Flying Qualities of Pitch Rate Command/Attitude Hold Control Systems for Landing

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Experience with in-flight simulations has shown that pitch rate command/attitude hold flight control systems exhibit mediocre to poor flying qualities for landing. Pilots report poor control of the flight path and tendencies to balloon and float and to exhibit pilot-induced oscillations. The origin of this flight control concept is traced to analytical models of the pilot/vehicle dynamic system, to such pilot-in-loop design criteria as the crossover model "law" of manual control, and to sensor redundancy considerations that discourage the use of air data and encourage the use of inertial sensors in flight control systems. Rate command systems reduce the bandwidth of the angle of attack and flight path rate control, alter the control feel for maneuvers, and force pilots to use a pulse control technique and to push to land. For conventional airplane dynamics, the phugoid mode has low residue in the angle of attack and high residue in the pitch attitude and, in this situation, pitch attitude provides the pilot with surrogate cues for control of the angle of attack, flight path angle, and airspeed. Through pole-zero cancellation, the attitude response of a rate command system is made independent of the low-frequency modes of the characteristic equation and these dynamic modes, which must be controlled by the pilot in landing, are rendered unobservable in the pitch response of the rate command system.

Nomenclature

$e^{-j\omega}$	= time display
h	= altitude
$\dot{h}/\delta_p$	= height rate transfer function
K	= gain
NZCG, NZPS	= normal acceleration c.g. and pilot
S	= Laplace operator
$1/T_q$	= control system lead factor
$1/T_{wo}$	= washout filter pole
$1/T_{\theta_1}$, $1/T_{\theta_2}$	= transfer function numerator factors
$1/T_{\theta 2}^{*}$	= numerator factor of lead/lag prefilter
α/δ_p	= angle-of-attack transfer function
ζ	= damping ratio
θ/δ_p	= attitude to elevator stick transfer function
U_0	= trim airspeed
Y_c	= controlled element transfer function
Y_p	= pilot describing function
ω	= frequency
ω_c	= crossover frequency
ω_n	= natural frequency
ω_α	= frequency of numerator quadratic
ζ	= damping ratio

Introduction

PERFORMANCE advantages in terms of improved fuel economy and increased range for transport-type airplanes and higher load factor capability for a given engine thrust for fighter airplanes has resulted in airplanes designed to have the center of gravity near or aft of the aerodynamic center. The airplane is then statically unstable and augmentation is required to restore stable flight and to achieve desirable flying qualities. Feedback of the angle of attack and pitch rate to the elevator would be an effective method for accomplishing this objective, but difficulties in measuring the angle of attack and providing redundancy in the measurement has tended to discourage this solution. If high gain is required in the angle-of-attack stabilization loop, the pitch response to turbulence can become objectionable. This problem can be alleviated through use of complimentary filtering of the aerodynamic and inertial measurements of the angle of attack, but the resulting complexity raises concern for reliability. An alternative design based on pitch rate feedback with proportional and integral paths in the forward loop is also capable of stabilizing statically unstable airplanes. This design, which is illustrated in Fig. 1, was chosen by the authors of Ref. 1 as exhibiting high potential for future flight control applications because it provides the following functions:

1) Creates a high degree of effective static stability for the augmented aircraft.
2) Improves the damping of the effective short-period mode.
3) Provides a pitch rate command/attitude hold platform for piloted control.
4) Regulates against external disturbances, with emphasis on pitch attitude maintenance rather than weathercocking.
5) Provides automatic up-elevator compensation for turning flight.

In Ref. 1 it is assumed that all of the system elements, except possibly those involved in turn compensation, are multiply redundant. The need for redundancy is cited as one reason for basing the system on pitch rate sensors, which are simple, hardy, relatively insensitive to bias errors, and easily made part of a minimum complexity multiple-redundant system.

