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Landing Approach Flying Qualities Criteria For Active Control Transport Aircraft

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ABSTRACT

Flying qualities databases and criteria have existed for fighter aircraft for several decades. However, there have been a lack of databases and criteria for active control transport aircraft. During the 1990's Boeing undertook a series of in-flight simulation experiments to generate a comprehensive longitudinal axis database for transport aircraft in the landing approach task. This database has subsequently been applied to the more established longitudinal flying qualities criteria that were developed for fighter aircraft. This paper summarizes the results of these analyses and appraises the performance of the various criteria for application to active control transport aircraft.

INTRODUCTION

Background

The earliest flying qualities requirements for an aircraft's dynamic responses were specified in terms of the frequency and damping characteristics of its rigid body modes of motion. In the longitudinal axis these concerned the short period and phugoid modes. As long as the frequencies of the short period and phugoid modes were well separated the requirements for each mode could be specified separately. Indeed, for fighters the two modes were well separated, about a decade apart, sometimes more. Additionally, the phugoid mode was usually stable, easily controlled by the pilot, and hence not a critical issue, leaving most attention to the short period mode.

The earliest requirements for the short period dynamics were task dependent graphical boundaries delineating acceptable combinations of short period frequency and damping ratio[1]. These boundaries were given the name "thumbprints", since that is how they appeared. Since they only included requirements for short period frequency and damping, they only addressed the aircraft's angle-of-attack response. The requirements did not capture the full pitch attitude response to elevator, or the flight path response to pitch attitude.

It soon became apparent that pilots' perceptions of an aircraft's flying qualities did not correlate directly with the thumbprint boundaries. Clearly, short period frequency and damping were not sufficient metrics to fully define an aircraft's apparent flying qualities. Resulting from an analysis of stick pumping characteristics, Birhle developed the Control Anticipation Parameter[2] (CAP), which is the ratio of the initial pitching acceleration to the steady state normal acceleration. Thus, CAP explicitly introduced requirements on the consonance between the pitch attitude and flight path responses, though only implicitly on the pitch attitude and flight path responses themselves. Correlation of CAP values and pilot ratings from flying qualities experiments led to the development of boundaries for acceptable flying qualities based upon CAP. These requirements were incorporated into the US military flying qualities specifications[3] and became the accepted means to characterize an aircraft's longitudinal flying qualities.

As the performance of aircraft increased, so did the complexity of their flight control systems. The elements of the flight control systems introduced their own dynamics in addition to those of the bare airframe, which is characterized by the short period and phugoid modes. When making control inputs the pilot no longer saw the bare airframe response, but now saw the "apparent" aircraft response, the combined dynamics of the bare airframe and flight control system. As a result a pilot's perception of an aircraft's flying qualities no longer correlated with the bare airframe parameters as specified by CAP. Alternative approaches were required that could correlate the total aircraft's dynamic response to the pilot's perception of the resulting flying qualities.

Since the 1960's several approaches have been developed to characterize an aircraft's flying qualities. By placing limits on these "characteristics", they have been developed into flying qualities criteria. The less successful have fallen by the wayside, but several have stood the test of time. After considerable development they have matured into established and accepted criteria for fighter aircraft. In line with the inherent dynamics of fighter aircraft, some of these criteria neglect the contribution of the phugoid response at short period frequencies. The criteria concern mainly two flight regimes, up-and-away tracking tasks and the approach and landing task. Additional elements or developments of the criteria also address the important issue of Pilot Induced Oscillations (PIO).

Transports

The evolution to augmented control and eventually fly-by-wire control in transport aircraft followed behind the developments in fighters. Fighters fully exploited the potential of fly-by-wire control by incorporating unstable airframes with their associated performance benefits. Initially, transports have remained statically stable, only incorporating slightly reduced static stability. Hence, many of the traditional design requirements emphasizing static stability have been retained, and have been essentially sufficient.

However, these static stability requirements do not account for the higher order dynamics of the fly-by-wire control system. Clearly, high order flying qualities requirements are required for active control transport aircraft, whether reduced static stability or not.

The main area of attention for transports is the terminal area, specifically the approach and landing task. Up-and-away flying qualities are less of a concern, although they should still be well behaved and predictable. An important consideration is high altitude flight, an area which is seldom flown manually on modern transports. If the flying qualities at high altitude are appreciably different from those at low altitude, with which the pilot is far more familiar, a pilot may adopt an improper control technique if he has to take manual control, such as after an autopilot disconnect.

The requirements for transports in up-and-away flight are very different from those for fighters, which are required to perform aggressive maneuvering. However, in the landing approach the task is similar to that for fighters, and so it is reasonable to consider the flying qualities criteria that were developed for fighters in this task.

However, there are distinct differences in the responses of the two classes of aircraft. Specifically, the separation between the short period and phugoid modes is not as great in transports as in fighters, the two modes often being in the same decade. As a result, the simplification that is employed in the analysis of many fighters, of neglecting the contribution of the phugoid response at short period frequencies, may not be successful in transports.

Databases

The results presented in this paper include only those configurations from the Boeing experiments. When developing the new criteria boundaries other databases were also considered. A review of available databases determined that the only applicable ones were those generated by Calspan during three experiments during the 1980's[4,5,6]. Additionally, only selected configurations from those databases were applicable, specifically, those that represented a conventionally configured aircraft (long aft tailed) and that exhibited a conventional response-type (angle-of-attack like). For clarity, only the Boeing configurations are presented in this paper.

THEORY

For pitch axis control tasks, pilots require precise and predictable control of pitch attitude and flight path, and their respective rates, pitch rate and normal acceleration. Therefore, most pitch axis flying qualities criteria address at least one of these responses, as do all the criteria appraised in this paper.

The frequency range of primary interest for piloted control is that between 0.1 and 10 rad/sec. Therefore, only the dynamics that affect the aircraft responses in this frequency range are of interest from a flying qualities, and hence flying qualities criteria, perspective. As discussed earlier, for most fighter aircraft the short period and phugoid modes are usually well separated. Hence, the phugoid can be neglected for flying qualities analyses concerning the short period maneuvering mode. The reduced order, constant speed approximation, transfer functions, commonly used in fighter flying qualities analyses, are:

$$\frac{\theta(s)}{\delta_{CC}(s)} = \frac{K_\theta\left(s + 1/\tau_{\theta_2}\right)}{s\left[s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2\right]}$$

$$\frac{\gamma_{CG}(s)}{\delta_{CC}(s)} = \frac{K_{\gamma_{CG}}}{s\left[s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2\right]}$$

$$\frac{q(s)}{\delta_{CC}(s)} = \frac{K_q\left(s + 1/\tau_{\theta_2}\right)}{\left[s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2\right]}$$

$$\frac{n_{z_{ICR}}(s)}{\delta_{CC}(s)} = \frac{K_{n_z}}{\left[s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2\right]}$$

