Prediction and Occurrence of Pilot-Induced Oscillations in a Flight Test Aircraft

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Flight testing of a high-performance aircraft was conducted several years ago and again during the past two years. During the first flight tests, a pilot-induced oscillation was experienced in the pitch axis during the time between the landing flare and touchdown. During the more recent flight tests two pilot-induced oscillations were experienced in the pitch axis during up-and-away flight. One of these occurred while the pilot attempted to track a cockpit display. Math models of the aircraft were used with three handling qualities criteria to determine the predicted handling qualities of the aircraft. These predictions were compared with flight test results. The handling qualities criteria used were the equivalent systems, bandwidth, and R. Smith criteria. The handling qualities predicted by each of these criteria agreed well with flight test results. The R. Smith criteria were especially interesting because they predicted the likelihood of pilot-induced oscillation explicitly and correctly and also predicted the frequency of each pilot-induced oscillation correctly. The predictions and flight test results also highlighted the impact that pilot displays can have on handling qualities.

Nomenclature

g	= gravitational acceleration, ft/s^2
n/α	= normal acceleration per unit of angle of attack change, g/rad
$n_{z_{cr}}$	= normal acceleration at the instantaneous center of rotation, g
n_{z_p}	= normal acceleration at the pilot station, g
q	= pitch rate, rad/s
s	= Laplace operator
T_{θ_2}	= pitch attitude numerator time constant, s
x	= attitude cue presented to the pilot on a cockpit display
$\dot{x}$	= rate of change of cockpit display attitude cue
δ_c	= pitch controller displacement, deg
ζ_e	= equivalent longitudinal short-period damping ratio
θ	= pitch attitude, deg
τ_e	= equivalent time delay, s
τ_p	= bandwidth criteria equivalent time delay, $= -(\phi_{2\omega_{180}}+180)/(57.3\times 2\omega_{180})$, s
ϕ	= phase angle, deg
$\Phi(j\omega_c)$	= R. Smith phase parameter for normal acceleration response dynamics, $\measuredangle n_{z_p}/\delta_c(j\omega_c) - 14.3\,\omega_c$, deg
ω	= frequency, rad/s
ω_{BW}	= bandwidth frequency, the lower of ω_{BW_ϕ} and ω_{BW_g}, rad/s
ω_{BW_g}	= bandwidth frequency established by the requirement for 6 dB gain margin, rad/s
ω_{BW_ϕ}	= bandwidth frequency established by the requirement for 45 deg phase margin, rad/s
ω_c	= R. Smith criterion frequency, $= 6.27 - 0.27\, d/d\omega\, \lvert\theta/\delta_c(j\omega)\rvert$, where $d/d\omega\,\lvert\theta/\delta_c(j\omega)\rvert$ is determined by a first-order fit between 2.0 and 6.0 rad/s, rad/s
ω_e	= equivalent longitudinal short-period natural frequency, rad/s

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Introduction

THERE is insufficient feedback of handling qualities data from the flight test community to the handling qualities specification and design communities. Consequently, the data base which is available to the specification and design communities is much too small. This paper is intended to augment the handling qualities flight test data base, and exercise three of the handling qualities criteria which are available to the specification, design, and flight test communities. More papers of this nature would stimulate additional interest and activity in the important area of handling qualities prediction.

Discussion

Approach and landing flight tests were conducted on a high-performance aircraft several years ago. During those tests a pilot-induced oscillation (PIO) was experienced in the pitch axis during a landing flare. Numerous simulator studies were conducted after the approach and landing tests. Changes designed primarily to suppress large-amplitude PIOs and control system saturation were made to the flight control system. However, these changes were not expected to completely solve the handling qualities problems which were experienced. During subsequent flight tests conducted within the past two years two PIOs were encountered in up-and-away flight. One PIO occurred at an altitude of 5,500 m (18,000 ft) and a true airspeed of 186 m/s (610 ft/s). Another PIO occurred at an altitude of 5,500 m (18,000 ft) and a true airspeed of 185 m/s (606 ft/s). When the latter PIO occurred, the pilot was attempting to zero a flight-path error indication on a cockpit display before engaging an automatic flight control mode.

