non-Terminal areas for Class III aircraft.



a) Terminal Area



b) Non-Terminal Area

Figure 1. Proposed flying qualities Level boundaries for roll control sensitivity from AIAA Paper No. 99-4094

The boundaries shown in Figure 1 define the optimum levels of initial roll acceleration per pound force of roll stick input ($\dot{p}/F_{as}$) versus roll mode time constant (τ_R). The suggested boundaries reflect areas where data was available; due to a lack of sufficient data, the Level 2-3 boundary was not fully defined, hence the use of the dashed line to indicate inconclusive regions. These results suggest that roll mode time constant for Level 1 flying qualities is in the range of 0.5-0.8 seconds, significantly faster than the 1.4 second Level 1 limit, thus indicating that this requirement was far too relaxed. The suggested 0.8 second time constant, however, is even more stringent than the 1.0 second Level 1 limit for Class IV aircraft. It is not recommended to require transports aircraft to have roll mode time constants that exceed the requirements for Class IV fighters. As such it is recommended that the current transport Level 1 limit of 1.4 seconds be decreased to match the 1.0 second limit currently set for fighters. The Figure 1 data also suggests that the current transport level 2 limit of 3 seconds is too relaxed. Thus, it is recommended that the current level 2 transport time constant limit of 3.0 seconds be decreased to approximately 2 seconds.

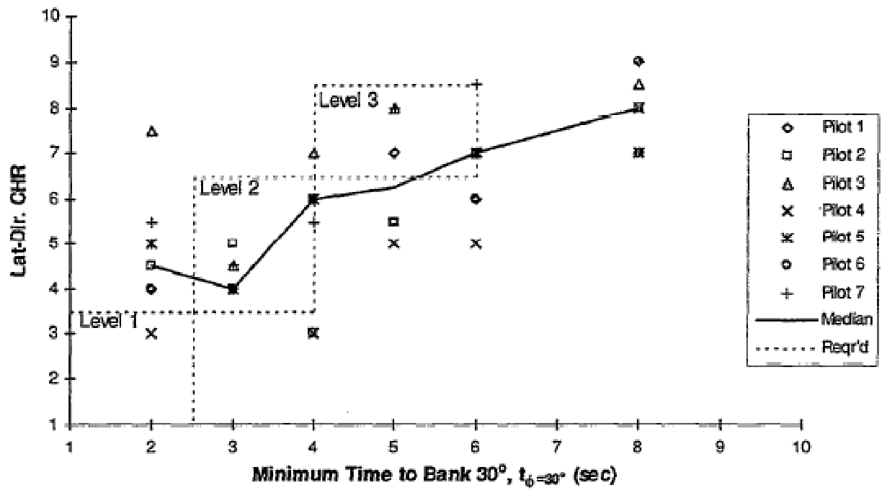
Recommendation for 5.2.3.5: Adopt new roll control effectiveness limits for transports

In AIAA Paper No. 99-4094, new Class III roll performance requirements were proposed based on results of a motion-based simulation study conducted at NASA Ames Research Center. The limits, shown in Table 1, confirmed the current MIL-STD-1797B terminal flight phase requirement and proposed new requirements for the non-terminal flight phases.

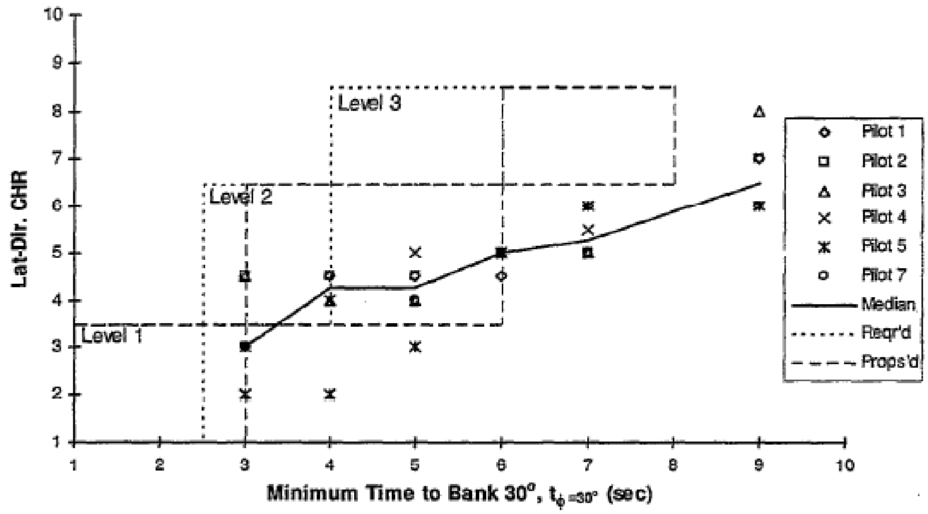
Table 1. Proposed roll control effectiveness criterion from AIAA Paper No. 99-4094

Levels	Minimum Time to Achieve 30 of Bank Angle Change, $t_{\phi=30}$° (seconds)		
	Terminal Flight Phases	Non-Terminal Flight Phases	
	V<200 KEAS	0.32≤M<0.85	0.85≤M<M_{MO}
1	2.5	3.0	3.5
2	4.0	6.0	
3	6.0	8.0	

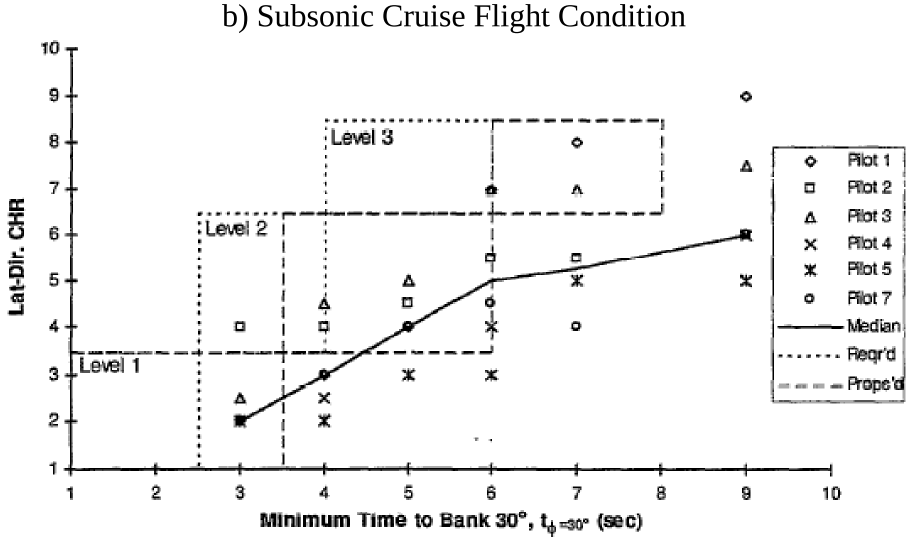
The supporting data from this experiment for these proposed requirements are shown in Figure 2. The results include handling qualities ratings as a function of the minimum time required to reach 30°of bank change, $t\varphi$=30°, for three flight regimes (landing, subsonic cruise, and supersonic cruise). In each figure, the original MIL-STD-1797B boundaries and the proposed boundaries are drawn. The results in Figure 2a confirm the current design requirements of MIL-STD-1797B. For the non-terminal area, however, the MIL-STD-1797B boundaries are shown to be too restrictive. Here, the data suggest that the minimum time to bank 30° for Level 1 performance should be no more than approximately 3.0 seconds for subsonic cruise and 3.5 seconds for supersonic cruise. For Levels 2 and 3, the maximum $t\varphi$=30° can be defined at 6.0 and 8.0 seconds for subsonic and supersonic cruise, respectively. These limits, and in particular that for Level 3, were selected with conservatism following the discovery that rudder inputs were applied by some of the test pilots while evaluating these degraded configurations, and hence, additional roll acceleration due to the subsequent sideslip was generated.



a) Landing Flight Condition



b) Subsonic Cruise Flight Condition



c) Supersonic Cruise Flight Condition

Figure 2. Lateral-directional Handling Qualities Ratings for changes in roll control effectiveness from AIAA Paper No. 99-4094

Add new reference:

AIAA Paper 99-4094	Proposed Roll Control Criteria for the Design of Lateral Control Stick Shaping Functions in Large Transport Aircraft, Shweyk, K. M., K. F. Rossitto; August 1999

2.4 Proposed New Requirement 5.2.2.1.X Pitch Instantaneous Normal Acceleration Response at the Pilot Station

Aircraft with unusual pitch control surface effectors or pilot locations can exhibit short-term accelerations at the pilot station that are confusing, including a sensation of incorrect motion (non-minimum-phase characteristics). This phenomenon was found in NASA CR-163108 to be linked to a pilot-induced oscillation experienced on the Space Shuttle Orbiter during an early landing test. Experiments performed by Calspan in the 1980s and by Boeing in the 1990s confirmed this effect.

In AIAA-2002-4799, the research from Calspan and Boeing was revisited and analyzed to generate a set of guidelines for best placement of the pilot station to produce a desirable instantaneous center of rotation (ICR) response. This research was limited to transports (Class III airplanes) in precision landing, and the guidelines are such that it is unlikely that they can be applied to any other class of aircraft. In addition, the authors of AIAA-2002-4799 state that the guidelines are not suitable as flying qualities criteria, so they are proposed here as guidance for a subjective new requirement.

While the bulk of the research cited in AIAA-2002-4799 was supported by NASA, US Air Force, and Boeing internal funding, the results of the study are sufficient to be considered a NASA-involved research program and to be recommended for inclusion in the next version of the flying qualities MIL Standard. As of this writing, a brief flight test program has been completed at the US Air Force Test Pilot School, using the F-16 VISTA airplane and the NASA Ames Vertical Motion Simulator, to determine if the ICR effects extend to Class IV airplanes. The outcome of that study may have an impact on a final recommended requirement for the MIL Standard.

5.2.2.1.x Pitch instantaneous normal acceleration response at the pilot station.

The instantaneous response of normal acceleration at the pilot station to the pitch controller shall not be objectionable to the pilot.

2.4.1 Requirement Rationale

Unusual aircraft configurations that result in undesirable location of the pitch instantaneous center of rotation (ICR) with respect to the pilot station can result in degraded handling qualities, especially in the landing flare. This was found to be true whether the pilot is located far behind, or far ahead of, the ICR, though the former has been demonstrated to be a contributor to PIO.

For a conventional transport airplane, the immediate flight path response to a nose-up pitch command will differ depending on where the response is measured, as sketched in Figure 3. The ICR is defined as the location where the initial response is zero; forward of the ICR the initial response is quickened, and aft of the ICR it is delayed. In the sketch, the ICR is in a typical location for conventional airplanes, ahead of the cg but behind the pilot. An abrupt nose-up command will generate an initial sensation of increased flight path angle (and normal acceleration) compared to that at the cg. In the case of the Space Shuttle Orbiter the ICR was actually not located on the aircraft at all, but several feet ahead of the aircraft: an initial nose-up command, such as in landing flare, would cause the entire aircraft to sink initially before climbing.

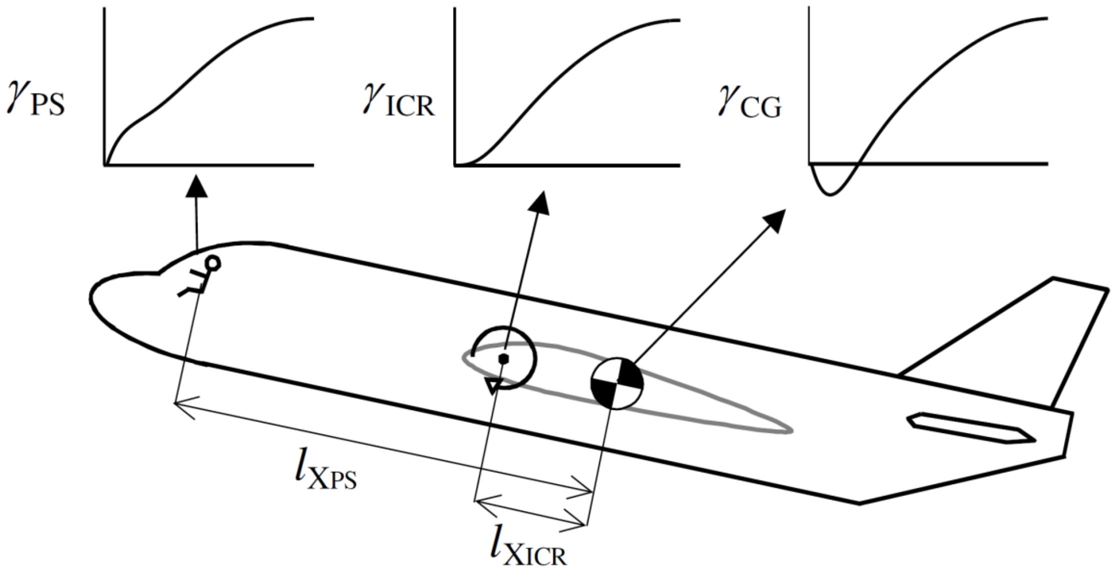


Figure 3. Aircraft geometry and flight path responses (from AIAA-2002-4799)

For conventional, aft-tailed airplanes, the ICR will naturally be in a region like that sketched in Figure 3. Canard-equipped airplanes, or configurations that generate an unusually large amount of lift-due-to-elevator (when compared to pitching-moment-due-to-elevator, such as the space shuttle), may exhibit less than desirable ICR responses. The research summarized in AIAA-2002-4799 suggests that the phenomenon is less likely on smaller (Class I, II, or IV) airplanes, simply because it will be difficult to generate the dynamics that move the ICR far from the pilot station.

While there are insufficient data to draw definitive Level boundaries, AIAA-2002-4799 provides a rough guideline for desirable ICR location relative to pilot station and center of gravity. Figure 4 is reproduced from AIAA-2002-4799, and the region labeled “Typical large aircraft response” is considered the best location. The diagonal lines on this figure are intentionally not drawn to the origin, the authors observe, because of the assumption that the regions do not apply for aircraft where the distances plotted are near zero.

While it is relatively easy to determine the locations of the center of gravity and pilot station, determination of the location of the ICR is a bit more challenging.

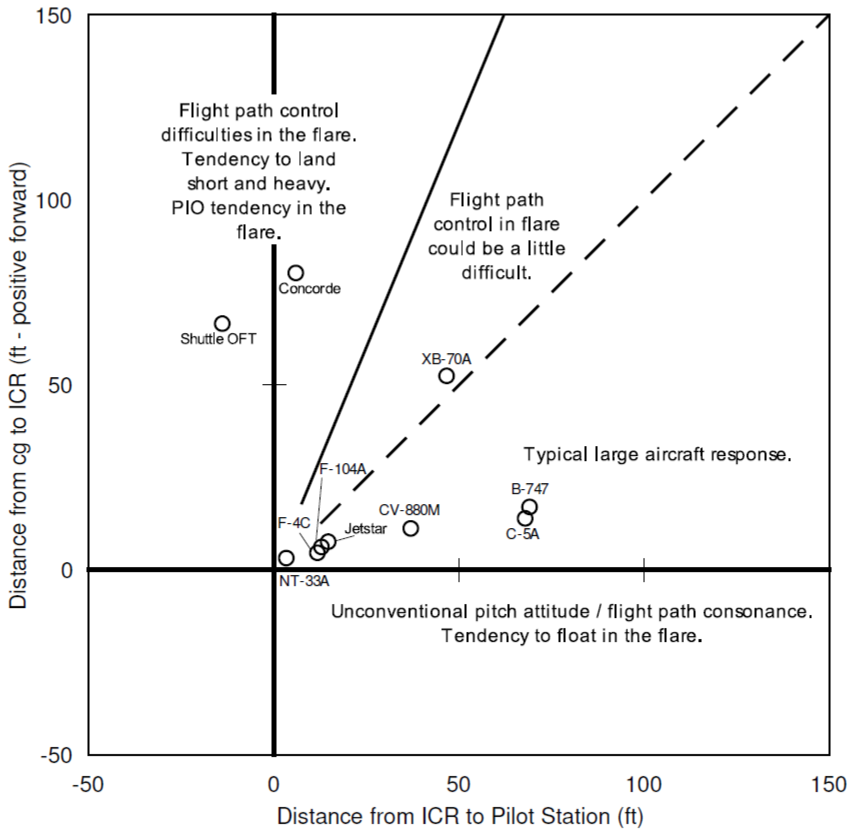


Figure 4. Proposed geometric criterion for ICR location (from AIAA-2002-4799)

AIAA-2002-4799 documents multiple definitions and measurement methods for the ICR. The most straightforward method is to plot the frequency response of the ratio of normal acceleration to pitch acceleration (as illustrated by the example plot in Figure 5), measured from a known reference point on the aircraft. The high-frequency asymptote of the magnitude response, with normal acceleration measured in g's and pitch acceleration in deg/s^2, is the distance from the center of gravity to the ICR,

$$l_{X_{ICR}} = g\left(\frac{180}{\pi}\right)10^{\left(\frac{n_z(s\to\infty)}{\dot{q}(s\to\infty)}/20\right)}$$

While this equation provides the magnitude of the moment arm, the phase response must be inspected to determine whether the ICR lies ahead of or behind the center of gravity. If the high-frequency phase response asymptotically decreases in value towards -180°, the ICR lies ahead of the center of gravity (a positive number), as is the case for the example in Figure 5. If the high frequency phase response asymptotically increases from a negative value towards 0°, the ICR lies behind the center of gravity (a negative number). The example in Figure 5 is most common for conventional, aft-tailed airplanes.

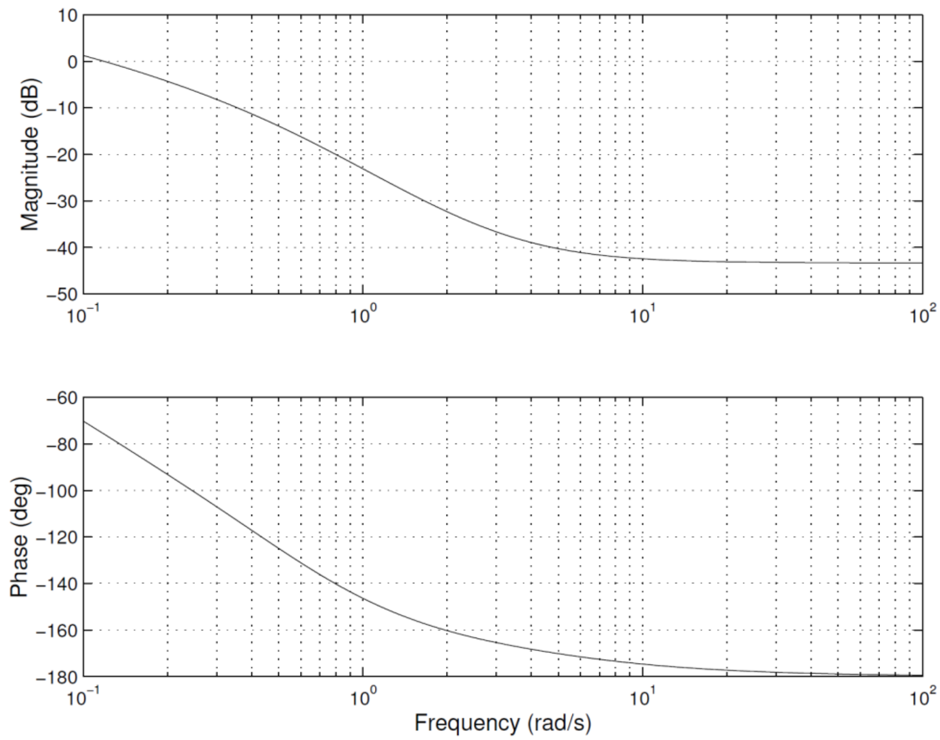


Figure 5. Example frequency response ratio of normal acceleration to pitch acceleration (from AIAA-2002-4799)

The value obtained from this method represents the distance from the cg to the ICR (in ft), the ordinate in the recommended criterion of Figure 4. The abscissa is given by the length (lXPS - lXICR), as can be observed in Figure 3. For most airplanes, this quantity is positive (ICR aft of pilot station), but for the Shuttle it was negative (ICR ahead of pilot station).

Add new reference:

AIAA Paper 2002-4799	Effects of Pitch Instantaneous Center of Rotation Location on Flying Qualities, Field, E.; J. Armor; K. Rossitto; and D. Mitchell; August 2002

3.0 Topics for Discussion in MIL-STD-1797C (Modified Requirements Not Justified)

3.1 Summary

In the review of NASA's flying qualities work over the past twenty years or more, several topics were identified that provide valuable insights into particular elements of MIL-STD-1797B, but from which specific modifications to the standard cannot be identified. This section documents reviews of such topics; the material here may be suitable for incorporation into discussions in the current standard as resources for future aircraft designs and flying qualities parameters. More thorough analysis of these topics could prove useful, but, on the basis of the documentation provided here, it was determined that such analysis is not justified.

Four subsets of the high-priority topics investigated in this study fall into this category, and this section provides information for them.

3.1.1 Effects of Flexible Structures on Flying Qualities

There are areas of MIL-STD-1797B where some attention is given to the critical interaction of structural modes on flying qualities. A prime example is **4.1.3 Defining Air Vehicle States**, where the following statement is included in Requirement Lessons Learned: "Since aeroelasticity, control equipment, and structural dynamics may exert an important influence on the air vehicle flying qualities, such effects should not be overlooked in calculations or analyses directed toward investigation of compliance with the requirements of this standard."

In addition, **5.2.1.7 Residual oscillations** explicitly addresses the effects of structural oscillations on flying qualities: "Any sustained air vehicle residual oscillations in Calm air shall not interfere with the pilot's ability to perform all flight phase tasks required in service use of the air vehicle. For Levels 1 and 2, with pitch control fixed and with it free, any sustained residual oscillations in Calm air shall not exceed __(1)__ in normal acceleration at the pilot station for any Flight Phase." The recommended limit for the blank is ±0.02g.

But this limit is overly simplistic, as the standard says: "Given the proper data, this threshold could be made a function of frequency in order to correspond more closely with human perception." Research into the effects of flexible modes has been conducted in ground-based simulations by engineers at NASA Langley Research Center. The first well-documented study, in support of the High-Speed Research (HSR) program, was conducted in the mid-1990s. The results of that study are summarized in this section, where it is evident that we simply do not have sufficient information to build quantitative requirements.

This discussion is included as a possible lesson learned for a future revision to MIL-STD-1797B.

More recent research at Langley is available.[12] The recent results should be folded into this material.

3.1.2 High-Speed Flying Qualities

Several flight research studies were conducted to investigate flying qualities of high-speed aircraft, especially in relation to the High-Speed Civil Transport (HSCT), a focus of the more general High-Speed Research (HSR) effort. Results of these studies have generated a valuable data base for future development of high-speed aircraft, but the overall outcomes are not sufficiently mature to directly affect the current requirements in MIL-STD-1797B. While every study investigated certain of the short-term pitch response requirements in 1797B, there were also efforts to find alternative definitions, axes, or measurements for the existing criteria that, while interesting, do not provide strong evidence that any of the existing criteria should be modified or new criteria adopted. A typical example is pitch attitude Bandwidth (5.2.2.1.3.1), which was applied as defined in 1797B or a predecessor document, and in addition, redefined based on other axes of control, such as vertical velocity; the results are of academic interest but are not sufficiently convincing to support a wholly new criterion.

Later in this section, a thorough summary of the results of the high-speed flying qualities programs is provided as background information. The summary could be inserted into 1797C as a lessons learned discussion.

3.1.3 Devices and Methods for Preventing Category II PIO

NASA has long been active in research and development of methods to prevent the occurrence of Category II pilot-induced oscillations (PIOs). Category II PIOs are those that involve a significant amount of nonlinearities in the vehicle response, most often surface actuator rate limiting. A brief review of NASA work is described, suitable for inclusion in the lessons learned material for **5.2.1.6 Pilot-in-the-loop oscillations** in MIL-STD-1797B. As is discussed in the next section of this report, however, much more must be – and can be – done to improve the PIO-related material in 1797B, including alternative criteria, prediction and detection methods, as well as background material. Such an endeavor should be a tri-service effort, as both the US Air Force and US Navy have conducted work in this area, along with NASA. The intent here is to highlight NASA-specific work on Category II PIO that is not currently documented in 1797B.

3.1.4 Cockpit Manipulator Feel Systems

Several NASA studies have contributed to our understanding of the importance to flying qualities of the force/deflection characteristics of cockpit feel systems. A brief summary of key studies is provided. More work is justified in this area, but it should be a multi-service effort with units of the Department of Defense, as discussed in the next section of this report.

3.2 Effects of Flexible Structures on Flying Qualities

The focus of this material is a piloted simulation experiment conducted in the Langley Visual Motion Simulator (VMS) on the effectiveness of the measures employed to reduce the impact of dynamic aeroservoelastic (DASE) effects on a High Speed Civil Transport (HSCT) aircraft.[13,14]

The investigated solutions were (1) stiffening the structure of the aircraft to increase the elastic mode frequencies, (2) increase the damping of the elastic modes, (3) reduce pilot excitation with a mode canceling control system, and (4) an active synthetic vision system (SVS) that compensates for the visual effects of the elastic modes on the VMS out-the-window scene presented to the pilot.

Six test pilots representing the Federal Aviation Administration (FAA), The Boeing Company, National Aeronautics and Space Administration (NASA), and Veridian Corporation (now Calspan Corporation) performed three piloting tasks to evaluate 20 parametric aeroelastic configurations. The Cooper-Harper Rating (CHR) scale and additional supplemental rating scales were used by the pilots after performing a nominal approach and landing task, a lateral-offset landing task, and a flight director tracking task.

3.2.1 Simulation Model

The vehicle used in this simulation experiment was a “Cycle 3” version of the “Reference-H” supersonic transport design, Figure 6, published by Boeing in 1996. The DASE portion of the model has 3 symmetric (SY) and 3 antisymmetric (AN) flexible aircraft modes. The general mode shapes with their in vacuo frequencies can be seen in Figure 7. The finite-element model used for the aeroelastic model was based on the NASTRAN version of the Elfini 892-STR-E. The dynamic elastic modes can be excitable by turbulence and control effectors. The landing gear and engine pylons were not modeled to have an effect on the aeroelastic model.