As long as the short period and phugoid modes are well separated, the reduced order transfer functions above adequately represent the maneuvering response of the aircraft. Correlation of observed flying qualities with parameters obtained from analyses using these transfer functions is usually successful. For transport aircraft where the phugoid is usually above 0.1 rad/sec and not well separated from the short period, contributions from the phugoid dynamics may be appreciable at short period frequencies. In these cases it is necessary to consider the full order, three degree of freedom model, which for a conventional unaugmented aircraft has the following transfer functions:

$$\frac{\theta(s)}{\delta_{CC}(s)} = \frac{K_\theta\left(s + 1/\tau_{\theta_1}\right)\left(s + 1/\tau_{\theta_2}\right)}{\left[s^2 + 2\zeta_p\omega_p s + \omega_p^2\right]\left[s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2\right]}$$

$$\frac{\gamma_{CG}(s)}{\delta_{CC}(s)} = \frac{K_{\gamma_{CG}}\left(s + 1/\tau_{\gamma_{CG_1}}\right)\left(s + 1/\tau_{\gamma_{CG_2}}\right)\left(s + 1/\tau_{\gamma_{CG_3}}\right)}{\left[s^2 + 2\zeta_p\omega_p s + \omega_p^2\right]\left[s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2\right]}$$

$$\frac{q(s)}{\delta_{CC}(s)} = \frac{K_q s\left(s + 1/\tau_{\theta_1}\right)\left(s + 1/\tau_{\theta_2}\right)}{\left[s^2 + 2\zeta_p\omega_p s + \omega_p^2\right]\left[s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2\right]}$$

$$\frac{n_{z_{ICR}}(s)}{\delta_{CC}(s)} = \frac{K_{n_z}\left(s + 1/\tau_{n_{z_1}}\right)\left(s + 1/\tau_{n_{z_2}}\right)\left(s + 1/\tau_{n_{z_3}}\right)\left(s + 1/\tau_{n_{z_4}}\right)}{\left[s^2 + 2\zeta_p\omega_p s + \omega_p^2\right]\left[s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2\right]}$$

While the transfer functions for pitch attitude and pitch rate above may be familiar, those for flight path angle and normal acceleration at the pitch Instantaneous Center of Rotation (ICR) may need a little explanation.

For flying qualities analyses flight path angle is usually considered at two locations, the center of gravity and the pilot station. The center of gravity represents "where the aircraft is going", which is what the pilot is trying to control, while the pilot station represents "what the pilot sees". During maneuvering flight the two are not the same. Also of interest during landing tasks may be flight path at the main gear, but this is usually close to that at the center of gravity. The transfer function given above is for flight path at the center of gravity. The lowest frequency zero $1/\tau_{\gamma_1}$ is below phugoid frequencies and determines whether the aircraft is on the front or back side of the drag curve. The other two zeros are of similar frequency to one another, but in opposite halves of the 's' plane. Their frequencies are above that of the short period. Their 's' plane location determines the degree of non-minimum phase in the flight path response due to the pitch ICR. For a conventional aft tail configuration, at the pilot station these two zeros combine to form a complex pair that provide an initial lead in the flight path response at this location. Their frequency is slightly faster than the short period mode.

Normal acceleration is a scaled derivative of flight path, and so shares similar zero locations. As with flight path, normal acceleration can be measured at any location on the aircraft. One common location (especially for Low Order Equivalent Systems analyses) is the pitch ICR. The ICR is the point on the aircraft that exhibits no initial normal acceleration due to pitching. For a conventional aircraft, it is located between the center of gravity and the pilot station, closer to the former. Thus, normal acceleration measured at the ICR contains no contributions from pitching activity. For conventional transports, at the ICR the two lowest frequency zeros are below 0.1 rad/sec and the highest frequency zero is well above 10 rad/sec. Although outside the range of 0.1 to 10 rad/sec, the residuals from these three zeros can also influence the response within the frequency range of interest, and so cannot be entirely neglected. The remaining zero, $1/\tau_{n_{z_3}}$, is usually between 0.1 and 10 rad/sec and so must be considered.

THE DATABASE

The database developed in the Boeing experiment totals 25 conventional response-type configurations, that were used for the criteria development reported here. The aircraft model used for the evaluations represented a large advanced technology active control transport aircraft in the one million pound category. The configurations were designed using a Low Order Equivalent Systems approach and included variations in pitch acceleration sensitivity (n/α), equivalent short period frequency (ω_{sp}') by the way of a selected CAP level, and equivalent time delay (T_θ). Additionally, two pitch sensitivities were evaluated. All seventeen dynamic variation

configurations were evaluated with a pitch sensitivity of 0.3 deg/sec^2/lb. Additionally, eight of these were evaluated at an increased pitch sensitivity of 0.45 deg/sec^2/lb. Details of the configurations and experiment implementation can be found in Field and Rossitto[7]. This paper only includes the seventeen lower pitch sensitivity configurations, although reference is made to the higher sensitivity configurations.

The experiment used the Calspan operated USAF Total In-Flight Simulator (TIFS). Five experimental test pilots participated in the evaluations, which consisted of a lateral offset approach corrected at around 200 feet AGL and flown to a simulated eye-height landing. Pilot comments were recorded throughout the evaluations for subsequent analysis. Task performance metrics and pilot awarded Cooper-Harper and PIO ratings were recorded.

THE CRITERIA

Four established flying qualities criteria were applied to the Boeing database to appraise their performance as predictors of the flying qualities of transport aircraft in the approach and landing task. All these criteria were developed for fighter aircraft. Some of the criteria, or elements of the criteria, were developed for up-and-away tracking tasks and may not be applicable to the active control transport aircraft landing task.

Flying qualities criteria vary in the way that they consider the contributions of the feel system dynamics. Some criteria include the feel system in their analyses, others exclude the feel system, and others can be applied either way (although different criteria boundaries apply). The preferred approach followed here is to exclude the feel system, unless the criterion specifically calls for its inclusion, in which case that will be noted.

It is recognized that the feel system is an integral element of any aircraft's flight control system. However, there are many issues with feel systems that can introduce problems into an aircraft's flying qualities. The cause of these problems can be hidden when including the feel system in the flying qualities analysis, hence the decision to exclude the feel system from the analyses. Separate criteria should then be applied to the feel system, ensuring that it is tuned to the aircraft's dynamics and will introduce no deficiencies. Currently, there is a lack of such requirements.

Control Anticipation Parameter (CAP) through Low Order Equivalent Systems (LOES)

CAP is defined as the ratio of the initial pitch acceleration divided by the steady state normal acceleration. It is therefore a measure of the predictability of the long term response from the initial response that the pilot observes. Consistant with most criteria, it was based on the short period approximation, permitting the following approximations to be made:

$$\text{CAP} \equiv \frac{\ddot{\theta}_0}{n_{z_{ss}}} \approx \frac{\omega_{sp}^2}{n/\alpha} \approx \frac{\omega_{sp}^2}{\dfrac{V}{g}1/\tau_{\theta_2}} \qquad \textbf{(Eq. 1)}$$

As discussed above, the CAP requirements formed the basis for specifying the short period frequency requirements of the US military flying qualities specifications[3] for unaugmented aircraft. While CAP does not explicitly define either the pitch attitude or flight path responses, it does so implicitly as a measure of the consonance between the pitch attitude and flight path responses. As aircraft flight control systems became more complex the bare airframe short period dynamics no longer described the total aircraft's dynamic response. As a result CAP, which was a measure of the bare airframe response, was no longer able to capture the flying qualities of the augmented aircraft that were apparent to the pilot.

However, the concept behind CAP remained valid. Regardless of how the aircraft response was produced, the precision and predictability of the aircraft's pitch attitude and flight path responses would still dictate the pilot's perception of the aircraft's flying qualities. CAP simply specified the desired characteristics of the pitch attitude and flight path responses, not how they are generated. It was therefore postulated that the requirements that previously were developed for an unaugmented aircraft should also apply to the "apparent" response of an augmented aircraft that the pilot observed. Thus, if a means could be derived to determine this "apparent" response, then the CAP criterion, and the military specification, could be retained.

The method that gained greatest acceptance was the frequency domain Low Order Equivalent Systems (LOES) approach. This method involves a frequency-domain matching of a Low Order Equivalent System to the aircraft model, that includes all the modes of the bare airframe plus all elements of the flight control system. Appropriate choice of the form of the LOES is important. The LOES must match the response-type of the augmented aircraft. Additionally, the LOES must properly represent all the dynamics in the frequency range over which the match is performed. For piloted control the frequency range of interest is from 0.1 to 10 rad/sec.

MIL-F-8785C[8] was the first specification to require the application of an "equivalent" model, although did not provide detailed guidance for the method. The replacement, MIL-STD-1797A[9], requires a simultaneous match to pitch rate and normal acceleration (at the ICR) responses for both control force and position inputs, over a frequency range of 0.1 to 10 rad/sec. The numerator for the normal acceleration response is specified to be only a single first-order lag, $1/\tau_{h_1}$.