Conceptual Models and Design Criteria

Piloted control of the flight path during approach and landing is modeled as a series structure in Ref. 1, with attitude control inner and outer loops. The series pilot model is illustrated in Fig. 2. In this model structure, high emphasis is placed on the inner attitude loop closure and design criteria have been proposed which specify the closed loop attitude response to pilot commands that must be satisfied for level 1 flying qualities. One of the design criteria for attitude control was developed by Neal and Smith.[2] The criterion requires that a

Received Sept. 12, 1985.
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minimum bandwidth be achieved in the control of pitch attitude without excessive droop or resonance, with a minimum of pilot lead generation at the bandwidth frequency. The crossover model "law" of manual control documented in Ref. 3 states that, in the frequency region of pilot/vehicle crossover, the product of the open-loop pilot describing function Y_p and the controlled element transfer function Y_c will have the following form:

$$Y_p Y_c = \frac{\omega_c}{\omega} e^{-j\omega} \qquad \text{for } \omega \doteq \omega_c$$

Minimum pilot effort in active closed-loop control is associated with little or no lead generation to compensate for the dynamic deficiencies of the controlled element. Consequently, the crossover "law" implies that the controlled-element dynamics in the region of crossover should be approximated by K/S. Application of this design criterion to the inner attitude control loop implies that

$$\frac{\theta}{\delta_{\text{ep}}}(S) = \frac{K}{S}, \qquad 0<\omega<\omega_b$$

where ω_b is the upper limit of the crossover frequency band. That is, the stick should order pitch rate. It has generally been assumed that good inner-loop control of pitch attitude would ensure good control of height and height rate through application of the series pilot model structure.

The generic root locus diagram in Fig. 3 illustrates use of the control system of Fig. 1 to stabilize an aft c.g. (unstable) airplane. The open-loop roots are indicated by the X symbols and the pitch rate transfer function zeros are indicated by the □ symbols. The loci of the closed-loop poles with loop gain are indicated in Fig. 3 and the specific location of the complex pair of poles for $K=1.06$ is identified by the ■ symbol. There are also closed-loop poles located near the numerator zeros at $1/T_{\theta_1}$ and $1/T_{\theta_2}$. Although not shown in Fig. 3, the forward path integration causes a pole at the origin, which is cancelled by the pitch rate transfer function zero located at the origin.

In Ref. 1, the idealized pitch rate command/attitude hold flight control system illustrated in the block diagram of Fig. 1 and by the root locus of Fig. 3 is called "superaugmentation." The superaugmentation distinction is made in Ref. 1 to highlight the difference that superaugmented aircraft have attitude characteristics which depend primarily on the crossover frequency, $\omega_{\text{ca}} \pm K_q M_{\delta}$, and the controller lead factor $1/T_q$. The airplane pitch attitude transfer function numerator terms $1/T_{\theta_2}$ is completely suppressed in the pitch attitude response and is replaced by the control system lead $1/T_q$.

Pitch Rate Control System Experiment

Experience gained during flying qualities demonstrations (unpublished) at the Air Force and Naval Test Pilot Schools using the Calspan Learjet and the NT-33A variable-stability airplanes indicated that pitch rate command/attitude hold flight control systems could provide level 1 flying qualities when landings were made in nonstressful conditions, e.g., good initial conditions and little crosswind or turbulence; but, under stressful conditions such as poor initial conditions, turbulence, and crosswind, the flying qualities can be level 2-3. This experience was verified in specific simulations of the Space Shuttle[4] and generic simulations[5] using the NC-131H total in-flight simulator (TIFS).

Pilots reported poor control of flight path and a tendency to balloon and float during landings with pitch rate command/attitude hold flight control systems. This type of control system required pilots to use a pulse-input control technique and to apply nose-down control to stop the float and force the airplane to land. The pilots also reported a tendency for pilot-induced oscillations (PIO) to occur in the stressful circumstances identified above. The PIO tendency was aggravated by time delay and dynamic lag in the command path.

Because this experience was at odds with the expected benefits for "superaugmented" pitch rate command/attitude hold flight control systems that the authors of Ref. 1 had anticipated, a formal in-flight simulation experiment was conceived and executed using the NC-131H TIFS.

Reference 6 reports the results of the experiment performed to investigate the flying qualities of pitch rate command/attitude hold flight control systems for the approach and landing task. The experiment matrix was designed to include pitch rate command/attitude hold cases and modifications to these cases achieved through use of command prefilters. The block diagrams and Bode diagrams in Fig. 4 illustrate the major features examined in the experiment. The Bode diagrams in Fig. 4 have been normalized, such that the midfrequency gains for the different cases are equal, to facilitate illustrating the variations in shape caused by the lead/lag prefilter, the washout prefilter, and the combination of both prefilters. Also shown in Fig. 4 are the Bode diagrams for a conventional stable airplane.