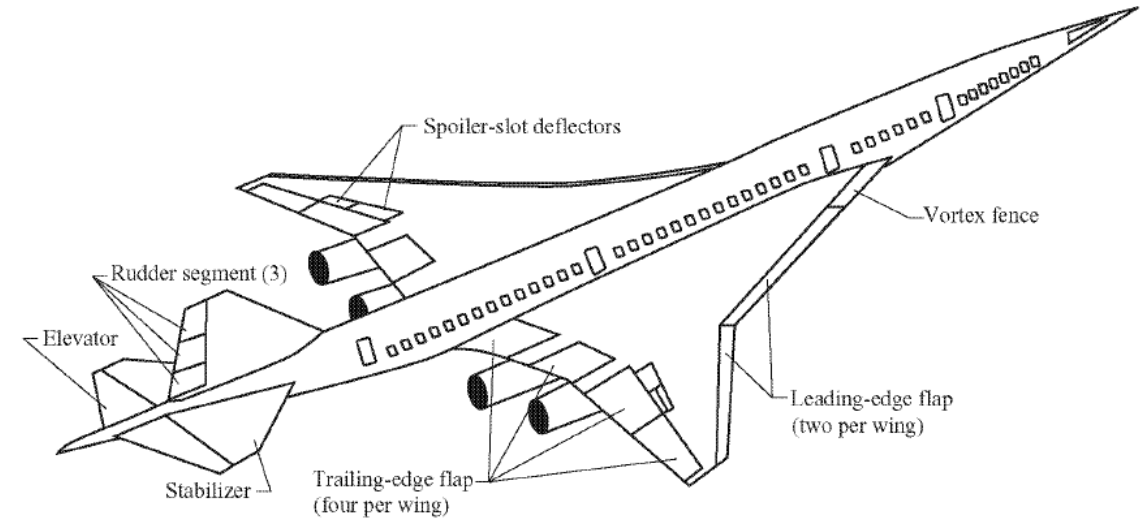


Figure 6. Reference-H configuration13

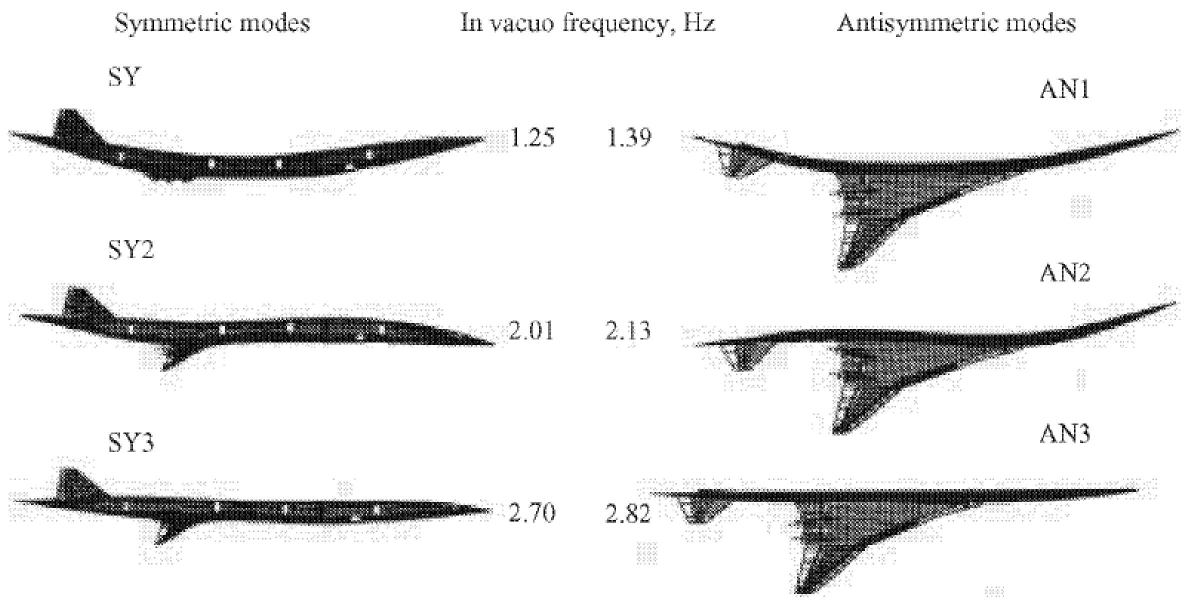


Figure 7. General elastic mode shapes and their in vacuo frequencies13

The landing flight condition was used for this experiment, where the model had a weight of 384,862 lbs with a center of gravity (C.G.) location at 53.2 percent of the mean aerodynamic chord (MAC) at Mach 0.24. The planforms of the Rockwell B-1 Lancer and the HSCT vehicle were overlaid for comparison, Figure 8. The HSCT model mimics the B-1 by featuring small horizontal active control surfaces at the sides of the cockpit, it also includes a vertical “chin fin.” These control surfaces are meant to damp out the vertical and lateral cockpit vibrations. The first symmetric bending mode occurs at a low frequency, 1.25 Hz, due the length and slenderness of the HSCT vehicle.

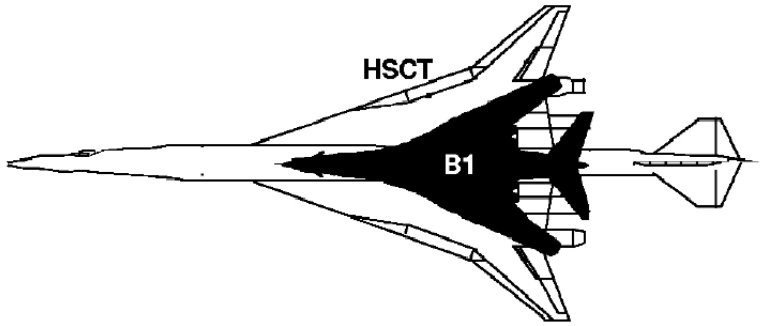


Figure 8. Comparison of HSCT and B-1 planforms[14]

3.2.2 Evaluation Scales

Three evaluation scales were used during the pilot evaluations: the traditional Cooper-Harper scale as well as a Ride Quality Rating (RQR) and Control Influence Rating (CIR) scale, shown in Figure 9a and Figure 9b, respectively. The RQR and CIR supplemental scales were developed from an earlier dynamic aeroelastic simulation study: Langley Research Center (LaRC) Piloted Simulation Assessment, or LaRC.1.[15] These supplemental scales were utilized to support the differentiation between the perceived deficiencies in the nominal flight control system and the dynamic aeroelastic characteristics of the configurations.

DASE INFLUENCE ON RIDE QUALITY	RQR
Cockpit vibrations do not impact ride quality.	1
Cockpit vibrations are perceptible but not objectionable - no improvement necessary.	2
Cockpit vibrations are mildly objectionable - improvement desired.	3
Cockpit vibrations are moderately objectionable - improvement warranted.	4
Cockpit vibrations are highly objectionable - improvement required.	5
Cockpit vibrations cause abandonment of task - improvement required.	6

a) Ride Quality Rating

DASE INFLUENCE ON PILOT'S CONTROL INPUTS	CIR
Pilot does not alter control inputs as a result of aircraft flexibility.	1
Pilot intentionally modifies control inputs to avoid excitation of flexible modes.	2
Cockpit vibrations impact precision of voluntary control inputs.	3
Cockpit vibrations cause occasional involuntary control inputs.	4
Cockpit vibrations cause frequent involuntary control inputs.	5
Cockpit vibrations cause sustained involuntary control inputs or loss of control.	6

b) Control Influence Rating

Figure 9. Additional rating scales[14]

3.2.3 Description of the Dynamic Aeroelastic Characteristics

The HSCT model was parameterized to allow for the variation of the dynamic aeroelastic characteristics. The four different methods mentioned previously are described in detail below.

Structural Stiffening

Frequencies of the dynamic elastic modes were directly increased with a frequency ratio to represent the stiffening of the aircraft structure without modifying the aerodynamic and mass characteristics, or the original mode shapes. The applied frequency ratios of 1.00 (BASE0), 1.16 (STIF1), 1.36 (STIF2), and 1.60 (STIF3) resulted in the structural stiffness increasing by 35, 85, and 156 percent, respectively. The resulting modal frequencies for the stiffened configurations are listed in Table 2. The migration of the dynamic elastic poles due to the increase of structure stiffness is illustrated by Figure 10.

The baseline aeroelastic configuration for the rest of methods was changed due to the first symmetric modal frequency being better represented by the STIF1 configuration through testing with a more mature finite-element structural model. This configuration was considered the "modified baseline." The structural stiffening method was an approximation as it assumed that the aircraft structure was uniformly stiffened. Consequently, this method was not physically practical as the frequency range varied would increase the weight beyond the designed conditions of the model.

Modal Damping

The Modal Damping method involved increasing the damping on the elastic modes to represent an active mode suppression system. Boeing flight control researchers were consulted to select acceptable damping ratios for the pilot evaluations. The selected damping ratios were 0.07, 0.15, and 0.30 and applied to specific elastic modes shown in Table 3. The migration of the dynamic elastic poles due to the various damping levels is illustrated by Figure 11. The frequency response plot in Figure 12 shows the reduction in the elastic response frequency with the various increased damping levels.

Table 2. Modal frequencies for stiffened configurations[13]

Config	Frequency ratio	Stiffness ratio	Stiffness increase, percent	1st Frequency, Hz		2nd Frequency, Hz		3rd Frequency, Hz	
				SY	AN	SY	AN	SY	AN
BASE0	1.00	1.00	0	1.25	1.39	2.01	2.13	2.70	2.82
STIF1	1.16	1.35	35	1.45	1.61	2.33	2.47	3.13	3.27
STIF2	1.36	1.85	85	1.70	1.89	2.73	2.90	3.67	3.84
STIF3	1.60	2.56	156	2.00	2.22	3.22	3.41	4.32	4.51

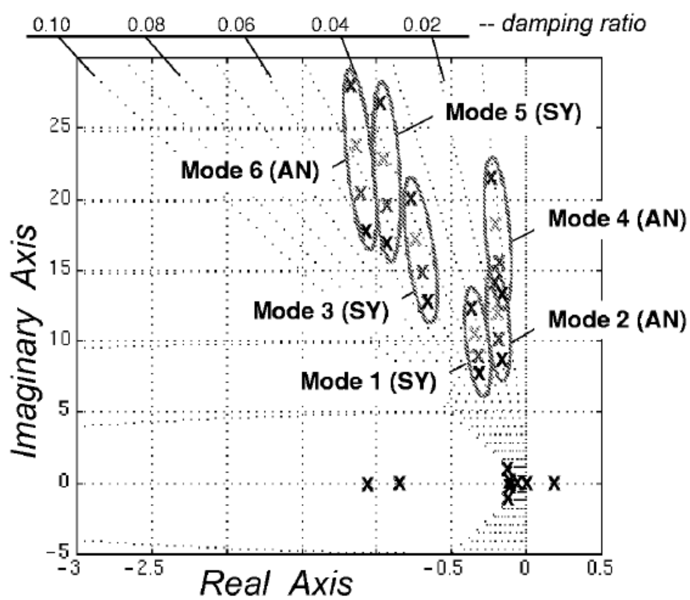


Figure 10. Migration of elastic mode poles with structural stiffness variation[14]

Ten configurations split into two sets of damping configurations were created to observe the suppression of the first fuselage bending modes. The first set consist of configurations with elastic mode frequencies less than 2 Hz: DAMP1 through DAMP5. The second set covered the rest of the configurations with elastic mode frequencies up to 3 Hz: DAMP6 through DAMP10. The mode damping groups were selected to observe the effects of damping the symmetric and antisymmetric modes together or separately.

Table 3. Damping levels and targeted modes for damped configurations[13]

Config	Damping ratio	Modes damped
STIF1	Nominal	None
DAMP1	0.07	SY1, AN1
DAMP2	0.15	SY1, AN1
DAMP3	0.30	SY1, AN1
DAMP4	0.30	SY1
DAMP5	0.30	AN1
DAMP6	0.07	SY1, SY2, AN1, AN2
DAMP7	0.15	SY1, SY2, AN1, AN2
DAMP8	0.30	SY1, SY2, AN1, AN2
DAMP9	0.30	SY1, SY2
DAMP10	0.30	AN1, AN2

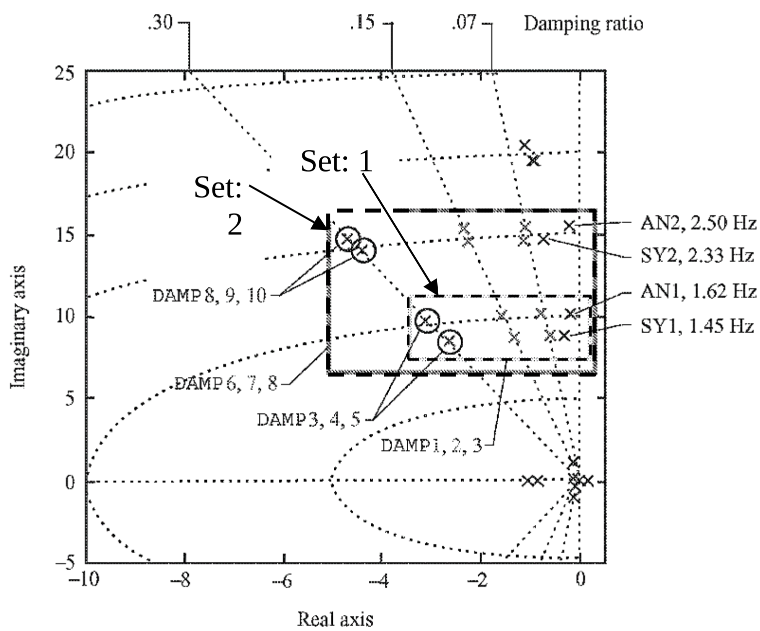


Figure 11. Migration of the dynamic elastic poles with damping level variation[13]

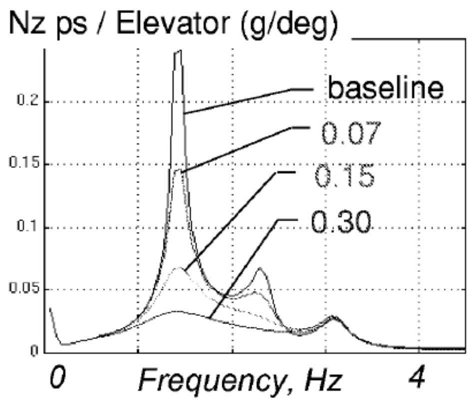


Figure 12. Frequency response of normal acceleration with various damping levels[14]

The damping level manipulations do not include nonlinearities and additional filter dynamics that may possibly be present in the actual system. Therefore, the active mode suppression system is an approximation as it directly modifies the model to generate the selected damping levels and does not realistically represent the model.

Mode Canceling Control

Another method explored involved using multiple control effectors in tandem to avoid exciting the elastic bending modes. This method represented command shaping by grouping control inputs such as canard and elevator inputs to prevent exciting the first symmetric bending mode or grouping the rudder and chin inputs to prevent exciting the first antisymmetric bending mode. This method is an approximation since it was accomplished by removing the relevant B matrix elements of the dynamic aeroelastic model. The modes canceled and the resulting damping ratio for the configurations for this method are listed in Table 4. Mode-canceling configurations CANC2, CANC3, and CANC4 directly relate to the modal damping configurations DAMP6, DAMP7, and DAMP8, from Table 3, to compare mode cancellation for each damping condition.

Figure 13 illustrates the effect of mode canceling control by showing the migration of the transfer function zeros for the CANC1 configuration. This effect is further demonstrated with the frequency responses for each mode canceled configuration in Figure 14. Mode canceling control was only applied to affect the first symmetric and antisymmetric elastic modes as additional control effectors would be required to cancel higher fuselage harmonics. That being said, coupling from symmetric bending mode 2 still remains and can be seen in Figure 14.

Table 4. Mode canceling control configurations[13]

Config	Modes canceled	Damping ratio of remaining modes
STIF1	None	None
CANC1	SY1, AN1	None
CANC2	SY1, AN1	0.07
CANC3	SY1, AN1	0.15
CANC4	SY1, AN1	0.30

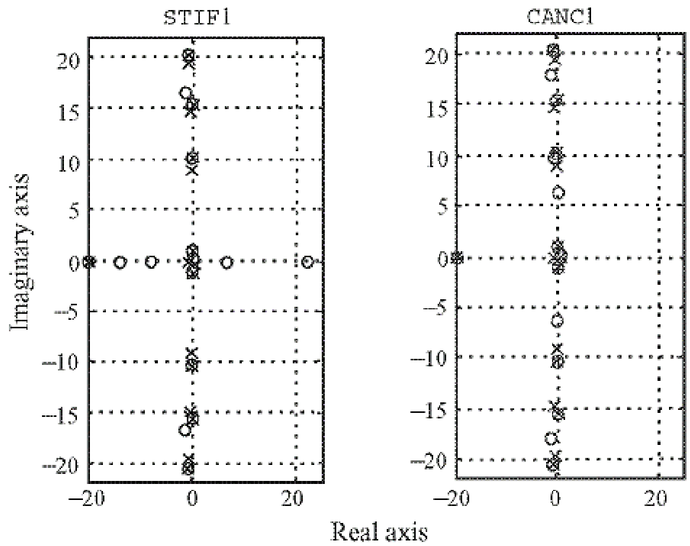


Figure 13. Migration of transfer function zeros with mode-canceled configuration[13]

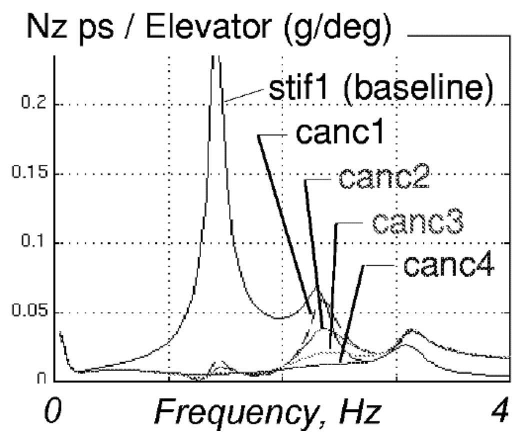


Figure 14. Frequency response of normal acceleration from various mode-canceled configurations[14]

This control system is an idealized approximation as it only eliminates the elastic mode excitation due to the control inputs in the dynamic aeroelastic model. The modal dynamics still exist in the model, however, so turbulence or other elastic modes were still capable of exciting the first symmetric and antisymmetric elastic modes.

Visual Display Compensation

An active synthetic vision system was implemented to compensate for the structural vibrations in the out-the-window scene from the VMS. This idealized compensation was only applied to the DAMP1 configuration and named DISP0. All other configurations included the visual effects caused by aeroelastic perturbations.

3.2.4 Summary of Results

Effects on Ride Quality and Control Influence

The accumulation of the DASE pilot-preference rankings for each of the aeroelastic configurations is presented in Table 5. These rankings were only based on the DASE RQR and CIR scores as they produced more useful distinctions of the DASE characteristics between the configurations compared to the CHRs. The rankings start with the best configuration, quasi-static elastic effects only (QSAE0), since it has no dynamic aeroelastic effects present. The Reference-H baseline aeroelastic (BASE0) configuration marks the end of the ranking as it is the worst due to having no DASE reduction methods. Configurations in the most desired region have the greatest difference in rating between each rank. Conversely, the configurations in the least desirable range do not show much variance in rating among each rank.

Table 5. Pilot preference ranking for configurations based on average RQR and CIR scores[13]

Ranking	Avg RQR	Avg CIR	Config	Description
1	1.4	1.0	QSAE0	Dynamic aeroelastic effects turned off
2	2.2	1.2	CANC4	SY1 and AN1 control excitation eliminated; 0.3 damping of remaining modes
3	2.6	1.4	CANC3	SY1 and AN1 control excitation eliminated; 0.15 damping of remaining modes
Ranking	Avg RQR	Avg CIR	Config	Description
4	2.6	1.4	DAMP8	Modal damping increased to 0.30 for modes SY1, AN1, SY2, and AN2
5	2.9	1.7	CANC2	SY1 and AN1 control excitation eliminated; 0.07 damping of remaining modes
6	3.2	1.8	DAMP3	Modal damping increased to 0.30 for modes SY1 and AN1
7	3.3	1.8	DAMP7	Modal damping increased to 0.15 for modes SY1, AN1, SY2, and AN2
8	4.1	2.3	DAMP2	Modal damping increased to 0.15 for modes SY1 and AN1
9	4.2	2.6	DAMP10	Modal damping increased to 0.30 for modes AN1 and AN2
10	4.3	2.6	CANC1	SY1 and AN1 control excitation eliminated
11	4.5	2.7	DISP0	Configuration DAMP 1 with CGI DASE perturbations relative to HUD turned off
12	4.6	2.7	DAMP1	Modal damping increased to 0.07 for modes SY1 and AN1
13	4.6	2.7	DAMP5	Modal damping increased to 0.30 for mode AN1
14	4.7	2.9	DAMP6	Modal damping increased to 0.07 for modes SY1, AN1, SY2, and AN2
15	4.6	3.1	DAMP4	Modal damping increased to 0.30 for mode SY1
16	4.7	3.1	STIF2	First mode increased to 1.80 Hz; all others by same frequency ratio
17	4.7	3.2	STIF3	First mode increased to 2.00 Hz; all others by same frequency ratio
18	4.9	3.2	DAMP9	Modal damping increased to 0.30 for modes SY1 and SY2
19	4.9	3.2	STIF1	First mode increased to 1.45 Hz; all others by same frequency ratio
20	4.9	3.4	BASE0	Baseline dynamic aeroservoelastic configuration

Figure 15 shows the Ride Quality Rating scale adjacent to the relationship between the RQRs and the pilot preference rankings from Table 5. The acceptable, marginal, and unacceptable ranges are seen with the shaded regions in both the RQR scale and the plot. (Color was added to the figure to clarify these ranges: blue for acceptable and red for unacceptable.) Mild turbulence was present during the tasks; therefore, the acceptable ride qualities would likely decrease with increasing turbulence. Just like Figure 15, Figure 16 shows a side-by-side view of the Control Influence Rating scale and the relationship between CIRs and the pilot preference ratings from Table 5. The unacceptable region is placed in which the vibrations at the cockpit station negatively affect voluntary control inputs. The CIRs may be slightly skewed as the pilots were sometimes unaware of the involuntary control stick inputs due to biodynamic feedthrough. The rankings of both the RQRs and CIRs of the twenty configurations were averaged among the six test pilots, arranged in an ascending order, and plotted in Figure 17.

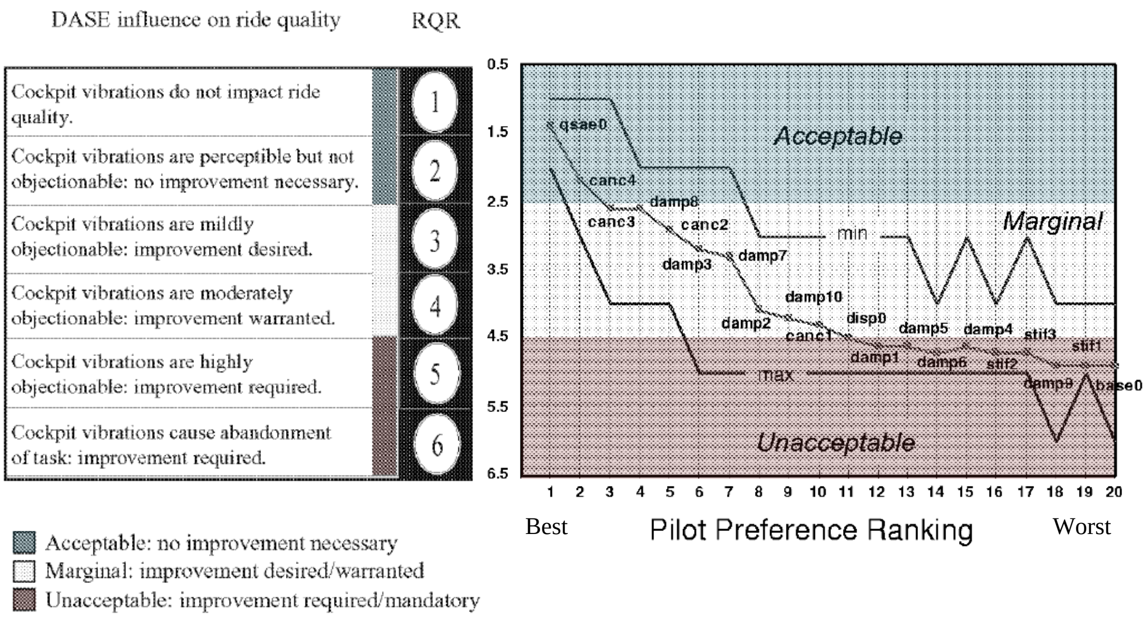


Figure 15. Average Ride Quality Rating vs. preference ranking[14]

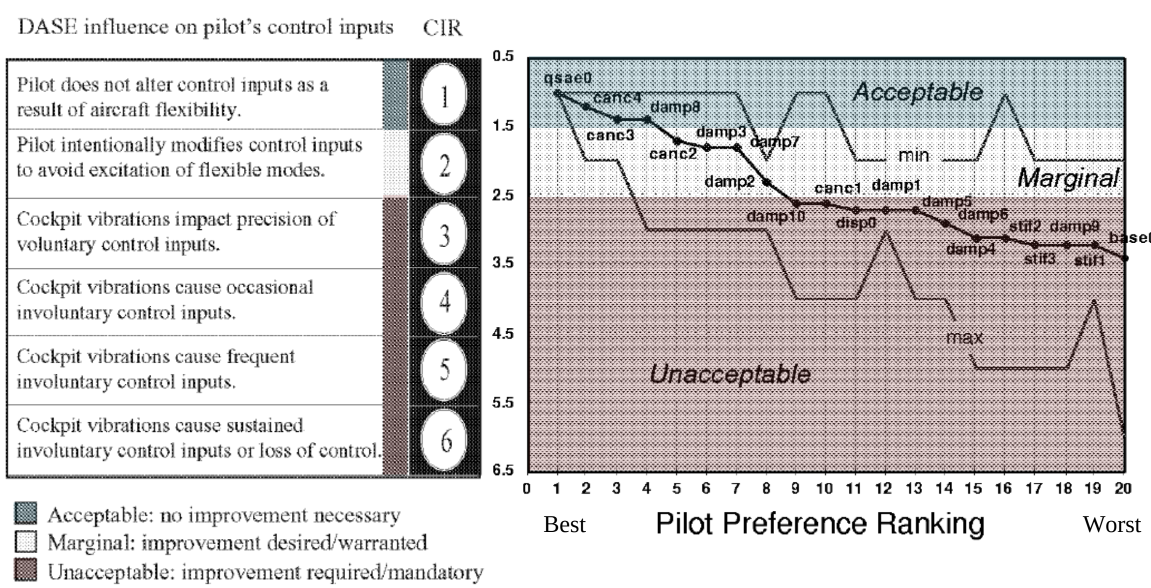


Figure 16. Average Control Influence Rating vs. preference ranking[14]

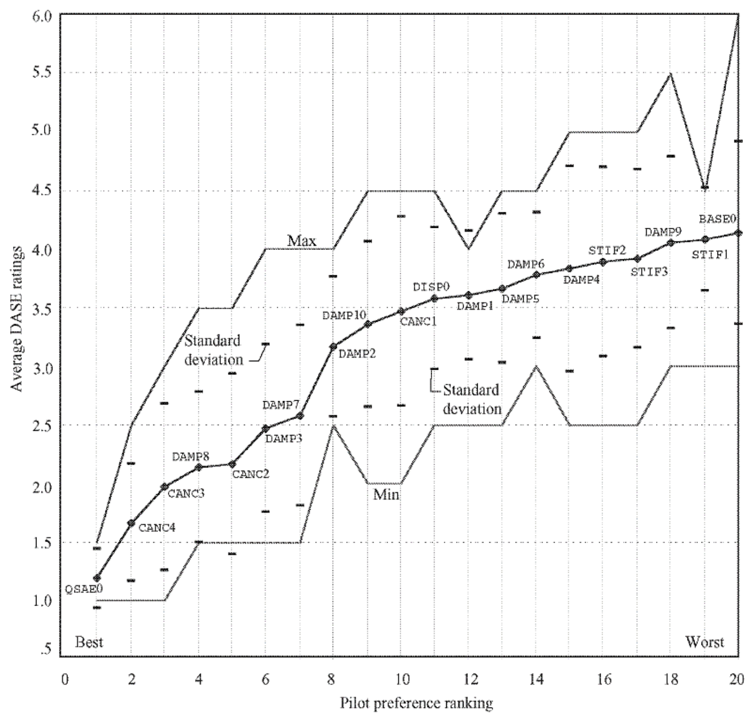


Figure 17. Pilot preference ranking of aeroelastic configurations based on DASE ratings[14]

Vibration spectrum envelopes were generated for all RQRs of the lateral-offset landing task to characterize the vibration levels based on the pilot's evaluations. Measured lateral accelerations at the cockpit station were collected for each configuration of a given RQR value and analyzed to produce rms lateral vibration spectrum plots for both lateral and vertical vibrations, Figure 18 and Figure 19, respectively. These plots indicate the range of vibrations experienced by the pilots.