Although the full-order model is specified in MIL-STD-1797A, for fighters it is common neglect the short period mode and use the two-degree-of-freedom forms for these responses. While this is sufficient for fighters, for active control transport aircraft it is necessary to include the phugoid mode, and so the full order aircraft model is used. Additionally, as discussed above, for the transport aircraft angle-of-attack response-type configurations of this paper it has been found that the fourth order normal acceleration at ICR transfer function is most appropriate. While $1/\tau_{n_{z_1}}$ and $1/\tau_{n_{z_2}}$ are usually below the fit range (below 0.1 rad/sec) and $1/\tau_{n_{z_4}}$ is usually well above the fit range (above 10 rad/sec), $1/\tau_{n_{z_3}}$ is usually within the fit range.

Thus, for active control transport aircraft the following low order forms are used:

$$\frac{q(s)}{\delta_{CC}(s)} = \frac{K_q s\left(s + 1/\tau_{\theta_1}\right)\left(s + 1/\tau_{\theta_2}\right)e^{-T_\theta s}}{\left[s^2 + 2\zeta_p'\omega_p's + \omega_p'^2\right]\left[s^2 + 2\zeta_{sp}'\omega_{sp}'s + \omega_{sp}'^2\right]}$$

$$\frac{n_{z_{ICR}}(s)}{\delta_{CC}(s)} = \frac{K_{n_z}\left(s + 1/\tau_{n_{z_1}}\right)\left(s + 1/\tau_{n_{z_2}}\right)\left(s + 1/\tau_{n_{z_3}}\right)\left(s + 1/\tau_{n_{z_4}}\right)e^{-T_{n_z} s}}{\left[s^2 + 2\zeta_p'\omega_p's + \omega_p'^2\right]\left[s^2 + 2\zeta_{sp}'\omega_{sp}'s + \omega_{sp}'^2\right]}$$

In addition to the dynamics discussed earlier, these forms include a time delay. This time delay element is included in the matching algorithm to account for the combined phase lags in the high order aircraft that are not accounted for by the equivalent roots of the transfer functions. A simultaneous fit is performed between the pitch rate and normal acceleration responses to ensure correct definition of the high frequency zero in the pitch rate transfer function, $1/\tau_{\theta_2}$.

The equivalent parameters ω_{sp}' and $1/\tau_{\theta_2}$ obtained from this low-order matching are then applied to the CAP criterion. The equivalent time delay, T_θ, which approximates the phase loss due to high-frequency dynamics, is compared against the Level boundaries for acceptable time delay. Separate requirements also exist for equivalent short period damping, ζ_{sp}'.

Bandwidth Criteria

A measure of the pitch axis handling qualities of an aircraft is its stability margins when operated in a closed-loop compensatory tracking task. The maximum frequency at which such closed-loop tracking can take place without threatening stability is defined as the pitch attitude Bandwidth (ω_{BW_θ}). It follows that aircraft capable of operating at a large enough value of bandwidth will have superior performance when regulating against disturbances. No assumption of pilot dynamics is necessary in applying the requirement, since any such assumption would simply shift the boundaries. Additionally, the criterion is identically applicable to all response-types and to both the reduced and full order aircraft models. No assumption of the aircraft order is necessary because the criterion uses the actual frequency response. A detailed description of the calculation of the Bandwidth criterion parameters can be found in Mitchell et al[10].

The flight path Bandwidth (ω_{BW_γ}) criterion requirement is an auxiliary requirement intended to insure that the consonance between flight path and pitch attitude is consistent with the pilot's expectations. When pitch attitude is the primary short-term controller of flight path, excessive abrupt or sluggish flight path response to attitude changes will cause problems for precise control and possibly lead to pilot induced oscillations.

The phase delay parameter (τ_{p_θ}) is a measure of the shape of the phase response at frequencies above the 180° phase lag frequency. Phase delay is similar to the equivalent time delay

from the LOES fit, and is a correlating parameter with PIO tendencies.

The original limits of the Bandwidth criteria, developed for fighters, were considered overly stringent. A major reduction in the limits was made when the pitch rate overshoot / dropback portion of Gibson's criteria was incorporated as an auxiliary requirement. Experience proved the time domain overshoot / dropback criteria difficult to verify in flight, so a frequency domain version of pitch rate overshoot replaced the time domain requirement. The current criteria consist of limits on pitch attitude Bandwidth frequency and phase delay, flight path Bandwidth, and pitch rate overshoot. The flying qualities Levels for these criteria are now in close agreement with the limits on CAP and equivalent time delay given in this paper.

Gibson Criteria

Gibson developed a series of flying qualities design guidelines for fighter aircraft that have become labeled the "Gibson Criteria". Gibson, himself, states that they are "less a set of precise criteria to be followed in design than observations of a general connection between physical measures of response characteristics and pilot opinion"[11]. Further, he states that the purpose of his criteria is "to provide control law design guidance, on the assumption that the FCS is going to be used to optimise handling rather than just for some augmentation, and they were never intended for general purpose handling analysis".

Consistent with most criteria developed for fighter aircraft, Gibson considers only the reduced order aircraft model. As discussed above, this approach may not be appropriate for transport aircraft. Also, Gibson excludes the feel system dynamics from his analyses, considering that these can be designed to be well behaved and non-intrusive.

Gibson's early work involved a series of frequency response templates, that were drawn around the best rated configurations of the Neal-Smith[12] and LAHOS[13] experiments. These boundaries were plotted on the Nichols chart and provided insight into both the gain and phase characteristics of the pitch attitude response. The boundaries were intended to ensure a "desirable" response shape in the range of the crossover frequency, approximately that of an unaugmented aircraft's short period. The templates were aimed at ensuring desirable *flying qualities*, ending at a phase of around -160°, short of the "*PIO region*".

Due to the problems inherent in all criteria based on response templates, Gibson dropped the frequency response boundaries as a way of defining the short-term like dynamics, moving instead to the time domain.

In the time domain Gibson developed two criteria for the specification of the short-term dynamics. His requirements on pitch attitude dropback (to a boxcar control input) effectively determined the flight path responsiveness, for the given $1/\tau_{\theta_2}$. Initially Gibson published boundaries defining desirable areas of dropback as a function of pitch rate overshoot. More recently he has dropped the boundaries, relaxing the guideline to specify the ideal of zero dropback

for tight pitch tracking tasks. However, zero pitch attitude dropback can result in a sluggish flight path response for tasks that require flight path changes. Gibson indicates that a wide range of dropback may be acceptable for such tasks depending on flight condition, for example the approach and landing in which dropback greater than 1.0 may appear excessively abrupt.

His second time domain criterion places limits on the flight path time delay, t_γ. This is a measure of the delay in the development of the response of the flight path to a control input. For the reduced order approximation of a conventional aircraft it is purely a function of short period frequency and damping, as given in Equation 2. Combining Equation 1 and Equation 2, t_γ can be written in terms of CAP, as given in Equation 3. Gibson suggests limits for acceptable values of flight path time delay of 1 second for up and away tasks, and 1.5 seconds for approach and landing tasks.

$$t_\gamma = \frac{2\zeta_{sp}}{\omega_{sp}} \qquad \text{(Eq. 2)}$$

$$t_\gamma = \frac{2\zeta_{sp}}{\sqrt{CAP(n/\alpha)}} \qquad \text{(Eq. 3)}$$

Much of Gibson's work has been aimed at addressing the specific flying qualities phenomenon of PIO. Here, Gibson works in the frequency domain. Gibson considers the area around the phase of -180° in the pitch attitude to stick position frequency response. Phase rate is defined as the slope of the phase response in the frequency range between the phase at -180° and twice that frequency. Except for a scaling factor, Gibson's phase rate is identical to Phase Delay of the Bandwidth Criterion. However, Gibson plots phase rate against the frequency at -180° phase, compared to -135° for the Bandwidth criterion. Hence, Gibson's phase rate requirement is only concerned with the response at frequencies beyond the -180° frequency, the PIO region. In comparison, the Bandwidth Criterion also considers the shape of the response between -135° and -180°, the flying qualities region. As long as the frequency response between -135° and -180° is well behaved, both requirements should yield virtually identical results.

