NASA Technical Memorandum 4791

Evaluation of High-Speed Civil Transport Handling Qualities Criteria With Supersonic Flight Data

Timothy H. Cox and Dante W. Jackson

April 1997

NASA Technical Memorandum 4791

Evaluation of High-Speed Civil Transport Handling Qualities Criteria With Supersonic Flight Data

Timothy H. Cox and Dante W. Jackson
Dryden Flight Research Center
Edwards, California

National Aeronautics and
Space Administration

Office of Management

Scientific and Technical
Information Program

1997

ABSTRACT

Most flying qualities criteria have been developed from data in the subsonic flight regime. Unique characteristics of supersonic flight raise questions about whether these criteria successfully extend into the supersonic flight regime. Approximately 25 years ago NASA Dryden Flight Research Center addressed this issue with handling qualities evaluations of the XB-70 and YF-12. Good correlations between some of the classical handling qualities parameters, such as the control anticipation parameter as a function of damping, were discovered. More criteria have been developed since these studies. Some of these more recent criteria are being used in designing the High-Speed Civil Transport (HSCT). A second research study recently addressed this issue through flying qualities evaluations of the SR-71 at Mach 3. The research goal was to extend the high-speed flying qualities experience of large airplanes and to evaluate more recent MIL-STD-1797 criteria against pilot comments and ratings. Emphasis was placed on evaluating the criteria used for designing the HSCT. XB-70 and YF-12 data from the previous research supplemented the SR-71 data. The results indicate that the criteria used in the HSCT design are conservative and should provide good flying qualities for typical high-speed maneuvering. Additional results show correlation between the ratings and comments and criteria for gradual maneuvering with precision control. Correlation is shown between ratings and comments and an extension of the Neal/Smith criterion using normal acceleration instead of pitch rate.

NOMENCLATURE

ADI	attitude direction indicator
bw	bandwidth
c.g.	center of gravity
CAP	control anticipation parameter, g^{-1} sec^{-2}
CH	Cooper-Harper (rating)
g	acceleration due to gravity
HSCT	High-Speed Civil Transport
IVSI	instantaneous vertical speed indicator
KEAS	knots equivalent airspeed
L_α	dimensional lift curve slope, lb
LOES	low-order equivalent system
N_y	lateral acceleration, g
N_{z_α}	slope of normal acceleration as a function of angle of attack, g/rad
p_{max}	maximum roll rate, deg/sec
PIO	pilot-induced oscillation
s	Laplace operator
SAS	stability augmentation system
β	sideslip, deg
θ	pitch attitude, deg
θ_c	pitch attitude command, deg
τ_p	bandwidth time delay parameter, sec
τ_r	roll mode time constant, sec

τ_ϕ	time delay of bank-angle-to-stick deflection frequency response, msec
ϕ	bank angle, deg
$\phi_{2\omega_{180°}}$	phase angle at twice the phase crossover frequency, rad/sec
$\omega_{bw\gamma}$	flightpath bandwidth parameter, rad/sec
$\omega_{bw\theta}$	pitch attitude bandwidth parameter, rad/sec
ω_{dr}	dutch roll frequency, rad/sec
ω_{sp}	short-period frequency, rad/sec
ω_ϕ	frequency of the second-order zero in the roll-rate-to-stick deflection transfer function, rad/sec
$\omega_{180°}$	phase crossover frequency, rad/sec
ζ_{dr}	dutch roll damping
ζ_ϕ	damping of the second-order zero in the roll-rate-to-stick deflection transfer function

INTRODUCTION

Good handling qualities are essential for aircraft performance and can be predicted during the design process. Handling qualities criteria used to evaluate aircraft designs are defined by experiential data obtained from previous aircraft. A problem exists, however, when an aircraft flies in a new flight regime. Airplanes cruising at speeds greater than Mach 2 or beyond exemplify this problem.

Since flying qualities criteria are based on subsonic data, they do not address some of the unique characteristics of high-speed flight. For example, many of the current criteria assume that good flightpath response follows from good pitch attitude response. For the high-speed case, however, this assumption may not be valid. As Mach number increases, an aircraft's lift curve slope (L_α) decreases proportionally, thereby increasing the lag between flightpath and pitch attitude response. Figure 1 compares responses from a step input in an SR-71 simulator at Mach 0.6 and 3.0, illustrating the increase in lag between flightpath and pitch attitude. For both

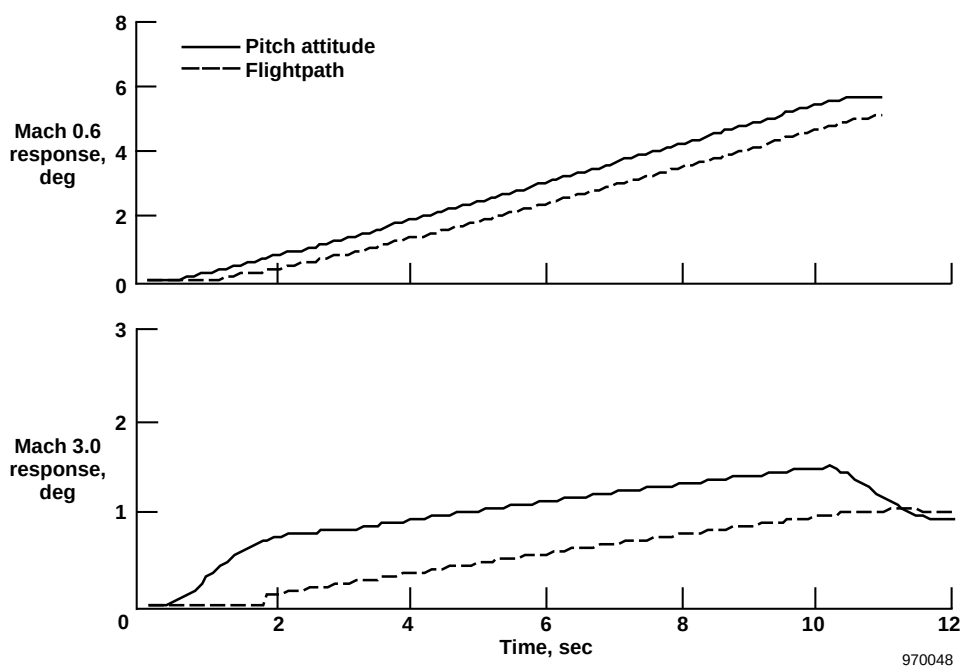


Figure 1. Comparison of the lag between pitch attitude and flight path responses at Mach 0.6 and 3.0.

responses the input is applied at 0 sec of time. For the subsonic case the flightpath lags the pitch attitude by 1 to 2 sec, whereas for the Mach 3.0 case the flightpath lags by 4 to 5 sec. If this lag characteristic is too large, the pilot's ability to control flightpath is impaired.

Figure 2 illustrates another unique characteristic of high-speed flight, which compares the responses of the SR-71 simulator to a longitudinal step input at Mach 0.6 and 3.0. The comparison reveals that as the speed increases, the pitch attitude change required to acquire the same rate-of-climb decreases. This characteristic, caused primarily by the large velocity term, implies that as speed increases the pilot must maintain more precise control of pitch attitude to establish the desired rate-of-climb response. Unless accurate pitch attitude or rate-of-climb information is fed back to the pilot, this characteristic could potentially cause the pilot to overcontrol the aircraft. Nevertheless flying qualities criteria are based on subsonic data, where the requirement for precise pitch attitude control is more relaxed than it is for the high-speed case.

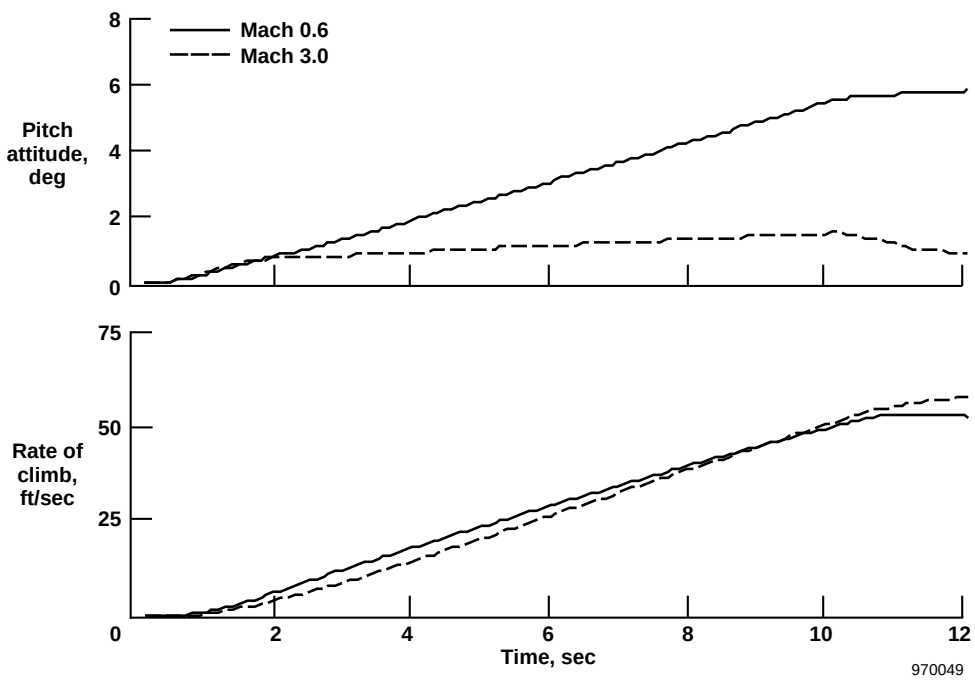


Figure 2. Comparison of pitch attitude changes at Mach 0.6 and 3.0 required to generate equivalent rates of climb.

Approximately 25 years ago NASA Dryden Flight Research Center researchers applied MIL-F-8785B criteria to YF-12 and XB-70 data (ref. 1). The military specification defined criteria for four classes of airplanes:

- Class I, general aviation.
- Class II, medium weight.
- Class III, transports.
- Class IV, fighter aircraft.

Each criterion defined boundaries for three levels of handling qualities:

- Level 1, satisfactory handling qualities.
- Level 2, acceptable handling qualities.
- Level 3, controllable handling qualities.

The criteria are applied, depending on the class of airplane, for three flight categories:

- Category A, rapid maneuvering and precision tracking (air-to-air combat).
- Category B, gradual maneuvering without precision tracking (cruise flight).
- Category C, gradual maneuvering with precision flightpath control (approach and landing).

The longitudinal tasks for the YF-12 and XB-70, class III aircraft, in up-and-away flight included precise flightpath tracking without gross maneuvering, which was considered category C flight. The researchers showed, for both the YF-12 (refs. 2, 3, and 4) and XB-70 (refs. 2 and 5), positive correlation between category C criterion on control anticipation parameter (CAP) and pilot comments and ratings. The researchers also indicated that the requirements for short-period damping may be relaxed, although these results were not considered conclusive (refs. 4 and 5). Since that time several more criteria have been developed, some of which are described in MIL-STD-1797 (ref. 6). The High-Speed Civil Transport (HSCT) program evaluated the flying qualities of their design based on some of these criteria (ref. 7). This memorandum addresses how these criteria apply to airplanes flying in the region of Mach 2 and beyond.

The flying qualities of the SR-71 at Mach 3 are evaluated using three well-defined maneuvers considered typical for a supersonic transport: a steady level turn, an ascending turn, and a vertical plane altitude change. Pilot ratings and comments of the maneuvers are documented and reasons are identified for cases where level 2 ratings were given. The goal of this research was to extend the high-speed flying qualities experience of large airplanes and to evaluate some of the more recent MIL-STD-1797 criteria against pilot comments and ratings. The XB-70 and YF-12 data from research conducted approximately 25 years ago supplement the SR-71 data. Evaluation of the criteria focuses on comparing terminal flight phase boundaries for the HSCT (ref. 7) with category C boundaries from MIL-STD-1797. The supersonic flight data are not compared with the HSCT nonterminal boundaries because these boundaries were undefined when reference 7 was published. The following longitudinal criteria are evaluated: low-order equivalent systems (LOES) (ref. 8), pitch bandwidth (ref. 9), flightpath bandwidth (ref. 10), and Neal/Smith (ref. 11). Additionally the memorandum evaluates the following lateral-directional criteria: LOES and lateral acceleration at the pilot station (ref. 6).

AIRCRAFT DESCRIPTION

The SR-71 (fig. 3) is a twin-engine, delta wing airplane that was designed to cruise at Mach 3.2 above 80,000 ft (fig. 4). The SR-71 is powered by two Pratt & Whitney J-58 afterburner engines with axisymmetric, variable-geometry, mixed compression inlets. Centerbody spikes and bypass doors on the forward part of the nacelle are automatically modulated to control the oblique and normal shock positioning associated with flying at high supersonic speeds. The data discussed in this memorandum were gathered with doors and inlets in this automatic configuration.

Most of the cockpit contains conventional instrumentation. Some of the main cockpit instruments used during this evaluation include a pressure-driven, instantaneous vertical speed indicator (IVSI) and a triple-display indicator that shows altitude, knots equivalent airspeed (KEAS), and Mach number in a digital format. The resolution of the IVSI is 100 ft/min. The resolutions of the triple-display indicator parameters are 50 ft, 1 knot, and 0.01 Mach, respectively. Because a lag in the response of the IVSI exists at high altitude, a horizontal needle on the attitude direction indicator (ADI) displaying inertial vertical speed provides a reference for climb/descent rates. With this, the SR-71 pilots get a more precise and reliable vertical speed indicator than from the IVSI. A vertical needle on the ADI displays the error between the actual and desired bank angle based on the navigation system. Thus, the SR-71 pilots have a reference bank angle for following a ground track.