The low vibration levels past 3 Hz are not due to the low tolerances of the pilots, but more likely due to the motion platform capabilities since the range of elastic response fidelity is from 2.5 to 3 Hz.

Effects on Handling Qualities

Configuration ranking based on CHRs was compared to the configuration rankings from the average DASE scores from Table 5, as shown in Table 6. In general, the configurations ranked comparably between the two sets of rating scales with some variations throughout the ranking. The overall agreement of these rankings reinforces the pilots' preferences of the various configurations. However, the handling qualities rankings did not have large variations among the configurations when compared to the DASE rankings.

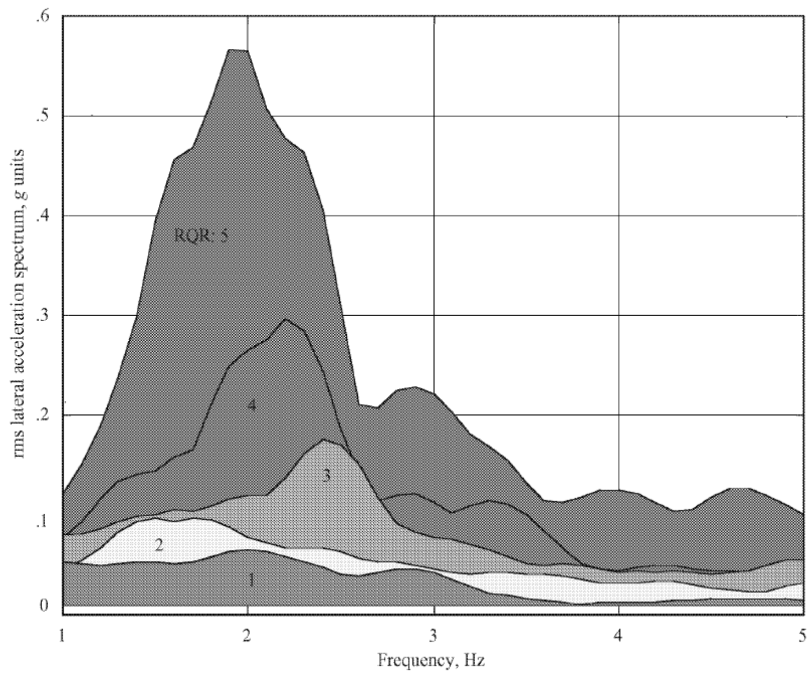


Figure 18. Lateral vibration spectral envelopes for various RQR levels[13]

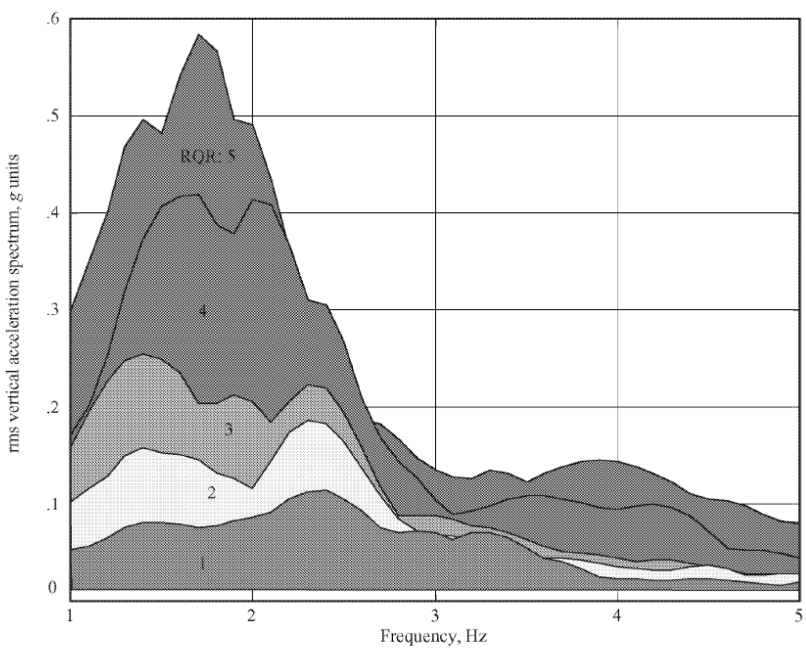


Figure 19. Vertical vibration spectral envelopes for various RQR levels[13]

Table 6. Pilot preference ranking for configurations based on average CHRs and ranking based on average DASE ratings[13]

Ranking	Preference order based on CHR scores	Average CHR	Preference order based on DASE Scores	Average RQR	Average CIR
1	QSAE0	3.45	QSAE0	1.4	1.0
2	CANC4	3.48	CANC4	2.2	1.2
3	CANC3	3.52	CANC3	2.6	1.4
4	DAMP8	3.67	DAMP8	2.6	1.4
5	CANC2	3.70	CANC2	2.9	1.7
6	DAMP2	3.83	DAMP3	3.2	1.8
7	DAMP3	3.88	DAMP7	3.3	1.8
8	DAMP7	3.88	DAMP2	4.1	2.3
9	CANC 1	4.10	DAMP10	4.2	2.6
10	DAMP5	4.10	CANC1	4.3	2.6
11	DAMP1	4.12	DISP0	4.5	2.7
12	DAMP6	4.20	DAMP1	4.6	2.7
13	DISP0	4.28	DAMP5	4.6	2.7
14	DAMP 10	4.33	DAMP6	4.7	2.9
15	STIF2	4.43	DAMP4	4.6	3.1
16	DAMP4	4.67	STIF2	4.7	3.1
17	STIF3	4.88	STIF3	4.7	3.2
18	STIFI	5.07	DAMP9	4.9	3.2
19	DAMP9	5.12	STIFI	4.9	3.2
20	BASE0	5.42	BASE0	4.9	3.4

The average CHR followed an improving trend with increasing structural stiffening, seen in Figure 20. Increasing the stiffness of the structure did not provide much significance in mediating the DASE effects, however. The configurations in the structural stiffness method received CHRs in the Level 3 region. Similarly, Figure 21 shows the improvement of CHR scores with increasing damping and modal cancellations, though the variation in CHRs from increasing damping and modal cancellation is much less than those of increasing structural stiffness.

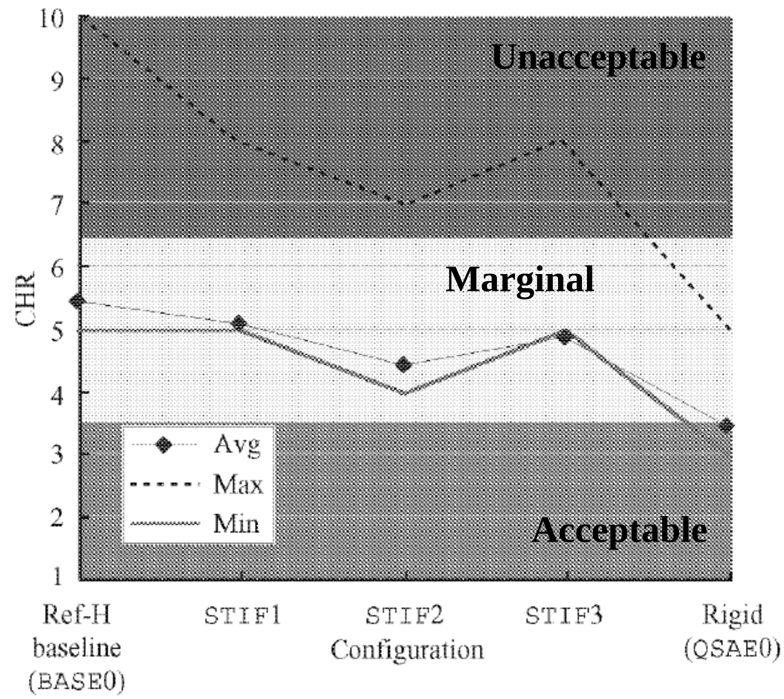


Figure 20. Variation of average CHR with increasing structural stiffness[13]

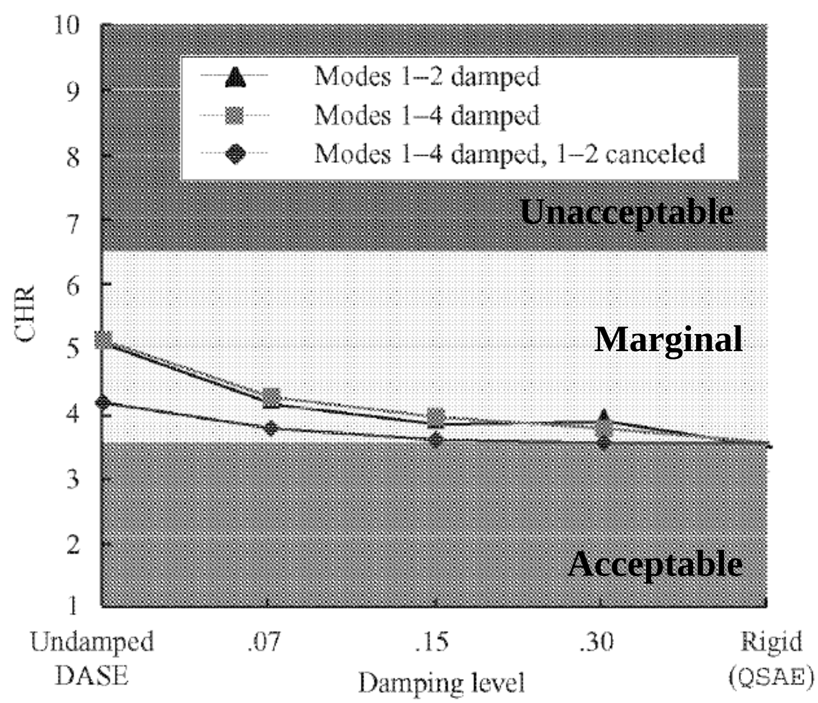


Figure 21. Variation of average CHR with increasing damping and modal cancellation[13]

3.2.5 Discussion

The potential solutions to addressing the impact of dynamic aeroservoelastic effects (DASE) on flying qualities was explored in this experiment. A summary of the configuration ranking shown in Table 5 and Figure 17 is as follows:

- The structurally stiffened configurations all ranked poorly.
- The highest ranked configurations were those with mode canceling control with damping and a configuration with damping on the first two symmetric and antisymmetric modes: CANC4, CANC3 DAMP8, and CANC2.
- CANC4 was the best configuration which had modal cancellation and the most modes damped. This configuration was still noticeably different compared to the rigid configuration (QSAE0), however.
- Pilots ranked undamped symmetric motions (DAMP10) better than undamped antisymmetric motions (DAMP9). This meant that pilots were more tolerable of vertical dynamic aeroelastic effects than lateral ones.
- Trivial variance seen between the visual display compensation configuration (DISP0) and DAMP1 shows that the active synthetic vision system was of little to no benefit.

Biodynamic coupling (BDC) was observed during the flare portion of the landing tasks with no active suppression on the lateral elastic modes. This phenomenon occurs when frequent or sustained vibrations from the cockpit feed into the pilot's upper body and arm causing involuntary inputs into the control stick. BDC was generally encountered with aeroelastic configurations with little to no damping of the elastic modes. All of the pilots expressed that their ability to precisely maneuver the vehicle was affected by the vibrations experienced during the simulations. Additionally, the DASE effects due to antisymmetric modes were more prevalent than the symmetric modes. This is due to the vibratory motions on the pilot's grip of the control stick, meaning side-to-side accelerations are more difficult to resist compared to vertical accelerations.

Structural stiffening and visual cue compensation provided little to no contribution in reducing the impact of dynamic aeroservoelastic effects. A realistic stiffness could not be achieved to prevent DASE effects in the lateral resonant frequencies that tend to affect pilots; in this experiment modeled at 1.6 and 2.2 Hz.

Increasing the damping and eliminating elastic mode excitations due to control effectors provided the greatest reduction in DASE effects. Damping the first two symmetric and antisymmetric elastic modes provided the most acceptable configurations. This was achieved with a damping level of 0.30 for this experiment. Likewise, a damping level of 0.15 to the first symmetric and antisymmetric elastic modes was sufficient to prevent biodynamic coupling for this experiment. Mode cancellation provided the most benefit as it broke the loop in biodynamic coupling. Therefore, no effects of biodynamic coupling were experienced due to control input when mode cancelling control was active.

Additionally, the handling qualities of the configurations improved with modal cancellations and the increase of structural stiffness and damping. Despite these methods, the Cooper-Harper Ratings (CHR) did not enter the acceptable region and remained in the marginal region.

3.3 High-Speed Flying Qualities

Multiple vehicles were considered in this evaluation: F-16XL,[16] SR-71,[17] Generic Hypersonic Aerodynamic Model Example (GHAME),[18] and Tu-144LL, SR-71, YF-12, and XB-70.[19] In every reference, aircraft were assessed using military flying qualities criteria from the relevant standards at the time. As these studies were performed at different times over a span of more than a decade, the criteria changed in boundaries and methods, and some came and went entirely, between MIL-STD-1797[6] in 1987, MIL-STD-1797A[20] in 1995 (and the re-released version, MIL-HDBK-1797[21] in 1997), and finally the current MIL-STD-1797B. As a result, it is difficult to draw a conclusion on the efficacy of any set of criteria. In addition, in most of the studies alternative measures for the existing criteria, or alternative criteria, were applied. Thus there is a wide variety of information on a disparate set of high-speed aircraft but little consensus.

This summary will hopefully eventually lead to a concerted effort to apply data for all of the aircraft to a single set of flying qualities criteria so a strong conclusion can be drawn. Until then, what follows serves as a summary of important NASA research into high-speed flying qualities.

A summary table of the relevant metrics considered, test condition limits, maneuvers and special notes, is shown in Table 7. More detailed information, including pilot comments and ratings, is provided in the following paragraphs.

Table 7. Vehicle summary

Vehicle	Metrics	Test condition limits	Test Maneuvers	Special Notes
F-16XL	Roll mode time constant Roll mode effective time delay LOES for longitudinal systems Neal-Smith Ralph-Smith Aircraft Bandwidth	Mach: 1.6 Altitude: 35kft AoA Limit: 18deg.	Doublets in all three axes Windup turns -1g pushovers Steady heading sideslips 360deg. rolls, Pitch and roll frequency sweeps (roll unusable) 180deg. over the top rolls Pitch roll and normal acceleration captures Loaded roll reversals Close trail formation flight Air to air tracking Maneuvers in up and away and power approach configurations	10 flights G-limiter set to 7.2 Roll rate limits less than for analog system
SR-71	Aircraft Bandwidth Flightpath Bandwidth Neil-Smith	Mach: 3	Steady level turn Ascending turn Vertical plan altitude change	2 pilots 5 total evaluations
GHAME	Phugoid and height modes	Mach: 10 Altitude: 110kft	Steady level turn	Seven test points flown by 4 pilots
Tu-144LL	Aircraft Bandwidth Flightpath Bandwidth Neal-Smith	Mach: 0.4-2 Altitude: 2-17km	Pitch attitude captures Bangle angle captures Heading captures Steady heading sideslips Deceleration and acceleration maneuver	2 pilots 4 flights

Vehicle	Metrics	Test condition limits	Test Maneuvers	Special Notes
	Short-period damping, time delay CAP Phase Delay		Stick pullback to achieve specified deceleration to capture a minimum speed (level and banked flight) Simulated engine failure	

F-16XL

The F-16XL originated as a "…prototype concept for derivative fight evaluation program…" from the early 1980s. It was used as a technology demonstrator for high speed aircraft, including but not limited to, supersonic commercial transports. The basic F-16 analog control system was replaced with a digital flight control system. With that change came adjustments to the vehicle dynamics and limitations. With the new system, roll rates were predicted to be 25% greater than for the analog system and the pitch system had a g-limiter that permitted more than the defined 9g limit. To compensate, the cockpit stores switch was engaged in CATIII mode, reducing the maximum possible commanded roll rate by 75 deg/s. This placed the maximum roll rate lower than for the analog system, though the reference does not explicitly state its value. The g-limit was set to 7.2g's to avoid the possibility of exceeding 9g's. Ten flights were conducted between December 1997 and March 1998. The test points are given in Figure 22.

<u>Air-to-Air Tracking Task</u>: The F-16XL pilot attempted to track a target airplane in a range of 1000 to 1500 feet. Once the F-16XL was in position behind the target, the target performed a 3g turn. When the target was about 30° off the nose, the F-16XL pilot acquire and track the target for 2 to 3 seconds. The F-16XL pilot then called for target reversal with a repeat in the opposite direction. The task was repeated with random maneuvering of the target up to 3.0g with unannounced reversals. For gross acquisition, the pilot tracked the target within a 50 mm diameter on the pipper, with one overshoot and no PIO for desired performance; adequate performance required that the target be kept within 75 mm with two overshoots and no PIO. In fine tracking, desired performance required the target within a ±10 mil diameter on the pipper for 2 sec without PIO. Adequate performance required ±20 mil without PIO. Pilots commented on undesirable motions, predictability, aggressiveness effects and compensation techniques, and assigned Cooper-Harper ratings for gross acquisition and for fine tracking.

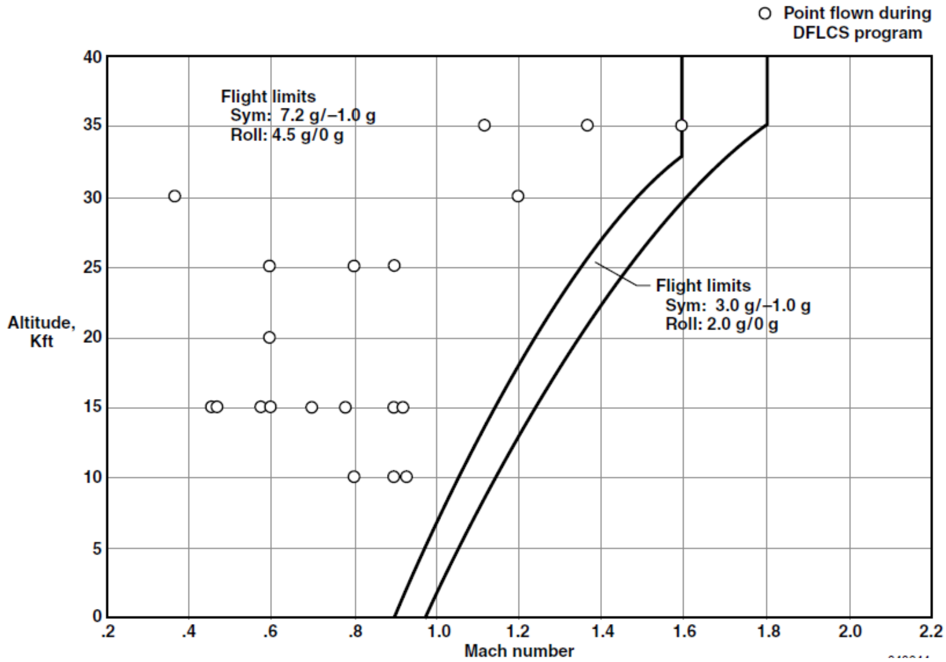


Figure 22. F-16XL flight envelope and limits for ship 1[16]

Close Trail Formation Flight Task: The F-16XL pilot followed the tail of the lead airplane with increasing aggressiveness though S-turn maneuvers. For initial evaluation, the lead airplane maneuvered up to 3.0 g. Desired performance required that both lateral and vertical displacement be kept within ±1 tailpipe diameter without PIO. Adequate performance allowed for lateral and vertical displacements of ±2 tailpipe diameters without PIO. Pilots evaluated response during steady state flight and during reversals. CHRs were given for both gross acquisition and fine tracking based on the desired and adequate performance margins.

Pilot Qualitative Assessments: Two pilots flew the tasks. CHRs are documented below in Table 8 and Table 9. The pilots' comments were favorable for lateral axis performance for both tasks and pilots stated that the airplane felt very similar to the analog version. The reversals were given ratings in the Level 2-3 region. As Table 8 shows, the steady state conditions were Level 2 throughout the formation flight tasks. For air-to-air tracking, the gross acquisition was given CHRs in the Level 1-2 region while the fine tracking was typically Level 2-3. It was noted in the comments that the pilots often mentioned a "pitch-bobble" behavior. This would be expected to impact the fine tracking performance and the ratings assigned.

SR-71

The SR-71, originally conceived of and flown as a supersonic reconnaissance aircraft, was repurposed for use by NASA as a research aircraft. It is joined by the XB-70 (supersonic prototype deep penetration strategic bomber from the 1960's), the YF-12 (the precursor to the SR-71) and the Tu-144LL (repurposed Soviet version of the Concorde supersonic passenger jet) as one of the few aircraft to be used for supersonic handling qualities evaluations. Data for a vertical altitude plane change maneuver was examined here. The maneuver is described below. The evaluation was performed with two different climb rate indicators, as described. Each was rated by the pilots and relevant commentary has been noted.

Table 8. F-16XL Pilot ratings given during formation flight tasks[16]

Altitude (ft)	Mach number	Steady state	Reversal
10,000	0.8	4	7
10,000	0.9	4	6
15,000	0.6	5	7
15,000	0.9	4	7
25,000	0.6	4	5 or 6

Table 9. F-16XL Pilot ratings given during air-to-air tracking tasks[16]

Altitude (ft)	Mach	Velocity (ft/s)	Dynamic Pressure (psi)	Gross Acquisition	Fine Tracking
10,000	0.8	449	653	4	7
10,000	0.9	507	826	3	7
15,000	0.6	304	301	6	7
15,000	0.5	250	206	3	4
15,000	0.69	350	395	2	3
15,000	0.78	400	510	3	4
15,000	0.9	465	678	4	7
25,000	0.95	407	496	3	not given
25,000	0.9	384	446	3	4
25,000	0.6	248	198	not given	7

Vertical Plane Altitude Change Maneuver: The vertical plane altitude change at constant knots equivalent airspeed (KEAS) entailed a wing-level pullup to capture a 2000 ft altitude increment at a climb rate of 1000 ft/min. Once the target altitude was established, it was to be held for an additional 10 sec. The pilots evaluated this maneuver with two variations of feedback displays: one using the instantaneous vertical speed indicator (IVSI) and the other using inertial vertical speed on the attitude director indicator (ADI). Desired performance limits were ±100 ft deviation from target altitude and ±5 KEAS deviation from target airspeed; adequate limits were ±300 ft deviation from target altitude and ±10 KEAS deviations from target airspeed.

Instrumentation and Impact on Ratings: The maneuver was flown with two different instruments: 1) IVSI and 2) inertially derived vertical speed. The IVSI was pressure driven and had a lag in the response at high altitudes. The pilots' CHRs for the task with the two indicators are provided in Figure 23. The task using the IVSI indicator received no better than mid-Level 2 ratings (5) while both evaluations of the inertially derived vertical speed were rated Level 1. For the IVSI evaluations the pilots noted difficulty with establishing and maintaining the desired rate of climb. With the inertially derived speed, the only noted difficulties were minor issues when attempting to establish the initial rate of climb and a need to lead the target altitude slightly.

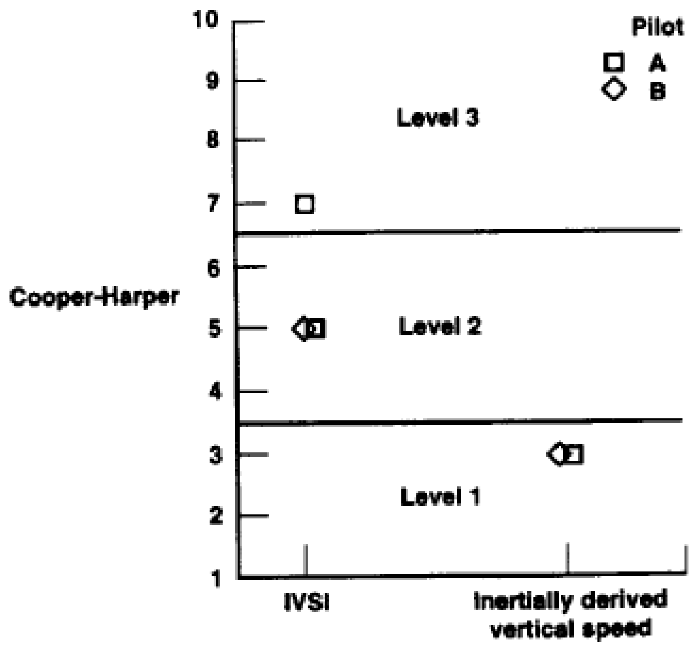


Figure 23. SR-71 Pilot ratings for vertical plane maneuver[17]

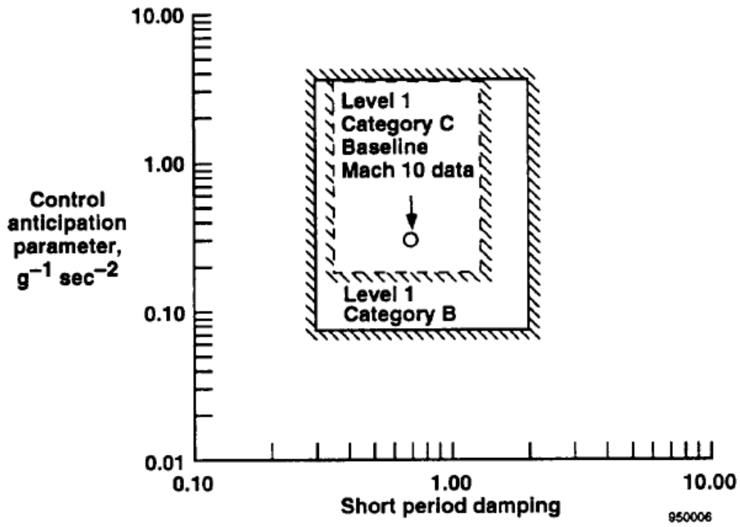
Generic Hypersonic Aerodynamic Model Example (GHAME)

GHAME was evaluated by four test pilots at seven test points in a fixed base simulator that was previously applied to the space shuttle and National Aerospace Plane (NASP) programs.[22] The focus of this effort was on understanding the impact on and establishment of design guidelines for height and phugoid mode instabilities for very high-speed flight (high supersonic to hypersonic).