There have been very few pilot comments on handling qualities based on flight test experience with the airplane. However, there have been a number of pilot comments based on simulation experience. This experience has included fixed- and motion-base ground simulation as well as in-flight simulation.

Typical pilot comments from simulated landing maneuvers stressed the unpredictable response of the airplane near the ground, the lack of precise control over flight path and sink rate, and the tendency to over-control and balloon when the airplane got close to the ground. PIO tendencies were frequently noted by the pilots during the simulator tests. In contrast, the pilots commented favorably on the pitch attitude

Table 1 Transfer functions[a] for the landing approach model

$$\frac{q}{\delta_c}(s) = \frac{-2.33\times10^{7}(-31)(1.8)(1.5)(0.661)}{(41.52)(0.778,\ 42.21)(0.567,\ 35.59)(8.852)(5.806)(0.703,\ 1.385)(0.831)}$$

$$\frac{n_{z_p}}{\delta_c}(s) = \frac{1.41\times10^{5}(-31)(-5.405)(3.886)(1.5)(1.8)(-0.0156)}{(41.52)(0.778,\ 42.21)(0.567,\ 35.59)(8.852)(5.806)(0.703,\ 1.385)(0.831)(0)}$$

$$\frac{n_{z_{cr}}}{\delta_c}(s) = \frac{2.909\times10^{4}(-31)(-16.235)(6.272)(1.5)(1.8)(-0.0156)}{(41.52)(0.778,\ 42.21)(0.567,\ 35.59)(8.852)(5.806)(0.703,\ 1.385)(0.831)(0)}$$

Notation: Gain $= a$, $(s+a) = (a)$, $(s^2\text{-}2\zeta\omega s+\omega^2) = (\zeta,\omega)$.

[a]Transfer functions include Pade approximation of time delay.

Table 2 Transfer functions[a] for the up-and-away model

$$\frac{q}{\delta_c}(s) = \frac{-2.217\times10^{7}(-31)(0.588)(0.578)(1.5)}{(40.965)(0.776,\ 41.84)(0.574,\ 35.45)(11.913)(0.753,\ 2.289)(0.989,\ 0.608)}$$

$$\frac{n_{z_p}}{\delta_c}(s) = \frac{1.484\times10^{5}(-31)(-5.833)(4.885)(1.5)(0.588)(-0.000909)}{(40.965)(0.776,\ 41.84)(0.574,\ 35.45)(11.913)(0.753,\ 2.289)(0.989,\ 0.608)(0)}$$

$$\frac{n_{z_{cr}}}{\delta_c}(s) = \frac{-140.9(-31)(1589.69)(18.873)(1.5)(-0.0009088)(0.588)}{(40.965)(0.776,\ 41.84)(0.574,\ 35.45)(11.913)(0.753,\ 2.289)(0.989,\ 0.608)(0)}$$

Notation: Gain $= a$, $(s+a) = (a)$, $(s^2+2\zeta\omega s+\omega^2) = (\zeta,\omega)$

[a]Transfer functions include Pade approximation of time delay.

Table 3 Transfer functions[a] for the up-and-away model plus cockpit display

$$\frac{\dot{x}}{\delta_c}(s) = \frac{-1.330\times10^{7}(-31)(0.588)(0.578)(1.5)}{(40.965)(0.776,\ 41.84)(0.574,\ 35.45)(11.913)(0.753,\ 2.289)(0.989,\ 0.608)(2.0)}$$

$$\frac{n_{z_p}}{\delta_c}(s) = \frac{1.484\times10^{5}(-31)(-5.833)(4.885)(1.5)(0.588)(-0.000909)}{(40.965)(0.776,\ 41.84)(0.574,\ 35.45)(11.913)(0.753,\ 2.289)(0.989,\ 0.608)(0)}$$

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Notation: Gain $= a$, $(s+a) = (a)$, $(s^2+2\zeta\omega s+\omega^2) = (\zeta,\omega)$

[a]Transfer functions include Pade approximation of time delay.

response of the airplane during the approach to the landing, where rapid, predictable pitch attitude and flight-path response were not as important.