Wing trailing edge elevons are used symmetrically as elevators and differentially as ailerons to provide longitudinal and lateral control, while twin, all-movable vertical tails supply directional control. The pilot controls

EC94 42883-04

Figure 3. SR-71 research aircraft shortly after refueling.

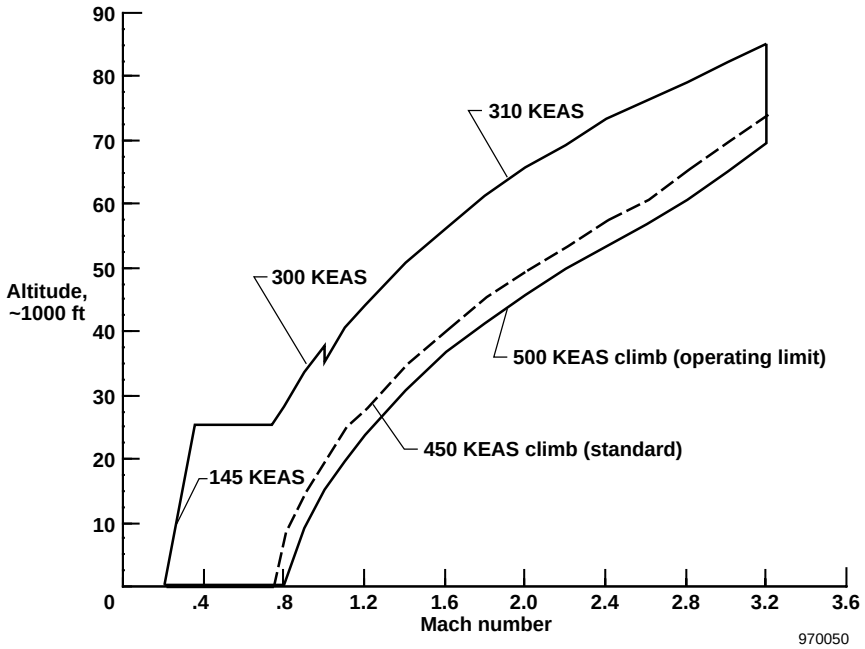


Figure 4. SR-71 flight envelope.

consist of a conventional stick for pitch and roll inputs, and rudder pedals for yaw inputs. The SR-71 has a conventional response with angle-of-attack and normal acceleration changes commanded by the pitch stick. The controls are irreversible and fully powered by two independent, 3000 lb/in^2 hydraulic systems that operate actuating cylinders at each control surface.

The SR-71 uses an automatic flight control system that provides stability augmentation or increased damping about all three axes. This damping is accomplished with conventional feedback of roll rate, pitch rate, and yaw rate. In addition, lateral acceleration is used in the yaw axis to reduce the severity of engine unstarts.

An autopilot is available to reduce the workload involved in flying the SR-71. The autopilot includes attitude hold in pitch and roll, Mach hold, and KEAS hold. Normal aircraft maneuvering is executed by pitch and roll attitude inputs through thumbwheels, while acceleration/deceleration to and from Mach 3 are performed with the KEAS hold engaged on the autopilot. The autopilot mode is used routinely in the climb, cruise, and descent portions of the flights. However, for the handling qualities evaluations all autopilot modes were disengaged, and the maneuvers were performed manually with the stick.

TASK DESCRIPTION

Three maneuvers were flown at Mach 3.0 to evaluate the handling qualities characteristics of the SR-71 aircraft: a steady level turn, an ascending turn, and a vertical plane altitude change. These maneuvers are considered typical of maneuvers to be flown by a large, supersonic transport aircraft. Each maneuver had two variations, and is discussed more fully in the following sections.

Pilot comments evaluating the maneuvers against the adequate and desired performance margins were collected immediately after performing each task and during postflight briefings. Adequate margins for all three maneuvers were ±300 ft deviation from target altitude and ±10 KEAS deviation from target airspeed. Desired margins for all three maneuvers were ±100 ft deviation from target altitude and ±5 KEAS deviation from target airspeed.

Vertical Plane Altitude Change

The vertical plane altitude change at constant KEAS entailed a wings-level pullup to capture a 2000 ft altitude increment at a climb rate of 1000 ft/min. After the target altitude was established, it was held for 10 sec. Constant airspeed was maintained throughout the maneuver. The pilots evaluated this maneuver with two variations: one using the IVSI and another using the inertial vertical speed.

Steady Level Turn

The first variation of the steady level turn involved rolling the aircraft to a constant bank angle of 30° and turning through a specified heading change while maintaining constant KEAS and altitude. After acquiring the final heading, a rollout to wings level was performed followed by holding constant altitude and airspeed at the final heading for 10 sec. For the second variation, instead of rolling to a constant bank angle, the pilot was required to follow the vertical ADI bank angle needle, which was commanded by the navigation computer to follow a specified ground track. At Mach 3.0 bank angles of around 30° were commanded.

Ascending Turn

The first variation of the ascending turn involved rolling the aircraft to a constant bank angle of 30°. After 10° of heading change the pilot began an ascent at a rate of 500 ft/min. This state was held for an additional 30° of heading change, where the pilot leveled off in altitude. Constant airspeed was maintained throughout the whole maneuver. As with the steady level turn the second variation of the maneuver was performed with the pilot following the vertical ADI bank angle needles.

PILOT EVALUATIONS

This section summarizes pilot comments for the three maneuvers described in the previous section. Two pilots flew the maneuvers, and their Cooper-Harper (CH) ratings and comments were recorded. Figure 5 presents the CH ratings for these maneuvers; it should be referred to throughout the discussion. Pilot comments for steady and ascending turns were consistent with each other, and are presented together in the following discussion. CH ratings are split into three handling qualities levels according to the following definitions:

- Level 1 = CH < 3.5
- Level 2 = 3.5 < CH < 6.5
- Level 3 = 6.5 < CH < 9.5

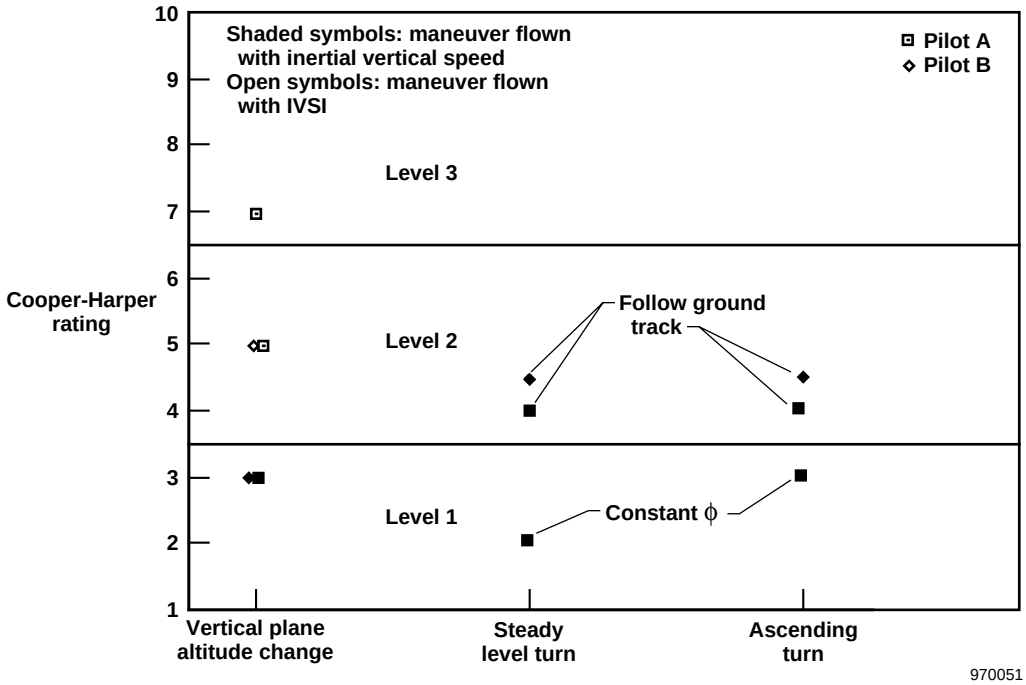


Figure 5. Pilot ratings for the vertical plane altitude change, steady level turn, and ascending turn maneuvers.

Vertical Plane Altitude Change

Comments from both pilots are summarized below for both variations of the vertical plane altitude change maneuvers.

With Instantaneous Vertical Speed Indicator

Sluggish initial response and excessive delay between the stick input and a reaction in the IVSI gauge made establishing and maintaining the desired rate of climb very difficult. The altitude change could be performed, but not without high concentration and some loss of performance. The pilot's ability to hold airspeed was difficult because of the excursions in rates of climb. These problems warranted CH ratings between 5 and 7 (levels 2 to 3).

With Inertial Vertical Speed Indicator

Achieving desired performance was relatively easy. The rate of climb was easy to establish and maintain when using inertial vertical speed as feedback. As long as enough range in throttle motion in afterburner was available, the airspeed was easily maintained as well. The only difficulty arose when searching to establish rate of climb and when leading the aircraft as it approached the target altitude. This minor compensation required in establishing flightpath, added to the basic concentration necessary to fly this airplane, warranted a CH rating of 3 (level 1).

Steady Level and Ascending Turns

Both levels 1 and 2 ratings were assigned for the steady level and ascending turns (fig. 5). The level 1 ratings were associated with the maneuver flown at constant bank angle, whereas the level 2 ratings were associated with the maneuver flown while following the bank angle steering bar for constant ground track. The following is a summary of both pilots' comments.

Turns Following Ground Track

For the turns where the ground track or bank angle steering bar was followed, the level of concentration required to perform the task was quite high, although the task was performed to within desired performance. Three sources exist for this concentration level:

- The high degree of baseline concentration required to fly the aircraft normally.
- Simultaneously maintaining small vertical speed and bank angle errors, which was of paramount concern because large errors were difficult to correct and manage.
- Maintaining airspeed, which was considered easy but still contributed to the level of concentration required.

The concentration from each of these sources was minimal when considered separately. When combining all the sources simultaneously, however, the required concentration level drove the CH ratings to level 2. Keeping the vertical speed error small was more demanding than following the bank angle command needle. Lags inherent in the aircraft's flightpath response made it more difficult to maintain a precise vertical speed than a precise bank angle. Although the roll response was a little abrupt, it was easy to acquire and maintain desired bank angle.

Turns With Constant Bank Angle

Flying the turn with a constant bank angle reduced the concentration required to perform the maneuver when following the bank angle needle. Because no problems existed with bank angle control, establishing the required bank angle was relatively easy with only a few minor adjustments required to maintain it. Therefore, less attention was placed on the lateral-directional axis. The reduction in the required concentration was enough for CH ratings of 2 and 3 (level 1).

Pilots' General Comments

Trimming the aircraft could be a tedious task because of poor resolution in the vertical speed indicator or lack of vertical acceleration feedback. The airplane would appear to be trimmed but many seconds later the inertial vertical speed would have drifted off and require further adjustments. This characteristic could be related to the lightly damped phugoid mode (ref. 12).

Although control harmony was a significant problem due primarily to heavy longitudinal forces, it became only a minor influence on the handling qualities when the longitudinal trim button was used to cancel stick forces. The pilots did not consider control harmony when giving the ratings and comments.

Summary for Comparison With Criteria

Longitudinal handling qualities were level 1 when using the inertial vertical speed as a feedback parameter. Vertical speed was an important feedback, as the pitch attitude display on the ADI did not provide enough resolution to be useful. Lags existed in the flightpath response; however, the aircraft was predictable and solid. These comments were based on gentle maneuvering, which is typical of the types of missions flown with this aircraft. Because of the inherent lags of the vehicle at high speeds aggressive maneuvering was not possible without control difficulties. Although airspeed response was sluggish, it was easy to maintain. An average CH rating of 3 for the vertical plane altitude change maneuvers using the inertial vertical speed indicator as feedback will be used to compare with the longitudinal criteria.

Specific lateral-directional axis ratings were not obtained during the SR-71 handling qualities evaluations. However, certain inferences could be made about these ratings. First, the vertical plane altitude change maneuvers were rated by both pilots as CH = 3. Because this maneuver was mainly a longitudinal one, these ratings represented the longitudinal task. Pilot comments indicate that lateral-directional dynamics had a “slightly abrupt, but predictable response” that was less demanding than the response in the longitudinal axis. Because the ratings of the longitudinal dynamics were CH = 3 for both pilots, it can be inferred that the ratings for the lateral-directional dynamics were CH = 3 or better.

The turns performed with the pilot following the bank angle steering bar on the ADI received CH ratings of 4 and 4.5. The comments indicate that the increase in ratings for this maneuver was caused by the increase in attention and concentration required to “juggle” the altitude task, bank task, speed task, and normal aircraft functions. These comments imply that a better estimate of lateral-directional dynamics alone would come from the constant bank angle turns. The averaged rating of these maneuvers, CH = 2.5, also fits within the requirement for CH = 3 or better. Thus, ratings for the steady level turn flown with constant bank angle will be used when comparing SR-71 data with the lateral-directional criteria.

LONGITUDINAL CRITERIA EVALUATION

Longitudinal criteria evaluated are LOES, bandwidth (pitch and flightpath), and Neal/Smith. These criteria were emphasized because they are identified as design criteria for the HSCT (ref. 7). To increase the value of this investigation, the LOES criteria were also applied to high-speed flying qualities data from the XB-70 (ref. 5) and YF-12 (ref. 3). Because the flight conditions where the data were collected were not recorded in the XB-70 report, the application of this data to the other criteria was not possible. However, enough information existed in the YF-12 report to extract the test condition of the data. Because of the similarity of the YF-12 and SR-71 in the longitudinal axis, a flight-validated linear simulation of the SR-71 supplemented as a model of the YF-12 data. The other longitudinal criteria were then applied to this model.