Smith-Geddes Criteria

Smith and Geddes have developed criteria for both flying qualities and PIO, all based in the frequency domain. Application of the criteria is referenced to force inputs, and so must include the feel system dynamics for position command systems. The results presented in this paper include the feel system dynamics. They define two requirements addressing flying qualities. The first is a requirement on the slope of the pitch attitude to stick force gain response in the crossover region, between 1.0 and 6.0 rad/sec. They define that for Level 1 flying qualities this slope must be less than -2 dB/Octave. While this is a requirement for Level 1 flying qualities, it does not guarantee Level 1 flying qualities. This requirement is designed to ensure a K/s like response in the crossover region, which is desirable for closed loop attitude

tracking tasks. However, it also allows for K/s^2 and greater slopes, which it is known can be undesirable.

The attitude phase criterion places limits on the pitch attitude phase angle at the criterion frequency, ω_c, which is calculated from the gain response slope in the crossover region:

$$\omega_c = 0.24s + 6 \quad \text{(rad/sec)} \qquad \textbf{(Eq. 4)}$$

where s is the slope in the crossover region. Level 1 and Level 2 limits are defined as -123° and -165°, respectively.

Addressing the phenomenon of PIO, Smith and Geddes define three types of PIO:

Type I   Initiated by resonance of pilot-in-the-loop control of attitude and pilot switches from attitude control to acceleration control;

Type II   Initiated by resonant open loop dynamics; and

Type III Initiated by resonance of the pilot-in-the-loop control of attitude, regardless of acceleration dynamics, and with no mode switching by the pilot.

Type III (attitude-dominant) PIO is predicted if the phase angle at the criterion frequency is more negative than -180°. Type II PIO is predicted whenever any open-loop mode has a damping ratio less than 0.2. To predict Type I (acceleration-dominant) PIO an additional parameter is defined, the Normal Acceleration Phase Parameter:

$$\Phi(j\omega_c) = \angle \frac{n_{z_{ps}}}{F_{cc}}(j\omega_c) - 14.3\omega_c \quad \textbf{(Eq. 5)}$$

Type I PIO is predicted when the Normal Acceleration Phase Parameter is less than -180°, provided that the attitude phase is less than -165°.

RESULTS

For clarity, the results presented only include the Boeing configurations. However, in determining the new boundaries for the CAP and Bandwidth criteria the other Calspan configurations were included. For the Gibson and Smith-Geddes criteria only the Boeing configurations have yet been analyzed. Further analysis is required before changes to these criteria can be recommended.
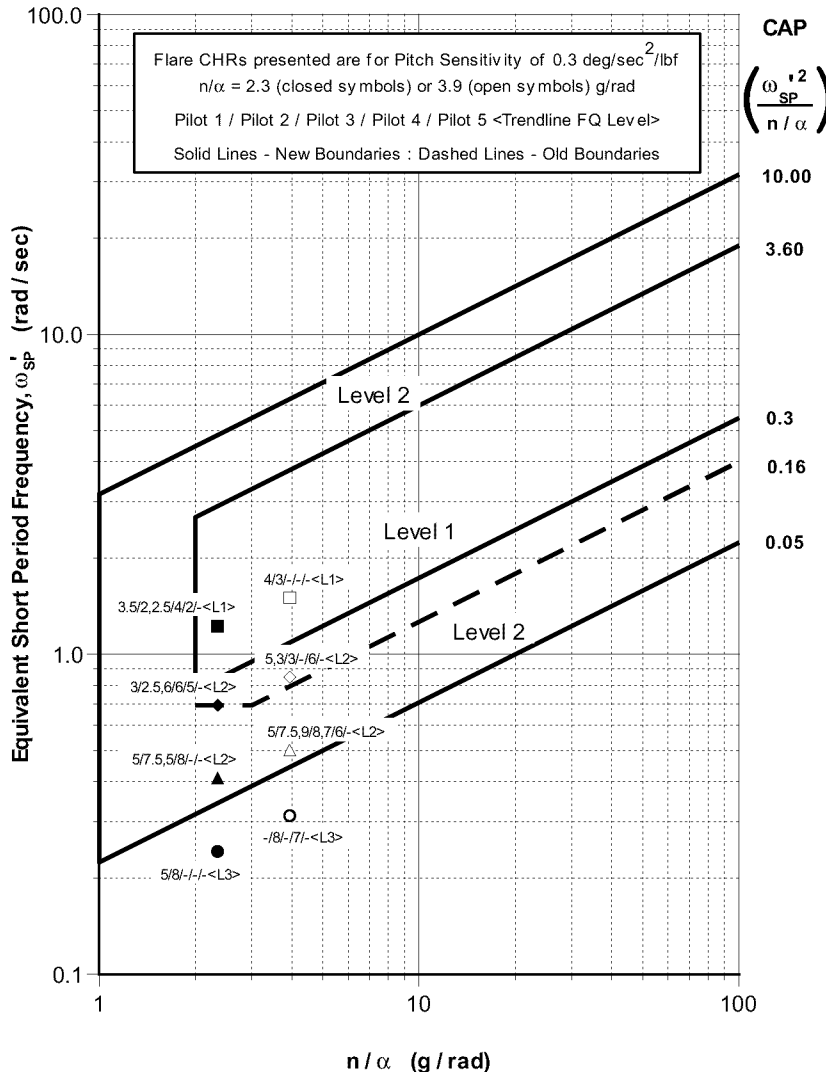
For each configuration of the Boeing TIFS experiment a "Trendline flying qualities level" was assigned[7]. This was determined from the individual Cooper-Harper ratings awarded, the median Cooper-Harper rating, the pilot comments and achieved performance. Additionally, model following and atmospheric condition issues were considered when weighting the relative contribution of the individual ratings. In the following sections only the trendline flying qualities level is annotated next to each configuration in the Figures, except in Figures 1 and 2 in which all the flare Cooper-Harper ratings are presented. Similarly, each configuration was assigned an overall PIO tendency and PIO severity classification. These classifications were based on pilot comments and, where available, PIO ratings.

In the criteria result Figures the configurations are identified by their LOES parameters. All configurations have an equivalent short period damping ratio of 0.7. Closed symbols represent configurations with an n/α of 2.3 g/rad, while open symbols represent an n/α of 3.9 g/rad. The shape of the symbol defines the value of CAP (see Figures 1 and 2). Equivalent time delay is annotated next to each configuration, except in Figures 1 and 2.

Figure 1. CAP Short Period Frequency Results

Control Anticipation Parameter (CAP) through Low Order Equivalent Systems (LOES)

In Figure 1 the configurations with no added time delay (minimum time delay of 0.125 seconds) are plotted against the CAP criterion requirements taken from MIL-STD-1797A, on the form of the requirement from MIL-F-8785C. Clearly, the existing Level 2 lower boundary is supported by these data. The published Level 1 lower boundary (dashed line) appears to be too relaxed. The modified lower Level 1 boundary, consistent with the data, has been established at a CAP of 0.3.

In addition to the requirements on CAP, MIL-STD-1797A also defines limits on acceptable levels of time delay. These separate requirements have been combined schematically in Figure 2 (dashed lines), together with the results of the Boeing experiment. Clearly the results reflect a multi-parametric correlation between CAP and time delay. This multi-parametric correlation is not reflected in the published requirements (dashed lines), but is reflected in the new boundaries developed from the database. The new boundaries stop as shown since there is no data to determine their extensions. The upper CAP limits of 3.6 for Level 1 and 10 for Level 2 are shown for equivalent time delays between 0 and 0.1 sec, taken directly from the limits of Figure 1.