The lead/lag prefilter was designed to reshape the high-frequency responses of the pitch rate command systems such that they approximated the responses of a conventional stable airplane. The washout prefilter altered the low-frequency responses of the pitch rate command system such that the pilot commanded pitch attitude, angle of attack, and rate of climb at low frequency rather than the rate of change of these responses. The rate command systems with the washout

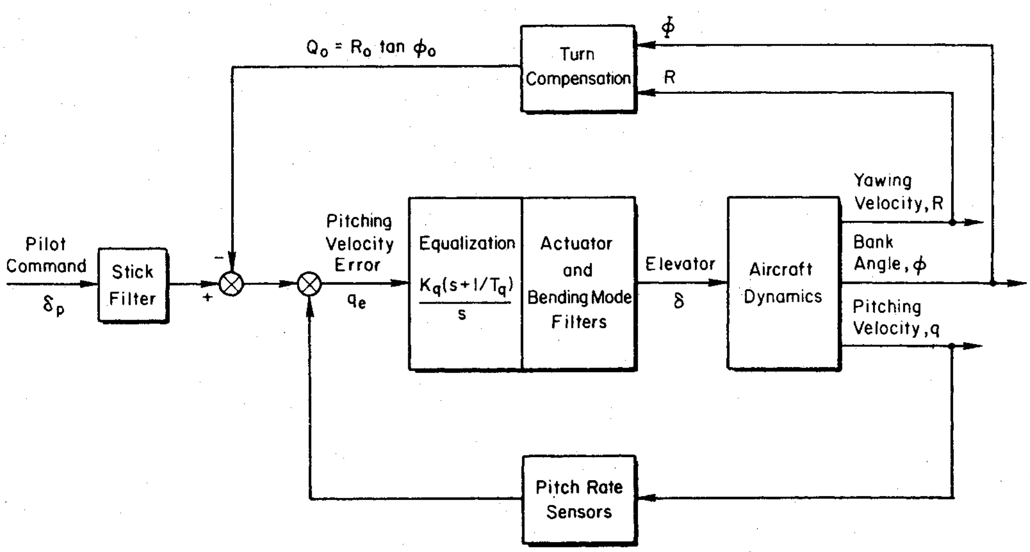

Fig. 1 Pitch rate command/attitude hold flight control system.

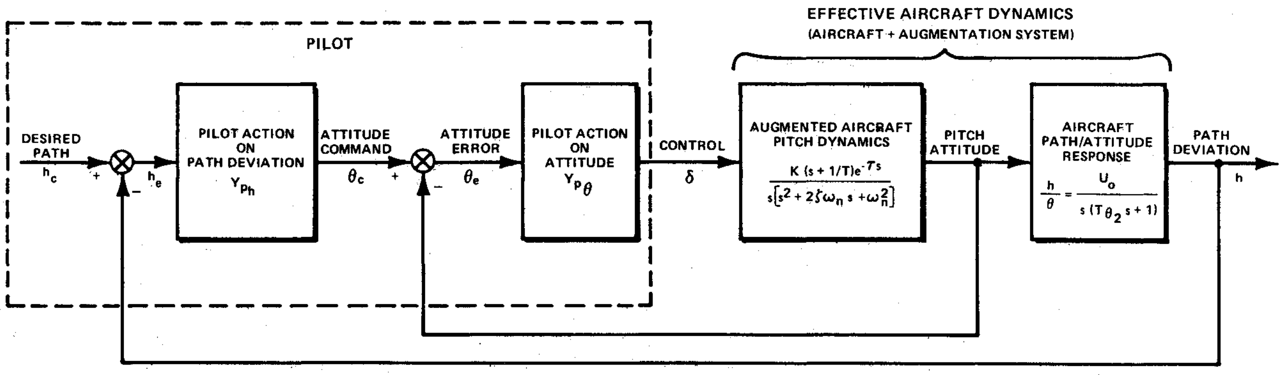

Fig. 2 Closed-loop precision path control with attitude control inner loop.