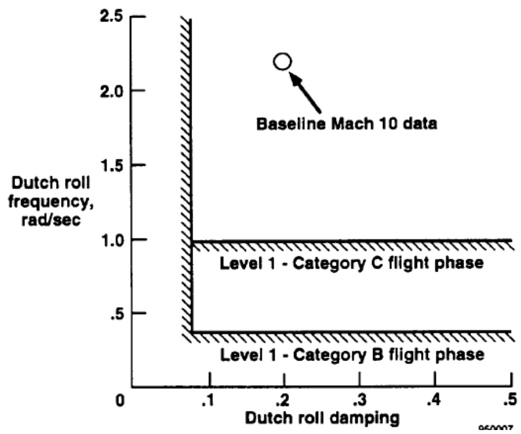
The GHAME model is a 6 degree of freedom hypersonic vehicle of generic design with a conventional control system implementation. This was implemented to provide Level 1 short-term longitudinal and lateral-directional flying qualities at a single flight condition (Mach 10, 110kft). The authors applied the control anticipation parameter (CAP) requirement to the longitudinal axis and the Dutch roll frequency/damping and roll mode time constant criteria to the lateral-directional axis. The properties of the GHAME model relative to these measures is given below in Figure 24.

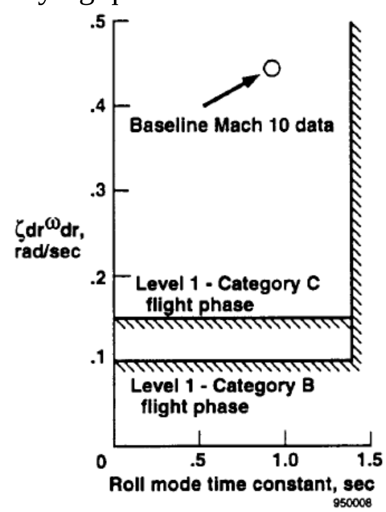
<u>Steady Level Turn Task:</u> Pilots flew a well-defined turning task to investigate the flying qualities implications and characteristics of various levels of height and phugoid stabilities. The maneuver was a 30° bank turn to capture a 12° heading change. This maneuver was performed while eliminating a vertical speed initial condition and maintaining constant airspeed and altitude. The turning portion of the maneuver lasted approximately 2 min and termination of the maneuver occurred 1 min after capturing the final heading. Initial conditions were wings level at Mach 10 and an altitude of 110,000 ft. A vertical speed initial condition of 20 ft/sec was introduced to increase pilot workload. Desired performance required capturing the final heading within ±0.5° while maintaining speed within ±5 knots of the initial speed and maintaining altitude within ±300 ft of the initial altitude. For adequate performance the limits were ±1°, ±10 knots, and ±600 ft.

The pilots evaluated phugoid mode instabilities with time-to-double amplitudes down to 1.7 sec and height mode instabilities down to 3.5 sec, which were empirically determined limits of controllability for this study. Similar levels of instability were previously studied using a large supersonic transport model with an aperiodic phugoid time-to-double-amplitude of 4.6 sec in the approach and landing condition.[23]



a) Longitudinal short-period flying qualities





b) Lateral-directional Dutch roll flying qualities

c) Lateral-directional roll mode and Dutch roll flying qualities

Figure 24. Baseline Mach 10 flying qualities designs[18]

Tu-144LL

The Tu-144LL was a repurposed and refurbished Tu-144 aircraft, a supersonic passenger transport aircraft created by the Tupolev Aircraft Company. It had a similar profile and shape relative to the Concorde and cruised at Mach 2. The Tu-144LL had a standard wheel-column input configuration with conventional rudder pedals. The relevant aircraft characteristics are listed below in Table 10.

Table 10. TU-144LL and Concorde aircraft characteristics[19]

Characteristic	Tu-144LL airplane	Concorde aircraft
Length (ft)	215.5	202.3
Wingspan (ft)	94.5	83.8

Characteristic	Tu-144LL airplane	Concorde aircraft
Maximum takeoff weight (lb)	447,500	389,000
Maximum fuel capacity (lb)	209,440	186,000
Estimated range (nmi)	1620	3450
Maximum ceiling (ft)	62,335	68,000
Maximum Mach number	2.4	2.17
Maximum static thrust for each engine (lbf)	55,000	38,050
Wing area (ft^2)	4714.5	3856

Evaluation Maneuvers: A description of the evaluation maneuver particulars[19] is repeated below. The authors noted that some maneuver target values were modified as required based on the flight condition but did not specify the alterations.

Deceleration and Acceleration: Reduce throttle from trim position to approximately 20°. Decelerate and capture an airspeed 70 km/hr less than trim. Advance throttle to military power setting. Accelerate and recapture original airspeed.

Pitch-Attitude Capture: From trim attitude, pull column back to capture a 3° pitch-attitude increment. Push column forward to capture original trim attitude. From trim attitude, push column forward to capture a -2° pitch-attitude increment. Pull column back to capture original trim attitude. Keep normal acceleration between 0.8 and 1.2*g*.

Bank-Angle Capture: From steady level flight, apply right wheel to capture a 30° bank angle. Apply left wheel to capture level flight. From steady level flight, apply left wheel to capture a -30° bank angle. Apply right wheel to capture level flight.

Heading Captures: From steady level flight, apply right wheel to capture a 30° bank angle. Maintain bank angle and capture 20° heading increment. Apply left wheel to capture a -30° bank angle. Maintain bank angle and capture original heading. Repeat in opposite direction.

Steady-Heading Sideslips: From steady level flight, apply a series of rudder deflections: 2°, 4°, 6°, and 7.5°. Apply appropriate wheel deflection to maintain constant heading, stabilizing for 5 sec on each rudder deflection. Repeat in opposite direction.

Simulated Engine Failure: From steady level flight, retard throttle number 1 to idle. Wait 5 sec and then stabilize transient, maintaining a bank angle less than +5°. Advance three remaining throttles to capture original airspeed. Perform heading capture maneuver. Recover by slowly advancing number 1 throttle and reestablish original flight condition.

Slow Flight: From steady level flight, pull column back and establish a (2 km/hr)/sec deceleration. At minimum airspeed or warning, stop deceleration and hold condition for 3 sec. Recover by pushing column forward and establishing original flight condition. From steady level flight, establish a 30° bank turn. Pull column back and establish a (2 km/hr)/sec deceleration. At 10 km/hr greater than the minimum airspeed or warning indication, stop deceleration and hold condition for 3 sec. Recover by pushing column forward, rolling wings level, and establishing original flight condition.

Data Collected: The authors noted that no CHRs were collected due to the limited number of flights, and a lack of simulator availability. Their fear was that the ratings might be indicative of a "learning curve" and that the flight time was insufficient to be able to repeat any of the runs and eliminate this potentiality. In addition, no adequate/desired performance criteria were defined for the tasks. The primary data collected were pilot comments from the postflight interviews to provide an assessment of flying quality "levels."

Pilot Comments for Lateral-Directional:

- Noted heavy wheel and pedal forces
- Dynamics assessed as Level 1
- Wheel forces for reasonable roll rates were noted as a "significant deficiency warranting modification"
- Roll response was considered "somewhat slow" but predictable and well damped
- Bank angle captures, steady level turns, and steady heading sideslips were noted as easy to perform
- Steady heading sideslips required large pedal forces
- Yaw damping considered satisfactory
- Heading captures were easy to perform
- All above comments extended to all configurations and flight conditions

Pilot Comments for Lateral-Directional: A summary of the main points from the pilot evaluation is shown in Figure 25. The authors also noted that the column forces in pitch were at a moderate to heavy level but were not "…as significant a deficiency as in the lateral axis."

Flight phase	Comments regarding pitch attitude	Comments regarding flightpath
Subsonic cruise	• Overshooting and bobbling. • Small column deflections produce large pitch-attitude transients with no motion cues. • Easy to compensate by reducing urgency.	• Leveling off and maintaining altitude easy.
Climb to and descent from supersonic cruise	• High workload. • Pitch-attitude sensitivity. • Small column deflections produce large pitch-attitude transients with no motion cues.	• Altitude rate control difficult because of combined effect of pitch-attitude sensitivity and flightpath angle lag. Leads to overcontrolling flightpath angle. • Difficult to find correct pitch-attitude.
Supersonic cruise	• Overshooting and bobbling. • Small column deflections produce large pitch-attitude transients with no motion cues. • Easy to compensate by reducing urgency.	• Leveling off and maintaining altitude easy.

Figure 25. Tu-144LL Summary of pilot evaluations for pitch attitude and flightpath control[19]

3.3.1 Application of Flying Qualities Criteria

As mentioned at the start of this discussion, multiple criteria were applied to one or more of the high-speed aircraft. What follows is a summary look at those criteria for the applicable aircraft. In some cases, the criteria applied are similar to those in the current MIL-STD-1797B, but for the most part the criteria, their application, or Level limits are quite different. The following is not meant to be a proof for the efficacy of any particular method, but rather a snapshot of the various methods that were applied to the different aircraft.

Neal-Smith Criteria

Vehicles: F-16XL, SR-71, Tu-144LL

Summary: The Neal-Smith requirement bounds for the F-16XL utilized updated requirements proposed in Ref. 24 while the SR-71 and Tu-144LL evaluations utilized the existing bounds as documented in the MIL-STD-1797B. The F-16XL results proved inconclusive as the predicted behavior from Neal-Smith did not reflect the comments made by the pilots. The caveat here is that no ratings were taken at the supersonic conditions. The SR-71 results demonstrated good agreement with the Neal-Smith criteria when using vertical speed to stick input instead of pitch attitude as the criteria were designed. This result was in agreement with the pilot commentary. The Tu-144LL data demonstrated good agreement with the existing category C requirements with bandwidths at 2.5 rad/s for subsonic evaluations and 1.5 rad/s for supersonic conditions. More detailed evaluations are below.

F-16XL: An exemplar closed loop response with the implemented pilot model is shown in Figure 26. A 0.2 to 10 rad/s frequency region was typically used, though some conditions used a reduced range due to poor coherence in the test data. The summary of results is shown against the Neal-Smith criteria in Figure 27 and tabulated in Table 11. The overwhelming majority of the results resided in the Level 2 region and appeared to indicate an improvement in handling qualities as the airspeed increased. This trend was noted in the modal estimations from the LOES method (as described later), but as with LOES, the pilot comments and ratings did not reflect this trend. While the Neal-Smith criteria indicated Level 2 handling qualities and the pilot ratings/comments supported this, the comments also indicated a regular problem with pitch bobble. The NASA assessment found that this was not consistent with the need for the large amount of lead compensation as the Neal-Smith criteria would indicate.

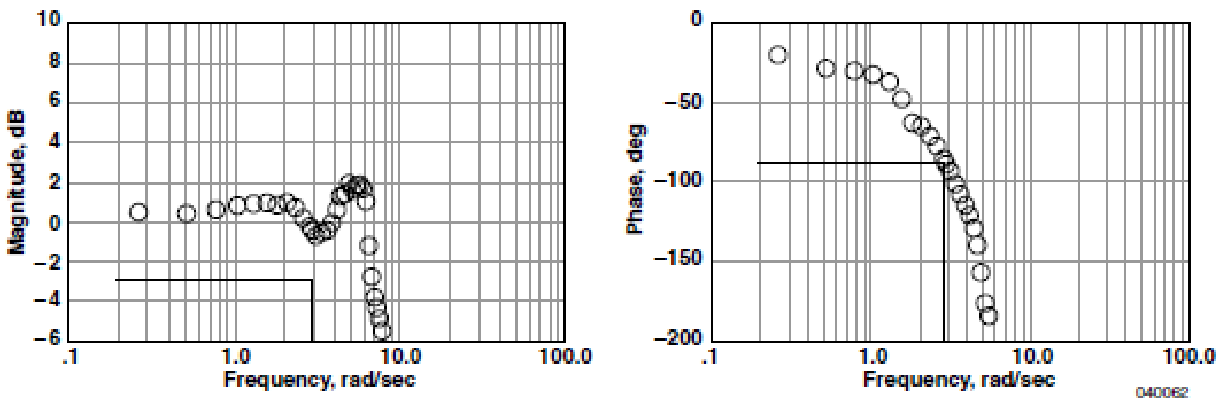


Figure 26. F-16XL compensated closed loop frequency response obtained using Neal-Smith method[16]

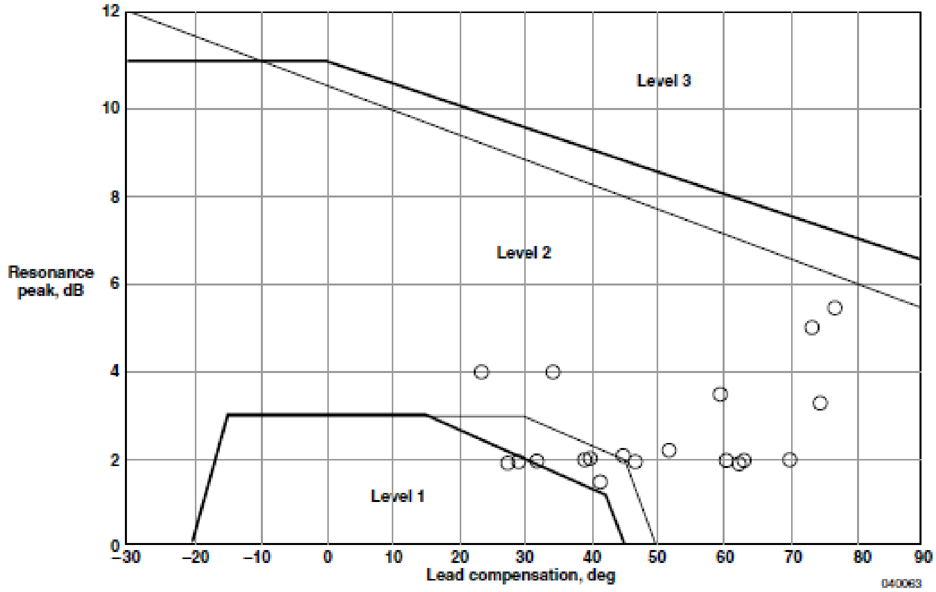


Figure 27. F-16XL Neal-Smith results[16]

Table 11. F-16XL results from Neal-Smith analysis[16]

Mach	Altitude (ft)	Lead (deg)	Peak (dB)
0.81	10,000	39.24	2.01
0.92	10,000	51.84	2.21
0.93	10,000	44.83	2.09
0.46	15,000	76.89	5.43
0.47	15,000	62.55	1.92
0.58	15,000	73.36	4.99
0.59	15,000	74.61	3.27
0.65	15,000	46.69	1.94
0.65	15,000	59.84	3.48
0.69	15,000	41.42	1.49
0.69	15,000	63.21	1.99
0.92	15,000	39.85	2.02
0.6	20,000	70	2.00
0.8	25,000	60.59	1.97
0.91	25,000	34.26	4.01
1.20	30,000	31.89	1.97
1.11	35,000	27.41	1.90
1.34	35,000	29.11	1.94
1.61	35,000	23.44	3.98

SR-71: A common theme in the SR-71 data analysis was the authors' concern with understanding which response, pitch attitude or flightpath, drove the ratings and comments during the test maneuver. Both responses were evaluated using the Neal-Smith criteria. The results of this comparison are shown in Figure 28. The authors note that the pitch attitude response required a large amount of lag to be introduced by the pilot, automatically placing the predicted handling qualities in the Level 2, moving to Level 3 region. The vertical speed response began Level 1 before moving to Level 2 and was more in line with pilot comments and ratings. The slope was also noted to have been smaller for the vertical speed response, indicating less of a sensitivity in flying qualities to increasing demands of the maneuver. The authors went a step further to examine the impact the abrupt pitch rate response might have on ratings, shown in Figure 29. As no comments were made to this effect, it was determined that the comments and ratings were driven primarily by the flightpath bandwidth. Finally, the authors examined the impact of the location of the inertial velocity measurement on the evaluations. The work presented in the figure was for acceleration measured near the pilot's station, providing lead due to the nature of its location. When compared to the response as measured from the c.g., the pilot station offers the more desirable and gradual slope as the bandwidth values are changed (Figure 30). This highlights the importance in signal selection and measurement location when considering this criterion.

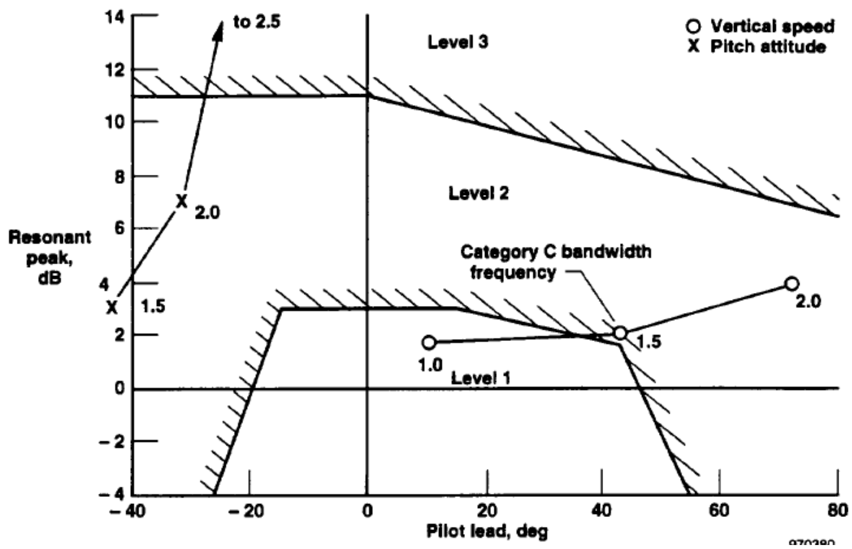


Figure 28. SR-71 Neal-Smith results using pitch attitude and vertical speed from stick position frequency responses as a function of bandwidth frequency[17]

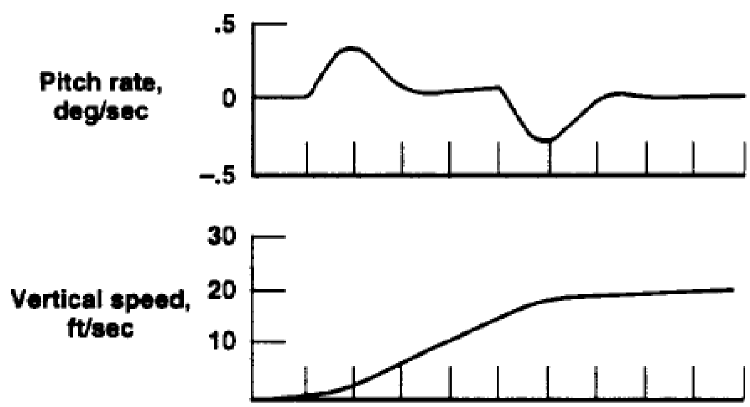


Figure 29. SR-71 comparison of pitch rate and vertical speed responses at Mach 3[17]

Tu-144LL: The Neal-Smith criteria were applied to the up-and-away data with a time delay of 0.25 sec and bandwidths from 1 to 2.5 rad/s, as summarized in Figure 31. For subsonic cruise the vehicle demonstrated Level 1 characteristics as the bandwidth increased from 1 to 2 rad/s. As the bandwidth value moved to 2.5 rad/s, the resonant peak and lead increased, resulting in Level 2. These results were consistent with the pilot comments regarding the pitch-attitude capture task. For the supersonic cruise conditions (Mach values between 1.25 and 2) for a like bandwidth in the subsonic regime, the supersonic conditions required more lag compensation. The 1 and 1.5 rad/s bandwidth indicated a Level 2 aircraft. The resonant peak for the 1 rad/s condition was low enough to have not been considered an issue. At bandwidths 1.5 rad/s and above, pitch sensitivity comments were expected given the resonant peak values. Moving from 1.5 to 2 rad/s, the resonant peak increased and pushed the vehicle into the Level 3 region. Moving up to the 2.5 rad/s bandwidth, the pilot lead continued to increase but the resonant peak in general decreased to the Level 2/3 border.

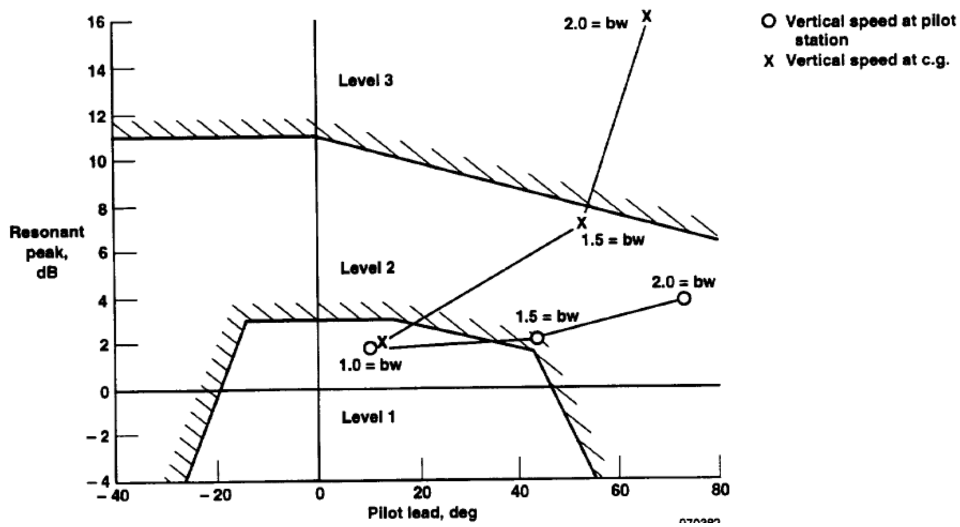


Figure 30. SR-71 Neal-Smith analysis using vertical speed at the center of gravity and vertical speed at the pilot station[17]

During the climb and descent phases, pilot lag in the 1.5 rad/s bandwidth region was not noted as an issue. This was supported by pilot comments indicating that the initial pitch response was not too quick or abrupt. The authors also noted that the climb/descent could be considered a category C task for which 1.5 rad/s was an appropriate bandwidth. The evaluation pilots had also stated that by reducing their urgency, analogous to reducing bandwidth, they could achieve a stable closed-loop pitch response. The increased lag compensation from the Neal-Smith criterion would predict an abrupt initial response but was inconsistent with the pilot comments.

The authors also noted the large lag compensation for the lower bandwidths that they explain by a decrease in the $1/T_{\theta 2}$ term primarily caused by increasing Mach number. This behavior was noted for the SR-71 analysis and is discussed in that section.

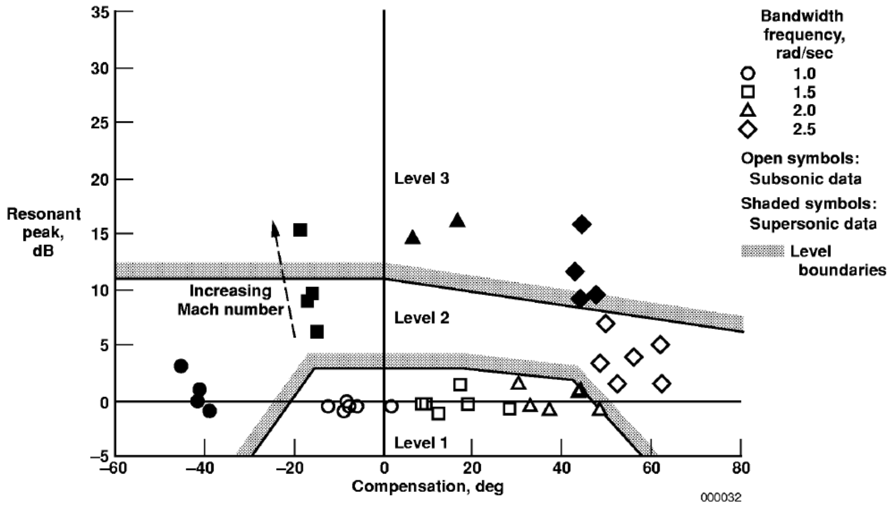


Figure 31. Tu-144LL Neal-Smith criteria[19]

Aircraft Bandwidth

Vehicles: F-16XL, SR-71, Tu-144LL

Summary: The F-16XL data had a select few points flown in the supersonic region though no pilot ratings were collected. The SR-71 data were examined for the pitch attitude and flightpath Bandwidth criteria for Category C. The Tu-144LL pitch attitude Bandwidth values were similar to the SR-71 and the ratings and commentary (where either were available) matched one another.

F-16XL: The aircraft Bandwidth parameters were computed for all conditions with frequency sweep data. Some conditions with poor coherence in the region for Bandwidth frequency or Phase Delay were omitted from these results. A summary of the points plotted against the requirements as published in MIL-STD-1797A is given in Figure 32. Bandwidth frequency and Phase Delay both appear to increase as dynamic pressure is increased. All conditions fell on or near the Level 2/3 border. The predicted handling qualities here were consistent with the pilot ratings and comments. If these data points are compared against current boundaries as documented in MIL-STD-1797B, all data points would be in Level 2.

SR-71: The authors of the original report[17] questioned whether the control of pitch attitude to affect flightpath as is conventionally done for subsonic vehicles would be applicable to high speed vehicles. Controlling flightpath directly would require using flightpath or a vertical speed indicator as feedback in place of pitch attitude. For the pitch attitude and flightpath Bandwidth evaluations, the more accurately-derived vertical speed gauge data were used. Additionally, simulated YF-12 data (reconstructed from a flight validated SR-71 simulation) were applied to the criteria.

The reconstructed YF-12 data had two conditions, one with the stability augmentation system (SAS) on, the other with it off. An example of the response with SAS off, resulting in a low damped condition, is given in Figure 33. There are multiple 0dB crossings, returning multiple gain Bandwidths (though the relevant number for the criteria is the lowest-frequency crossing). This characteristic is the result of a large “shelf-like” profile that is the result of large differences between the $1/T_{\theta 2}$ numerator and the low-damped short period mode, such as seen in Figure 34. This shelf has been indicative of poor handling qualities because the gain margin can change dramatically with only minor variations in phase.

Due to the items mentioned above, the extremes of the determined Bandwidths (phase and lowest gain Bandwidth), are plotted with the average CHRs given for each condition, in Figure 35. The SAS on indicates Level 1 handling qualities in both bandwidth and pilot ratings. Pilot ratings for the SAS off condition are indicative of Level 2 handling qualities; if these data were plotted for the current MIL-STD-1797B limits, agreement would be greatly improved, as the two SAS-on points would be in the Level 1 region and all of the other points would be in the Level 2 region.

The authors of the report[17] speculated that the attitude results may be misleading because the criteria presume the pilot is closing on attitude while the focus of the pilots is on the vertical speed indicator, a flightpath feedback. As such, the flightpath Bandwidth criterion was examined as well. For this evaluation, the phase Bandwidth values were used for the SAS-off points, Figure 36.

The SAS-on data points fell well within the Level 1 region. The SAS off evaluations saw a decrease in the pitch attitude Bandwidth but an increase in the flightpath Bandwidth. The shifts in Bandwidths were enough to move the data points into Level 3, inconsistent with the Level 2 HQRs.