Evaluation of the criteria focuses on comparing terminal flight phase boundaries for the HSCT with category C boundaries from MIL-STD-1797. Comparison of the supersonic flight data with HSCT nonterminal boundaries was not done because these boundaries were undefined when reference 7 was published. Although category C is typically associated with approach and landing, the high-speed maneuvers for the SR-71, XB-70, and YF-12 were considered category C because precise flightpath control without rapid maneuvering was required (ref. 5). Flying qualities ratings from the previous research correlated well with the category C borders. To further investigate this assumption, comparisons between category A and B criteria from MIL-STD-1797 were conducted as well. If the flying qualities ratings and comments continue to correlate best with category C across all the criteria, HSCT criteria used for the terminal flight phase may be appropriate for the high-speed flying qualities design as well.

Low-Order Equivalent System

The LOES technique was developed to apply classical boundaries of handling qualities to higher order aircraft. The technique fits second-order transfer function models of pitch rate and normal acceleration from stick deflection

to higher order models or flight data. A time delay model is added to the second-order transfer functions to account for differences in phase angle between the lower and higher order models. As a result, LOES estimates of short-period frequency, damping, and the lift curve slope (L_α) can be applied to classical criteria on these parameters. A criterion for the time delay estimate has also been developed.

A LOES fit was performed using a Fast Fourier Transform of an SR-71 flight data frequency sweep. The LOES fit was performed with simultaneous pitch rate from stick deflection and normal acceleration from stick deflection frequency responses. Figure 6 shows an example of the fit using the normal acceleration near the instantaneous center of rotation. A good fit with a cost of approximately 50 was obtained. In addition, a LOES fit was performed with just the pitch rate from stick deflection frequency response, where the first-order zero was fixed at the value of L_α calculated from flight data. The frequency, damping, and time delay estimated from this fit and the simultaneous fits were within 10 percent.

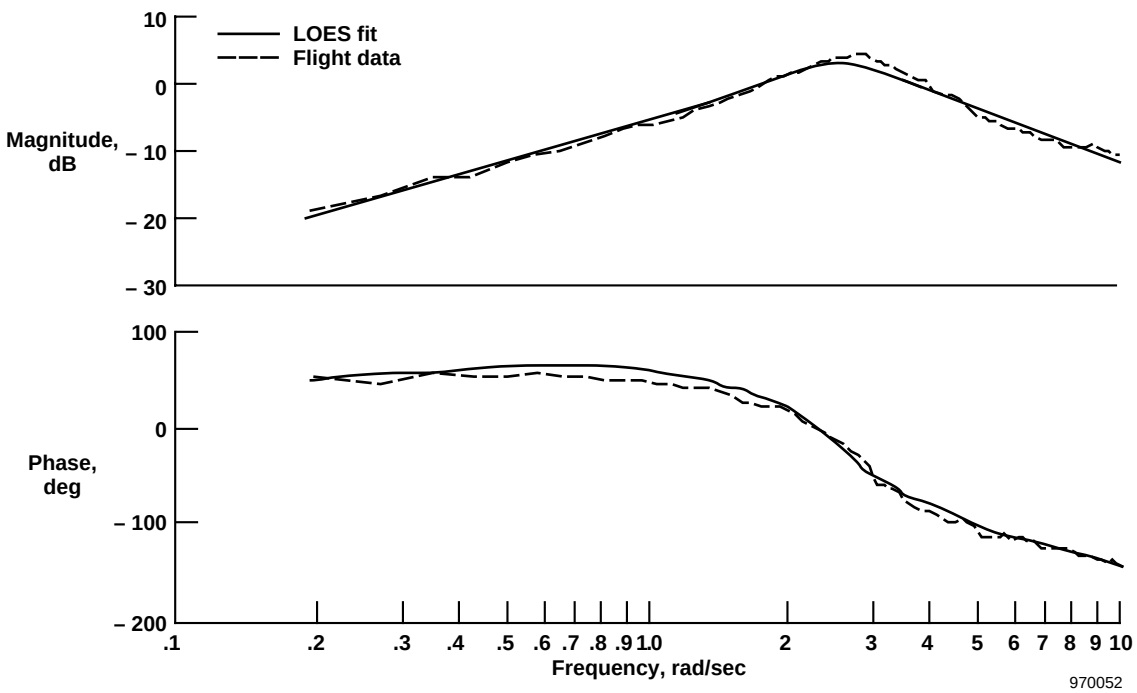
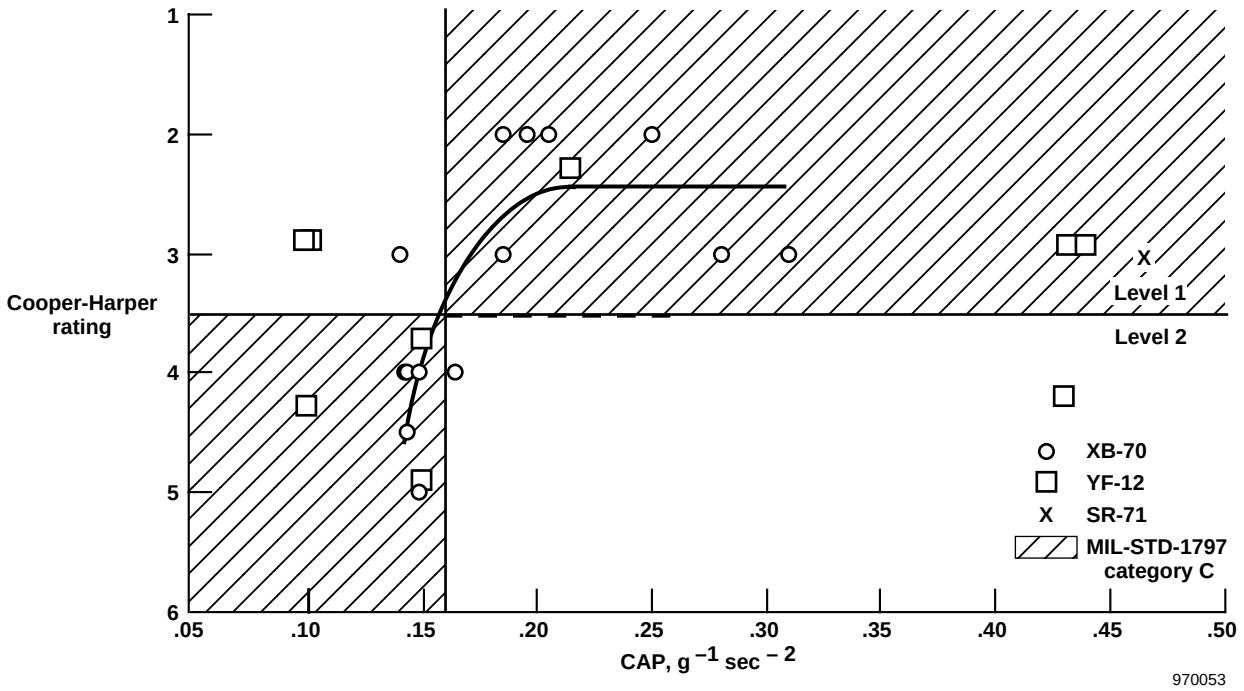


Figure 6. Typical LOES fit of the pitch rate from stick deflection frequency response.

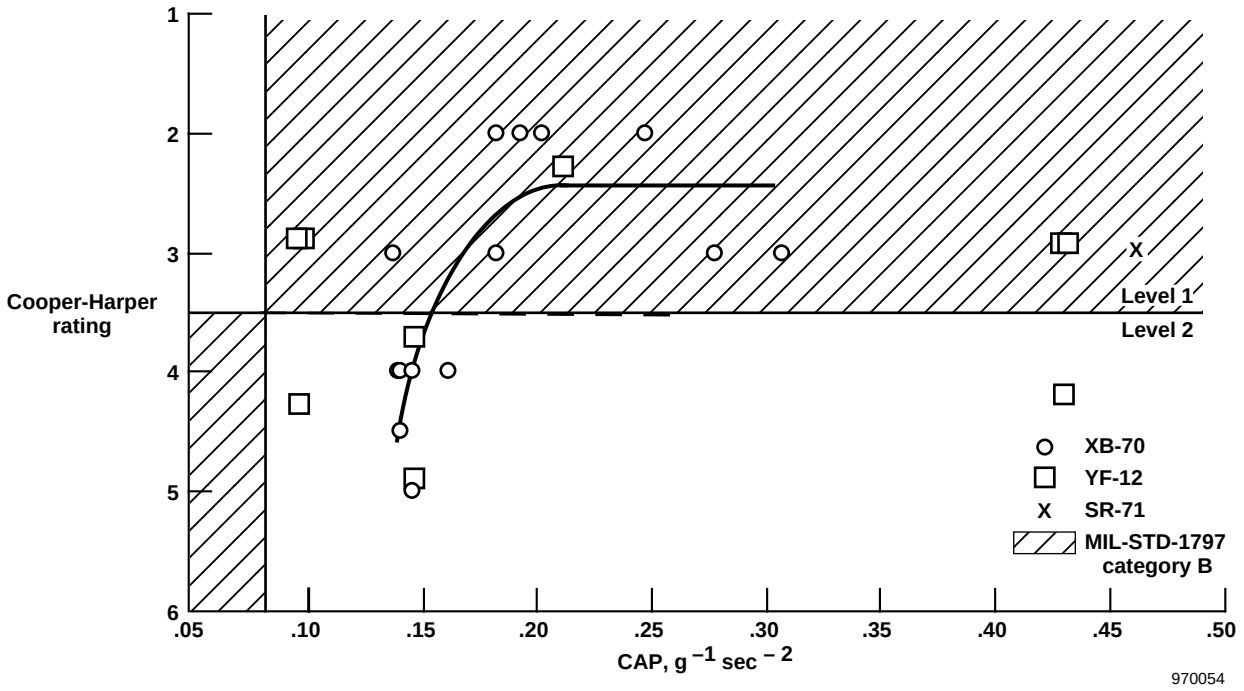
Figures 7, 8, and 9 show the CAP, damping, and time delay of the XB-70, YF-12, and SR-71, respectively. CAP was approximated using equation (1) between the short-period frequency (ω_{sp}) and the change in normal acceleration with angle of attack N_{z_α}:

$$\mathrm{CAP} \approx \frac{\omega_{sp}^{2}}{N_{z_\alpha}} \tag{1}$$

Data are compared with the criterion on CAP from the MIL-STD-1797 for categories A, B, and C, and from HSCT design guidelines. The HSCT criterion for CAP is equivalent to the category A, level 1 region of MIL-STD-1797. The traditional CAP as a function of damping format was not presented to be consistent with the previous XB-70 and YF-12 analysis. The solid line in figure 7 is faired through the XB-70 data and came from reference 5. The shaded region shows where the data should fall if the criteria correlate with pilot ratings.

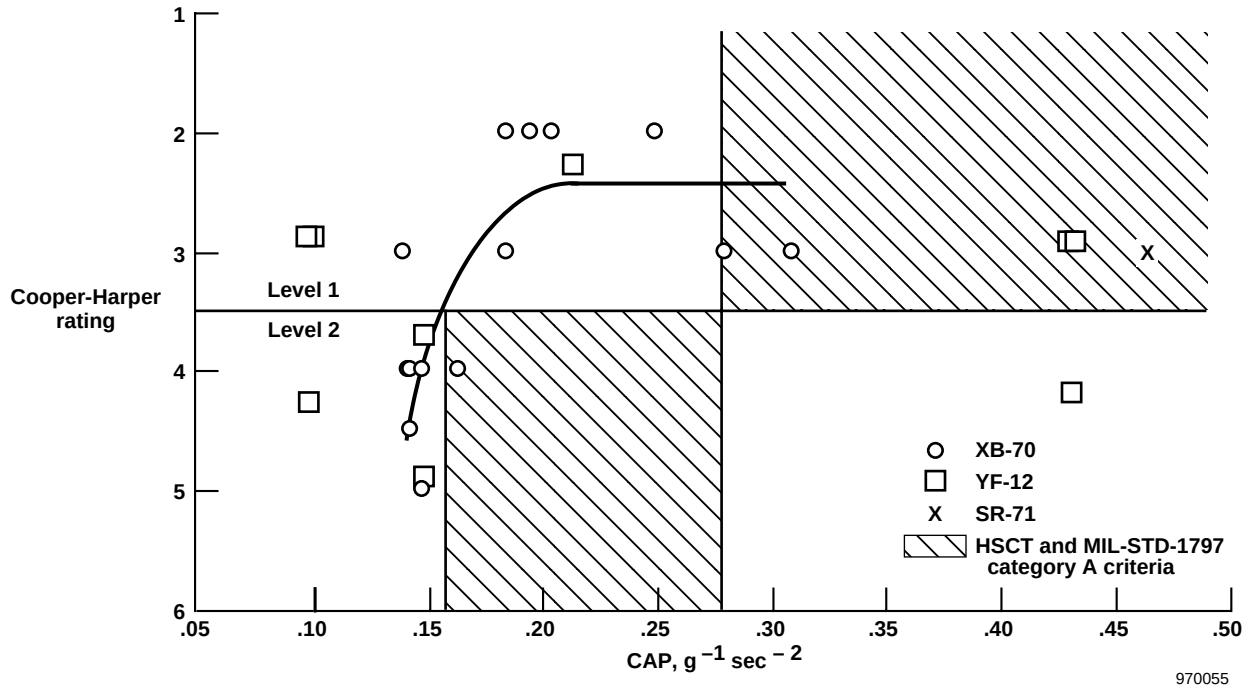


(a) Category C criteria.



(b) Category B criteria.

Figure 7. LOES estimates of CAP compared with categories A, B, and C criteria from MIL-STD-1797 and HSCT criteria.