Figure 2. CAP / Time Delay Results

Bandwidth Criteria

The results from the Boeing experiment are applied to the pitch attitude Bandwidth / phase delay criterion in Figure 3. The old boundaries (solid line, Level 1 and dashed line, Level 2) are based on those proposed by Mitchell et al.[10], and have been adjusted to reflect the removal of the feel system in the application of the criterion. Clearly the data support the criterion, however, support relaxing the Level 2 boundary to the solid line shown. As discussed in Field and Rossitto[7], the reason for this dramatic relaxation of the Level 2 boundary is pitch control / response sensitivity.

The original boundaries were developed from the configurations of the Calspan experiments[5,6] which employed a pitch sensitivity of 0.42 $deg/sec^2/lb$. These boundaries correlated with the seven increased sensitivity configurations of the Boeing experiment, which employed a pitch sensitivity of 0.45 $deg/sec^2/lb$. Clearly the effects of control / response sensitivity on flying qualities must be considered, although sufficient requirements are currently lacking.

Consistent with the modifications to the boundaries for the pitch attitude Bandwidth / phase delay requirements, the data

also support the relaxation of the Level 2 boundary for the pitch attitude / flight path Bandwidth requirements as shown in Figure 4. Insufficient data exist to determine whether changes to the slopes of these boundaries may be appropriate. It should be noted that two configurations rated Level 3 plot in the Level 2 region. This is because this requirement is auxiliary to that for pitch attitude Bandwidth / phase delay. These configurations correctly plot in the Level 3 region of the pitch attitude Bandwidth / phase delay requirement. Hence, the two requirements must be applied together.

The pitch attitude Bandwidth / phase delay requirements have been further developed as a PIO criterion[14]. The Boeing configurations are plotted in the somewhat busy Figure 5, annotated with their observed PIO severity. It should be noted that the pitch rate overshoot ($\Delta G(q)$) requirements were met for all configurations. A few configurations are noteworthy. Two configurations with low bandwidths plot in the Level 3 region with a prediction of "Severe" PIO, and yet were observed to only exhibit Moderate PIO. These mismatches are not of concern, since the configurations
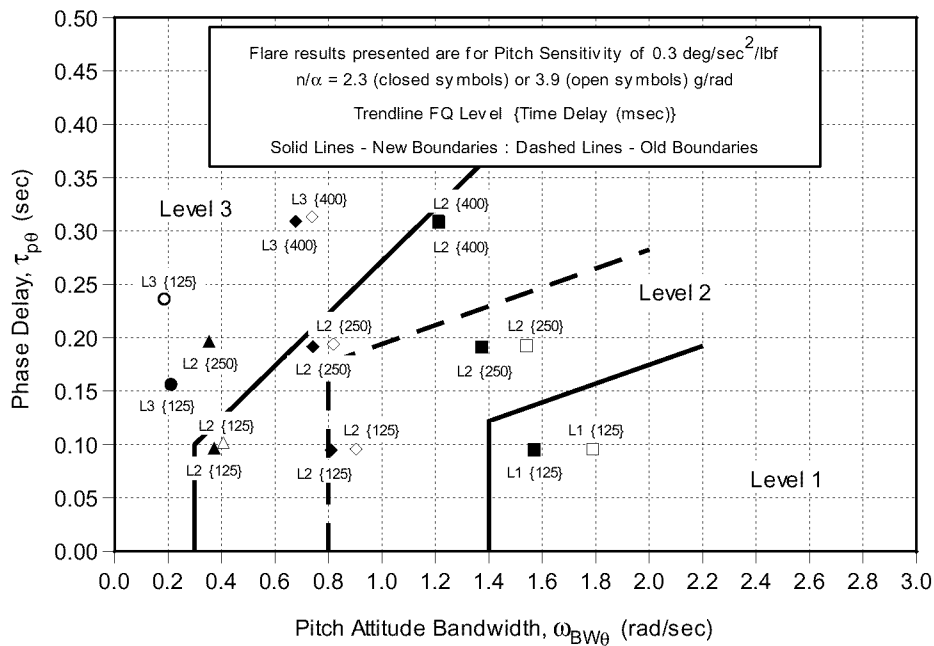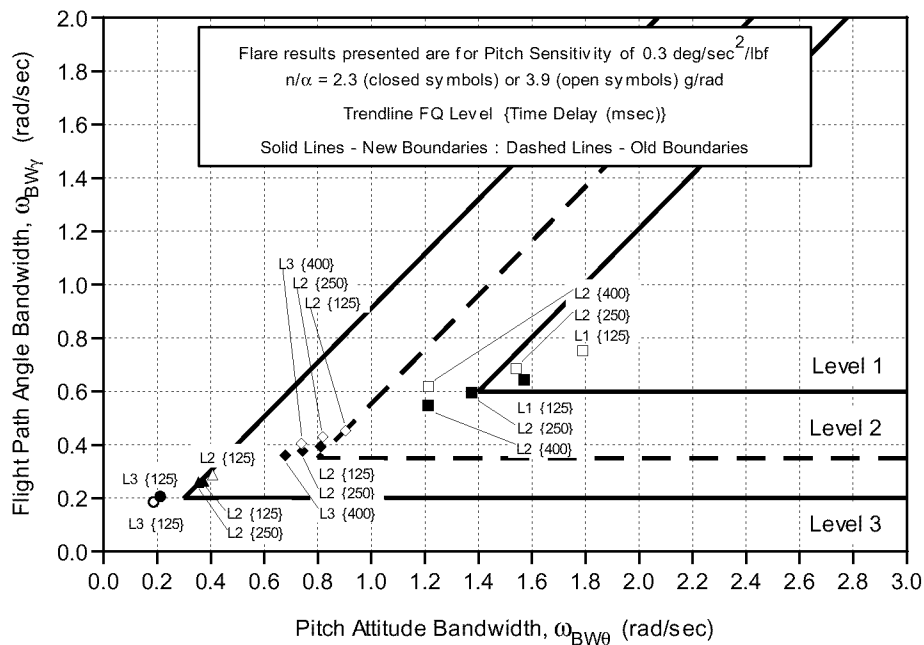
Figure 3. Pitch Attitude Bandwidth Results

Figure 4. Flight Path Bandwidth Results

Hence, for the lower pitch sensitivity configurations of this database it is recommended that this area be re-classified as predicting Moderate PIO. Otherwise, the Boeing database concurs with the Bandwidth PIO criterion.

Gibson Criteria

The results from Gibson's phase rate analyses are presented in Figure 6 and Figure 7. In the former, the configurations are annotated with their observed flying qualities, while in the latter they are annotated with their observed PIO severity. The distribution of the configurations in Figure 6 is almost identical to that for pitch attitude Bandwidth / phase delay in Figure 3. While phase rate and phase delay are identical (except for a scaling factor), differences in horizontal distribution between the criteria is possible if the responses between -135° and -180° are unconventional. The similarity between the two figures reflects the very conventional nature of the Boeing experiment configurations. Although Gibson's Level 1 boundary is close to correlating with the data, the Level 2 boundary is clearly too restrictive.

The phase rate criterion is not intended as a predictor of flying qualities, but of PIO severity. In Figure 7 observed PIO severity is annotated next to each configuration. Again, the distribution of the configurations is almost identical to that in Figure 5 for the Bandwidth PIO criterion. It is observed that the published boundaries are far too restrictive, although they do follow the form of the data. Further analysis, including the addition of the Calspan configurations, is required before new boundaries could be determined.