Extensive simulator experience resulted in a piloting technique which emphasized solving flight-path problems early in the approach so that corrections would not have to be made close to the runway. Considerable pilot training using this technique has minimized the number of problems which have been encountered in flight test. However, this technique has resulted in high pilot workload during flight test approaches and landings. One pilot's comment from flight test was that he had to work extremely hard to land the airplane, even though the landing was smooth and incident-free.

The aircraft that encountered the up-and-away PIO was slightly different from the aircraft that encountered the landing flare PIO. The aircraft that experienced the up-and-away PIOs was 39% heavier than the aircraft that experienced the landing flare PIO and had a 38% higher pitch inertia. The differences in aircraft response dynamics resulting from the differences in weight and inertia were fortuitous in the respect that they provided an opportunity to see how well three handling qualities criteria worked in evaluating different aircraft dynamics.

Aircraft math models were provided by the NASA Dryden Flight Research Facility at Edwards AFB. These models included the aerodynamics and the flight control system, including third-order actuator dynamics and a Pade approximation of flight control system transport time delay. These models reflected the test weight, inertias, and flight conditions for which each PIO was experienced. The models used are presented in Tables 1-3. Frequency response functions were derived from these models and used with the

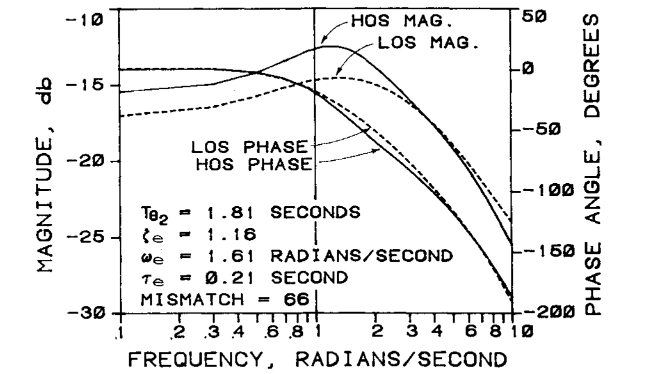

Fig. 1 Equivalent system match of $q/\delta_c(j\omega)$ for the landing approach model.

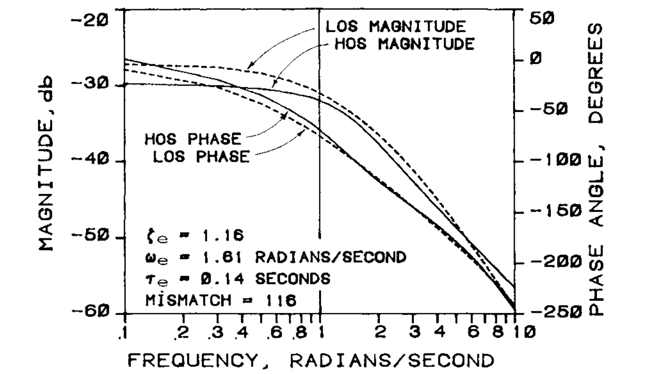

Fig. 2 Equivalent system match of $n_{z_{cr}}/\delta_c(j\omega)$ for the landing approach model.

handling qualities criteria to predict the handling qualities for each model.

Three handling qualities criteria were used: equivalent systems,[1] bandwidth,[2] and R. Smith.[3,4] The equivalent systems criteria are included in the current military specification for flying qualities, MIL-F-8785C.[5] The bandwidth criteria and portions of the R. Smith PIO criteria are presently being considered for inclusion with equivalent systems in the military standard for flying qualities that is being developed by the Air Force Wright Aeronautical Laboratories.[6,7] The equivalent system and bandwidth assessment rules and criteria are presented in Refs. 1, 2, 6, and 7. The R. Smith assessment rules and criteria are documented in Refs. 3 and 4. The formula proposed in Ref. 3 was used to determine the R. Smith criterion frequency.