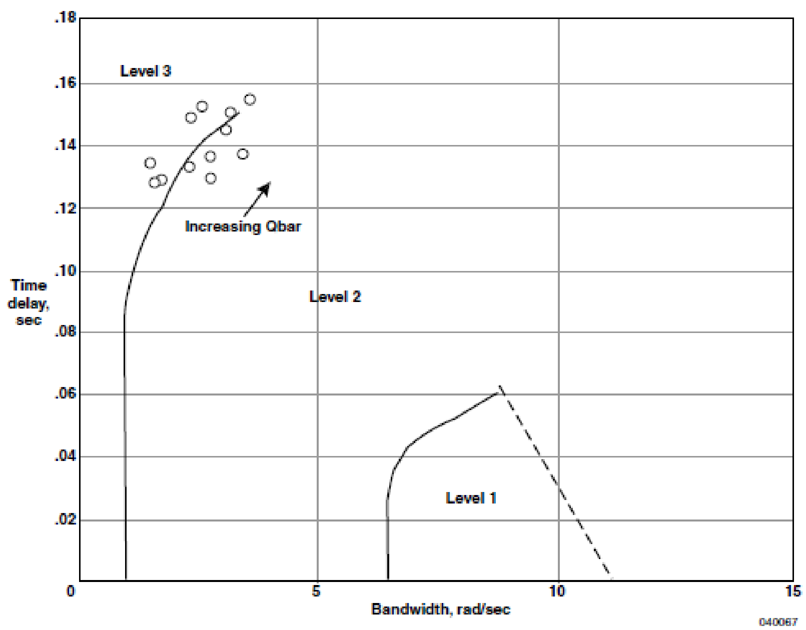


Figure 32. F-16XL Bandwidth results compared with MIL-STD-1797A requirements, Category A[16]

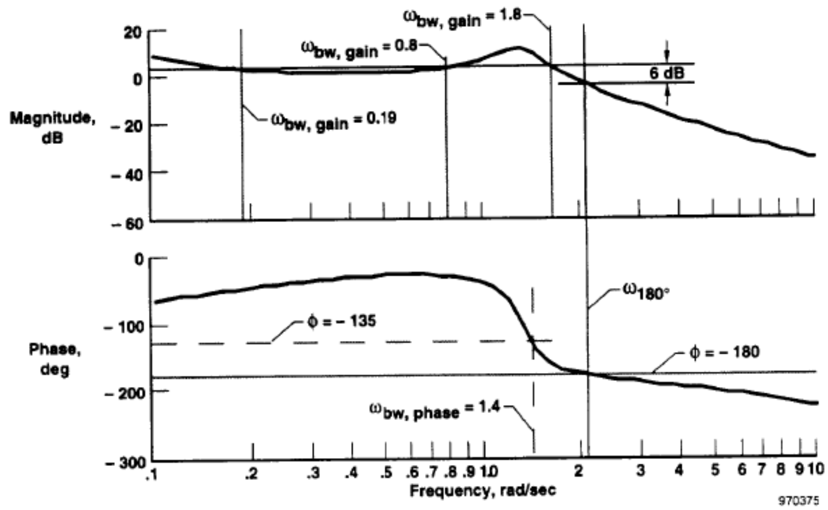


Figure 33. YF-12 example pitch attitude Bandwidth calculation typical of a low-damped test point[17]

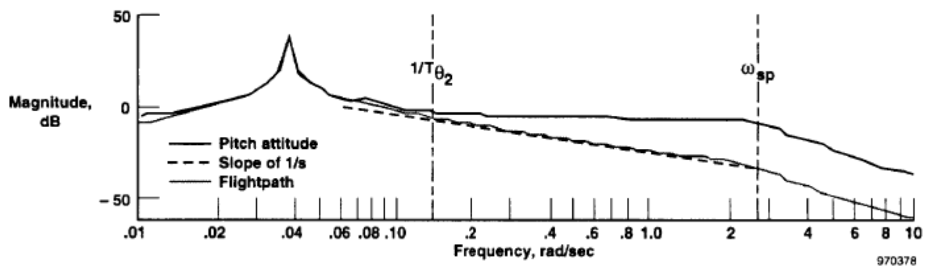


Figure 34. SR-71 comparison of pitch attitude and flightpath frequency responses (magnitude plot only)[17]

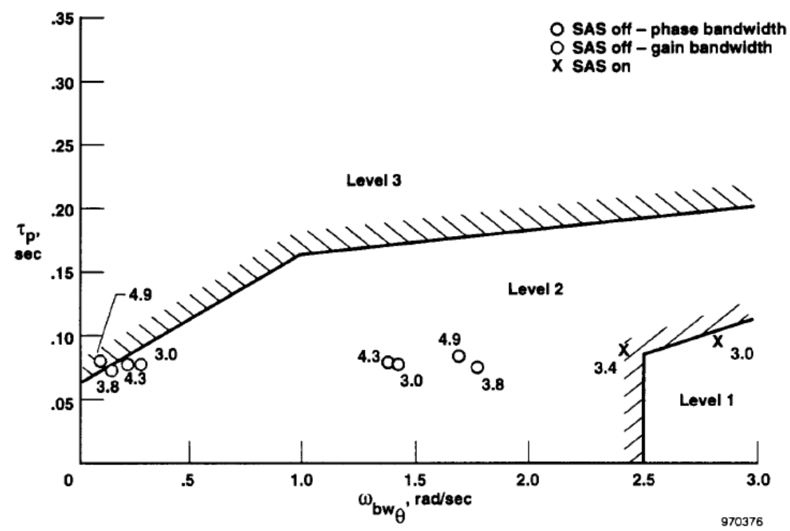


Figure 35. SR-71 MIL-STD-1797(USAF) pitch attitude Bandwidth criteria for Category C flight[17]

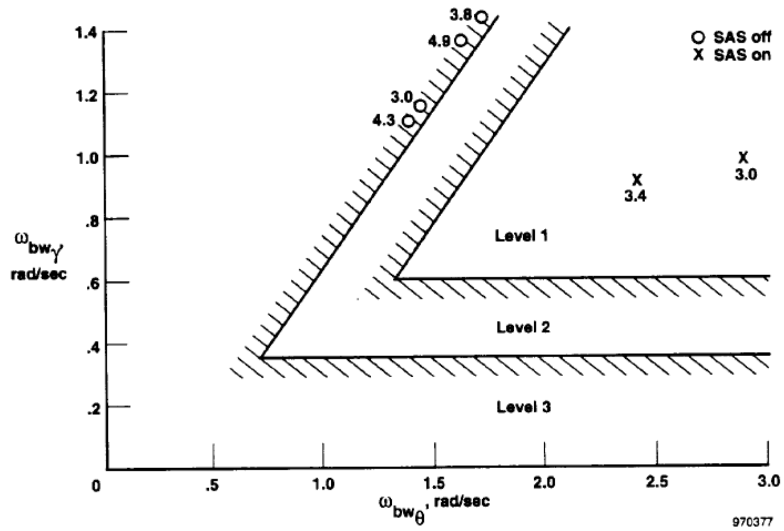


Figure 36. SR-71 MIL-STD-1797(USAF) pitch and flightpath Bandwidth criteria for Category C flight[17]

Tu-144LL: Attitude Bandwidth was computed for the Tu-144LL and is shown in Figure 37. The pilot comments indicated issues with attempting high gain control. Once the pilot reduced aggressiveness the vehicle was more manageable. This is in line with the results shown in Figure 37. These requirements are from MIL-STD-1797A for Category C flight phases. Data from the SR-71 and YF-12 (Ref. 25) along with Cooper-Harper ratings from level turns and altitude changes were overlaid with the Tu-144LL Bandwidths, . The Tu-144LL Bandwidths were consistent with those from the SR-71 and YF-12 data. The authors of the study[19] also applied requirements that were proposed for the HSCT program[26] for terminal area flying, shown in Figure 39. These requirements are similar to MIL-STD-1797B for Category C flight phases. These requirements do not appear to be stringent enough for both the supersonic and subsonic maneuvering.

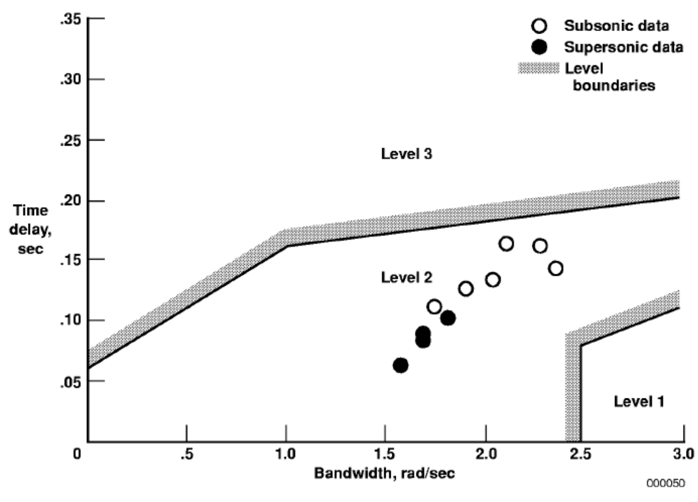


Figure 37. Tu-144LL Bandwidth for Category C Flight Phase[19]

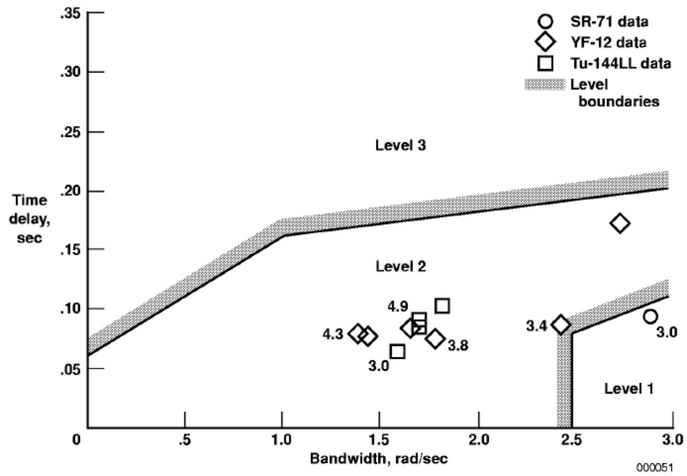


Figure 38. Tu-144LL Bandwidth for Category C Flight Phase with YF-12 and SR-71 data[19]

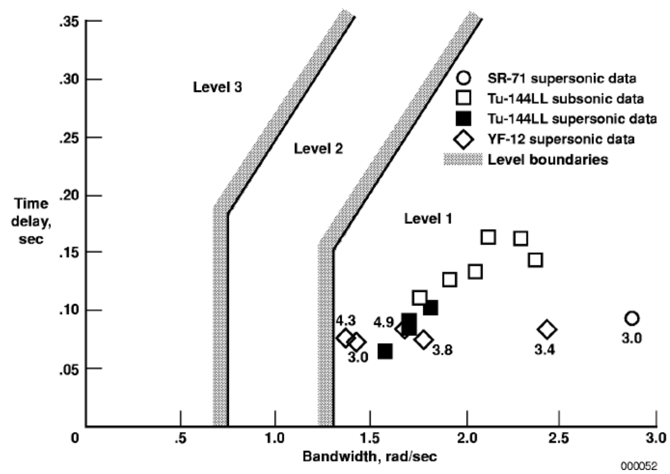


Figure 39. Tu-144LL Bandwidth for Category C Flight Phase with YF-12 and SR-71 data[19] compared with proposed HSCT limits[26]

The flightpath Bandwidth criterion was applied as well to the same set of data, Figure 40. Handling qualities ratings are provided with the SR-71 and YF-12 data. The Tu-144LL data indicates that it is borderline Level 1 to Level 2. These data were for a task considered more in line with a Category B task as the pilot did not attempt the precision control of altitude. As such, given that this criterion was developed for a Category C task, meeting Level 1 requirements could be misleading. In addition, a precision control task was attempted by one of the pilots during the climb to Mach 2.0 and the pilot noted difficulty controlling vertical speed. This does not mesh with the larger flightpath Bandwidth values for the supersonic Tu-144LL data. The authors also noted that the SR-71 and YF-12 flightpath Bandwidths were larger as well. They attributed this tendency to the reduced short-period damping estimated for the higher Mach values. Per their example in Figure 41, the short-period damping for Mach 2.0 was smaller than that for Mach 0.9, hence the more gradual roll-off. If this trend were true in general, that could explain the results seen here, where even borderline Level 1 ratings (YF-12) are ending up in the borderline Level 2 or 3 region.

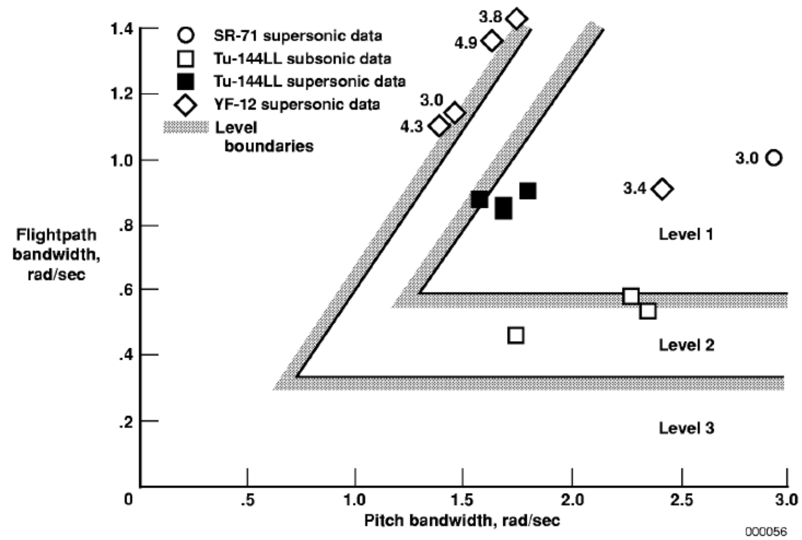


Figure 40. Tu-144LL, SR-71, and YF-12 pitch attitude vs. flightpath Bandwidth[19]

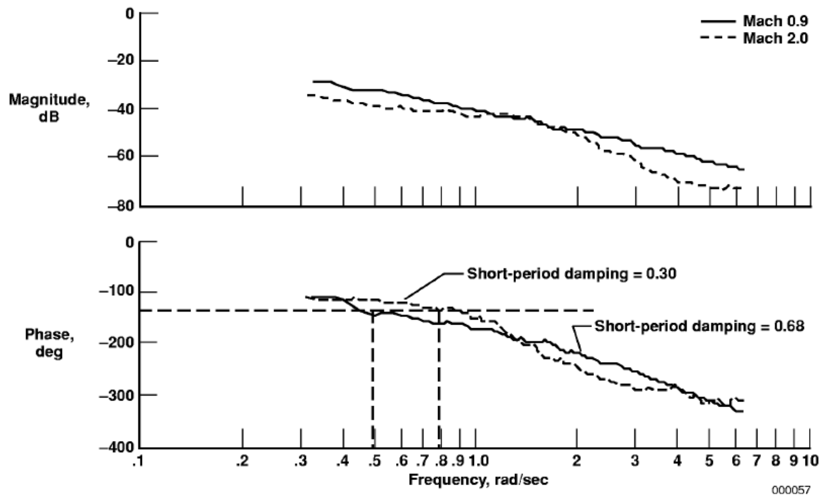


Figure 41. Tu-144LL comparison of integral of normal acceleration to column frequency responses for subsonic and supersonic cruise conditions[19]

Modal Requirements

Vehicles: F-16XL (roll mode time constant and effective time delay), GHAME (phugoid root, height mode root, performance), Tu-144LL (short period damping, time delay estimate, CAP, $\omega sp*T_{\theta 2}$)

Summary: The existing Level 1 roll mode time constant requirements (MIL-STD-1797B) were easily met by the F-16XL. The ratings assigned for the gross acquisition maneuvers were Level 1 to Level 2 and consistent with these results. The same was noted for the effective delay in roll and the time to bank 90°. These requirements were originally plotted against MIL-STD-1797 requirements, but they are unchanged in MIL-STD-1797B. The requirements on the time delay, short-period frequency and damping are unchanged from MIL-STD-1797. A similar examination of the short period damping estimates for the Tu-144LL, XB-70 and YF-12 aircraft and simulation data suggested that the short period damping requirements may be too restrictive The GHAME evaluations recommended a time to double amplitude of 15 seconds for the height mode and

3 seconds for the phugoid as acceptable limits, presuming that Level 2 ratings are permitted for backup control modes. The Tu-144LL evaluations, inclusive of the YF-12, XB-70 and SR-71 data, demonstrated that the CAP requirements were suitable at the levels defined and correlated better with pilot ratings and comments. The levels considered were the same as provided in MIL-STD-1797B.

F-16XL

Roll Mode Time Constant and Effective Delay: The F-16XL performed full stick, 360° rolls over a range of altitudes and Mach numbers. These runs were used to determine the maximum roll rate, roll mode time constant, effective time delay[iii], and time to bank (90°). The method of computation for the first three measures is given in Figure 42. This method was validated using a simple model and flight test data, see Figure 43 and Figure 44. Using this method, the pertinent parameters were estimated from the flight test data and inserted into the model. The flight test input was then run through the model to generate the roll rate output, compared against the flight response in Figure 44. Though there are some discrepancies later in the response, the region of interest matches well, proving out the method. These results were then compared against the MIL-STD-1797 criteria, Figure 45.

Maximum Roll Rate and Time to Bank 90°: For the F-16XL, the maximum achieved roll rate and time to 90° bank evaluations were performed under the same CATIII mode restrictions, reducing the maximum roll rate by 75 deg/s. The maximum roll rate achieved with this restriction is provided in Figure 47 while the time to roll 90° is overlaid with the requirements of MIL-STI-1797, Figure 48. Level 1 and 2 handling qualities were present dependent upon the flight condition being evaluated.

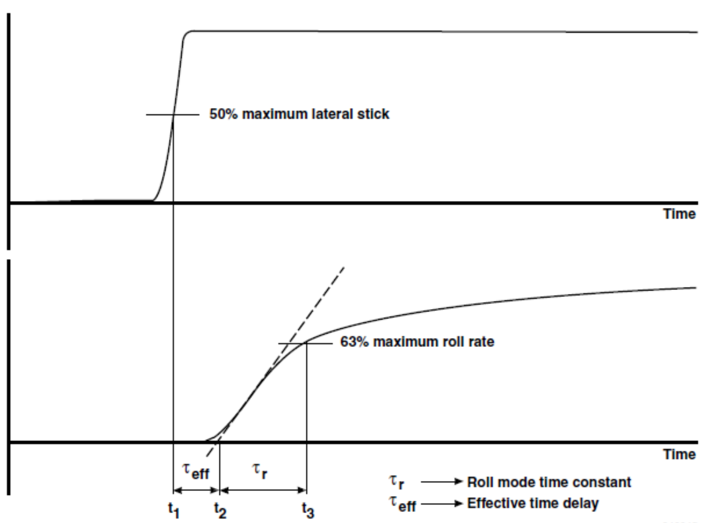


Figure 42. F-16XL time history method for τ_r and τ_{eff} calculation[16]

[iii]"Effective time delay" as discussed here is not a formal requirement in the roll axis in MIL-STD-1797B, though it is a part of a set of requirements in the pitch axis. It is used here as a time-domain substitute for equivalent time dely.

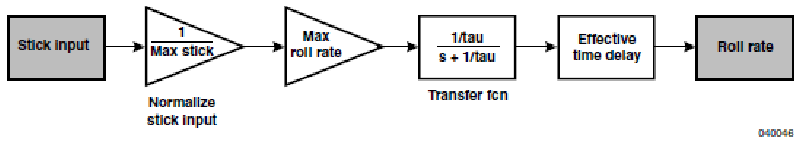


Figure 43. F-16XL model used for τ_r and τ_{eff} time history method validation[16]

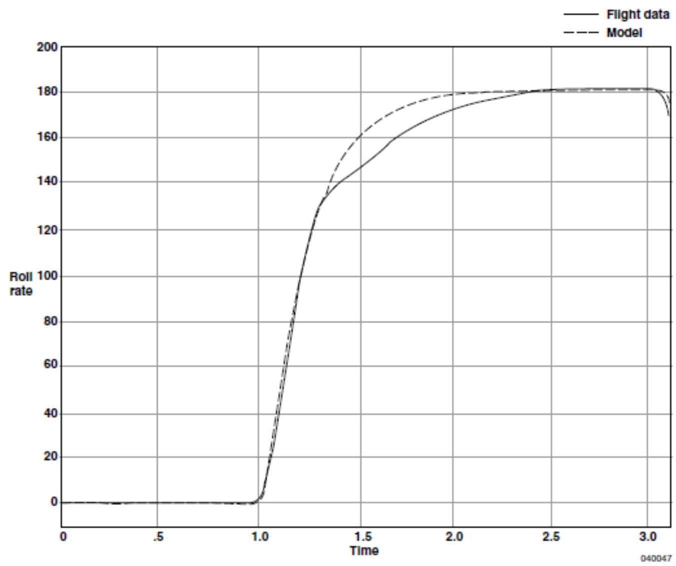


Figure 44. F-16XL sample result of comparison between model and flight data[16]

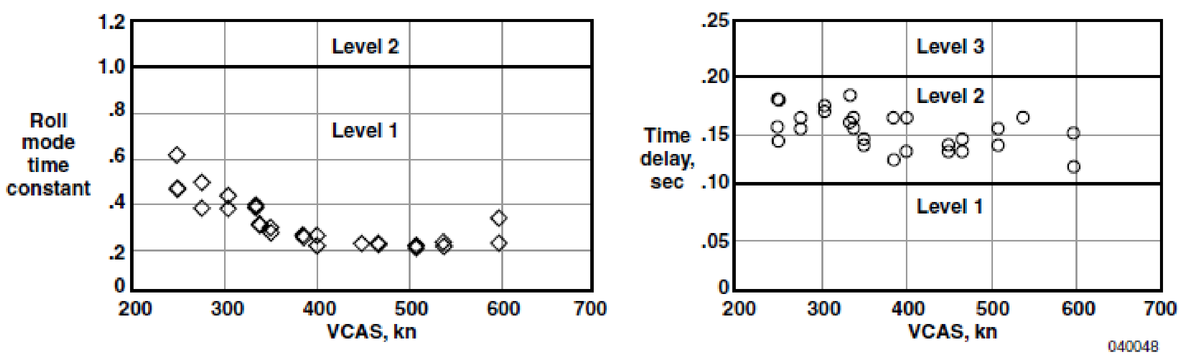


Figure 45. F-16XL roll mode time constant and effective time delay as a function of airspeed[16]

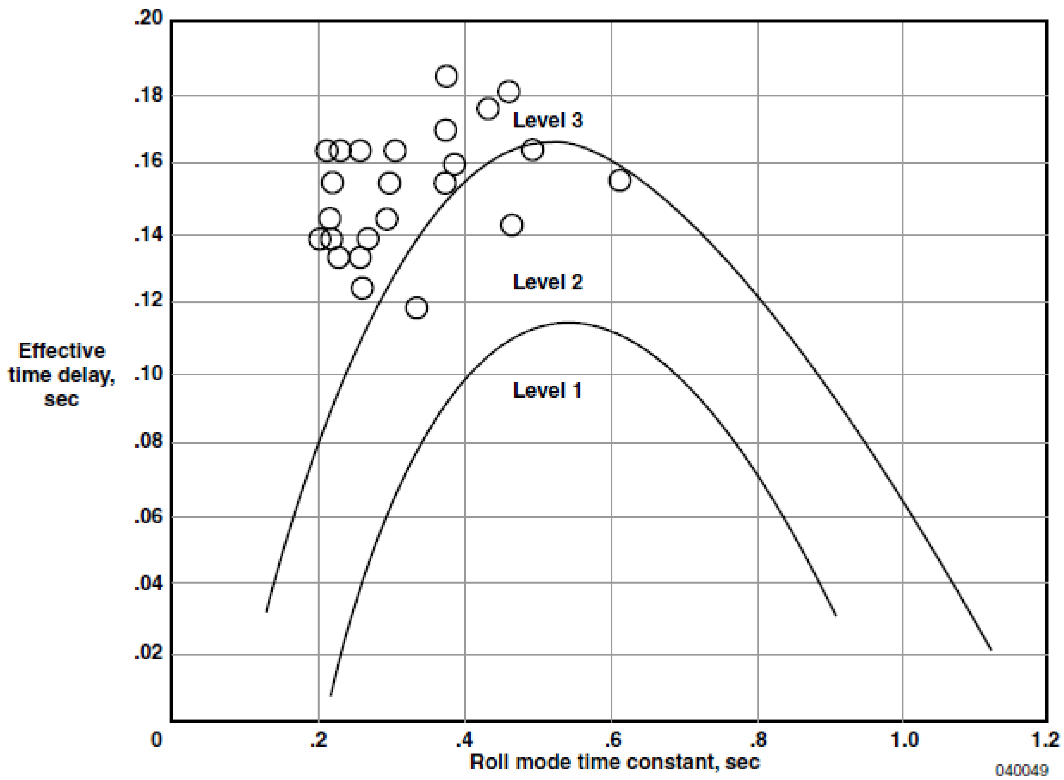


Figure 46. F-16XL roll mode time constant as a function of effective time delay[16]

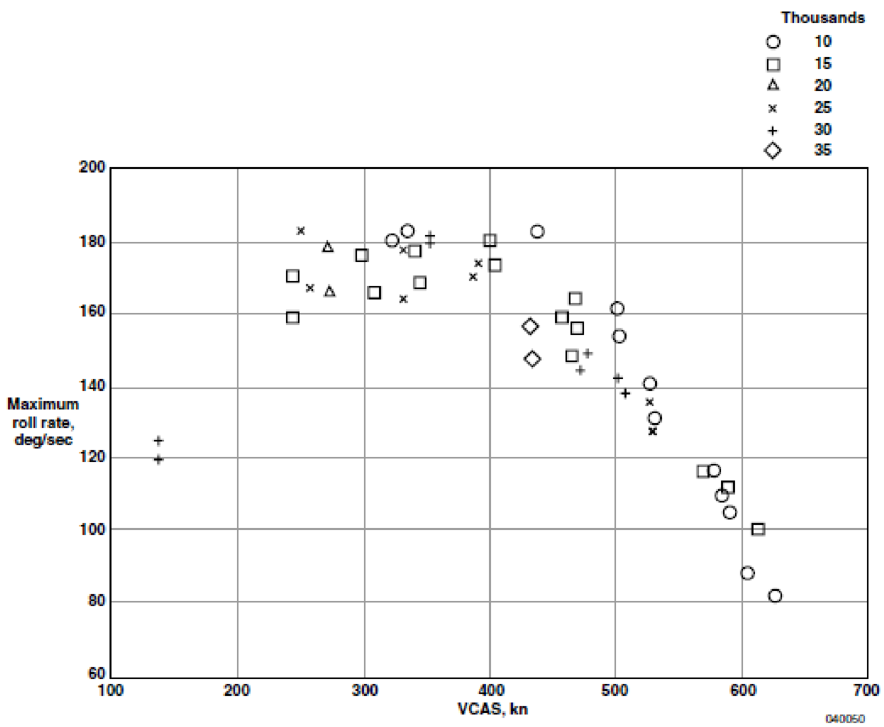


Figure 47. F-16XL maximum roll rate versus airspeed[16]

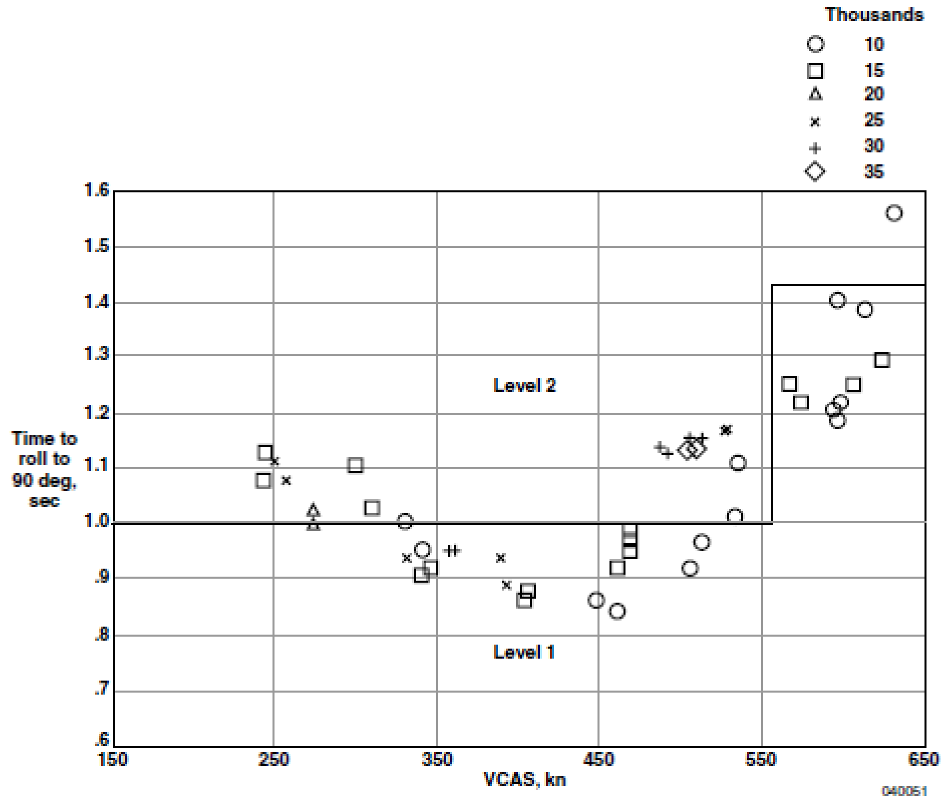


Figure 48. F-16XL time to roll to 90 deg bank angle as a function of airspeed[16]

Longitudinal Equivalent Time Delay, Short Period Frequency and Damping

Frequency Sweep Background: Frequency sweep data (θ/δ_{ec} or q/δ_{ec}) were collected at 1g only (Figure 49), while the comparative test maneuvers with associated CHR were performed at 3g. In order to leverage the ratings from the 3g maneuvers against the predicted handling qualities from the 1g sweeps, frequency sweep simulation data were generated at 3g. These data were compared against the flight-generated 1g sweeps. Typical responses are given in Figure 50. The comparative results are shown in Figure 51. The results overlaid well and as such, the CHR and comments can be used as for comparison against the quantitative metrics.