(c) HSCT and category A criteria.

Figure 7. Concluded.

From figure 7 CAP correlates better with category C guidelines from MIL-STD-1797 than it does with the HSCT and category B guidelines. Reference 5 noted this correlation with category C for XB-70 data. The addition of the YF-12 data from reference 3 supports this conclusion, and the SR-71 point falls within the level 1 region as expected. A total of 83 percent of all the data falls within the boundaries predicted by category C criterion on CAP. The HSCT criterion appears too stringent for the type of altitude-tracking maneuvers flown because several level 1 ratings fall outside that region. Only 33 percent of the level 1 ratings fall within the HSCT guidelines, whereas 79 percent of the level 1 ratings fall within the category C, level 1 criterion. For the MIL-STD-1797 category B criterion, 60 percent of the data fall within the predicted boundaries, worse than the 83 percent estimated by the category C criterion.

Figure 8 shows the XB-70, YF-12, and SR-71 short-period damping estimates. MIL-STD-1797 criteria for category A and C and the HSCT criterion are superimposed on the data. The shaded region shows where the data should fall if the criteria correlate with pilot ratings. All the criteria for damping appear to be too restrictive for the high-speed maneuvers, even if category B requirements on damping (0.3) were considered. Short-period damping is less significant as a flying qualities parameter in high-speed flight than in low-speed flight. A relaxation of the allowable damping limits for high-speed flight might be possible, although other factors not accounted for in the XB-70 and YF-12 ratings, such as turbulence, may increase the damping requirement. However, references 4 and 5 noted that aircraft response due to turbulence may be reduced at high Mach number because of the reduced L_α.

In figure 9 the MIL-STD-1797 and HSCT criteria for equivalent time delay are superimposed on the SR-71 and YF-12 equivalent system time delay estimate. The shaded regions show where the data should fall if the criteria correlate with pilot ratings. The HSCT criteria predict level 1 for time delays less than 200 msec. No distinctions are made among categories A, B, and C in the time delay criterion of MIL-STD-1797. The military standard states that although not enough time delay data exist for class III (transport) aircraft to be conclusive, it is apparent that a relaxation in the time delay criterion is in order. This is because the standard's criteria are based on class IV (fighter) airplanes. Class III aircraft data have shown that delays as much as 250 msec have been evaluated as level 1 (ref. 6). Thus, the HSCT criterion appears reasonable. The single SR-71 data point supports a criterion less restrictive than MIL-STD-1797, but is obviously not enough to be conclusive.

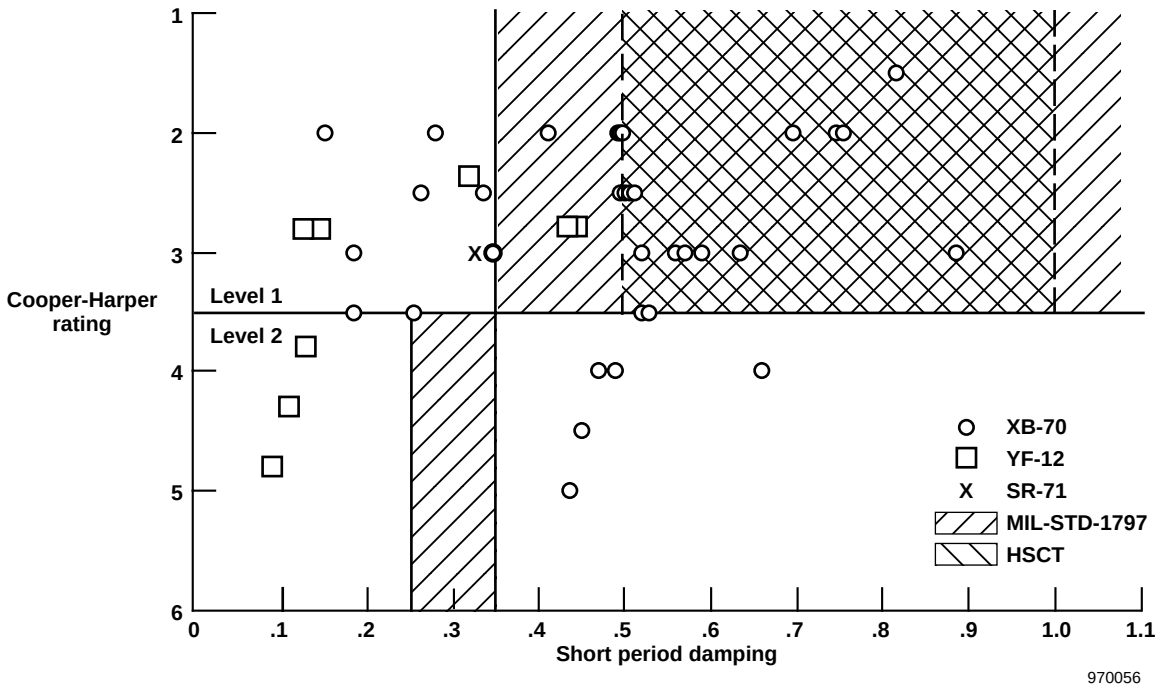


Figure 8. LOES estimates of short-period damping compared with HSCT and MIL-STD-1797 criteria.

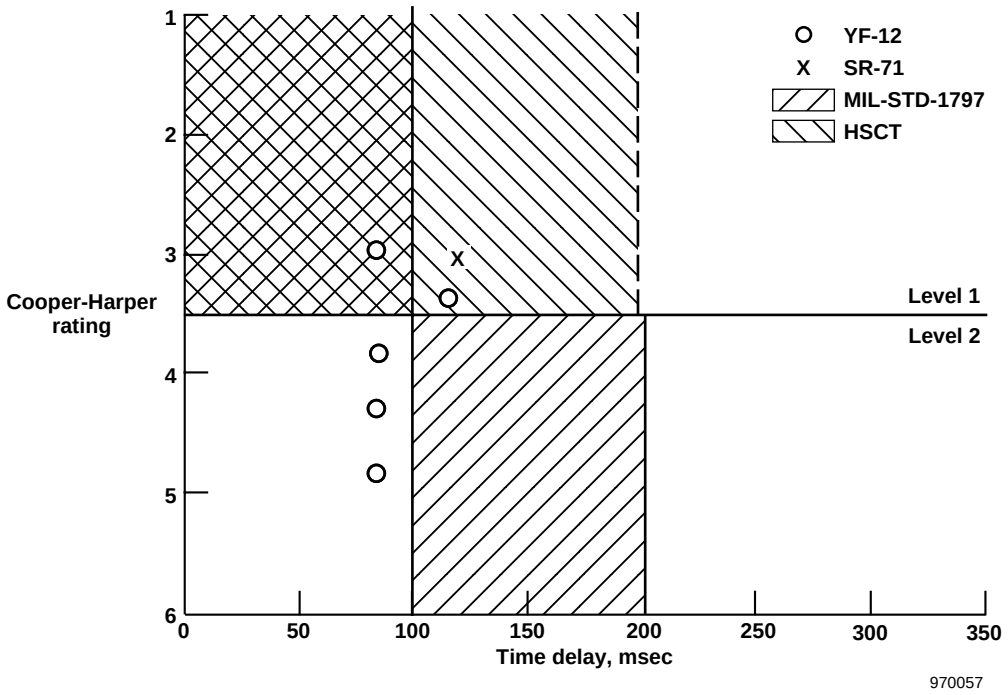


Figure 9. LOES estimates of time delay compared with MIL-STD-1797 and HSCT criteria.

Bandwidth Criterion

The bandwidth criterion as defined in MIL-STD-1797 was used to analyze both the SR-71 and (reproduced) YF-12 data. The gain-limited bandwidth (defined as the frequency at the magnitude that is 6 dB more than the magnitude at the phase crossover frequency) and phase-limited bandwidth (defined as the frequency where 45° phase margin exists) were calculated from a pitch attitude from stick deflection frequency response. The lesser of the two frequencies was considered the bandwidth frequency. The criterion places limits on the bandwidth frequency as a function of the time delay (τ_p), which is estimated from the phase at twice the phase crossover frequency ($\phi_{2\omega_{180°}}$), and phase crossover frequency ($\omega_{180°}$):

$$\tau_p = \frac{\phi_{2\omega_{180°}} + 180°}{57.3(2\omega_{180°})} \tag{2}$$

The calculation of the bandwidth frequency for SR-71 and YF-12 data with the stability augmentation system (SAS) turned on proved straightforward. However, the YF-12 data included four test points where the SAS was turned off. Figure 10 shows a typical example of the pitch attitude bandwidth calculation for low damped, YF-12 data. The calculation of the phase bandwidth value, the frequency where the phase is –135°, is straightforward. However, the calculation of the gain bandwidth value is more confusing. Applying the definition of the gain-limited bandwidth to the data in figure 10 results in three possible gain bandwidth values: 1.8, 0.8, and 0.19 rad/sec. Note that a slightly increased phase crossover frequency, $\omega_{180°}$, would prevent this phenomenon from occurring. If the value of 1.8 rad/sec is considered the gain bandwidth value, then the phase bandwidth value would be compared with the criterion because it is less than 1.8 rad/sec. However, if either the 0.8 or 0.19 rad/sec values are the appropriate gain bandwidth value, then these would be compared with the criterion because they are less than the phase bandwidth value.

This phenomenon results mainly from the large, "shelf-like" characteristic created by the large difference between L_α and the short-period frequency and the low short-period damping. The low short-period damping characteristic produces the three possible gain bandwidth values. Standard procedure for this situation would be to

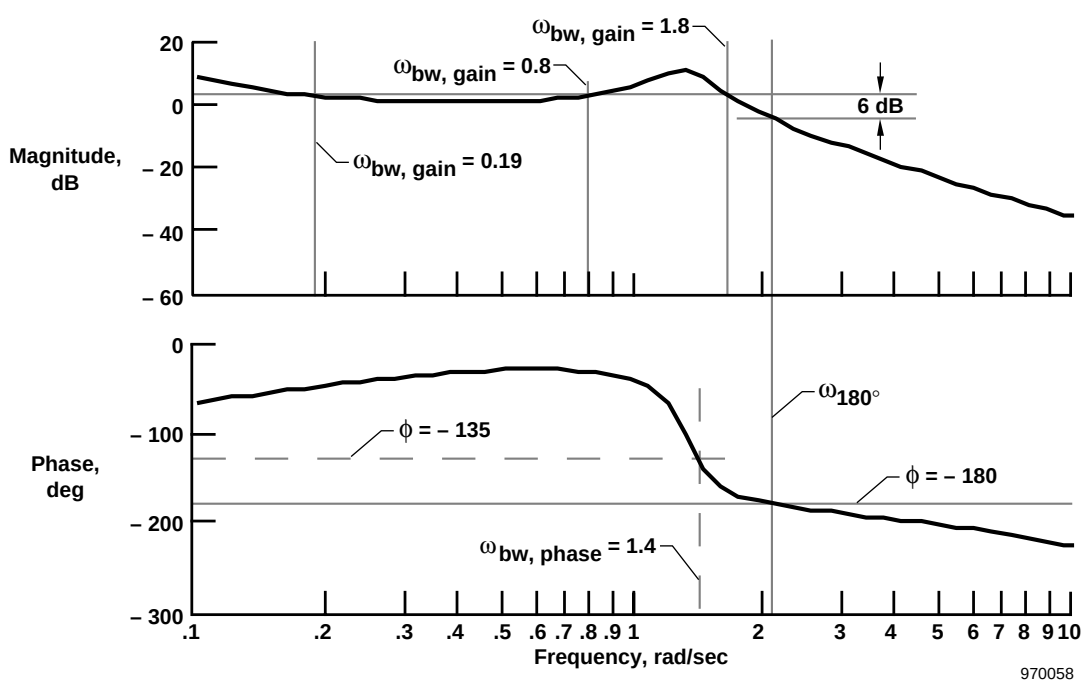
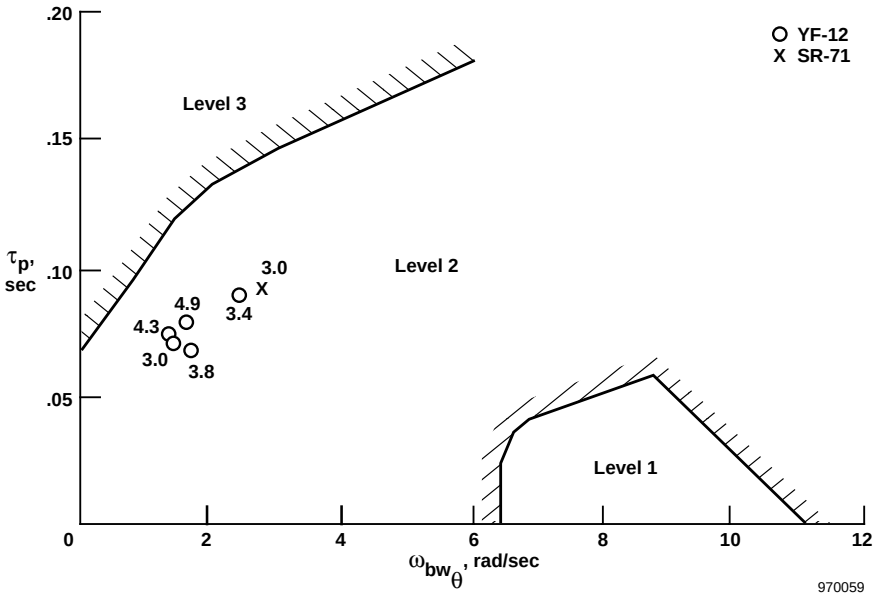