In the discussion below, flight phase categories A and C refer to MIL-F-8785C designations. Category A flight phase requires rapid maneuvering, precision tracking, or precise flight-path control. We considered tracking a cockpit display to be a category A flight phase because it required precision tracking of the flight-path error indicators in the cockpit display and because it required precise flight-path control. Category B flight phase is normally accomplished using gradual maneuvers and without precision tracking, although accurate flight-path control may be required. Category C flight phase is normally accomplished using gradual maneuvers and usually requires accurate flight-path control. MIL-F-8785C designates landing as a category C flight phase." Level 1 refers to the MIL-F-8785C characterization for flying qualities that are "clearly adequate for the mission flight phase. Level 2 flying qualities are "adequate to accomplish the mission flight phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists." Level 3 flying qualities are such that "the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both."

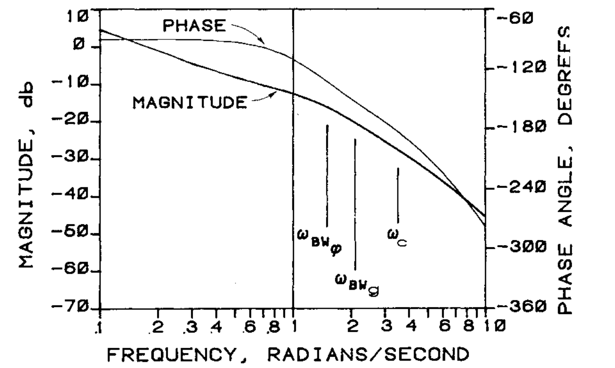

Fig. 3 $\theta/\delta_c(j\omega)$ for the landing approach model.

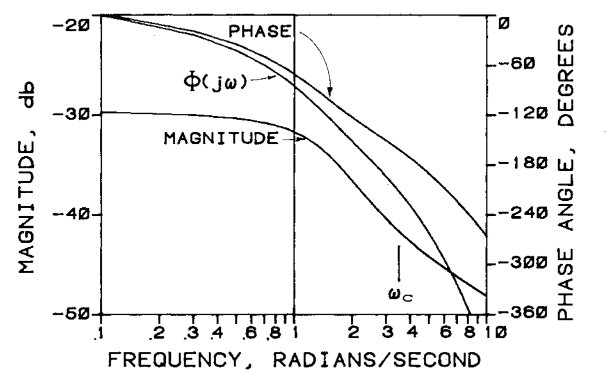

Fig. 4 $n_{z_p}/\delta_c(j\omega)$ and $\Phi(j\omega)$ for the landing approach model.

Handling Qualities Predictions for the Landing Approach Model (PIO During Landing Flare)

The results of the equivalent system, bandwidth, and R. Smith criteria for this configuration are summarized in Table 4.

Equivalent System Predictions

To use the equivalent system criteria the frequency response curves of $q/\delta_c(j\omega)$ and $n_{z_{cr}}/\delta_c(j\omega)$ were matched using a fixed numerator time constant, T_{θ_2}. For the landing approach model, T_{θ_2} was fixed at 1.81 s based on the flight-test-derived value of $n/\alpha = 6.1$ g/rad. The results of this fit are presented in Figs. 1 and 2. The equivalent short-period frequency of 1.61 rad/s was level 1 for $n/\alpha = 6.1$. The equivalent damping ratio of 1.16 was also level 1. However, the equivalent time delay of 0.21 s for pitch rate response was level 3. Such a large time delay would likely have dominated the pilots' perception of handling qualities and would have contributed to the unpredictable response of the airplane. In this important sense the equivalent system results predicted poor handling qualities that were substantiated by flight test.

Bandwidth Predictions

The frequencies for 6 dB gain margin and 45 deg phase margin for $\theta/\delta_c(j\omega)$ are shown in Fig. 3. The bandwidth frequency is the lower of these, $\omega_{BW} = 1.5$ rad/s. This bandwidth frequency together with the bandwidth equivalent time delay, $\tau_P = 0.14$ s, predicts level 3 handling qualities for landing approach. This prediction of poor handling qualities was substantiated by flight test.