Lower Order Equivalent Systems Estimation: For the F-16XL, the lower order equivalent systems approach was applied to the longitudinal flight test data to provide estimates of select flying qualities criteria: 1) time delay, 2) short period frequency, and 3) short period damping. Those conditions where good fits could not be found were excluded from consideration here.

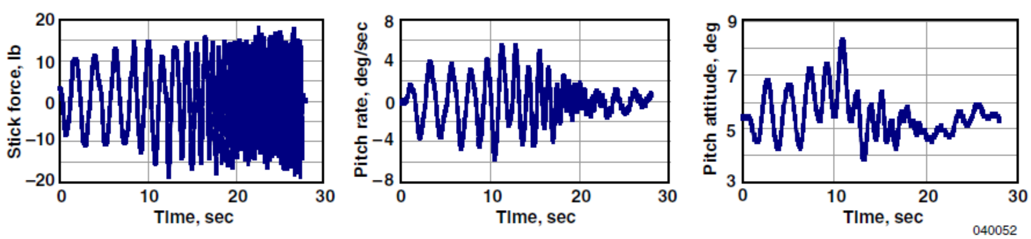
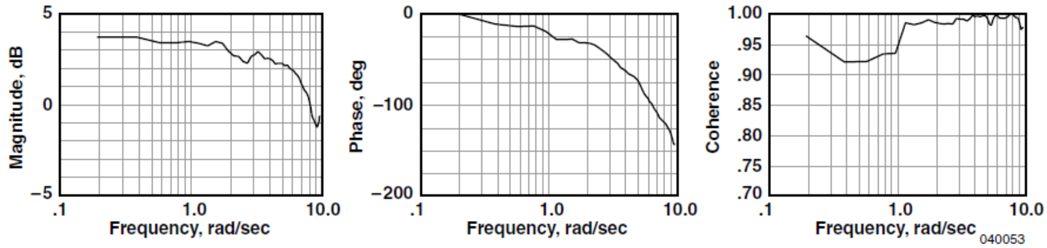
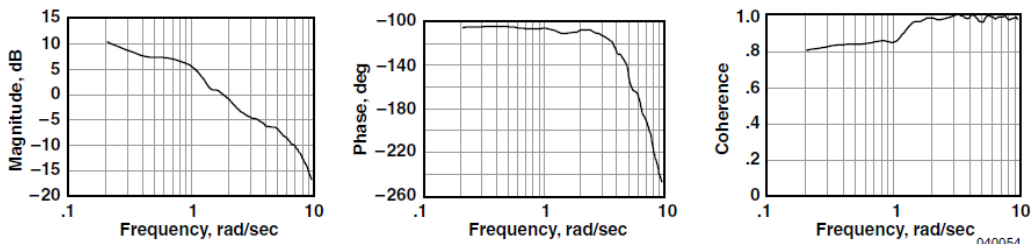


Figure 49. F-16XL typical frequency sweep time history[16]



a) q/δ_{ec}



b) θ/δ_{ec}

Figure 50. F-16XL sample pitch rate and attitude to stick input transfer function[16]

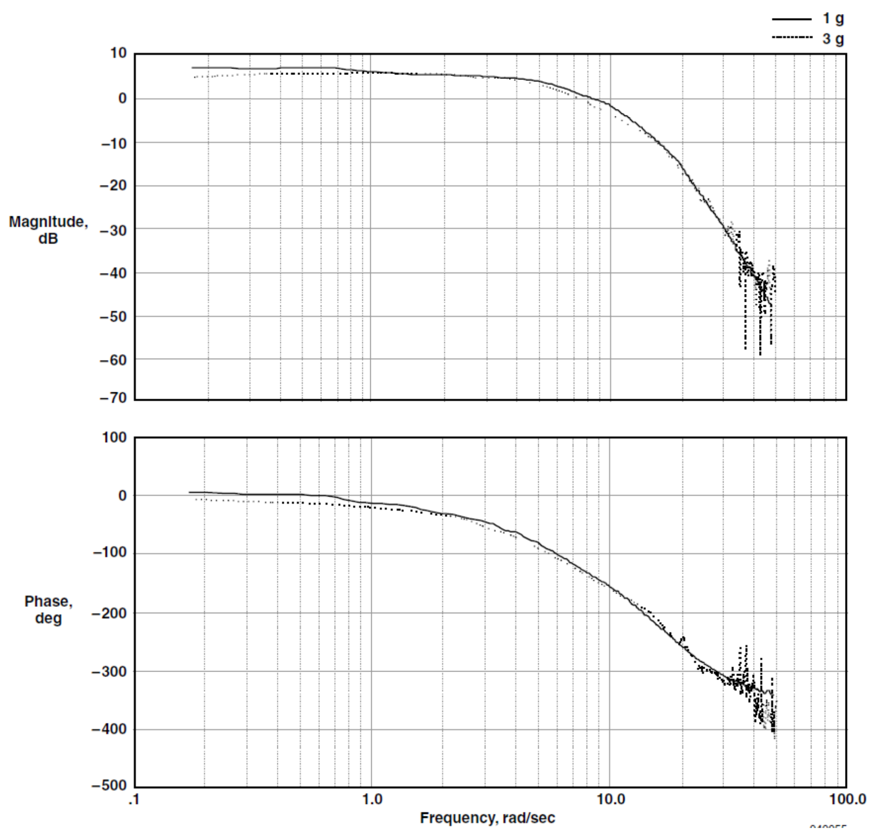


Figure 51. F-16XL pitch stick to pitch rate transfer function comparison for frequency sweeps at 1g and 3g[16]

The estimated measures were plotted against the requirements in MIL-STD-1797, Figure 52 and Figure 53. The estimated time delay is Level 2, though near Level 3. The estimated damping ranges from borderline Level 1 to solidly Level 2. The short period frequency fell within the Level 2 and

3 regions. The ratings given for the equivalent test points during the formation flight and air-to-air tracking maneuvers were generally consistent with these estimations. There was also a prediction that the handling qualities would improve as airspeed increased that was not seen in the pilot comments or ratings.

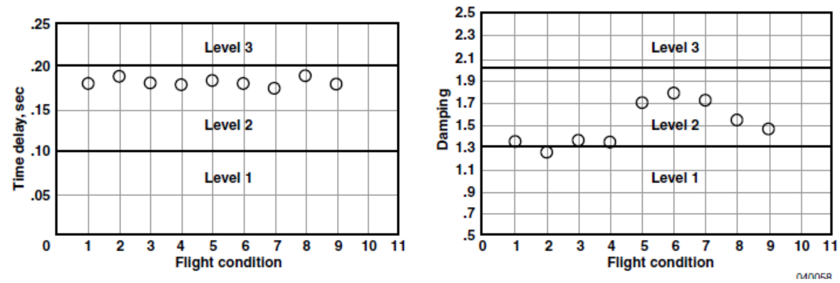


Figure 52. F-16XL LOES results: equivalent time delay as a function of flight condition[16]

Table 12. F-16XL longitudinal LOES results[16]

Flight Condition	Altitude (ft)	Mach	Normal load per α (g/rad)	Equivalent Frequency (rad/s)	Equivalent Damping	Equivalent Time Delay (s)	Dimensional Lift Curve Slope (1/sec^{-1})
1	10,000	0.81	30.3	2.81	1.35	0.18	1.16
2	15,000	0.47	9.98	1.52	1.25	0.19	0.65
3	15,000	0.6	14.51	1.36	1.36	0.18	0.77
4	15,000	0.6	12.91	1.34	1.34	0.18	0.67
5	15,000	0.7	18.74	1.7	1.7	0.18	0.83
6	15,000	0.78	24.16	1.78	1.78	0.18	0.95
7	20,000	0.6	10.64	1.72	1.72	0.17	0.55
8	25,000	0.6	10.15	1.54	1.54	0.19	0.54
9	25,000	0.8	12.85	1.46	1.46	0.18	0.51

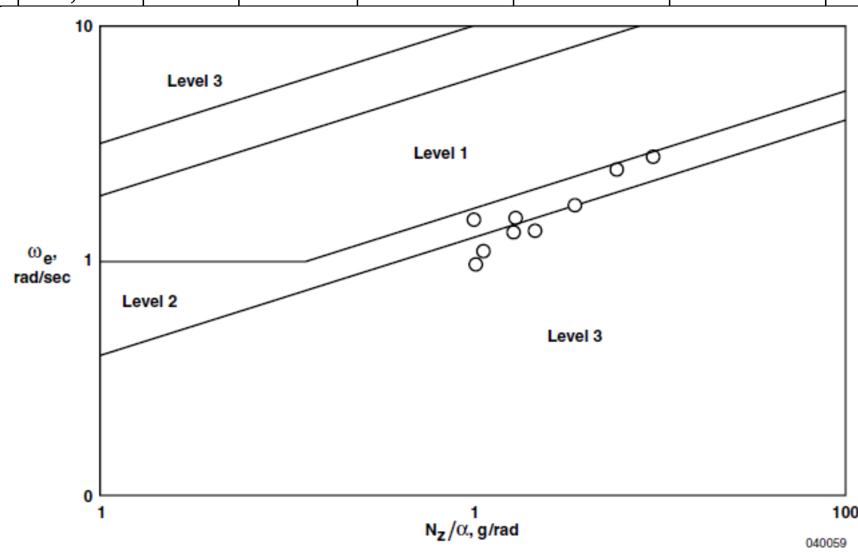


Figure 53. F-16XL LOES short period frequency estimates[16]

Generic Hypersonic Aerodynamic Model Example (GHAME): Phugoid and Height Instability

Real phugoid root locations spanning a range of 0 to 0.42 rad/s with a time to double of 13.6 seconds (0.05 rad/s root location) to 1.7 sec (0.42 rad/s root location) were evaluated by three pilots, generating 5 data points at each root location, Figure 54. ~83% of the data was within 1 CHR, indicating the consistency of the results. Ratings were solidly Level 2 up to 0.16 rad/s (4.4 sec time to double) before rapidly degrading to Level 2/3 and solid Level 3 ratings (2.3 sec time to double or less). The behavior is not unexpected as the time to double amplitude shortens with increasing phugoid root location.

Note: There were some minor discrepancies between the values reported in the text and those tabulated. The tabulated values are reported here and used for the purposes of this discussion.

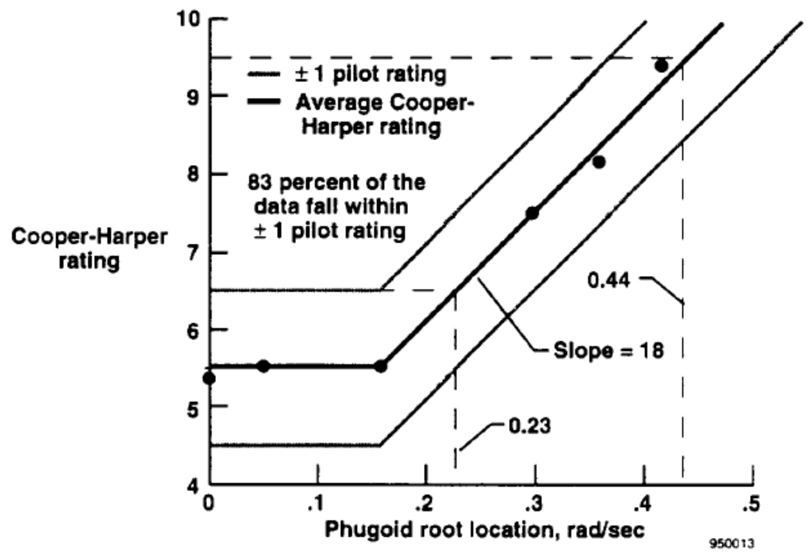


Figure 54. Average Cooper-Harper Rating as a function of phugoid instability[18]

Figure 55 presents the averaged ratings for the height mode instabilities investigated, -0.01 to 0.2 rad/s and 40.8 (at 0.02 rad/s) to 3.5 sec (at 0.2). Seven data points were generated at each instability by four pilots. Like with the phugoid results, the ratings were consistently within ±1 rating (73% of the time). Also, like the phugoid behavior, there was a cliff-like behavior noted with higher ratings present beyond ~0.015 rad/s. The ratings for root locations lower than this were consistently Level 2 while above this the Level 2/3 and Level 3 borders were exceeded at ~0.045 and 0.14 rad/s (15 and 5 sec time to double).

The authors suggest that the results of this experiment would indicate that a time to double amplitude of 15 seconds for the height mode and 3 seconds for the phugoid are acceptable limits, presuming that Level 2 ratings are permitted for backup control modes. [18] Given the cliff-like behavior in each of these modes, extra margin and consideration is likely warranted and care given to these regions in the design. The authors noted that the pilot may be more sensitive to the height mode instabilities given that the cliff occurs at larger time to double amplitudes. They postulate that this sensitivity may be due to the fact that the height mode involves both energy and flight path control, requiring both pitch inputs and throttle control while the phugoid primarily requires pitch inputs to control.

The authors also noted that in observing the flight data, there were instances where the pilot simply appeared to run out of control authority to maintain stable control of the aircraft. A small study was made to understand the impact of modifying the control surface deflection limits on the phugoid mode instabilities. Figure 56 presents the results of this effort by examining CHR against phugoid root location as control power is adjusted. Note that as the power is reduced relative to the baseline, the CHR in general mirror the profile of the baseline results but shifted upwards. The increased control power case is consistently rated better and the fitted slope of CHR vs. phugoid root is more gradual than for the other control power cases. This would seem to indicate that with more control power, larger instabilities in the phugoid mode can be controllable, everything else equal.

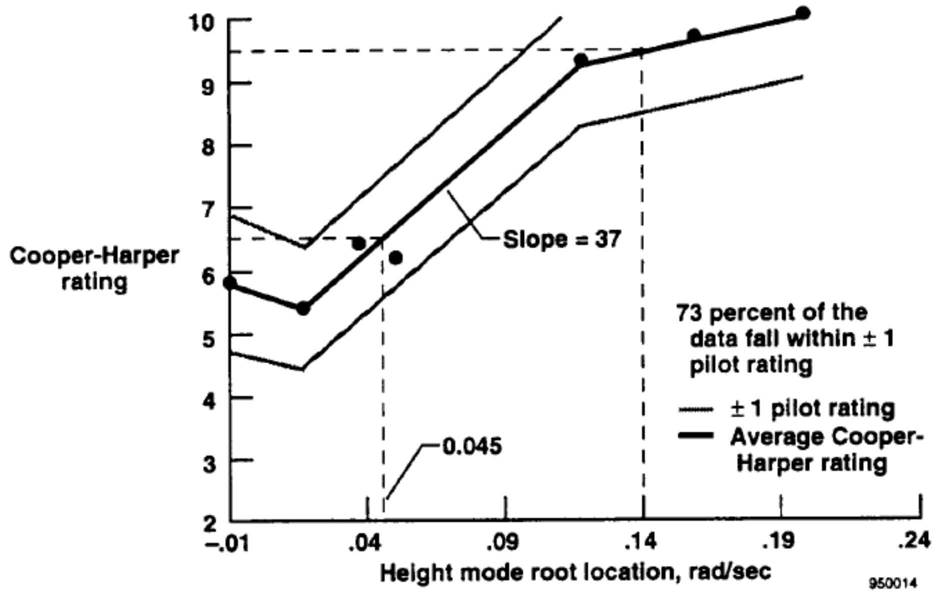


Figure 55. Average Cooper-Harper Rating as a function of height mode instability[18]

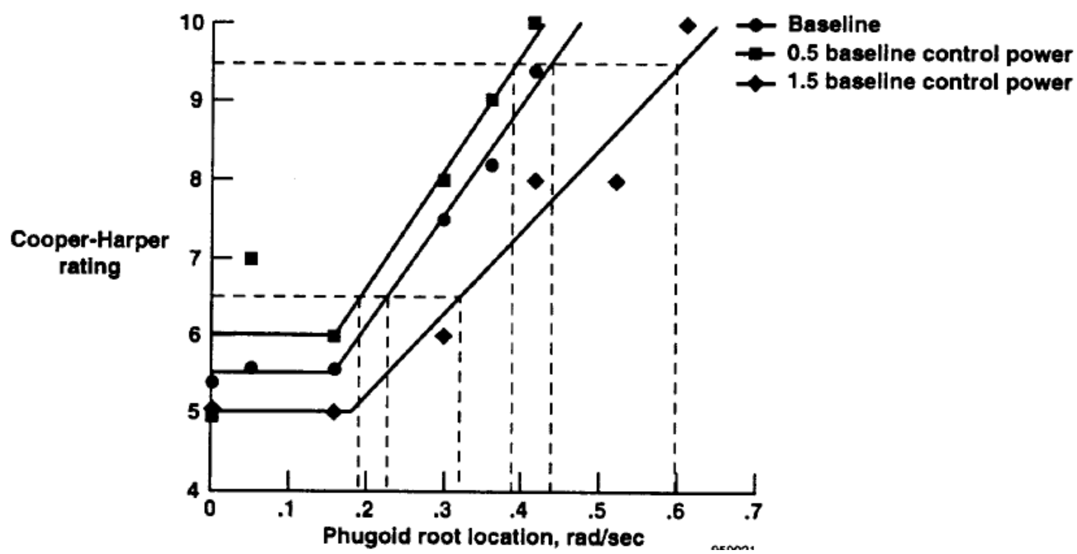


Figure 56. Effects of available control power on Cooper-Harper Pilot Ratings of phugoid mode instabilities

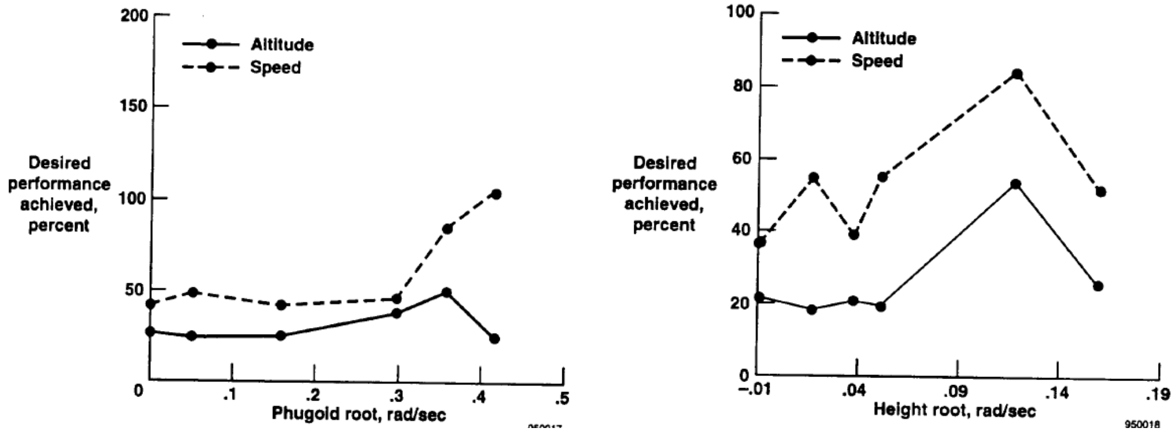


Figure 57. Percentage of desired performance achieved by the pilot[18]

Tu-144LL: Using the LOES approach, estimates of the short-period frequency, damping, time delay, CAP, and $T_{\theta 2}$ parameters were determined for the Tu-144LL.

Short-Period Damping: Estimates of the short period damping relative to Mach number are plotted in Figure 58 against the MIL-STD Category C requirements. The damping decreased as Mach number increased with a sharp drop at Mach 1.2. The damping decreased slowly afterwards and was borderline Level 1/2. Considering previously compiled data from like flight regimes in Figure 59, these damping values are supported as Level 1. Other aircraft that received Level 1 ratings had short period damping values less than those required by the MIL-STDs for Category C values[25] and support the Level 1 designation of the damping values estimated for the Tu-144LL. All of this suggests that the requirements may be too restrictive for this aircraft type and for the mission considered.

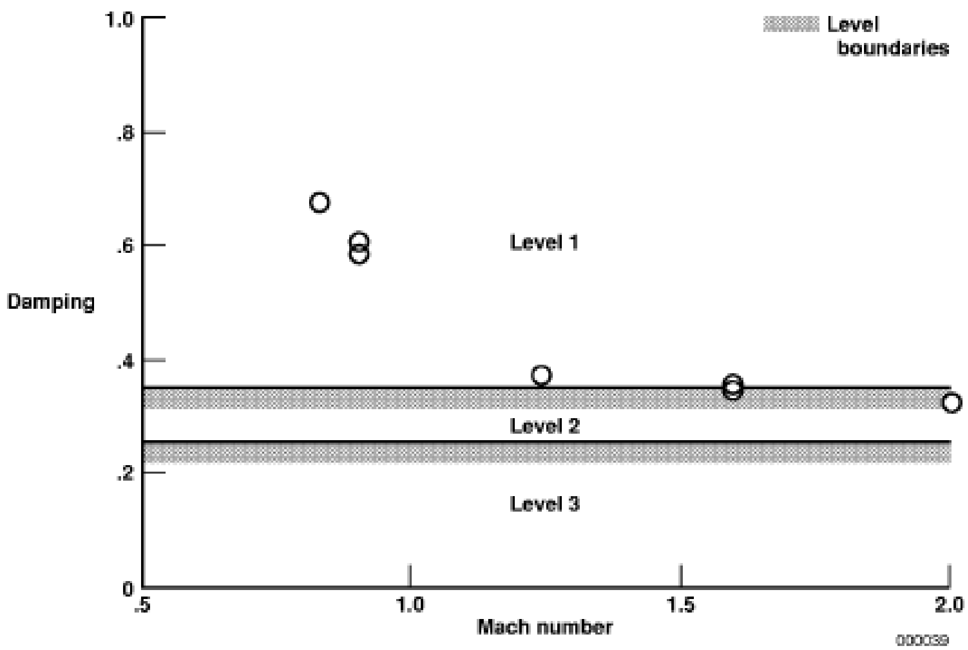


Figure 58. Tu-144LL short period damping estimation[19]

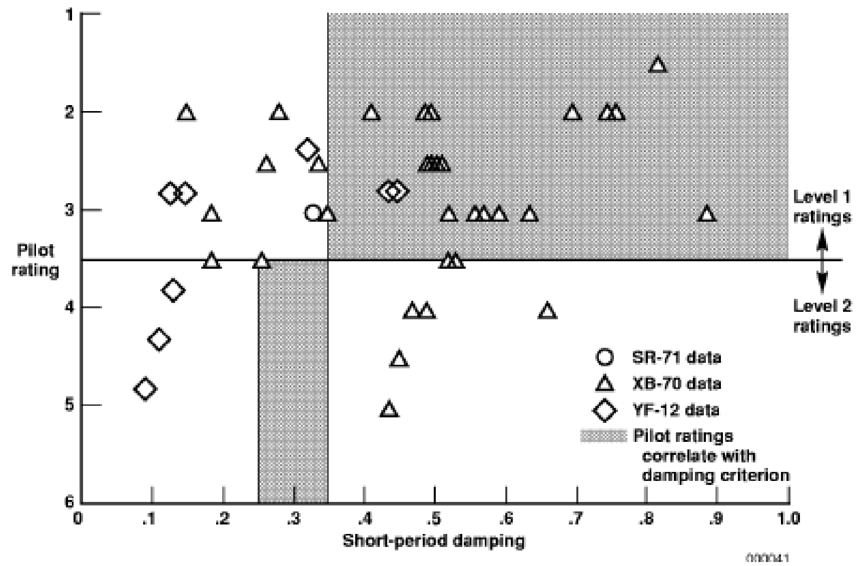


Figure 59. Tu-144LL short period damping estimates of YF-12, XB-70 and SR-71 against Category C requirements[25]

Time Delay Estimate: The authors note that at Mach 0.9, the time delay is ~150 msecs with convergence to 110 msecs as the Mach number increased, Figure 60. Against the MIL-STD-1797B requirements, this vehicle would be considered Level 2. Per the authors, the standard itself had suggested that these requirements may be too restrictive with the possibility that the true Level 1 limit may be on the order of 250 msecs for Class III aircraft. The authors suggested that given this information, combined with the lack of comments or perception of time delay, the vehicle could be considered as a Level 1 vehicle.