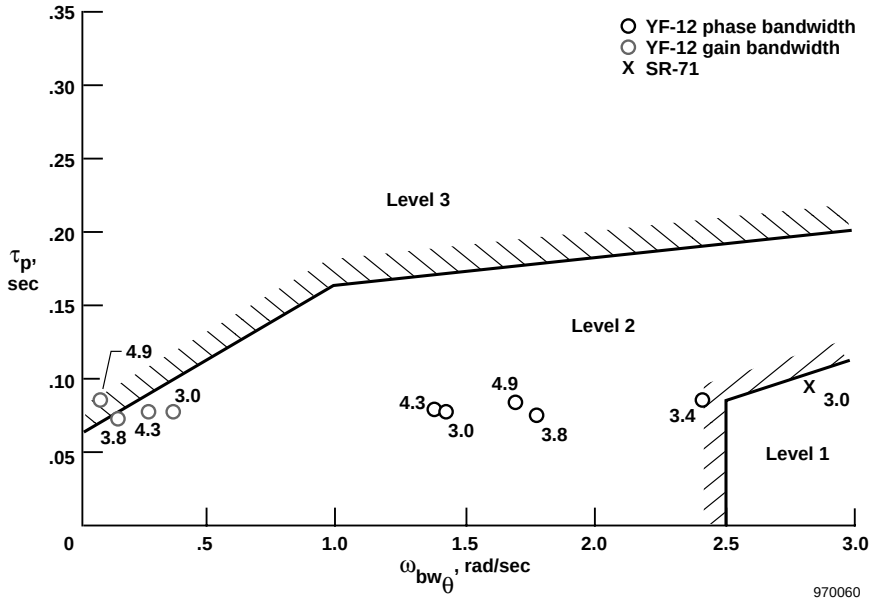
Figure 10. Example pitch attitude bandwidth calculation typical of a low damped YF-12 test point.

choose the lesser value, 0.19 rad/sec, as the gain bandwidth. The rationale is that if the pilot tries to close the loop at the higher gain bandwidth values a tendency to oscillate will occur because of the lightly damped peak. The large, shelf-like characteristic results in a large separation between the three gain bandwidth values. The existence of a large shelf is generally an indication of poor handling qualities, because the gain margin is very sensitive to slight changes in phase (ref. 6). In the following discussion the pitch attitude bandwidth for the cases when the SAS was off will be based on the phase bandwidth value, unless otherwise mentioned. Some comparison with the criterion will also be done using the lowest value of gain bandwidth, represented by 0.19 rad/sec in figure 10.

Figure 11 shows the results using categories A and C criteria from MIL-STD-1797. All the data rated level 1 falls within the level 2 region for the category A criterion. The category A criterion appears too stringent on pitch



(a) Category A.



(b) Category C.

Figure 11. MIL-STD-1797 pitch bandwidth criteria for categories A and C flight.

attitude bandwidth. However, the category C criterion reduces the restriction on pitch attitude bandwidth. For the category C criterion the ratings and comments correlate better with the border between the level 1 and 2 regions. Overplotted on the category C criterion is the gain-limited pitch attitude bandwidth values for the four YF-12 test points that were conducted with the SAS off. As is expected the pitch attitude bandwidth is drastically reduced to around 0.25, near the level 3 border. Correlation with pilot comments and ratings appears better with the phase-limited bandwidth values than the gain limited value, although the reason behind this phenomenon is unknown.

Although good correlation was obtained with the phase bandwidth values, it may be a misleading result. A large shelf exists in the pitch attitude frequency response, which is normally associated with poor pitch attitude control. However, the large shelf is actually the cause of good flightpath control. Figure 12 compares the magnitude of pitch attitude and flightpath frequency responses. For the frequency range where the large shelf is prevalent in the pitch attitude frequency response, the flightpath frequency response has a “1/s” characteristic. The 1/s characteristic is typical of airplanes with good flying qualities. Thus, pilot control of flightpath should be better than pitch attitude control. A flightpath command control is approximated with a conventional aircraft because pitch attitude deviations are small in supersonic flight. Other types of control systems, such as pitch rate command systems, could remove the shelf making pitch attitude control good, but would cause flightpath control to deteriorate.

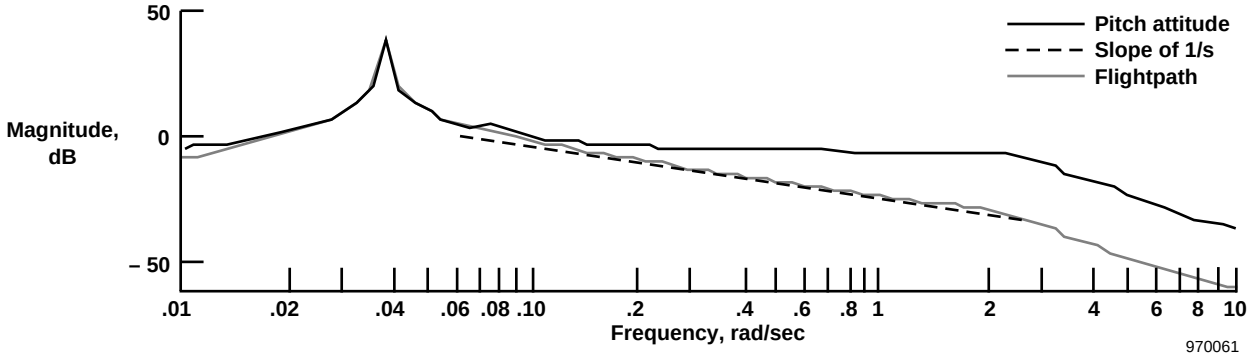


Figure 12. Comparison of pitch attitude and flightpath from stick position frequency response.

Figure 13 presents the pitch bandwidth using the HSCT criterion (ref. 7). The HSCT criterion is based on the terminal flight phase, which is equivalent to a category C flight phase. Note that the HSCT criterion is less restrictive on level 1 pitch attitude bandwidth than the MIL-STD-1797, category C criterion. Although there is some correlation with the HSCT criterion, less correlation exists using the HSCT criterion compared with the category C criterion from MIL-STD-1797 because level 2 ratings fall within the level 1 region. Either the criterion is not restrictive enough in pitch attitude bandwidth, or other factors are creating the level 2 ratings that this criteria does not account for. As was mentioned before, many of the flying qualities criteria, based on subsonic data, place restrictions on pitch attitude and assume that a good flightpath response follows. This assumption works in subsonic flight, where the criteria were defined. However, in supersonic flight, unique flightpath characteristics might invalidate the criteria. Flightpath control could be the factor not accounted for in the HSCT criterion presented in figure 13.

A criterion comparing flightpath bandwidth with pitch attitude bandwidth, presented in figure 14, had also been identified by the HSCT program. Again this criterion was based on the terminal flight phase or category C flight phase. At first glance good correlation exists between the ratings and the HSCT criterion. The three level 2 ratings that were predicted to be level 1 in figure 13 are now predicted to be level 2/3. However, a closer scrutiny of the data reveals some problems. This criterion sets requirements on the amount of lag between pitch attitude and flightpath response. The flightpath bandwidth values in figure 14 are above the level 1 region. This finding implies that the flightpath response lags the pitch attitude not by too much, as is expected, but by too little. This result is counter intuitive because physically the lag between pitch attitude and flightpath increases with Mach number.

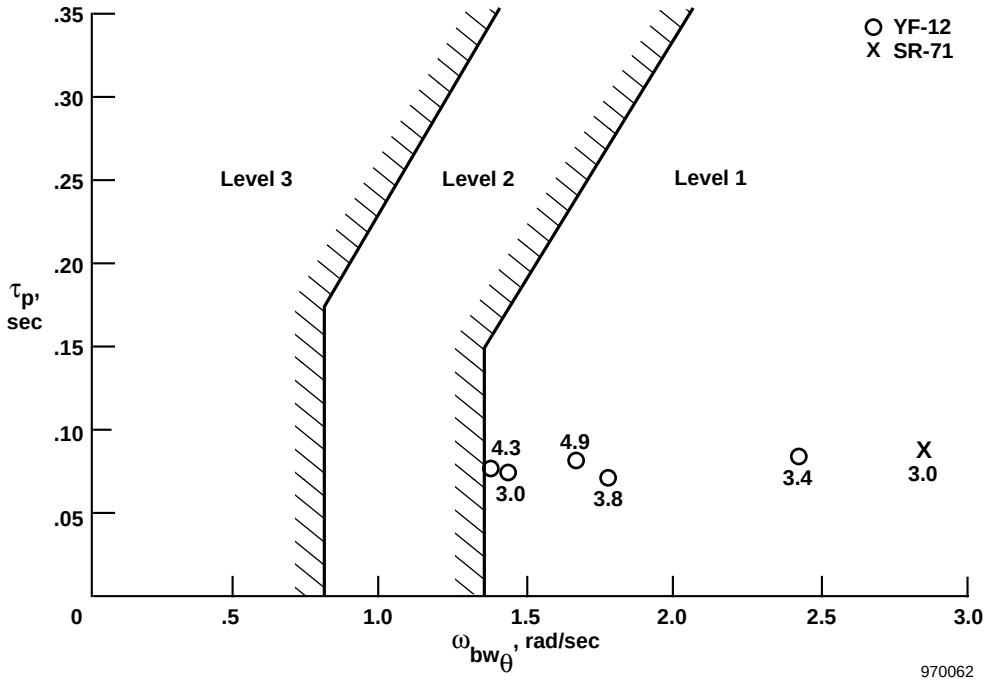


Figure 13. HSCT criteria on pitch bandwidth.

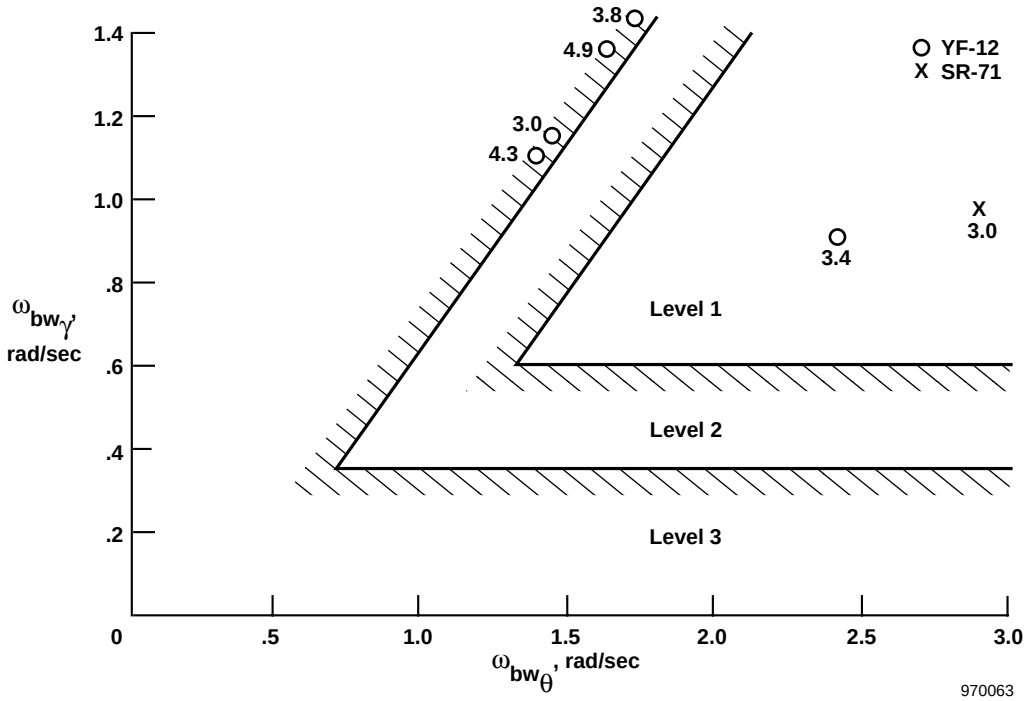


Figure 14. HSCT criteria on pitch bandwidth as a function of flightpath bandwidth.

One possible explanation for this data is that the upper limit on flightpath bandwidth was set based on precision approach and landing. In this flight phase both pitch attitude and flightpath response are controlled by the pilot. For the data of figure 14 the pilot ratings and comments were based on cruise flight during a vertical plane altitude change using an inertial vertical speed feedback. The requirement for consonance between flightpath and pitch attitude response may not be as important for these conditions. The pilot simply may not care as much about the smaller pitch attitude response in cruise flight compared with landing, especially if vertical speed is fed back. As a result, adjustment of the level 1 upper borders may be required for precision flightpath control at cruise conditions.

Neal/Smith Criterion

The Neal/Smith criterion involves closing the loop around a pitch attitude to stick deflection transfer function and a lead-lag compensator, modified by the addition of pure time delay, to meet specific closed-loop characteristics. The characteristics of the closed-loop frequency response are defined as –90 degrees of phase at the bandwidth frequency and no less than –3 dB of droop (fig. 15). The bandwidth frequency represents the piloting task that is being conducted and is generally chosen based on flight phase. Criteria are established based on the lead required of the compensator to meet the characteristics and the maximum amplitude, or resonant peak, of the frequency response of the closed-loop (i.e., the compensator and airplane) system.