Due to the insufficient separation between the short period and phugoid modes of the configurations, determination of the time domain parameters from the full order aircraft model was not successful, especially for the slower configurations. As a result the reduced order model was used, developed from the parameters from the equivalent systems analyses.

exhibited poor flying qualities and in time might well be expected to exhibit more severe PIO, if pilot gain were increased. Of more concern is the over-prediction of PIO severity in the Level 2 flying qualities region. For all these configurations the flight path Bandwidth was less than 0.6 rad/sec, resulting in a prediction of Level 3 flying qualities with "Severe" PIO. However, no worse than Moderate PIO was observed for any of these configurations. Once again, the classifications of the *criterion* were based on the results of the Calspan experiments[5,6] that used the increased pitch sensitivity of 0.42 deg/sec^2/lb. As discussed in Mitchell and Field[14], the combined effect of high pitch sensitivity with time delay (high phase delay) is increased PIO tendencies.

The results of the dropback analyses are presented in Figure 8. Correlation of the results with the observed flying qualities is poor. Never the less, several interesting observations can be made. First, the addition of time delay moves the configuration to the left. In some cases this could be interpreted as an improvement in flying qualities. Second, the difference between the two values of n/α (open versus closed symbol) is far more evident than for the CAP or Bandwidth criteria (compare Figure 8 with Figures 2 and 3). As stated earlier, the ideal of zero dropback is specified for tight pitch tracking tasks. It is not clear what are the dropback requirements for the landing task, if applicable at all.

The results of the flight path time delay analyses are presented in Figure 9. The boundaries of Figure 9 are an exact transformation of those for CAP from Figure 1, transformed via Equation 3, for a short period damping ratio of 0.7. However, whereas the results for CAP in Figure 1 are only applicable to the short period dynamics without added time delay, all configurations are plotted on Figure 9, since the addition of time delay only increases the flight path time delay (moves the configuration up in Figure 9). And this produces an inconsistency in the results. Configurations with shorter flight path time delays are rated worse than those with longer flight path time delays, due to

Figure 5. Bandwidth PIO Criterion Results

Figure 6. Phase Rate Results versus Flying Qualities

the added equivalent time delay. Clearly the equivalent short period dynamics are more dominant in determining t_γ than is the equivalent time delay.

Gibson suggests upper limits for t_γ of 1.0 sec for up and away tasks and 1.5 sec for landing. A horizontal line has been drawn across Figure 9 at 1.5 sec, representing the upper limit for landing. Clearly, the two configurations rated Level 1 fall below this limit, correlating with Gibson's requirement. However, three configurations rated Level 2 also fall below the 1.5 sec limit line. It is interesting to note that the results appear to be dependent upon n/α, that is correlation of the results follow the diagonal boundaries converted from CAP. Since n/α generally increases with speed, it is fair to assume
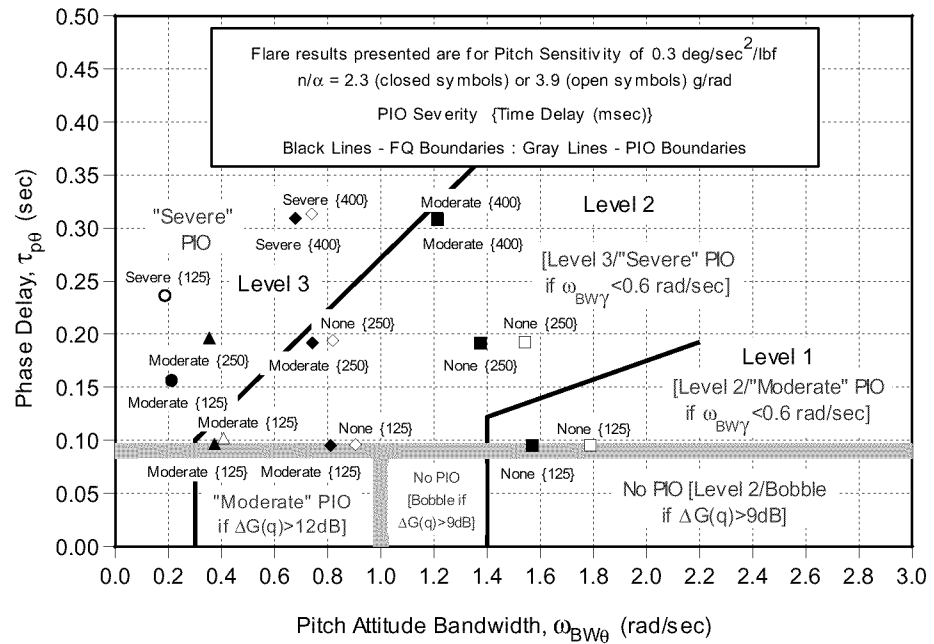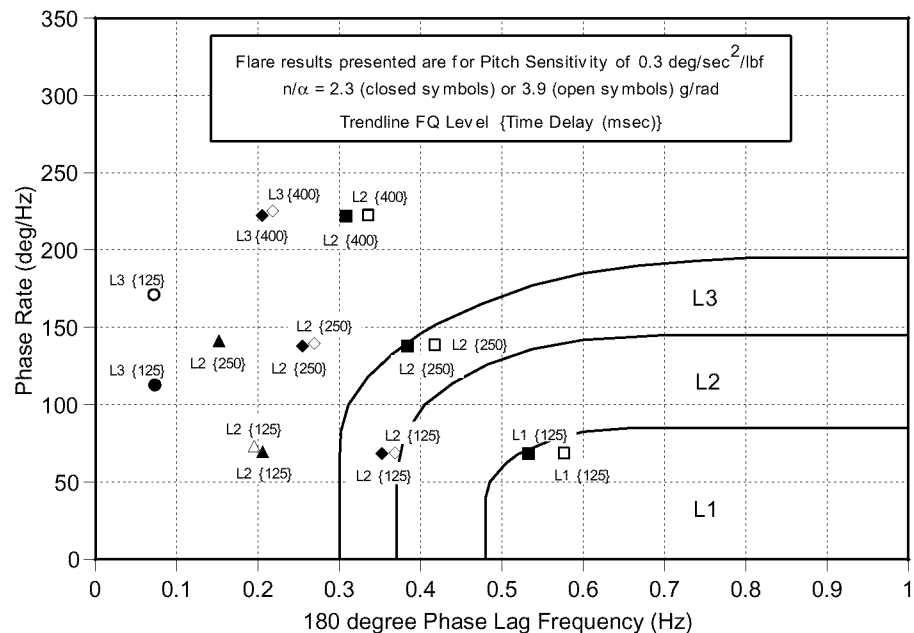
that for up and away tasks n/α will be greater than for landing. Thus Gibson's lower limit on t_γ for up and away tasks is reflected by the diagonal boundaries converted from CAP.