R. Smith Predictions

The $\theta/\delta_c(j\omega)$ and n_{z_p}/δ_c $(j\omega)$ frequency response curves used for the R. Smith criteria predictions are presented in Figs. 3 and 4. The R. Smith criteria predicted a criterion

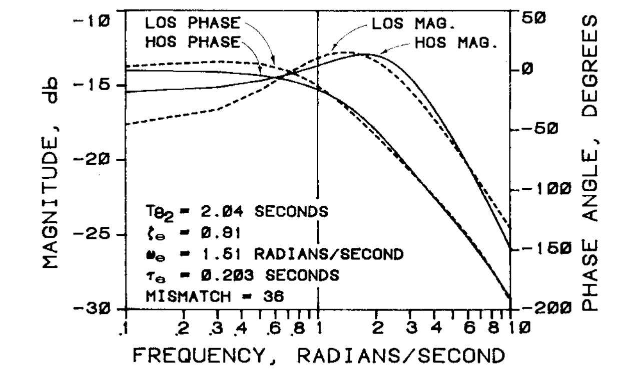

Fig. 5 Equivalent system match of $q/\delta_c(j\omega)$ for the up-and-away model.

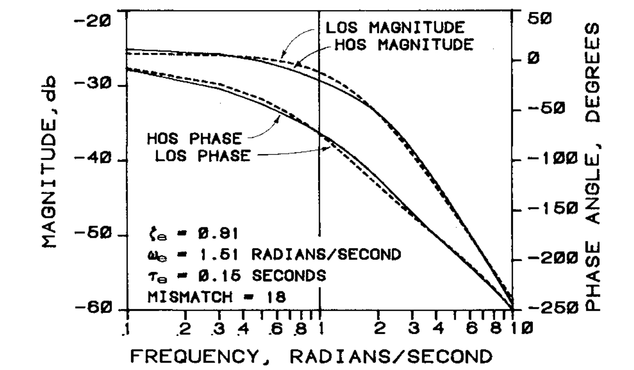

Fig. 6 Equivalent system match of $n_{z_{cr}}/\delta_c(j\omega)$ for the up-and-away model.

frequency ω_c of 3.5 rad/s. The predicted Cooper-Harper pilot opinion rating range was about 7-8.5 (level 3). The phase angle of $\theta/\delta_c(j\omega_c) = -182$ deg resulted in a prediction of pitch attitude PIO susceptibility and the phase parameter, $\Phi(j\omega_c) = -211$ deg resulted in a prediction of normal acceleration PIO susceptibility. The criterion frequency $\omega_c = 3.5$ rad/s, which is the predicted PIO frequency when PIO susceptibility is predicted, was almost exactly the flight test measured PIO frequency of 3.6 rad/s during the landing PIO.

Handling Qualities Predictions for the Up-and-Away Model (PIO at Altitude)

The results of the equivalent system, bandwidth, and R. Smith criteria for this configuration are summarized in Table 4.

Equivalent System Predictions

The $q/\delta_c(j\omega)$ and $n_{z_{cr}}/\delta_c(j\omega)$ frequency response curves were matched using a fixed numerator time constant, T_{θ_2}. For the up-and-away model, T_{θ_2} was fixed at 2.04 s based on the flight-test-derived value of $n/\alpha = 9.2$ g/rad. The results of this fit are presented in Figs. 5 and 6. The equivalent short-period frequency of 1.51 rad/s was level 2 for $n/\alpha = 9.2$ g/rad. The equivalent damping ratio of 0.91 was level 1. However, the equivalent time delay of 0.20 s for pitch rate response was on the borderline between levels 2 and 3. The level 2 short-period frequency and the large time delay suggest poor handling qualities.