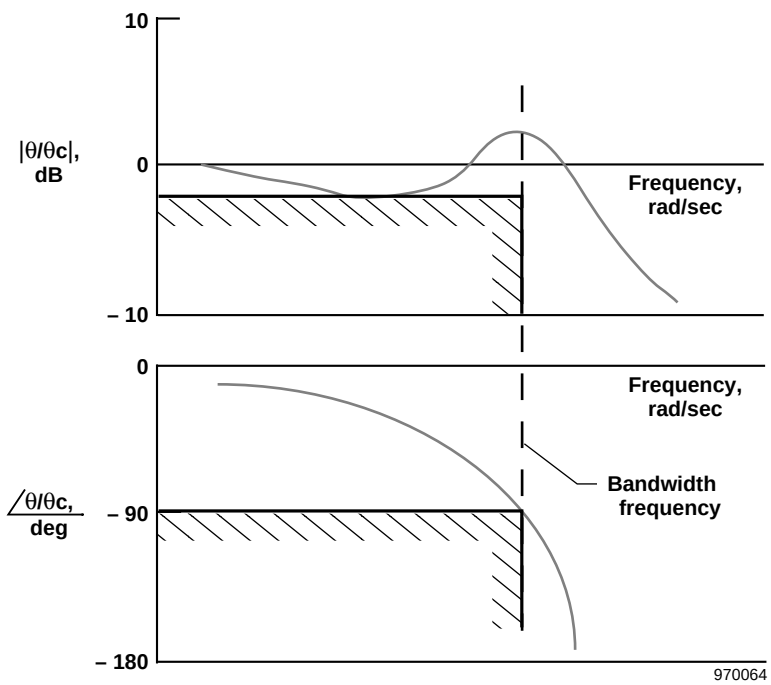


Figure 15. Illustration of application of Neal/Smith criteria.

For the data presented here, the time delay of the compensator was chosen to be 0.3 sec. Three bandwidths ranging from 1.0 to 2.5 were analyzed to represent increases in the demands of the task. Figure 16 presents the results from applying this criterion to SR-71 data. From this figure the compensator requires large amounts of lag, which drives the ratings into the level 2 region. These results would be consistent with the large shelf in the pitch attitude from stick position frequency responses. Data in this region of the Neal/Smith plane predict pilot comments of abruptness in the initial response with tendencies to bobble. Pilot comments from flight data are contrary to this prediction. One pilot commented during the vertical plane altitude change maneuver that “a great deal of lead is required (to acquire the target altitude) in terms of time.” This comment suggests that the Neal/Smith analysis should

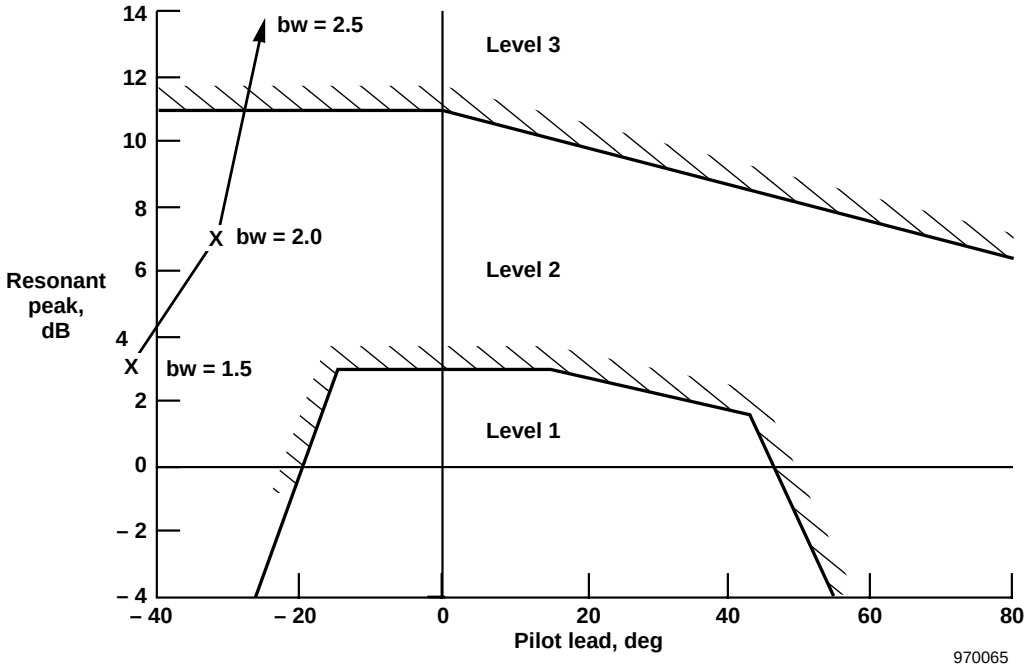


Figure 16. Neal/Smith analysis of the pitch attitude to stick deflection frequency response.

yield results on the lead side of the plane, where pilot comments of sluggish initial responses are predicted. However, the pilot later commented that “the workload for this maneuver is acceptable because of the low rates of change involved,” and gave the aircraft a CH of 3, which implied that the workload was not significant. Thus, one would expect the Neal/Smith analysis to yield results within the level 1 region.

A contradiction exists between the pilot ratings and comments and the Neal/Smith analysis. The solution to this contradiction may be found through closer examination of the instrumentation available to the pilot for the evaluations. Typically a pilot uses pitch attitude as a primary feedback to his commanded inputs to the stick. However, the SR-71 and YF-12 had inertial vertical speed displayed through needles on the ADI and driven by an inertial navigation system. This display allowed direct feedback to the pilots on vertical speed without the lags of a pressure-driven vertical speed display. The pilots on both the SR-71 and YF-12 took advantage of this feature by flying these maneuvers using these needles as their primary feedback parameter. Reference 3 described the advantage of using the inertial vertical speed indication. If this is the case, perhaps the Neal/Smith results would correlate better with ratings and comments if the integral of normal acceleration, or vertical speed, would be used in the analysis instead of pitch attitude.

The Neal/Smith analysis was repeated for the SR-71 data, this time using the integral of normal acceleration at the center of gravity (c.g.) and normal acceleration at the pilot station to approximate vertical speed. Figure 17 presents the results for bandwidth frequencies of 1.0, 1.5, and 2.0 rad/sec. The data fall on the lead side of the Neal/Smith plane as expected. Superimposed on the results are the MIL-STD-1797 criterion and the HSCT criterion. Note that the level 1/2 HSCT border is nearly equivalent to the MIL-STD-1797 border, but that the level 2/3 border is more restrictive. Quite a bit of difference exists between the results using c.g. and pilot station vertical speed. The rate of flying qualities degradation as a function of increasing bandwidth is much higher for the vertical speed at the c.g. than for the vertical speed at the pilot station. The inertial system used to calculate the vertical speed that is fed back to the pilot is located close to the pilot station. Therefore, using the vertical speed calculated for the pilot station in the Neal/Smith analysis is more representative of the actual vertical speed indicator than the vertical speed at the c.g. The Neal/Smith results using vertical speed calculated at the pilot station also indicate that there can be a beneficial effect in modifying the c.g. vertical speed with, in this case, pitch acceleration lead.

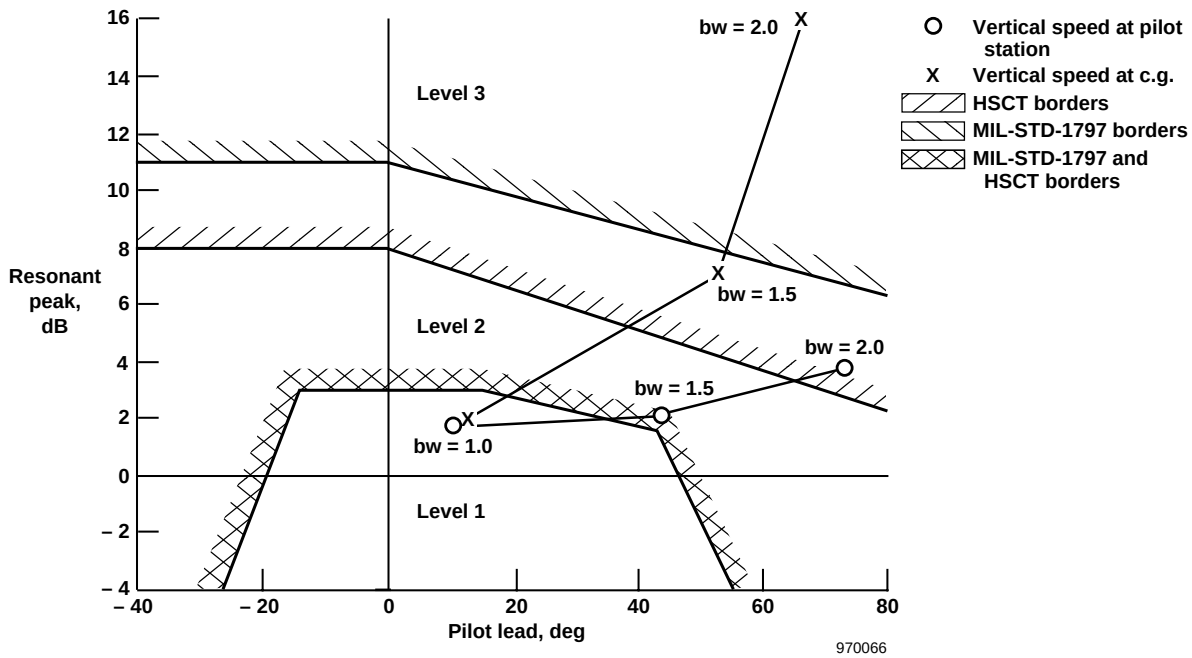


Figure 17. Neal/Smith analysis of the vertical speed at the c.g. and the vertical speed at the pilot station from stick deflection frequency response.

As described previously, the aircraft was rated level 1, with noticeable lead required. As the bandwidth increases, the c.g. vertical speed results enter the level 2 region with relatively low levels of lead required, whereas the pilot station vertical speed results enter the level 2 region with significant amounts of lead. Thus, using the vertical speed at the pilot station correlates better with ratings and comments than using the c.g. vertical speed. Bandwidths within the 1.0 to 1.5 rad/sec range correlate best with SR-71 pilot comments and ratings.

Both MIL-STD-1797 and HSCT criteria use 1.5 rad/sec as the bandwidth for the terminal, or category C, flight phase. From figure 17 the use of this value of bandwidth correlates well with the ratings and comments from high-speed flight, although the 1.5 rad/sec bandwidth is at the high end of bandwidths that correlate. Thus, as long as the vertical speed at the pilot station transfer function is used instead of the pitch attitude transfer function, the category C requirement should provide a conservative analysis for normal maneuvering in high-speed flight.

To further examine the Neal/Smith criterion figure 18 shows the reproduced YF-12 data along with the SR-71 data for a bandwidth of 1.0 rad/sec. Two of the test points correlate well with the level 1 region. However, the rest of the points predict a great deal of oscillatory characteristics. The oscillatory prediction is great enough to be pilot-induced oscillation (PIO) prone and level 3. Pilot comments in no way suggest these characteristics. All the test points that do not correlate well were gathered without the SAS. Short-period damping was reduced from approximately 0.5 to 0.15 by turning off the SAS. Increases in the oscillatory tendency of the aircraft would be expected, as well as a large sharp peak in the magnitude and a large phase dropoff in the frequency response used in the Neal/Smith analysis. These frequency response characteristics would result in higher calculations of resonant peak in the Neal/Smith analysis.

Because the data from figure 18 show that level 2 ratings exist in the level 3 region because of large values of resonant peak, the Neal/Smith criterion may be too restrictive in short-period damping and may require adjustment of the border between the level 1 and 2 regions. This finding is supported by the short-period damping analysis in figure 8. From this data it was shown that a relaxation of the damping criterion was necessary to define the border between the level 1 and 2 regions for normal maneuvering in high-speed flight.

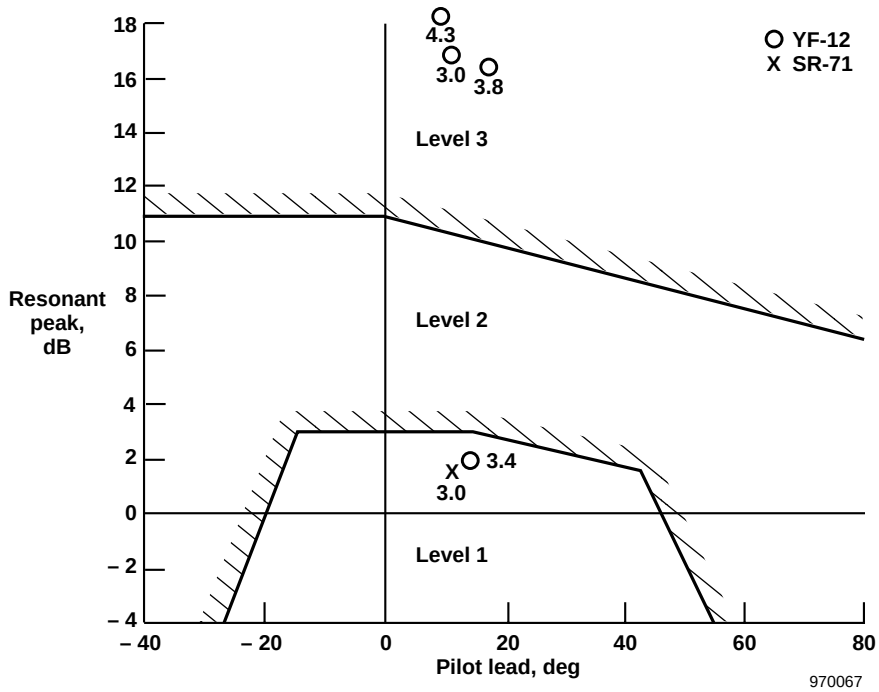


Figure 18. Neal/Smith analysis of the vertical speed at the pilot station from stick deflection frequency response using 1.0 rad/sec bandwidth.

LATERAL-DIRECTIONAL CRITERIA EVALUATION

Lateral-directional criteria were evaluated using the LOES technique and lateral acceleration at the pilot station. These criteria were used in the design of the HSCT. The SR-71 flight data were compared with MIL-STD-1797 and HSCT criteria. Unfortunately, test conditions of previous XB-70 and YF-12 lateral-directional evaluations were not available. Therefore, it was not possible to reproduce any of this data, as was done in the longitudinal axis. Pilot evaluations did exist for the XB-70, and these results were compared with the criterion on dutch roll damping.