In summary, for the conventional configurations considered, the form of Gibson's phase rate requirements correlate with the Boeing results, although the boundaries appear over-restrictive. In the time domain, problems were encountered due to the insufficient separation between the short period and phugoid modes, a feature of transport aircraft. Application of the criteria to the reduced order approximations provides some insight, but correlation with the observed flying qualities appears poor. Some of the
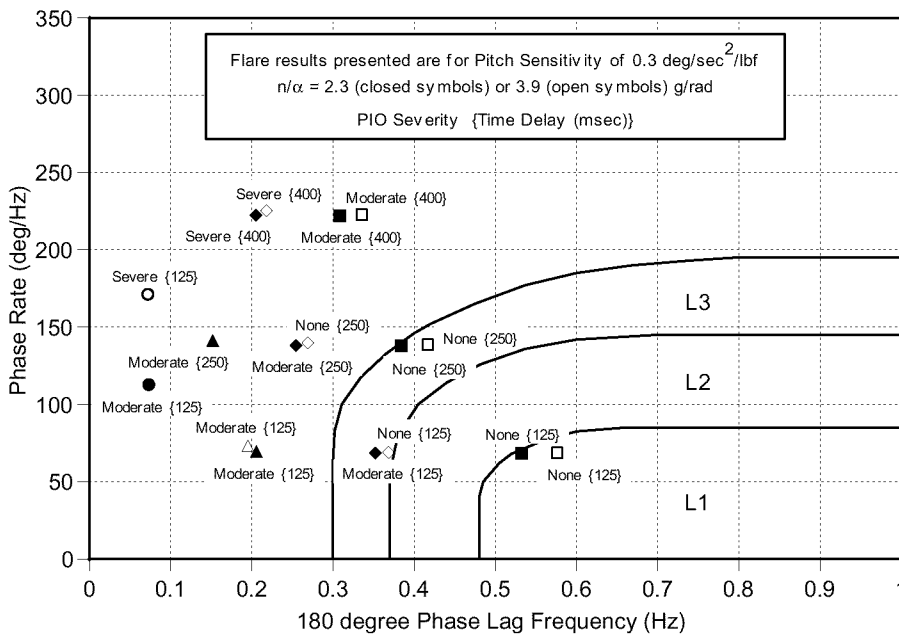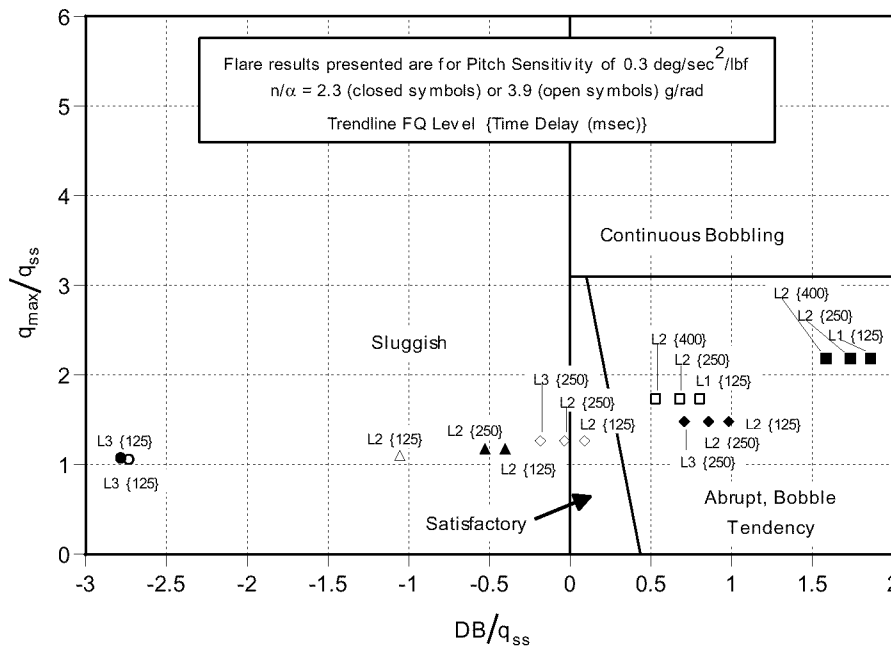
Figure 7. Phase Rate Results versus PIO Severity

Flare results presented are for Pitch Sensitivity of 0.3 deg/sec^2/lbf
n/α = 2.3 (closed symbols) or 3.9 (open symbols) g/rad
PIO Severity {Time Delay (msec)}

Figure 8. Dropback Results

Flare results presented are for Pitch Sensitivity of 0.3 deg/sec^2/lbf
n/α = 2.3 (closed symbols) or 3.9 (open symbols) g/rad
Trendline FQ Level {Time Delay (msec)}

were predicted Level 3. Clearly, this latter criterion does not correlate with the observed flying qualities.

The pitch attitude phase angle is plotted against the criterion frequency in Figure 10. Clearly, all configurations have a pitch attitude phase angle less than -180°, and so are predicted to exhibit Type III PIO. Due to these predictions, it is not necessary to calculate the normal acceleration phase parameter. It can be seen in Figure 10 that of the 17 configurations, PIO was observed with only eight, three exhibited a tendency to PIO while six exhibited no PIO tendencies. Clearly the predicted PIO tendencies do not correlate with those observed.

CORRELATION OF THE CRITERIA

While the various criteria appraised in this paper all address pitch axis flying qualities, they all define different parameters that they correlate with observed flying qualities. As has been shown in this paper several of these parameters are similar. Others are unique to a specific criterion. Low Order Equivalent Systems defines equivalent modal parameters from the high order aircraft frequency response, thus preserving classical modal criteria such as CAP. The other three criteria, in the frequency domain, all consider the overall aircraft frequency response, irrespective of order.

With the adoption of the multi-parametric boundaries for the CAP / time delay requirement, the form of this requirement and the pitch attitude Bandwidth requirement are now similar. However, the two requirements are not identical. The CAP / time delay requirement includes a measure of the consonance between the pitch attitude and flight path responses, and has a separate requirement for equivalent short period damping. In comparison, pitch attitude Bandwidth includes consideration of the short period damping, and has a separate requirement for the consonance between the pitch attitude and flight path responses. Therefore, results from these two criteria may differ for aircraft with damping ratios distant from 0.7. Additionally, two configurations with the same CAP but different values of $1/\tau_{\theta_2}$ can have appreciably different Bandwidths.

problems encountered are due to the application to Level 2 and Level 3 configurations. As Gibson states, the purpose of his criteria are to optimise handling, they were never intended for general purpose handling analysis.

Smith-Geddes

The results of the Smith-Geddes slope criterion analyses determined all configurations to have a slope more negative than -2 dB/Octave. Thus, all configurations passed this requirement, which is necessary, but not sufficient for Level 1 flying qualities. These results properly correlate with the two Level 1 configurations. The attitude phase criterion analyses determined all configurations to have a pitch attitude phase angle at the criterion frequency of less than -165°, and so all

Gibson's phase rate requirement is of similar form to the pitch attitude Bandwidth requirement, both giving almost identical results, unless the phase response between -135° and -180° is unconventional. Indeed, phase rate and phase delay are identical to one another, except for a scaling factor. They are also similar to equivalent time delay.

Gibson's flight path time delay parameter maps well with the CAP criterion, for the minimum time delay configurations. With the addition of time delay to the configurations, correlation was less clear. The effect of changes in $1/\tau_{\theta_2}$ on t_γ were shown, exposing a correlation between n/α and observed trends in preferences for t_γ.

The Smith-Geddes criteria do not appear to correlate with any of the other criteria, nor with the experiment results.

Despite these various correlations, each criterion is a measure of a combination of different parameters. As a result, it is not possible to achieve an exact correlation of the criteria boundaries for all parameters.

SUMMARY

The criteria that have been appraised in this paper are of use at different stages of the design and development of an aircraft. Together with appropriate pole placement algorithms, LOES and CAP are applicable at all stages, from initial design through to analysis of flight test data. The Bandwidth criteria are less suited to the design phases, but are easily applicable to the pre-flight evaluation and flight test stages. Gibson's time domain criteria are most suited to the initial design stage, while his phase rate criterion is well suited to pre-flight evaluation. The Gibson criteria are less suited to the analysis of flight test data. Due to the poor correlation of observed flying qualities with the Smith-Geddes criteria, it is not recommended that these criteria be applied to transport aircraft in the landing task until these criteria have been further appraised. The applicability of the different criteria is summarized in Table 1.