Bandwidth Predictions

The frequencies for 6 dB gain margin and 45 deg phase margin for $\theta/\delta_c(j\omega)$ are shown in Fig. 7. The bandwidth frequency is the lower of these; $\omega_{BW} = 1.8$ rad/s. This bandwidth frequency, together with the bandwidth equivalent time

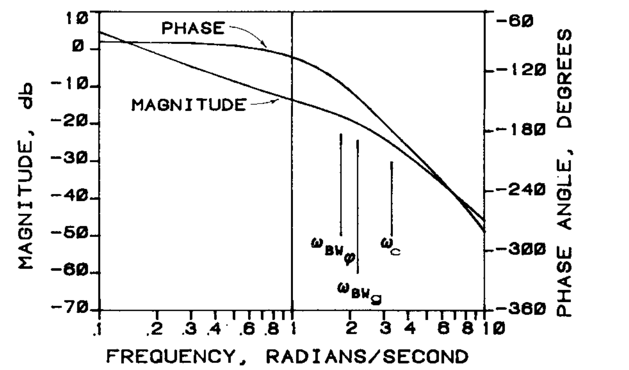

Fig. 7 $\theta/\delta_c(j\omega)$ for the up-and-away model.

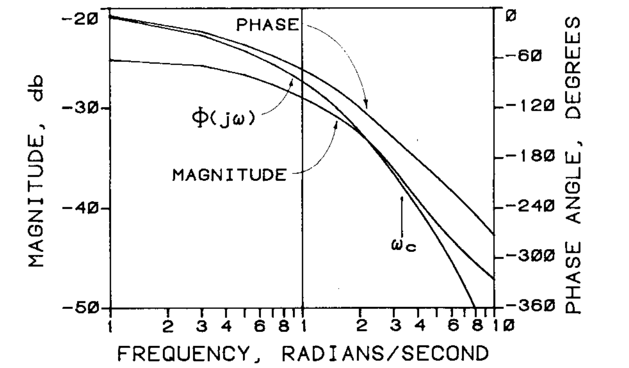

Fig. 8 $n_{z_p}/\delta_c(j\omega)$ and $\Phi(j\omega)$ for the up-and-away model.

delay, $\tau_p = 0.15$ s, predicts level 3 handling qualities for category A flight phases such as tracking.

R. Smith Predictions

The $\theta/\delta_c(j\omega)$ and n_{z_p}/δ_c frequency response curves used for the R. Smith criteria predictions are presented in Figs. 7 and 8. The R. Smith criteria predicted a criterion frequency ω_c of 3.3 rad/s. The predicted Cooper-Harper pilot opinion rating range was about 7-8.5 (level 3). The phase angle of $\theta/\delta_c(j\omega_c) = -179$ deg resulted in a prediction of non-susceptibility to pitch attitude PIO, although the value of -179 deg is borderline. The phase parameter $\Phi(j\omega_c) = -211$ deg resulted in prediction of normal acceleration PIO susceptibility. The criterion frequency $\omega_c = 3.3$ rad/s, which is the predicted PIO frequency when PIO susceptibility is predicted, was very close to the flight-test-measured PIO frequency of 3.1 rad/s.

Handling Qualitites Predictions for the Up-and-Away Model plus Cockpit Display Dynamics (PIO While Tracking a Cockpit Display)

This PIO was especially interesting because the measured frequency of 2.0 rad/s was quite different from the 3.1 rad/s frequency of the up-and-away PIO just discussed, and it was not close to the R. Smith predicted frequency of 3.3 rad/s. While pondering this discrepancy it was remembered that during this PIO the pilot had been tracking a cockpit display in an effort to zero out a flight-path error before engaging an automatic flight control mode. The dynamics of this display were approximately $0.6/(s+2)$ with an additional frequency-dependent phase lag. Since these display dynamics were in the loop being closed by the pilot, they should be included in the handling qualities evaluation. Therefore, the display dynamics were added to the up-and-away model and each of the three handling qualities criteria were used to predict the handling qualities of the airplane plus cockpit display.

Table 4 Summary comparison of predictions with flight test results

		Handling qualities level		PIO			
Model	Criterion	Predicted levels	Agrees with flight test results?	Predicted?	Agrees with flight test results?	Predicted PIO frequency, rad/s	Flight test PIO frequency, rad/s
Landing approach	Equivalent system	1-3	Yes	–	–	–	–
	Bandwidth	3	Yes	–	–	–	–
	R. Smith	3	Yes	Yes	Yes	3.5	3.6
Up-and-away	Equivalent system	1-3	Yes	–	–	–	–
	Bandwidth	3	Yes	–	–	–	–
	R. Smith	3	Yes	Yes	Yes	3.3	3.1
Up-and-away plus display	Equivalent system	1-3	Yes	–	–	–	–
	Bandwidth	3	Yes	–	–	–	–
	R. Smith	3	Yes	Yes	Yes	2.0	2.0