Low-Order Equivalent System

The LOES technique was developed to apply classical boundaries for handling qualities to higher order aircraft. The technique fits fourth-order transfer function models of roll attitude from stick deflection and sideslip from rudder pedal to higher order models or flight data. A time delay model is added to the fourth-order transfer functions to account for differences in phase between the lower and higher order models. As a result, LOES estimates of dutch roll frequency (ω_{dr}) and damping (ζ_{dr}), roll mode (τ_r), and spiral mode can be applied to classical criteria on these parameters. An additional criterion on the time delay estimate has also been developed.

An LOES fit was performed on a Fast Fourier Transform of a lateral stick frequency sweep performed during flight. Unfortunately, a good measurement of sideslip was not available. Therefore, simultaneous fits of flight-data-recorded sideslip from rudder pedal and bank-angle-to-stick deflection frequency responses were not possible. However, dutch roll damping and frequency estimates from flight data were still desired. To obtain these estimates an LOES fit was performed on the bank-angle-from-stick deflection frequency response with the second-order numerator zero fixed at a value estimated by the linear simulation model.

The LOES estimates of roll mode time constant, dutch roll frequency, time delay, and dutch roll damping are plotted in figures 19 through 22, respectively, against categories A, B, and C criteria from MIL-STD-1797 and

against HSCT criteria. The shaded regions show where the data should fall if the criteria correlate with pilot ratings. Except for the time delay criterion, HSCT criteria are either the same as or more restrictive than MIL-STD-1797 criteria. For the roll mode time constant (fig. 19) and dutch roll frequency (fig. 20) both MIL-STD-1797 and HSCT criteria predict level 1 flying qualities, which agrees with pilot ratings and comments. Time delay estimates (fig. 21) fall outside the MIL-STD-1797 criterion. However, the MIL-STD-1797 criterion appears to be too restrictive, especially for a class III vehicle (ref. 13). Although not enough data exist to be conclusive, the SR-71 data support a less restrictive time delay criterion than MIL-STD-1797.

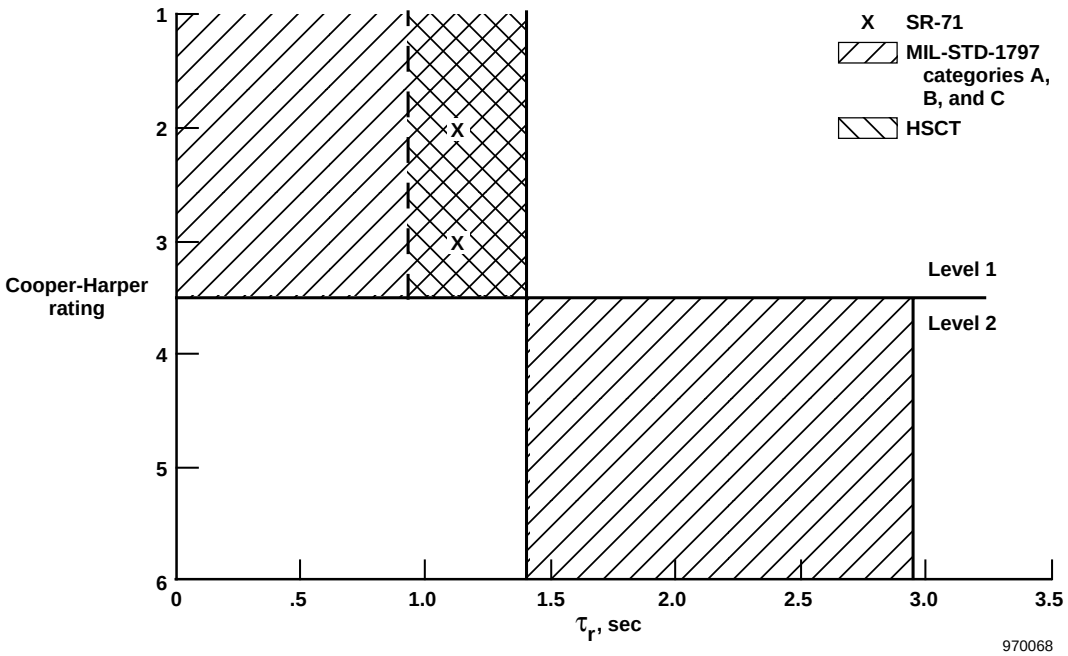


Figure 19. LOES estimates of roll mode time constant compared with HSCT and MIL-STD-1797 criteria.

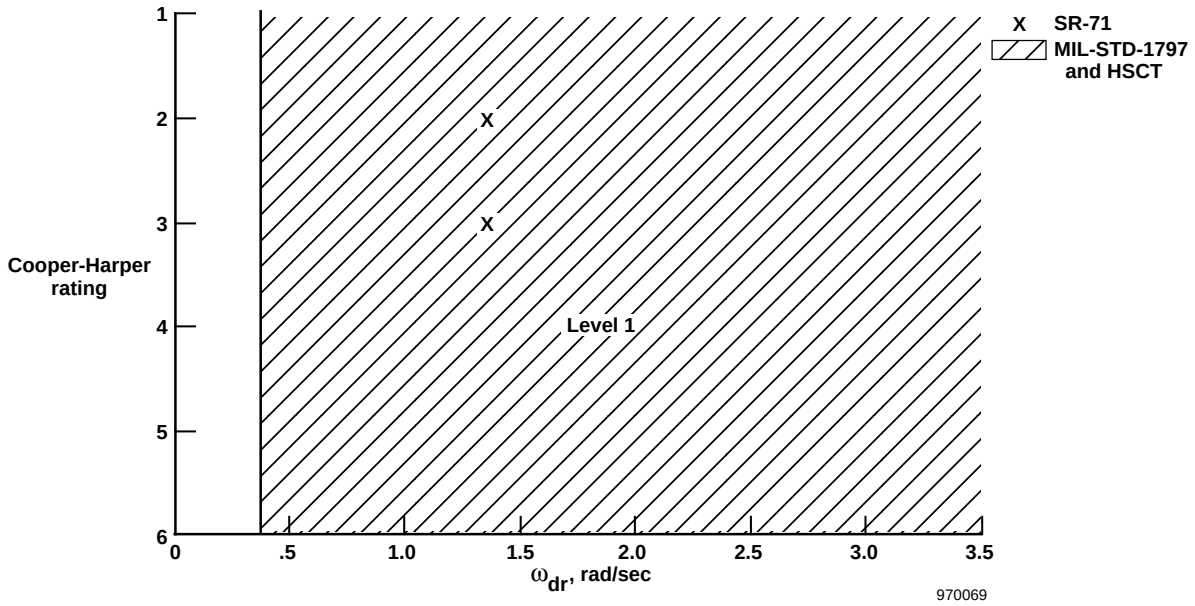


Figure 20. LOES estimates of dutch roll frequency compared with MIL-STD-1797 and HSCT criteria.

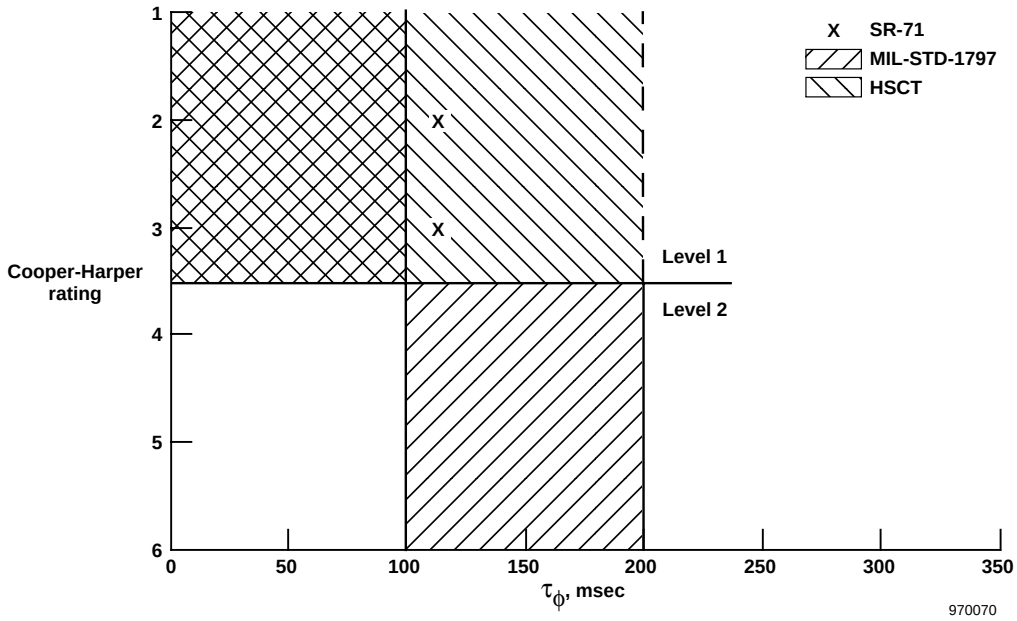
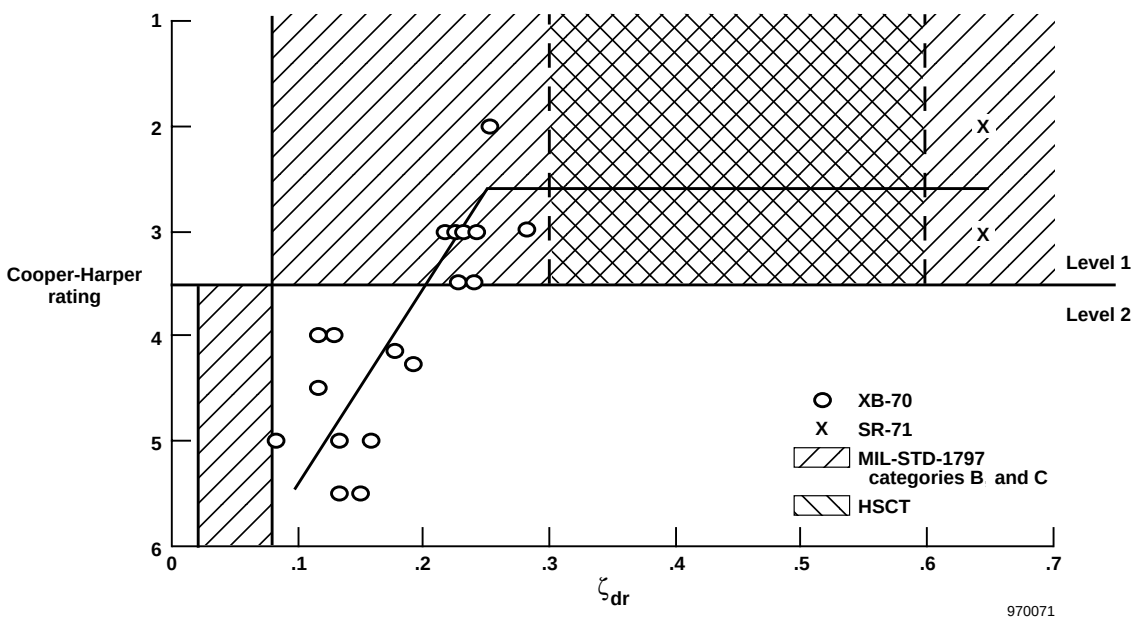


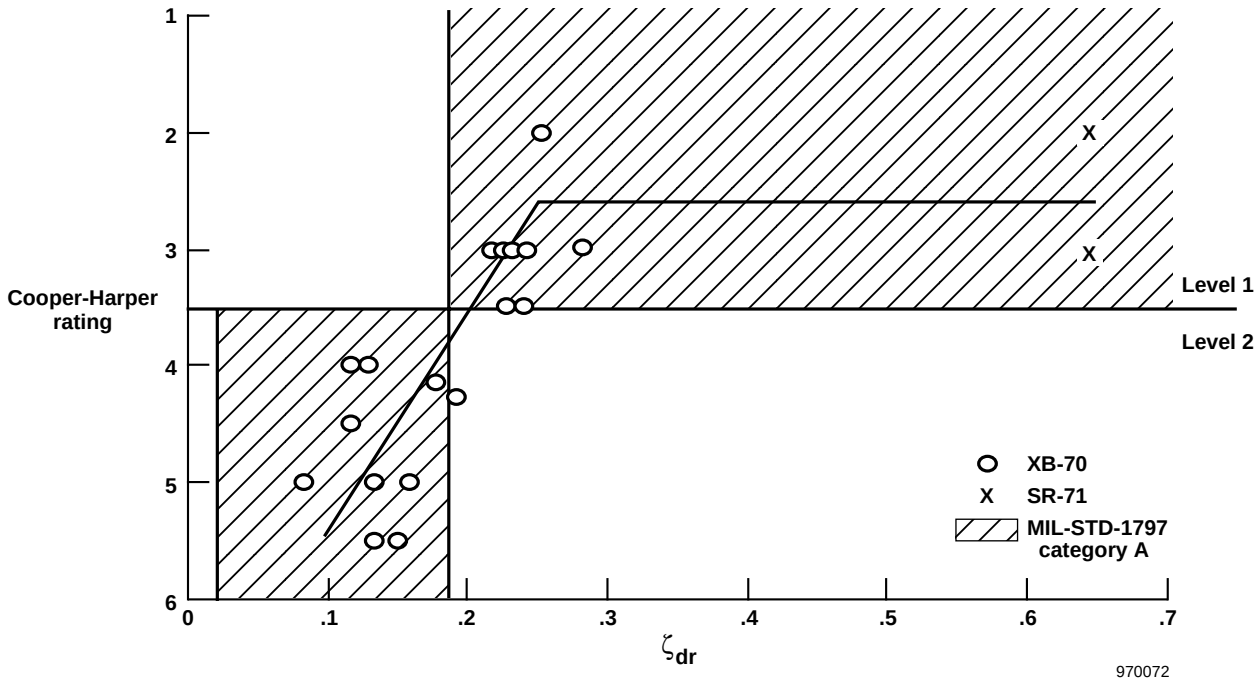
Figure 21. LOES estimates of time delay estimate compared with HSCT and reference 5 criteria.