Table 1. Applicability of Different Criteria

	Initial Design	Detail Design	Pre-Flight Evaluation	Flight Test
CAP	✓	✓	✓	✓
Bandwidth			✓	✓
Gibson	✓		✓	
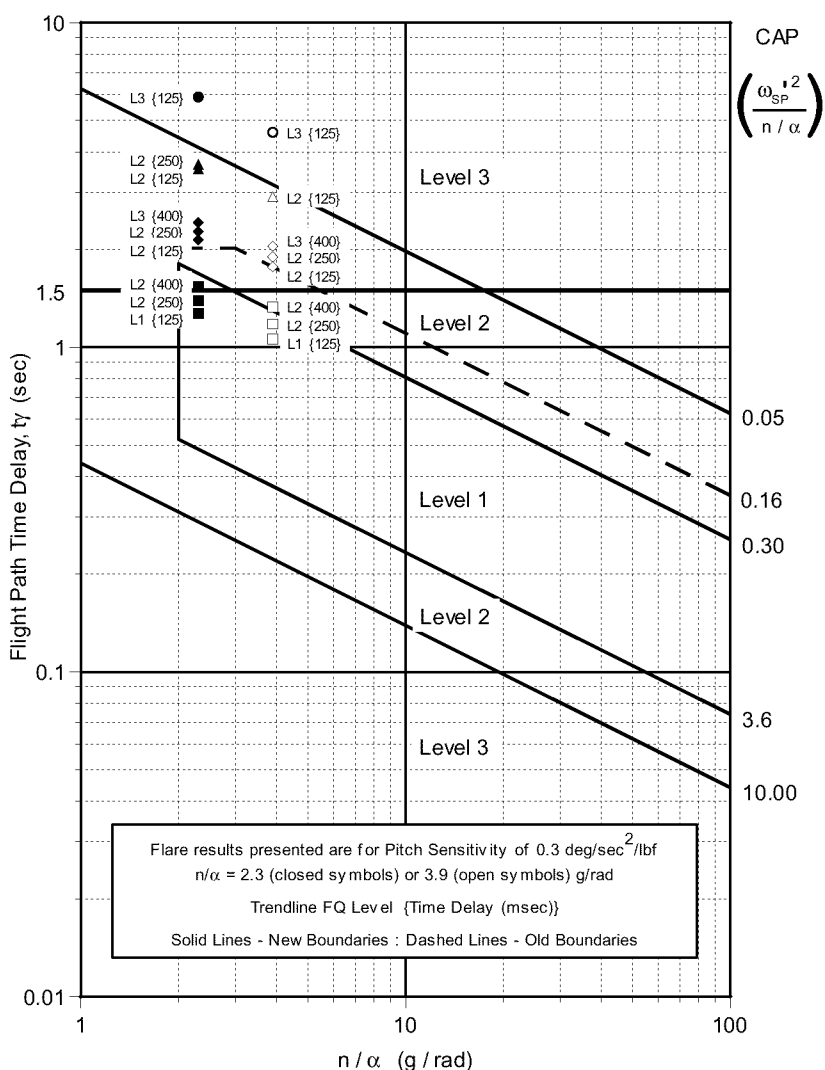
Figure 9. Flight Path Time Delay Results

CONCLUSIONS

Several flying qualities criteria were appraised against a validated flying qualities database for active control transport aircraft in the terminal flight phase.

The results support the raising of the lower Level 1 CAP criterion boundary to 0.3. A multi-parametric correlation between CAP and time delay was identified and reflected in a new criterion.

The Level 2 Bandwidth criterion boundaries were overly restrictive. New boundaries have been developed that fit the database. A modification to the Bandwidth PIO criterion classification was also recommended.

Gibson's phase rate analyses were found to produce almost identical results to Bandwidth. However, the criterion boundaries are overly restrictive, especially as a predictor of PIO severity. The Dropback criterion results did not correlate with the transport aircraft database. The results from the flight path time delay analyses were correlated with the CAP

criterion and exposed a correlation between desired values of t$_\gamma$ and n/α.

None of the Smith-Geddes criteria for flying qualities or PIO correlated with the database. They appear to be not applicable to active control transport aircraft.

ACKNOWLEDGEMENTS

The Gibson and Smith-Geddes criteria analyses reported in this paper were performed by Dharminder Chahal, of Delft University of Technology, while working as an intern at the Boeing Company, Long Beach. John Gibson reviewed the paper and provided welcome feedback. The contributions of both of these individuals are gratefully acknowledged.

Figure 10. Smith-Geddes PIO Results

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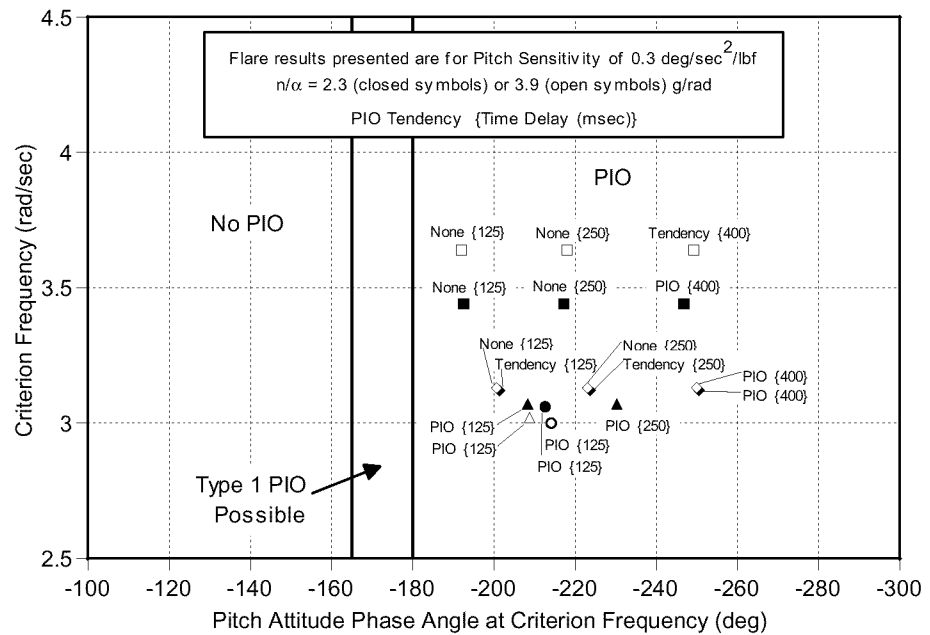
Paper #33

Q by Chris Fielding: Where do you go from here, in terms of getting your results accepted by the large aircraft Flight Control Community?

A. (Edmund Field): We are already using the new boundaries in Long Beach, will publish them all in an Air Force report soon, and hope to have the Air Force accept them for future use.

Q by David Moorhouse: The landing requirements lower CAP boundary is affected by required touchdown precision. What touchdown precision was required for the task or was it a conventional landing?

A. (Edmund Field): The task was a 300 feet lateral offset approach corrected at around 200 feet AGL. The pilot was then required to perform a precise landing with the following performance standards:

Desired performance: Landing box 20 feet wide by 500 feet long,
                        touchdown sink rate less than 4 feet/sec.
Adequate performance: Landing box 54 feet wide by 1500 feet long,
                        touchdown sink rate less than 7 feet/sec.

This seems to be about the standard landing task that is now being used for transport aircraft, and is sufficiently tight to expose handling deficiencies.

You bring up an interesting point by stating that the lower CAP boundary is defined by landing precision. The upper CAP boundaries (certainly for transports) seem to be defined by issues of structural modes and pilots' tolerances for "jerky" type rides. We agree that the lower Level 1 CAP boundary is dictated by the task performance, however we feel that the lower Level 2 boundary is not. We feel that it is dictated by the ability to land the aircraft at all. By the time the pilot has given up on desired performance, the boundary between making adequate performance or not is determined by his ability to control the aircraft at all. At this point the idea of performance standards is probably "out the window". Thus, we don't think that the lower Level 2 boundary is dictated by the definition of adequate performance, but more by the pilot's ability to land the aircraft at all, with a tolerable pilot workload. Interestingly, in our experiment we expected the Lower Level 2 boundary to be relaxed, in fact it stayed in the same place. It was the Level 1 boundary that was raised, perhaps reflecting the tighter performance standards that we used in our experiment.

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