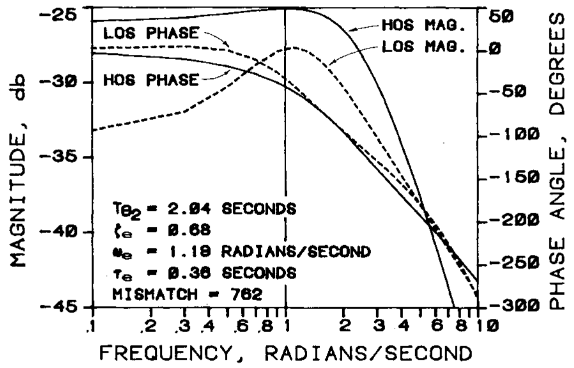

Fig. 9 Equivalent system match of $\dot{x}/\delta_c(j\omega)$ for the up-and-away model plus cockpit display.

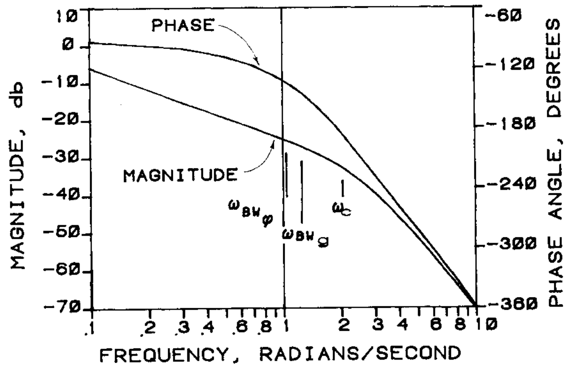

Fig. 11 $x/\delta_c(j\omega)$ for the up-and-away model plus cockpit display.

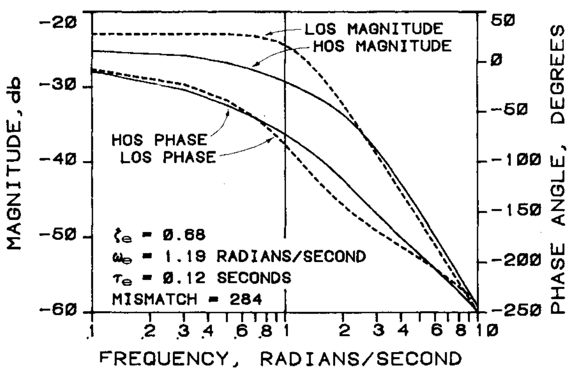

Fig. 10 Equivalent system match of $n_{z_{cr}}/\delta_c(j\omega)$ for the up-and-away model plus cockpit display.

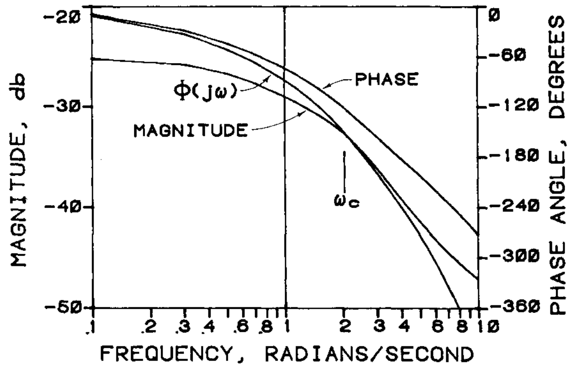

Fig. 12 $n_{z_p}/\delta_c(j\omega)$ and $\Phi(j\omega)$ for the up-and-away model plus cockpit display.

The $0.6/(s+2)$ display dynamics were added to the $q/\delta_c(j\omega)$ and $\theta/\delta_c(j\omega)$ frequency response functions for the up-and-away model because the pilot was receiving pitch attitude cues from the display. The displayed attitude cue the pilot was tracking will be referred to as x, and the rate of change of that cue as $\dot{x}$. The display dynamics were not added to the $n_{z_{cr}}/\delta_c(j\omega)$ and $n_{z_p}/\delta_c(j\omega)$ frequency response functions because the display did not alter the way in which the pilot sensed normal acceleration.