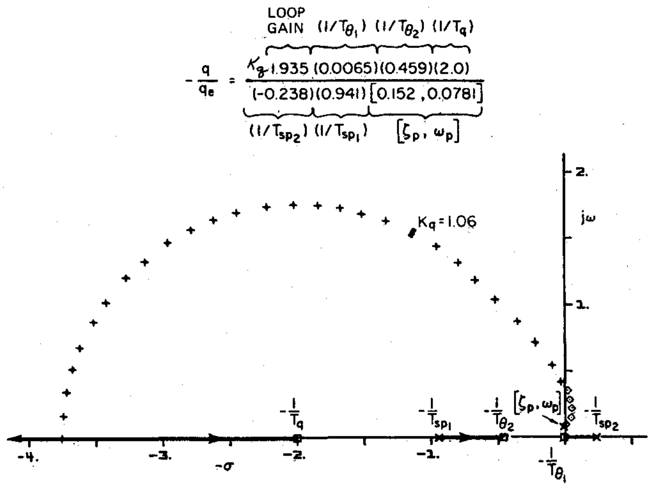

Fig. 3 S-plane root locus.

prefilter approximated the low-frequency responses of a conventional stable airplane. Configurations with both the washout and the lead/lag prefilters approximate the conventional airplane over the entire frequency range. Transfer functions and complete equations of motion for the configurations evaluated are contained in Ref. 6.

The responses to a pilot command, which is removed after 5 s, are shown in Fig. 5 for a pitch rate command/attitude hold design and for a conventional stable airplane. The time histories are scaled to reflect the command gain used by the pilots during evaluation. In general, it was found that setting the command gain such that the high-frequency pitch attitude gain was nearly constant for the various configurations was acceptable to the pilots. The pilot ratings for the rate command system and the conventional stable airplane are noted on Fig. 5. The conventional stable airplane was rated level 1 by both pilots in the experiments. The pitch rate command system was rated level 2 by pilot B and level 3 by pilot S.

The lead/lag prefilter altered the responses at high frequency, with the result that the pilot ratings were improved over the ratings given to a series of pitch rate command configurations. The improvement in pilot ratings attributed to the lead/lag prefilter are shown in Fig. 6. The washout prefilter altered the response of the pitch rate command system only at low frequency, but this modification to the dynamic system also improved the pilot ratings as shown in Fig.7. The configuration identification codes in Fig. 6 and 7 are from Ref. 6.

The results of attempts to correlate the pilot rating data using design criteria based on inner-loop control of pitch attitude are documented in Ref. 6. These included application of the "bandwidth frequency" criteria of Ref. 7 and of the Neal-Smith[2] design criteria based on attitude control. None of the existing design criteria were successful in correlating the pilot rating data.The results of a closed-loop analysis of direct pilot control of rate of descent is also reported in Ref. 6. This analysis tended to correlate with the pilot comments concerning flight path control and the improvement in pilot ratings realized for the lead/lag prefilter, but did not explain the improvement in pilot rating realized by adding the washout prefilter to the pitch rate command designs.

Based on a study of frequency responses, time histories of responses to simple pilot commands (see Fig. 5), and pilot comments documented in Ref. 7, the author hypothesizes that the improved pilot ratings associated with addition of the lead/lag and washout prefilters to the pitch rate command systems can be attributed to the following factors. Feedback of the pitch rate and pitch rate integral to the elevator will cause closed-loop poles to approach the transfer function zeros at the origin, at $1/T_{\theta_1}$, $1/T_{\theta_2}$, and $1/T_q$. See the root locus diagram in Fig. 3. The trajectory of the complex poles in Fig. 3 is determined by the location of the control system zero at $1/T_q$. To achieve the natural frequences of $\omega_n = 1.8$, 2.3, and 2.8 with damping ratios of 0.6, 0.5, and 0.8 that were evaluated in the experiment, the control system zero $1/T_q$ was always larger than $1/T_{\theta_2}$. The frequency responses of the rate command systems therefore had the characteristic shape illustrated in Fig. 4; i.e., the $\theta/_{\delta_p}$ frequency response has a -1 slope out to $\omega = 1/T_q$, but the α/δ_p and $\dot{h}/\delta_p$ frequency responses break at $\omega = 1/T_{\theta_2}$ because there is a closed-loop pole near $1/T_{\theta_2}$ that is not cancelled by a zero in either of these transfer functions. This feature of pitch rate command systems tends to limit the bandwidth of the pilot's control of the airplane responses. The lead/lag prefilter restores the high-frequency response to control by cancelling the closed-loop pole near $1/T_{\theta_2}$ and the control system zereo at $1/T_q$. This prefilter also reduced the phase lag at intermediate frequencies, which is beneficial in avoiding PIO problems.