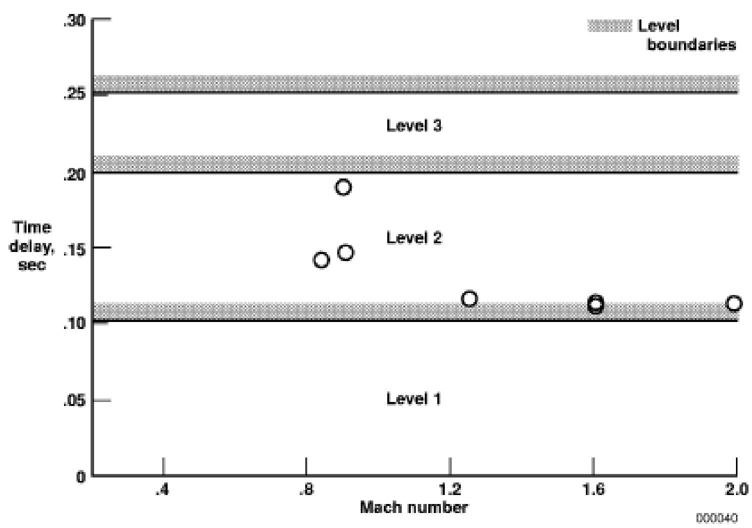
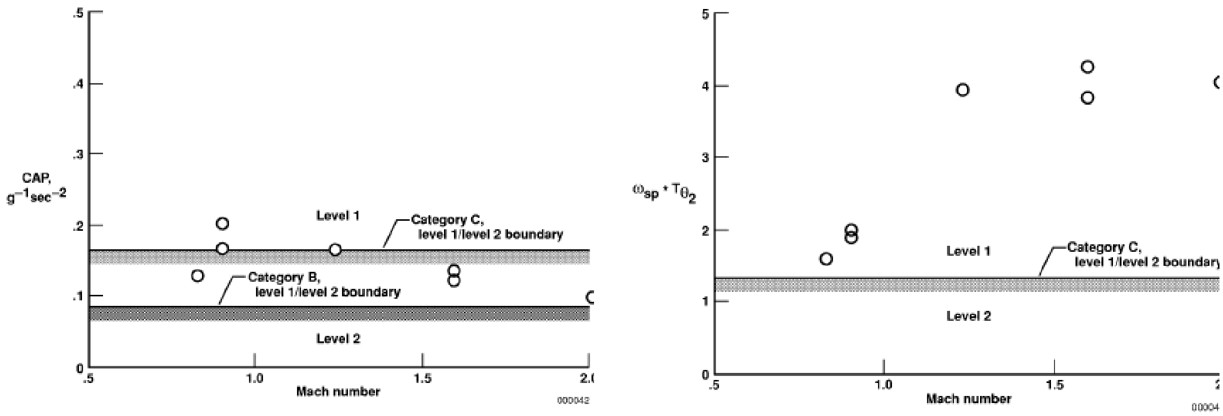


Figure 60. Tu-144LL time delay estimation[19]

*CAP and ω_{sp}*$T\theta 2$:* The expectation when considering the CAP and $\omega_{sp}*T_{\theta 2}$ is that the results would trend in the same manner when considering their variation against Mach number, Figure 61. The authors were able to trace this down to the variations in the numerator and denominator of the CAP approximation, shown in Figure 62. When considering the CAP denominator, the variation in airspeed was much greater than the slight decrease in $T_{\theta 2}$. This has the overall impact of increasing

CAP through the transonic region but decreasing it in the supersonic region. The short period damping in general does not change above Mach 1 resulting in a CAP that decreases as Mach increases. When considering the $\omega_{sp}*T_{\theta 2}$ term, the $T_{\theta 2}$ term offsets the changes in ω_{sp} to net an increase as Mach increases. Given the short period damping and time delay were considered Level 1, this leads to the question as to which is the better indicator of handling qualities and best reflects the pilot experience.



a) CAP

b) $\omega_{sp}*T_{\theta 2}$

Figure 61. Tu-144LL $\omega_{sp}*T_{\theta 2}$ and CAP vs. Mach number against Category C requirements[19]

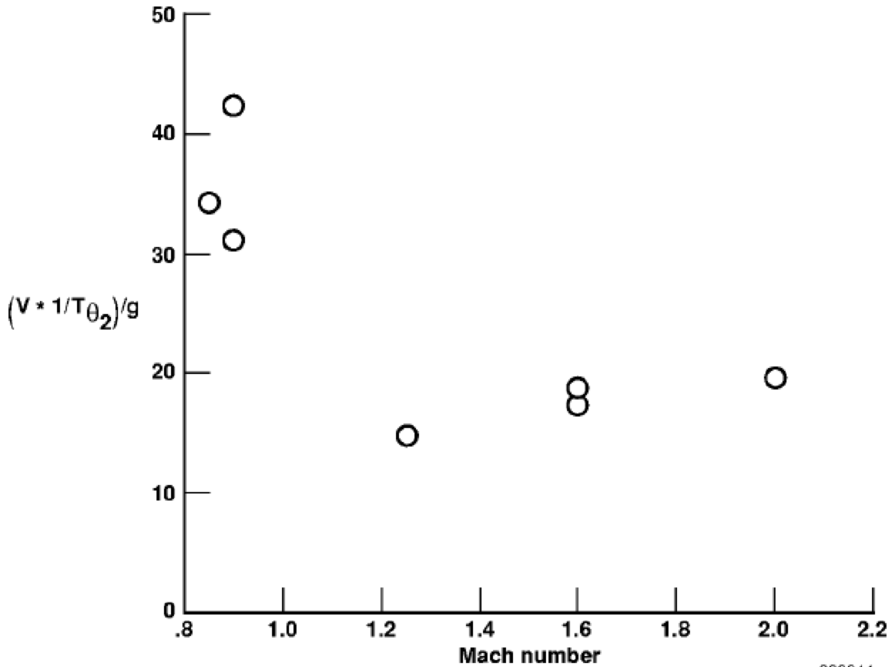


Figure 62. Tu-144LL CAP denominator vs. Mach[19]

To address this question, the authors considered related vehicle data for the XB-70 and SR-71 vehicles, Figure 63. The shaded regions indicate areas where the pilot comments supported the CAP parameter and assigned level. The tasks flown for those vehicles included precise altitude control as a requirement. As such, the CAP parameter was shown to correlate well with Category C maneuvers requiring precise altitude control.

The time histories in Figure 64 present an overlay of the SR-71 and Tu-144LL control and response for a supersonic cruise turn. Note that the Tu-144LL has much larger pitch attitude and altitude deviations than for the SR-71. Pilot comments support that altitude was not closely tracked for the Tu-144LL while it was closely tracked for the SR-71. This would seem to indicate that the turns for supersonic cruise are more of a Category B task here and the pilot comments on the goodness of the control are properly mirrored in the CAP values.

The authors also examined the ability of the pilots to maintain the VRI profile while climbing to Mach 2 cruise condition as this is a task expected to require precise flightpath control. One of the pilot's made a comment regarding the overcontrol of flightpath that was believed to be from pitch attitude sensitivity and perceived lag among pitch attitude and flightpath. When the variation in CAP and $\omega_{sp}*T_{\theta 2}$ terms are compared against Cooper Harper ratings for a like aircraft and configuration, the CAP parameter matches more closely with pilot observations, Figure 65.

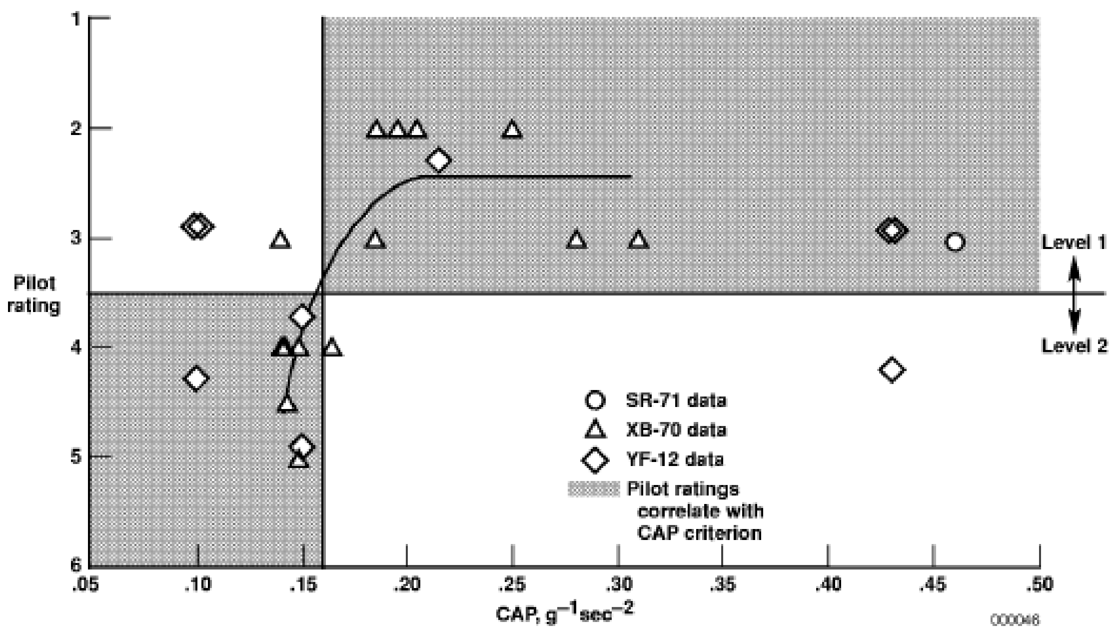


Figure 63. Tu-144LL CAP for YF-12, XB-70 and SR-71 against Category C requirements[19]

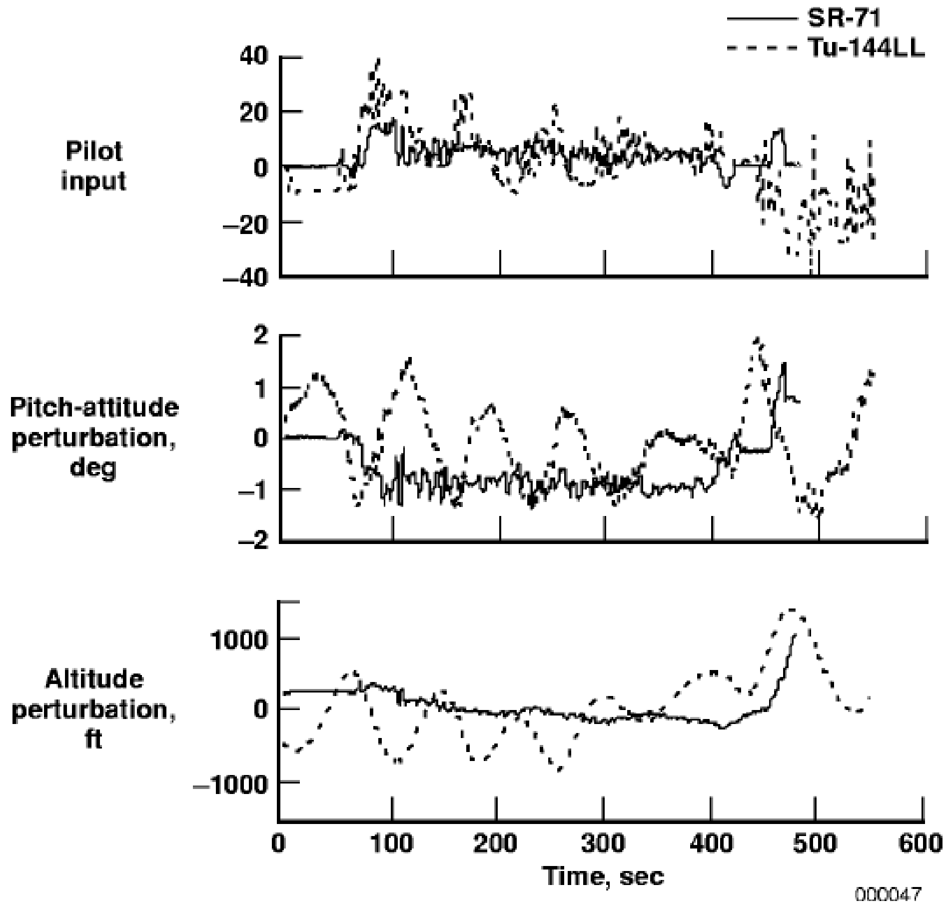


Figure 64. Tu-144LL supersonic turn time histories

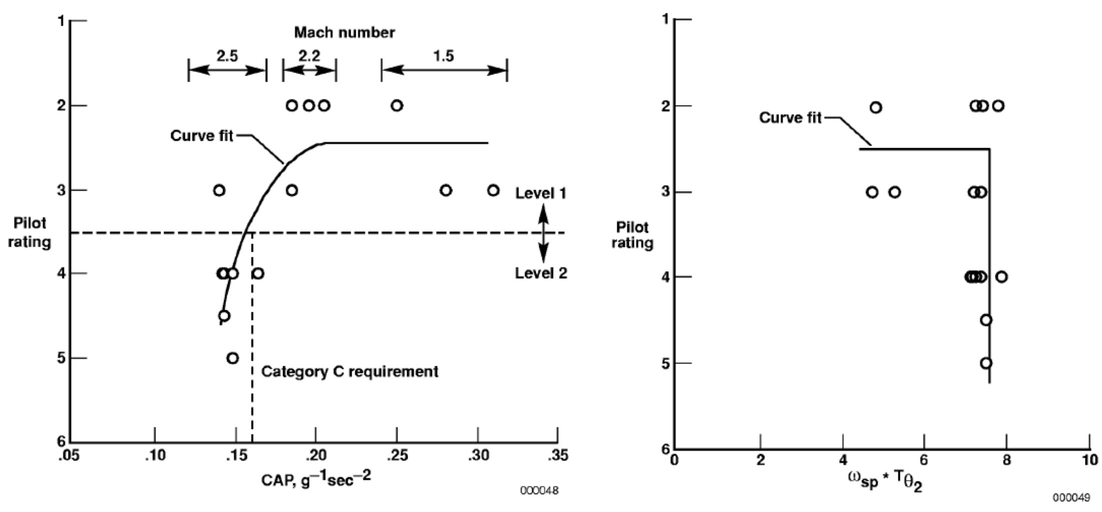


Figure 65. XB-70 CAP and ω_{sp}*$T_{\theta 2}$ against pilot rating

3.4 Devices and Methods for Preventing Category II PIO

3.4.1 Introduction

This subsection summarizes past work related to Category II Pilot-Induced Oscillations (PIO) that involve control surface rate limiting. The emphasis is on information that is not currently included in MIL-STD-1797B.

3.4.2 The Space Shuttle PIO Suppression Filter

Repeating an observation from 2004, nothing seems to inspire significant new handling qualities research like a high-profile PIO event.[27] A PIO during landing on the Space Shuttle Enterprise ALT-5 in October, 1977 is a prime example. This landing was the first attempted precision landing to an actual runway, rather than the dry lakebed (see Figure 66). This PIO resulted from a combination of basic shuttle handling qualities, time delay through the digital flight control computers, and rate limiting of the elevon actuators.[28] Subsequent analysis and simulation[29] identified the unusual pilot location relative to the aircraft's center of rotation as a significant factor as well.

Figure 66. Shuttle ALT-5 runway landing (NASA photo)

Methods for mitigating PIO on the Space Shuttle were investigated by NASA. References 30 and 31 describes a PIO suppression (PIOS) filter that was designed to reduce pilot gain when potential for PIO is high, while minimizing any additional phase lag. To achieve the desired gain reduction, the filter modifies the stick shaping function as a function of the amplitude and frequency of the pilot's input, thereby reducing the amount of rate limiting. The filter logic and resulting shaping function is shown in Figure 67. Note that the filter EDEP term provides an estimate of the frequency of the pilot's control activity. This frequency estimate is then used to set the SKQ gain in the stick shaping function. The SKQ gain schedule is shown in Figure 68. The overall impact is to attenuate the input commands of the pilot at essentially all frequencies, since SKQ = 1 corresponds to an input at zero frequency.

Since the PIOS filter was implemented in the Shuttle control laws, no approach and landing pitch PIO events have been reported in the open literature. Whether this is due to the PIOS is difficult to say. Shuttle pilots practice hundreds of landings prior to a given mission, so that proper command inputs become almost precognitive.

Based on the apparent success of the application of the Shuttle PIO suppression filter, two types of filters were evaluated by NASA Armstrong Flight Research Center in three flight test programs.[32] These evaluations found that PIO suppression filters can reduce susceptibility to PIO resulting from excessive time delay. The evaluators also found that the suppression filter was, at best, a temporary solution until a control system upgrade could be made. Note that this experiment looked only at pure time delays and not rate limiting, so the evaluation was limited to linear pilot-vehicle system behavior.

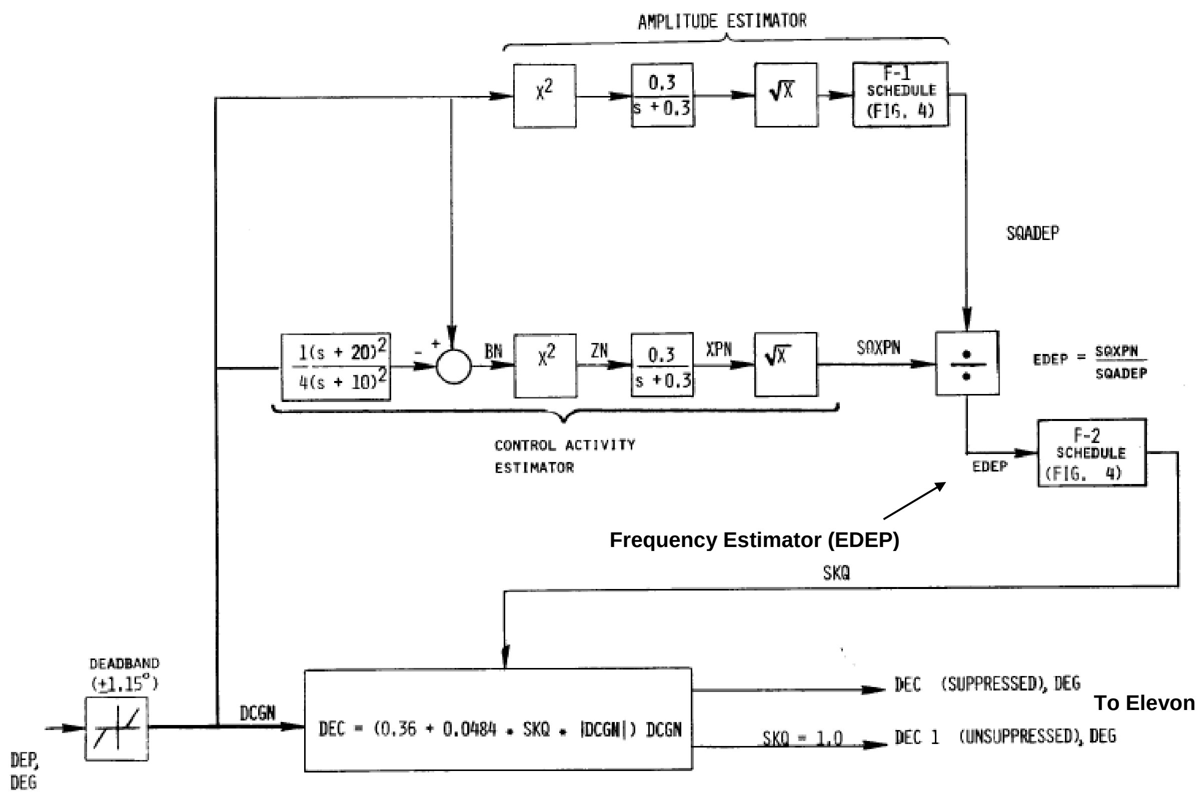


Figure 67. Shuttle PIOS and pitch stick shaping function[31]

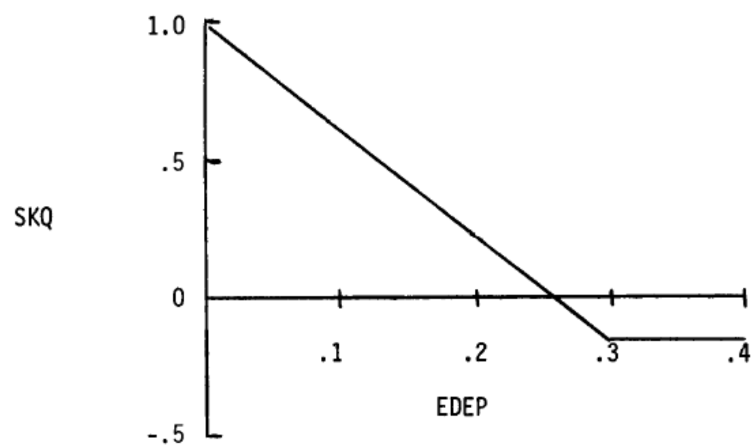


Figure 68. Shuttle PIOS SKQ gain schedule[31]

3.4.3 The A'Harrah Rate Limit Concept

Background: Mr. Ralph A'Harrah in his previous work at the Naval Air Development Center (NADC) and later at NASA HQ has long been concerned with the impact of rate limiting on PIO. In the late 1980's and early 1990's he strongly advocated the development of a concept that he referred to in its earliest form as the rate limit concept (RLC) and in its later form as the alternate control scheme (ACS) that would eliminate the added phase lag associated with rate limiting. A'Harrah advocated the concept to a number of parties including, the U.S. Navy, NASA, DLR, and others. This led to several diverging research paths. First, the U.S. Navy analyzed and then patented an algorithm that operates within an actuator digital loop closure. Second, NASA and the U.S. Air Force in conjunction with Calspan investigated the RLC/ACS concept as a command path compensator through several flight test investigations. Finally, DLR developed a unique phase compensation scheme based on a describing function interpretation of the A'Harrah concept. The paths associated with NASA sponsored work are described below beginning with a description of the concept as represented by Mr. A'Harrah in a conference paper.

The Alternate Control Scheme (ACS): A'Harrah's concept was formally documented in a 1994 conference proceedings paper.[33] It should be noted that this paper comes seven years after the original Navy work had commenced and several years after NASA/Calspan had begun their investigations. Simply stated,

"the concept is to alter the relationship governing the surface deflection during rate limiting to minimize the associated time delay… In other words, for rate limiting conditions, the actuator rate is set at a designated value slightly less than, or equal to the limiting rate, and will use the logic necessary to keep the surface moving in the proper direction, regardless of the actual surface position."

The ACS will switch on if two simultaneous conditions are met: (1) the control surface commanded input rate is greater than the control surface output rate; and (2) the ratio of the input to output rate is less than zero. Taken together these two requirements indicate that the actuator is rate limited and the commanded rate is in the opposite direction of the surface rate. Implementing the ACS in this manner will result in a bias in the actuator error signal that needs to be corrected.

NASA/Calspan Investigation of the A'Harrah Alternate Control Scheme (ACS): Mr. A'Harrah discussed his RLC/ACS concept with Calspan during a visit to the Flight Research Department in September, 1992. Based on this discussion, Mr. Chick Chalk of Calspan conducted an independent assessment based on his interpretation of the A'Harrah concept.[34] Mr. Chalk concluded that the command path concept showed sufficient potential to warrant a pilot-in-the-loop evaluation, and he recommended that NASA sponsor such an evaluation using the Calspan Learjet 25B in-flight simulator.

Acting on the recommendation of Mr. Chalk, the NASA Ames Dryden Flight Research Center funded a limited flight test evaluation of the RLC/ACS concept. Two data flights[35] were flown on 25 and 26 March 1993 for a total of 3 flight hours using the Calspan Variable Stability Learjet.

The RLC/ACS concept as implemented in the Learjet flight control software is described as follows beginning with the following pseudocode listing:[34,35]

IF $\left|\delta_c(n)-\delta_c(n-1)\right| \rangle \dot{\delta}_{o_{Limit}}\Delta T$ THEN

$\delta_o(n)=\delta_o(n-1)+Sign\left[\delta_c(n)-\delta_c(n-1)\right]\dot{\delta}_{o_{Limit}}\Delta T$

ELSE IF $\left|\delta_c(n)-\delta_c(n-1)\right| \langle \dot{\delta}_{o_{Threshold}}\Delta T$ THEN

$\delta_o(n)=\delta_o(n-1)+\left[\delta_c(n)-\delta_c(n-1)\right]+\left(1-e^{-K_f\Delta T}\right)\left[\delta_c(n-1)-\delta_o(n-1)\right]$

ELSE $\delta_o(n)=\delta_o(n-1)+\left[\delta_c(n)-\delta_c(n-1)\right]$

Table 13. RLC/ACS Parameters as interpreted by Calspan[34,35]

Variable	Description
n	Frame count
ΔT	Sample time
δ_c	RLC/ACS input position command
δ_o	RLC/ACS output position
$\dot{\delta}_{o_{LIMIT}}$	Rate limit
$\dot{\delta}_{o_{THRESHOLD}}$	Rate threshold for activation of bias removal
K_f	Bias removal inverse time constant

A verbal description of the above pseudocode is as follows:

1. The compensator becomes active if the absolute value of the change in command position over the frame count is greater than the limit position increment. Then the output position equals the output position from the previous frame plus an increment given by the product of the sign of the difference in command position over the frame multiplied by the limit position increment.
2. Furthermore, if when the compensator is active, the absolute value of the change in command position over the frame count is less than a threshold increment, then the output position is the output position from the previous frame plus the change in commanded position over the frame count plus a bias removal factor.
3. When the compensator is inactive, the output position is simply the output position from the previous frame plus the change in commanded position over the frame count.

The RLC/ACS command path algorithm was assessed using a precision offset landing task with the Learjet in the powered approach configuration (i.e., gear extended, flaps set to 20 deg, spoilers retracted, and power as required). Both roll and longitudinal axis evaluations were made with a centerstick configuration. Parameters that were varied included the roll axis rate limit (20 or 50 deg/sec), bias removal inverse time constant (0, 4, or 6 deg/deg), rate threshold (2 or 4 deg/sec), transport delay (90, 150, or 165 msec), roll command gain (-25, -50, or –75 deg/in), and roll stick gain (0.2 or 0.067 in/lb). The transport delay was added to make the configurations more prone to PIO. From this limited evaluation, it was found that the RLC/ACS improved handling qualities from Level 3 to high Level 2 with no tendency for PIO. It was further concluded[35] that further development, test, evaluation and demonstration of the rate limiter concept was clearly warranted.

Follow-on NASA/Calspan Investigation of the A'Harrah Alternate Control Scheme (ACS): The seemingly divergent results between the original NASA/Calspan study[35] and the USAF/Calspan study[36] was a concern to the parties involved. Thus, a new study was undertaken to investigate if the RLC/ACS performance was influenced by the characteristics of the cockpit controllers. A new flight test program was sponsored by NASA to investigate RLC/ACS performance with sidestick versus centerstick controllers. Sensitivity of the algorithm to noise and computer cycle time and varying feel system dynamics were also investigated. The evaluations were again conducted with the Calspan Learjet 25B in-flight simulator.[37]

Several changes were made in the implementation of the RLC/ACS algorithm as described below:[37]

1. The algorithm was implemented in C-code generated from Matlab/Simulink;
2. A rate limit equal to the algorithm rate limit was placed on the bias removal function to prevent large command biases resulting from full-travel pilot command inputs;
3. The bias removal inverse time constant was increased using an empirically derived formula, $K_f = \dfrac{\dot{\delta}_{\lim}}{0.05\delta_{\lim}}$
4. Parameters were added to the code so that the state of the algorithm could be recorded.