In the evaluations below, tracking a cockpit display in an attempt to zero a flight-path error was considered to be a category A flight phase task.

The results of the equivalent system, bandwidth, and R. Smith criteria for this configuration are summarized in Table 4.

Equivalent System Predictions

The frequency response curves of $\dot{x}/\delta_c(j\omega)$ and $n_{z_{cr}}/\delta_c(j\omega)$ were matched using a fixed numerator time constant, T_{θ_2}. For the up-and-away model, T_{θ_2} was fixed at 2.04 s based on the flight-test-derived value of $n/\alpha = 9.2$ g/rad. The results of this fit are presented in Figs. 9 and 10. Including the cockpit display dynamics resulted in a large mismatch between the higher-order system (HOS) airplane dynamics and the equivalent lower-order system (LOS) dynamics. This large mismatch may be an indication of poor handling qualities. The equivalent short-period frequency of 1.19 rad/s was level 2 for $n/\alpha = 9.2$ g/rad. The equivalent damping ratio of 0.68 was level 1. The equivalent time delay of 0.36 s for pitch rate response was level 3. The large pitch rate and normal acceleration mismatches, the large time delay, and the level 2 equivalent short-period frequency suggested poor handling qualities, a prediction that was in agreement with flight test results.

Bandwidth Predictions

The frequencies for 6 dB gain margin and 45 deg phase margin for $x/\delta_c(j\omega)$ are shown in Fig. 11. The bandwidth frequency is the lower of these, $\omega_{BW}=1.0$ rad/s. This bandwidth frequency together with the bandwidth equivalent time delay, $\tau_p=0.34$ s, predicts level 3 handling qualities for category A flight phases. This prediction was in agreement with flight test results.

R. Smith Predictions

The $x\,\delta_c(j\omega)$ and $n_{z_p}/(j\omega)$ frequency response curves used for the R. Smith criteria predictions are presented in Figs. 11 and 12. When the display dynamics were included, the R. Smith criteria predicted a criterion frequency of 2.0 rad/s. This prediction agrees exactly with the measured PIO frequency of 2.0 rad/s. The predicted Cooper-Harper pilot opinion rating range was about 8-9 (level 3). The phase parameter $\Phi(j\omega_c)=-151$ deg resulted in a prediction of nonsusceptibility to normal acceleration PIO. However, the phase angle of $x/\delta_c(j\omega_c)=-187$ deg resulted in a prediction of susceptibility to pitch attitude PIO. This case is interesting because pilots are trained to ignore seat-of-the-pants and vestibular motion cues when they are flying on instruments. For this reason we assume that normal acceleration PIO would not have occurred even if it were predicted. However, a pitch attitude PIO could have occurred if the pilot were attempting to track an unstable airplane plus instrument dynamics. The R. Smith criteria predicted pitch attitude PIO susceptibility when the display dynamics were included, which is apparently what happened during flight test.

Conclusions

In each case evaluated, the equivalent system, bandwidth, and R. Smith criteria correctly predicted the poor handling qualities which were experienced during flight test.

The R. Smith criteria were especially interesting because they explicitly and correctly predicted the aircraft would be susceptible to pilot-induced oscillation and also correctly predicted the oscillation frequencies. These predictions were substantiated by flight test, where three pilot-induced oscillations were experienced and the measured frequencies of the oscillations were in agreement with the predicted frequencies.

In the case evaluated, it was evident that displays, such as head-up or head-down displays, can have a substantial impact on handling qualities. (Pilots are familiar, for example, with the degrading effect a lead computing gunsight can have on handling qualities.) Each of the three handling qualities criteria predicted that the addition of the display would degrade some measure of handling qualities. The R. Smith criteria predicted that, with the display, the aircraft would still be prone to pilot-induced oscillations but the oscillation frequency would change substantially. Flight-test experience confirmed these predictions.

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