The most interesting results are observed in the dutch roll damping ratio estimates presented in figure 22, which have XB-70 data overplotted. The solid line in figure 22 is a fairing of the data. The shaded region shows where the data should fall if the criteria correlate with pilot ratings. From this data it is obvious that the HSCT criterion is too restrictive and that the categories B and C criteria from MIL-STD-1797 are not restrictive enough. The data fit within the category A criterion with nearly 100-percent correlation. This fit implies that either (1) the lateral-directional tasks being flown by the XB-70 are better represented by the category A flight phase, or (2) that some other parameter



(a) HSCT, categories B and C criteria.

Figure 22. LOES estimates of dutch roll damping compared with HSCT criteria and criteria from categories A, B, and C of MIL-STD-1797.



(b) Category A criteria.

Figure 22. Concluded.

was affecting the flying qualities, which is not accounted for in this plot. Reference 5 mentioned that the ratings were collected during sonic boom measurement runs, where precise heading was crucial to fly over sonic boom equipment on the ground.

Two HSCT criteria were defined to evaluate the roll rate oscillations due to the dutch roll mode. These two criteria are defined as (1) the cost of an LOES first-order fit to the bank-angle-to-stick deflection frequency response must be less than 25, and (2) $\zeta_\phi\omega_\phi/\zeta_{dr}\omega_{dr}$ must be between 0.95 and 1.05. Both criteria were applied to SR-71 flight data. Application of an LOES first-order fit to the bank-angle-to-stick deflection frequency response resulted in a cost of approximately 11. Thus, the SR-71 data are acceptable according to the first criterion. The second criterion was applied through an LOES fit to the bank-angle-from-stick deflection frequency response with the second-order numerator parameters fixed at values estimated by a linear model. The dutch roll parameters were then estimated in the LOES fit. The results show that $\zeta_\phi\omega_\phi/\zeta_{dr}\omega_{dr}$ is equal to 0.90, just outside the acceptable range. Pilot comments indicated no problems with roll rate oscillations because of the dutch roll mode.

Lateral Acceleration at Pilot Station

The next criterion addresses the acceptable level of lateral acceleration at the pilot station during a roll. The criterion is based on a parameter calculated by dividing the lateral acceleration at the pilot station by the maximum roll rate encountered during the first 2.5 sec of a lateral step input. The criterion is applied to SR-71 flight data and presented in figure 23. HSCT and MIL-STD-1797 criteria are superimposed on figure 23. The shaded regions show where the data should fall if the criteria correlate with pilot ratings. Note that the HSCT criterion is slightly more restrictive than the MIL-STD-1797 criterion. The SR-71 data, although inconclusive because of their scarcity, do support both HSCT and MIL-STD-1797 criteria.

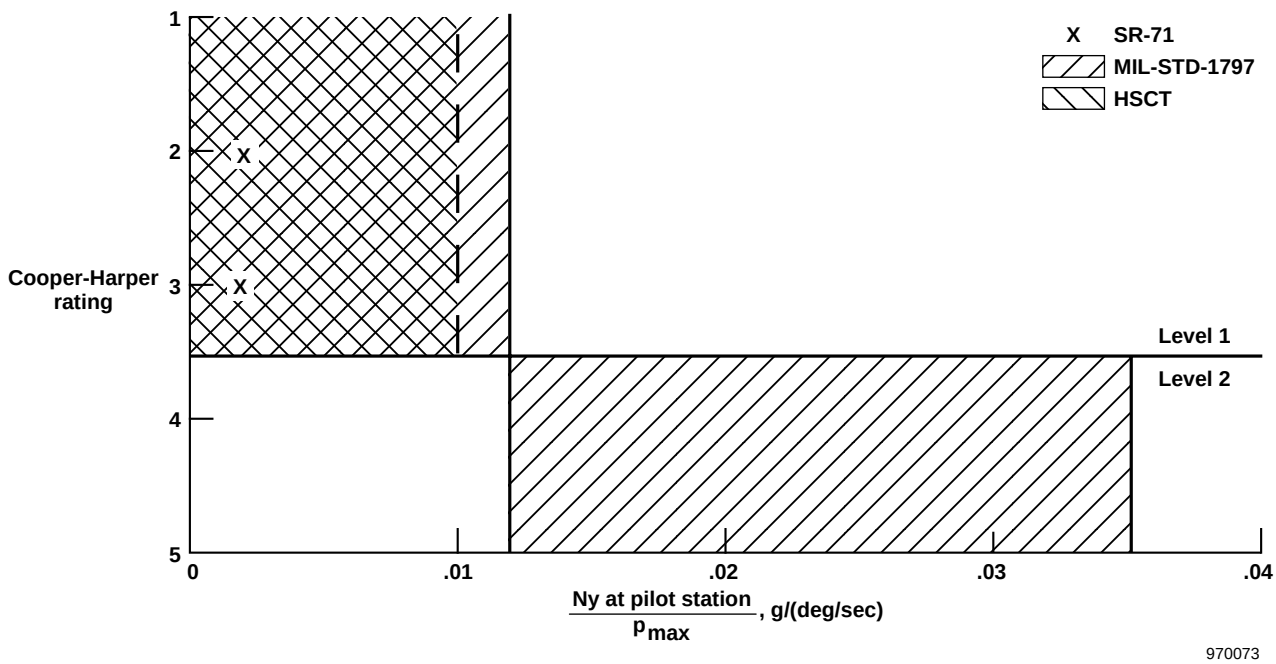


Figure 23. Criteria on lateral acceleration at the pilot station.

CONCLUSIONS

NASA Dryden Flight Research Center evaluated the flying qualities of the SR-71 at Mach 3 through three well-defined maneuvers: steady level turn, ascending turn, and a vertical plane altitude change. The flying qualities of the SR-71 were documented and reasons were identified for cases where level 2 ratings were given. The goal of this research was to extend the high-speed flying qualities experience of large airplanes and to evaluate some of the more recent MIL-STD-1797 criteria against pilot comments and ratings. The XB-70 and YF-12 data from research conducted approximately 25 years ago supplemented the SR-71 data. Emphasis was placed on evaluating the criteria used for the design of the High-Speed Civil Transport (HSCT). The following longitudinal criteria were evaluated: low-order equivalent system (LOES), pitch bandwidth, flightpath bandwidth, and Neal/Smith. Additionally, the memorandum evaluated the following lateral-directional criteria: LOES and lateral acceleration at the pilot station. The results indicate the following:

1. In general, MIL-STD-1797, category C, or terminal flight criteria on pitch bandwidth and control anticipation parameter (CAP) correlate well with the evaluations of high-speed flying qualities. The tasks flown are considered typical maneuvering for high-speed flight. Application of these category C criteria to aircraft in high-speed flight should result in an accurate evaluation of the longitudinal flying qualities.

2. Evidence exists for relaxing the short-period damping criterion for high-speed flight. The relaxation of the short-period damping requirement may also affect the Neal/Smith borders on resonant peak as well. However, other factors not accounted for in the XB-70 and YF-12 ratings, such as turbulence, may increase the damping requirement.

3. High-speed handling qualities data, in general, support the HSCT terminal phase criteria as sufficient to provide a good flying qualities airplane for typical high-speed maneuvering. Borders in the criteria specified for the design of the HSCT were more restrictive, or conservative, in nature than both the MIL-STD-1797 criteria and the high-speed flying qualities evaluations. Criteria on CAP and short-period damping proved too restrictive. Application of the flightpath bandwidth criterion to the data did not predict the expected pitch attitude and flightpath consonance characteristics.

4. Applying the Neal/Smith criteria with the standard pitch attitude from stick deflection frequency response yielded results that did not match pilot comments of lead compensation. To correlate the Neal/Smith analysis with pilot ratings and comments, an extension of the technique using the vertical speed at the pilot station was required. Only the Neal/Smith criterion for cases with high damping appears consistent with evaluations of high-speed handling qualities.
5. Estimates of dutch roll damping for the XB-70 correlate well with category A criterion from MIL-STD-1797. However, category C and HSCT criteria do not correlate well, which is opposite to the relationship seen in other parameters.
6. Using inertial vertical speed, instead of the instantaneous vertical speed indicator (IVSI), which is driven by pressure, is important in the pilot control of flightpath.

Although not enough data exist in high-speed flight to be conclusive, the results of this study indicate that category C criteria may be applicable to the high-speed flight regime. Many of the criteria matched pilot ratings and comments, with the HSCT criteria on the conservative side.

Dryden Flight Research Center
National Aeronautics and Space Administration
Edwards, California, January 27, 1997

REFERENCES

1. Anon., “Flying Qualities of Piloted Airplanes,” MIL-F-8785B, Aug. 7, 1969, U.S. Military Specification.

2. Berry, Donald T., “Some Handling Qualities Problems of Supersonic Cruise Aircraft,” in *NASA Aircraft Safety and Operating Problems Conference, Volume II*, NASA SP-271, May 1971, pp. 25–38.

3. Berry, Donald T., “A Summary of YF-12 Handling Qualities,” in *YF-12 Experiments Symposium, Volume 2*, NASA CP-2054, Sept. 1978, pp. 31–57.

4. Berry, Donald T., Donald L. Mallick, and Glenn B. Gilyard, “Handling Qualities Aspects of the NASA YF-12 Experience,” *Proceedings of SCAR Conference*, NASA CP-001, Nov. 1976, pp. 193–213.

5. Berry, Donald T. and Bruce G. Powers, “Flying Qualities of a Large, Supersonic Aircraft in Cruise and Landing Approach,” AIAA 70-566, AIAA Atmospheric Flight Mechanics Conference, Tullahoma, Tennessee, May 13–15, 1970.

6. Anon., “Flying Qualities of Piloted Vehicles,” MIL-STD-1797 (USAF), Mar. 31, 1987, U.S. Military Standard.

7. Princen, N. H., M. A. Page, and K. F. Rossitto, “High Speed Civil Transport Preliminary Controls Sizing and Flying Qualities Issues and Requirements,” MDC report 94K0269, May 16, 1994.

8. Hodgkinson, J. and W. J. LaManna, “Equivalent System Approaches to Handling Qualities Analysis and Design Problems of Augmented Aircraft,” AIAA 77-1122, Aug. 1977.

9. Hoh, Roger H., David G. Mitchell, and John Hodgkinson, “Bandwidth—A Criterion for Highly Augmented Airplanes,” AFWAL-CR-80-3604, Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, Ohio, June 1982.

10. Hoh, Roger H., “Recommendations for Approach and Landing Flying Qualities,” STI Working Paper 2361-1, Dec. 1988.

11. Neal, T. Peter and Rogers E. Smith, “An In-Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes, Volume 1,” AFFDL-TR-70-74, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, Dec. 1970.

12. Powers, Bruce G., *Phugoid Characteristics of a YF-12 Airplane With Variable-Geometry Inlets Obtained in Flight Tests at a Mach Number of 2.9*, NASA TP-1107, Dec. 1977.

13. Meyer, Robert T., John R. Knox, and Stephen A. Tingas, “Suggested Revisions to MIL-F-8785C for Large (Class III) Aircraft,” AFWAL-TR-83-3015, Feb. 1983.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
April 1997

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Evaluation of High-Speed Civil Transport Handling Qualities Criteria With Supersonic Flight Data

5. FUNDING NUMBERS
WU 529-50-24

6. AUTHOR(S)
Timothy H. Cox and Dante W. Jackson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Dryden Flight Research Center
P.O. Box 273
Edwards, California 93523-0273

8. PERFORMING ORGANIZATION REPORT NUMBER
H-2153

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-4791

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified—Unlimited
Subject Category 08

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Most flying qualities criteria have been developed from data in the subsonic flight regime. Unique characteristics of supersonic flight raise questions about whether these criteria successfully extend into the supersonic flight regime. Approximately 25 years ago NASA Dryden Flight Research Center addressed this issue with handling qualities evaluations of the XB-70 and YF-12. Good correlations between some of the classical handling qualities parameters, such as the control anticipation parameter as a function of damping, were discovered. More criteria have been developed since these studies. Some of these more recent criteria are being used in designing the High-Speed Civil Transport (HSCT). A second research study recently addressed this issue through flying qualities evaluations of the SR-71 at Mach 3. The research goal was to extend the high-speed flying qualities experience of large airplanes and to evaluate more recent MIL-STD-1797 criteria against pilot comments and ratings. Emphasis was placed on evaluating the criteria used for designing the HSCT. XB-70 and YF-12 data from the previous research supplemented the SR-71 data. The results indicate that the criteria used in the HSCT design are conservative and should provide good flying qualities for typical high-speed maneuvering. Additional results show correlation between the ratings and comments and criteria for gradual maneuvering with precision control. Correlation is shown between ratings and comments and an extension of the Neal/Smith criterion using normal acceleration instead of pitch rate.

14. SUBJECT TERMS
Bandwidth criteria, Flightpath bandwidth, Flying qualities, High-speed civil transport, Low-order equivalent systems, Neal/Smith criteria, SR-71 aircraft, Supersonic flying qualities

15. NUMBER OF PAGES
31

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
Unlimited

NSN 7540-01-280-5500

Available from the NASA Center for AeroSpace Information, 800 Elkridge Landing Road, Linthicum Heights, MD 21090; (301)621-0390

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102