Four evaluation flights were conducted for a total of 6.5 flight hours. The Learjet was flown in the powered approach configuration (i.e., gear extended, flaps set to 20 deg, spoilers retracted, and power as required) and a precision offset landing task was used to assess the various configurations. Two of the three evaluation pilots that participated in the previous NT-33A program[36] took part in this program.

The baseline fly-by-wire Learjet configuration was degraded from a Level 1 configuration to a solid Level 3, PIO prone configuration by increasing the roll command gain (i.e., added sensitivity), adding 50 msec of time delay to the roll command path, and by reducing the maximum aileron deflection rate to 20 deg/sec. With the addition of the RLC/ACS algorithm, the Level 3 airplane with strong PIO tendencies was improved to a Level 2 airplane with little tendency to PIO. Yet these favorable effects were offset by[37] "(1) attenuated response to abrupt inputs, (2) reduced predictability of the aircraft response, and (3) out-of-trim conditions." These effects were made worse by the presence of noise or high frequency content. Regarding the sidestick versus centerstick, the force and position sensing sidesticks and the force sensing centerstick all featured higher frequency content inputs than the position sensing centerstick. Variations in feel system natural frequency and damping did not lead to reduced PIO tendencies.

Assessment of the RLC/ACS Flight Test Evaluation Programs: Upon reviewing the documentation[35,36,37] regarding the evaluations of the RLC/ACS algorithm, the following assessments are made:

1. The first limited NASA/Calspan flight test of the RLC/ACS[35] produced positive results for the lateral axis evaluations conducted with a precision offset landing task.
2. The results of the follow on flight tests conducted by USAF/Calspan[36] were not so clear cut even though the RLC/ACS did reduce PIO tendencies. In this more extensive evaluation, significant problems with the bias removal surfaced that had a direct impact

on roll performance and predictability. Furthermore, the improvements seen with the RLC/ACS algorithm in the precision offset landing task were not seen in the more aggressive up-and-away discrete tracking task.

3. To investigate the apparent discrepancies of the previous two flight test evaluations, a third limited evaluation was conducted by NASA/Calspan. Because of the limited scope, only precision offset landing evaluations were made. Thus, to a large extent the more favorable results of the first NASA/Calspan evaluations[35] were duplicated. The issues with the bias removal were, however, still noted and problematic.
4. One stark difference between the two NASA/Calspan programs and the USAF/Calspan program was the lack of up-and-away evaluations with the Learjet. In the USAF/Calspan study, the largest degradations in handling qualities with the RLC/ACS algorithm engaged occurred with the more aggressive up-and-away discrete tracking task. This task further exacerbated the bias removal problems, and also exposed the differences between the sidestick and centerstick.
5. In summary, the RLC/ACS appears to work well for those tasks that involve small amplitude, precision control maneuvers, but the bias removal remains an important shortcoming. The algorithm does not work well for large amplitude, precision control maneuvers, and the negative impact of the bias removal is more significant.

3.5 Impact of Cockpit Manipulator Feel Systems on Flying Qualities

3.5.1 Introduction

This subsection summarizes past work related to feel systems and flying qualities.

3.5.2 Background

Aircraft cockpit controls are either force or position sensing. As shown in Figure 69a the feel system is in series for position sensing. Position sensing does not include the feel system dynamics, while measurements made in terms of force do include these dynamics. For the force sensing feel system shown in Figure 69b the feel system dynamics are in parallel. Thus, neither force or position measurements include the feel system dynamics, since they are "downstream" of this point. Although new aircraft continue to be designed with both types of controls, the force sensing feel system generates less lag during closed-loop piloted control (Ref. 38). Examples of force sensing cockpit feel systems include the side stick controller found on the F-16, while position sensing examples include the center sticks found on the F/A-18 Hornet and Super Hornet fighters and the C-17 military transport as well as the center wheel column control found on the Boeing 777 commercial transport.

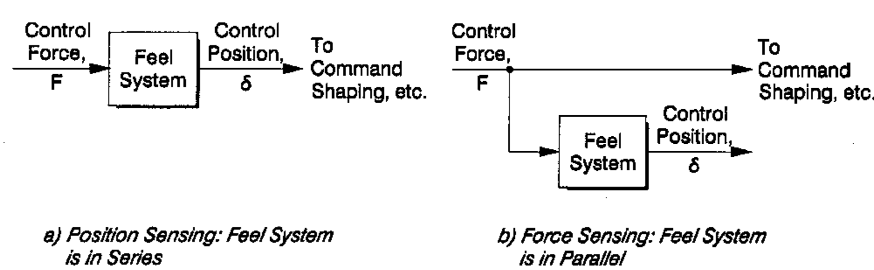


Figure 69. Mechanization of feel systems

Within the handling qualities community a debate continues as to the importance of cockpit feel systems in a pilot's assessments of aircraft handling qualities. As detailed in an AIAA paper[39] much of the debate centers on how to best account for the effect of the feel system dynamics, if any, when applying handling qualities criteria. Although it has generally become accepted practice to include the lags associated with control surface actuators when modeling aircraft dynamics for handling qualities assessments, no similar agreement has been found regarding the feel system. By reviewing the existing flight test databases involving the evaluation of cockpit feel systems, it is concluded[39] that the feel system dynamics do indeed impact handling qualities. Unfortunately, no comprehensive flight test database yet exists to effectively set requirements for the many types of feel systems.

Early STI Studies for NASA. Two Air Force studies were used to initiate the development of higher order pilot models that include neuromuscular dynamics associated with the human operator. This work was formalized in several research studies conducted by STI for NASA in the late 1960's and early 1970's[40,41] and led to the development of the neuromuscular-limb-manipulator portion of the STI Structural Isomorphic pilot model, a version of which is shown in Figure 70. In the figure, two manipulator feedback pathways are highlighted. The force sensing pathway is represented by the thick grey (dash/dot) line. Note that this pathway alone is available for fixed isometric manipulators. The position sensing (proprioceptive) pathway is represented by the thick dashed line. Note that as discussed further below more elaborate equalization options are available with this pathway active.

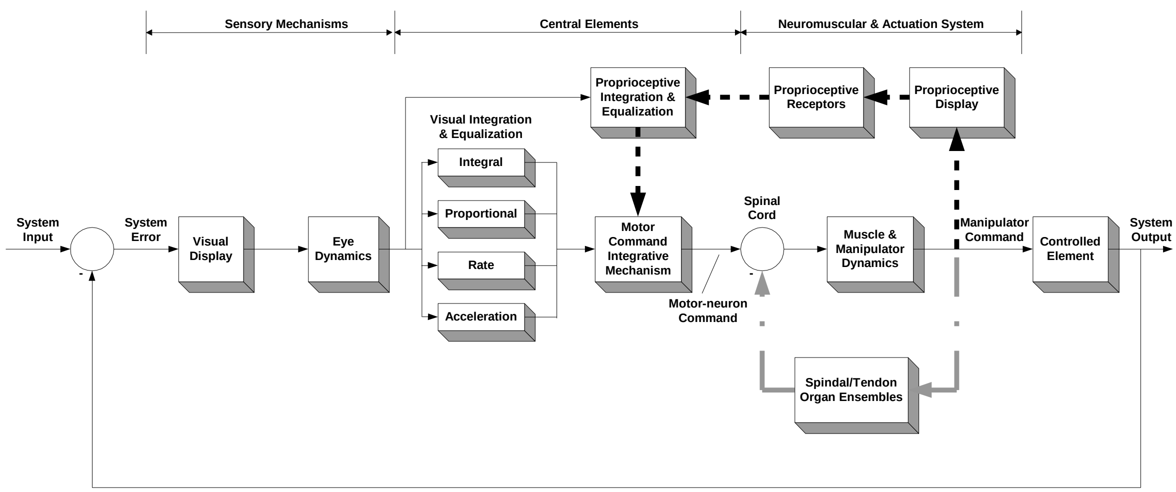


Figure 70. Structural Isomorphic pilot model with highlighted manipulator feedback pathways

Using the ideal crossover model,[42] a frequency domain comparison can be made that illustrates the overall effect of isometric versus isotonic manipulators. In general, an isometric stick produces less lag than does an isotonic stick. This result is shown in Figure 71 where the difference at frequencies in the crossover region was identified to be equivalent to a time delay of approximately 0.1 sec. This characteristic may certainly have been an attractive feature to the designers of the F-16 sidestick controller. As described below, however, numerous unanticipated handling qualities problems can result from a pure isometric manipulator.

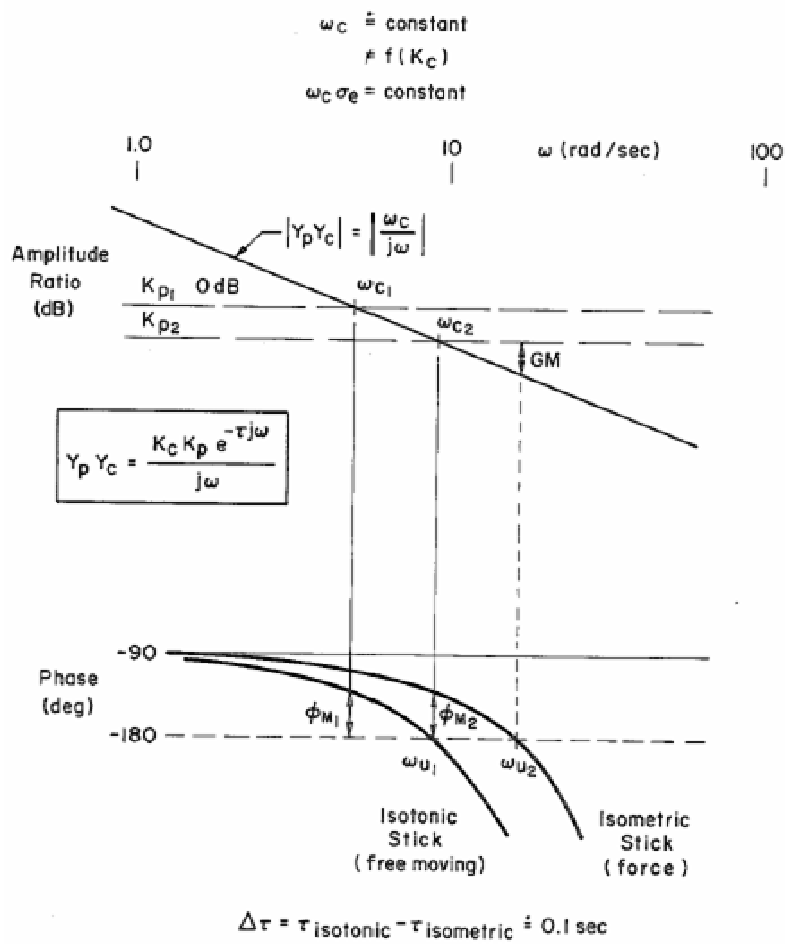


Figure 71. Impact of isotonic versus isometric manipulators for the ideal crossover model

In contrast to isometric devices, aircraft designers have realized that proprioceptive devices can be used to provide appropriate feedback signals to the pilot, using force-stability augmentation, smart sticks, and so on. STI's experience in both flight and simulator situations suggest that proprioceptive displays can be beneficial in at least the following four ways:

1. As force stability augmenters, in which appropriate aircraft variables are fed back to the pilot. These include, but are not confined to, modern replacements of the functions provided by bobweights, dual bobweights, stick pushers, etc. in older manual control systems.
2. As flight command directors that, for example, lead the pilot through recovery procedures for extreme and/or unexpected situations.
3. As alerting and warning indicators. A standard use of this display modality is the stick shaker that warns of approach to stall or buffet. This information can also be provided by changes in force gradient, for example on the Boeing 777 the column force gradient increases when the bank angle passes 45 degrees.
4. As a partial surrogate for motion cues. Previous research at STI has demonstrated that appropriate feel systems for the pilot's inceptors can go a very long way towards alleviating the system performance deficits that distinguish fixed base situations from those where full scale motion is available.

Lateral Axis Feel System Evaluations Conducted by STI: In the mid 1980's STI began a series of studies for NASA that investigated the impact of feel system characteristics on lateral axis handling qualities. In the first study[38] human neuromuscular actuation is reviewed, albeit in what the reference calls a greatly oversimplified manner, as a two loop system. The inner loop involves short pathways from the Golgi and muscle spindle receptors directly to the spinal level and back again to the musculature. The time lags associated with information flow are low because of these short neural pathways. Thus, the effective bandwidth of this loop that is primarily sensitive to forces can be quite high. The outer loop features joint and other receptors (e.g., peripheral vision) as the major feedback elements. Here the pathways and associated delays are longer and thus result in a lower outer loop bandwidth. With a force sensing stick there is little or no joint movement, so the higher bandwidth inner loop should dominate. With a position sensing stick, on the other hand, the joint receptors are key elements, so the lower bandwidth outer loop should dominate. The higher bandwidth closure achieved with a force sensing feel system thus produces less lag.

As part of the study, a fixed-base simulation was conducted to identify and quantify interactions between the pilot's limb neuromuscular system and the feel system, effective vehicle roll mode time constant, and the flight control system effective time delay. The simulation results demonstrated that force-sensing sidestick command gradients, command prefilters, and effective time delays need to be carefully adjusted to minimize neuromuscular system mode peaking that can lead to roll ratchet without restricting roll control bandwidth.

A follow-on fixed-base simulation study was performed by STI to identify and quantify interactions observed[38] and to assess force versus displacement sensing feel systems. The experiment encompassed some 48 manipulator/filter/aircraft configurations. The simulation results found that force sensing manipulators minimize forward loop lag because the feel system lag is relegated to the feedback path of the pilot's neuromuscular limb position system, produce lower tracking errors, and require command prefilters to prevent roll ratchet but with inverse time constants that double the closed-loop control bandwidth to avoid PIO. Displacement sensing manipulators, on the other hand, move the feel system dynamics to the forward loop command path, slightly increase neuromuscular mode peaking compared to force sensing, increase high frequency phase lag and command attenuation, reduce or eliminate any tendency to induce roll ratchet, and reduce or eliminate the need for command prefilters.

The final program in this series[43] provided an analysis of the effects of cockpit lateral control stick characteristics on handling qualities. Variations in feel-system natural frequency, damping, and command sensing reference (force and position) were investigated, in combination with variations in the aircraft response characteristics. The primary data for the report were obtained from a flight investigation[44] conducted with the USAF variable-stability NT-33A, with additional information taken from other flight experiments and ground-based simulations for both airplanes and helicopters. The study consisted of analysis of handling qualities ratings and extraction of open-loop, pilot-vehicle describing functions from sum-of-sines tracking data, including, for a limited subset of these data, the development of pilot models. The study confirms the findings of other investigators that the effects on pilot opinion of cockpit feel-system dynamics are not equivalent to a comparable level of added time delay. The effects on handling qualities ratings are however very similar to those of time delay. Thus, until a more comprehensive set of criteria are developed, it is recommended that feel system dynamics be considered a delay-inducing element in the aircraft response. The best correlation with time-delay requirements was found when the feel system dynamics were included in the delay measurement, regardless of the command reference (i.e., position or force).

The study[43] also used flight test data[44] to assess the interaction of the pilot's limb neuromuscular mode with the feel system. There are several schools of thought regarding whether or not the feel system lag is altered by pilot loop closures around the stick itself. As outlined elewhere[39] and alluded to in the earlier STI work discussed above, strong evidence now exists through experiments and analysis[43] that the pilot couples with the feel system dynamics to form a combined limb-manipulator mode, often approximated as a second order lag. The analysis techniques employed included extensive use of Fast Fourier Transform techniques (FFT) to compute pilot and pilot-vehicle system describing functions. The describing functions for runs in which roll ratchet was noted by the pilots featured significantly greater peaking at the limb-manipulator mode frequency, when compared with runs where no ratchet was noted or observed.

The describing function assumes time-stationary pilot dynamics, and is a measurement of the mean or average pilot behavior for the analyzed run time. Roll ratchet is described as a time-varying, non-stationary phenomenon that would be expected to be related to pilot gain and compensation variations throughout the run.[44] Thus wavelet-based techniques recently developed at STI were used to investigate the time-varying nature of key pilot-vehicle system parameters, including the limb-manipulator mode. The results of this analysis[45] suggest that a lightly-damped mode in the open-loop system is introduced by the human pilot at frequencies higher than the task bandwidth and this corresponds to the previously identified limb-manipulator mode. A direct relationship was found to exist between the peak amplitude of the limb-manipulator mode and the occurrence of roll ratchet. From the data, a threshold appears to be at approximately -2dB, above which ratchet occurs. Even for a case where the pilot did not report ratchet, the pilot stick time history shows short intervals of ratchet-like behavior during which the estimated limb-manipulator peak approached 0 dB in the total open-loop pilot-vehicle system describing function.

3.5.3 NASA AFRC Evaluations

Assessment of the JAS 39 Gripen Ministick Controller: From 23 February to 2 March 1999, NASA AFRC conducted a handling qualities assessment of the F/A-18 Systems Research Aircraft (SRA) shown in Figure 72 with a JAS 39 Gripen ministick.[46] Five pilots with extensive F/A-18 experience participated in the six flight test program. One of the five had previously flown a JAS 39 Gripen. The pilots evaluated the handling qualities with an emphasis on the impact of the feel system while performing bank angle and pitch attitude captures, echelon (wing) formation flight, column formation flight, and target tracking.

Figure 72. NASA F/A-18 Systems Research Aircraft (NASA photo)

The SRA research flight control laws replicated the baseline F/A-18 control laws. The ministick as installed in the F/A-18 SRA rear cockpit is shown in Figure 73. The ministick is a position sensing, center-mounted device that is located on a pedestal between the pilot's legs similar to a standard F/A-18 stick. The pivot point, however, is just below the handgrip, while it is near the floor for the standard stick. For roll control the ministick pivots 7 degrees left and right, while for pitch it pivots 7 degrees forward and 15 degrees aft. The baseline Gripen software deadbands for both pitch and roll are 0.20 degrees.

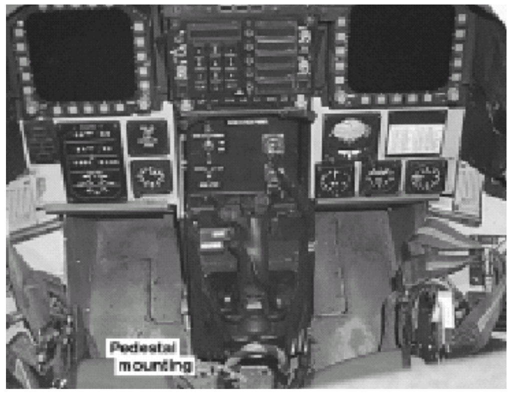


Figure 73. Gripen Ministick as installed in the NASA DFRC F/A-18 SRA (Ref. 46)

The results of the evaluation[46] found no serious handling qualities deficiencies associated with the ministick installation. The pilots commonly used a loose grip technique, sometimes using only three fingers to move the top of the control stick. The authors[46] assert that improved performance may be gained by more closely tuning the deadband and stick gearing.

Assessment of Two Sidestick Controllers: A piloted simulation study was conducted by NASA AFRC[47] to evaluate two large motion sidestick controllers versus a conventional centerstick configuration. The sidestick controllers were designed and constructed by Dynamic Controls, Inc. with unique motion characteristics. The first stick was known as the X-Theta X stick. This stick translated fore and aft for pitch control and rotated about the longitudinal axis at the base of the stick for roll control. The second stick was known as the X-Theta Z stick. Longitudinal control remains the same in this configuration, but roll control is accomplished by rotations about the vertical axis located near the elbow of the pilot. Thus, yaw motion of the pilot's hands is required to produce roll commands. In contrast to most contemporary sidestick controllers, these sticks require full arm motion (i.e., no bending of the wrist). To accommodate the full arm motion, both sticks include a translating and rotating arm rest. The two sticks are shown in Figure 74 with identified direction of motion.

The sidesticks were incorporated into the fixed-base F/A-18 simulator at NASA DFRC. The control stick gains were selected to provide the same authority as the conventional F/A-18 centerstick controller. Three evaluation tasks were used to assess the stick designs; target acquisition, target tracking, and offset landing.[47] Seven NASA DFRC pilots participated in the evaluation, all with extensive fighter aircraft experience including the F/A-18. Only one of the seven pilots had no experience with sidestick controllers. The pilots flew all three tasks with each stick configuration, beginning always with the conventional centerstick that served as the baseline.

As is common with handling qualities evaluations, a "black and white" result was not obtained from this study. In a nutshell, the more aggressive pilots preferred the centerstick. For these pilots, large motions brought about oscillations and overshoots with the sidesticks. The less aggressive pilots, however, preferred the sidesticks with their smooth motion and lower breakout forces. The elbow cup was not found to be a positive feature. Although it did reduce fatigue, using the entire arm for control was found to inhibit precision. There also may have been a simulator influence at play. The simulator was found to be more sensitive than the F/A-18 aircraft, and hence more prone to PIO, especially with the more aggressive pilots.

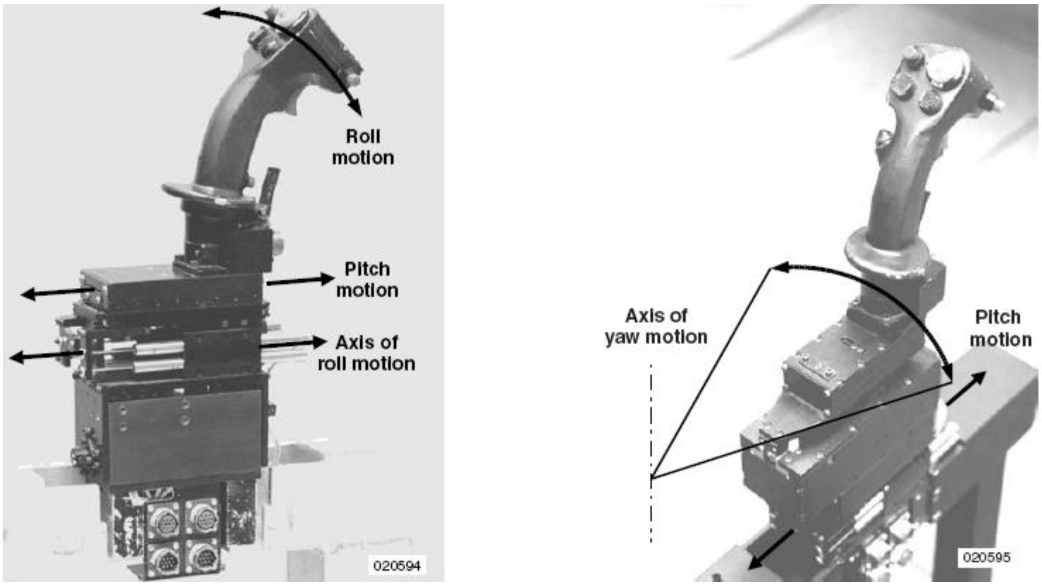


Figure 74. Evaluation sidesticks (Ref. 47) – X-Theta X (left) and X-Theta Z (right)

Rate Limited Feel System: A subset of a larger flight test evaluation program conducted by NASA/Calspan[48] investigated the utility of a rate limited feel system to provide tactile cueing of flight control system rate limiting. The Calspan Learjet 25B in-flight simulator, shown in Figure 75, was used to conduct the evaluations. The aircraft was flown in the powered approach configuration (i.e., gear extended, flaps set to 20 deg, spoilers retracted, and power as required) and a precision offset landing task was used to assess the various configurations.

Figure 75. Calspan Learjet 25B In-Flight Simulator

The concept was to have the feel system move at a maximum rate that matched the maximum surface rate. The limit provides a proprioceptive cue that the commanded input rate exceeds the maximum rate of the surface. Unfortunately, a mechanization error resulted in a maximum feel system rate (i.e., 10.5 deg/sec) that was roughly half of the maximum surface rate (i.e., 20 deg/sec). The pilots reported extremely poor roll performance with this configuration, but no tendency to PIO.[48] The nonlinear force feel and heavy forces required were also found to be objectionable.

4.0 Topics for Further Investigation

4.1 Purpose

This report is a summary of work performed for NASA Langley Research Center under funding from the NASA Engineering and Safety Center. The scope and focus for this effort were restricted by the desire to submit proposed contributions to MIL-STD-1797C by a deadline date provided by the U.S. Air Force. More work clearly can be done, given the time and funding necessary.

It is the view of the authors of this report that future work would be much more efficient if some of the technical areas were expanded to include cooperative efforts from both the Air Force and the Navy. Topics covered in this report, as well as important technical areas not covered, often have seen contributions from entities of the Department of Defense (DoD) that should be considered along with those from NASA.

What follows are critical research topics led by NASA that deserve more investigation. We have identified those topics where DoD led or funded similar work, and where the joint work should be included in a future MIL-STD-1797.

4.2 High Alpha Departure Criteria

An immense amount of high alpha research was conducted by NASA (and other contributors) in the late 20th century, particularly in the 1980s and 1990s. Only a fraction of this research base is reflected in background sections of MIL-STD-1797B. The current report makes a small additional contribution. It should be possible to assemble a cogent summary of the findings from all areas of the work, and ostensibly to propose criteria for departure resistance.

This was initially to be a prime focus of the current work, but it quickly became clear that the wide and disparate sources of information on the topic, combined with the limited time frame, made it a candidate for a future effort. Distribution limitations on many of the NASA documents on the topic have recently been lifted, making it an easier subject to address, given the necessary time and funding.

4.3 PIO Research and Prevention: Criteria, Testing, Devices

This is another general area that has garnered considerable attention, from both NASA and DoD entities. Much of what is addressed in MIL-STD-1797B is outdated, and the bit of discussion in this report only scratches the surface of a couple of specific research topics. Since the Air Force directed multiple studies in the mid- to late-1990s, and the Navy has experience with PIO and prevention methods, this area deserves tri-service attention.

4.4 Biodynamic Coupling

What is presented in this report represents work done in support of the High-Speed Research (HSR) program from the 1990s. More work has been done, and it is possible that folding in the new data might lead to possible criteria and methods to reduce the risk of biodynamic coupling.

4.5 Inceptor Characteristics, With Emphasis on Sidesticks

Requirements on sidestick design – force and deflection limits, and aircraft response dynamics in particular – are either missing or not well supported in MIL-STD-1797B. We have gained decades of practical experience with sidesticks on operational fighter and transport airplanes, so it should be possible to tap into that experience to update the existing requirements. This topic should include at least the Air Force, though there is a connection to commercial air transports (Airbus aircraft in particular) that might necessitate other contributors.

4.6 Advanced Flight Control Law Designs

While perhaps more suited for units of the DoD, NASA has conducted research into advanced control concepts, including adaptive controllers for failed surface effectors. While a review of the control law designs in modern aircraft, including both fighters and transports, may not lead to any new criteria, it is possible that new test methods may be identified. At the least, a discussion of the advanced control designs and the proper application of the existing flying qualities criteria would represent a valuable background for future procuring activities.

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14. ABSTRACT
U.S. Department of Defense Interface Standard for Flying Qualities of Military Aircraft, MIL-STD-1797B, contains requirements based on decades of research and testing. An update is planned in the future. NASA has conducted or sponsored research projects that can contribute to the update. Results from some of these studies are already included, while others have received little or no mention. This report summarizes the most significant of NASA's contributions to handling qualities for incorporation into MIL-STD-1797C. Topics are classified into one of three areas: directly supporting modifications or additions; amplifying information for existing requirements; or worthy of more detailed investigation.

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