As was noted above, the pitch rate command/attitude hold control system drives the closed-loop poles into the zeros of the pitch rate to elevator transfer function. The poles have no residue in the pitch rate response to stick commands. This does not mean, however, that these roots are totally suppressed. In fact, they are roots of the augmented characteristic equation and can have a residue in the other airplane responses that need to be controlled, such as angle of attack, airspeed, and flight path. That this is true can be seen from examination of the frequency response sketches in Fig. 4 and the time histories for the pitch rate command system shown in Fig. 5. The time history of pitch rate q and pitch attitude θ in Fig. 5 exhibits only the residue of the complex closed-loop poles and the pole at the origin. The time histories for the angle of attack α and flight path angle γ exhibit residues of the close-loop poles at $1/T_{\theta_1}$ and $1/T_{\theta_2}$ as well as the other closed-loop poles. The pitch rate command system does not eliminate the closed-loop poles at $S = 0$, $-1/T_{\theta_1}$, or $-1/T_{\theta_2}$ from the dynamic system; it only removes their residue from the pitch responses. In the opinion of this author, this feature of pitch rate command systems is a disadvantage to the pilot because it

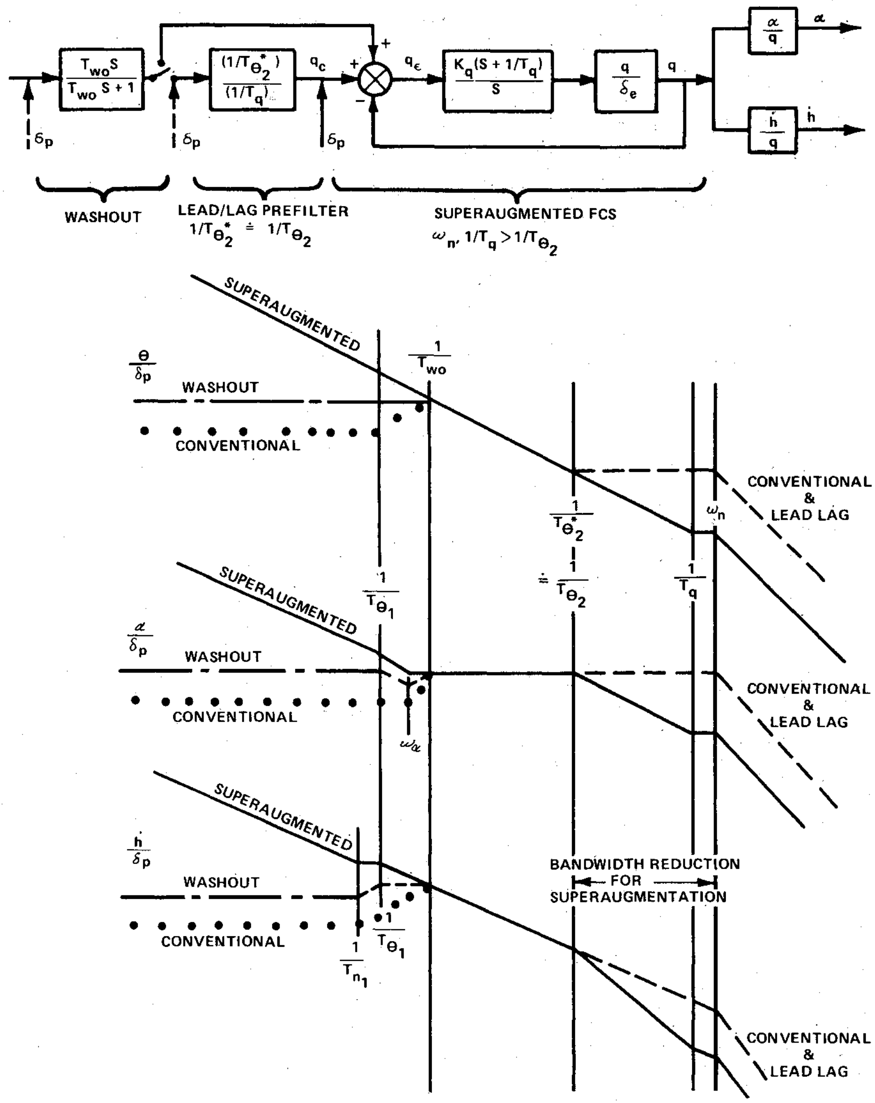

Fig. 4 Block diagram and Bode diagram.

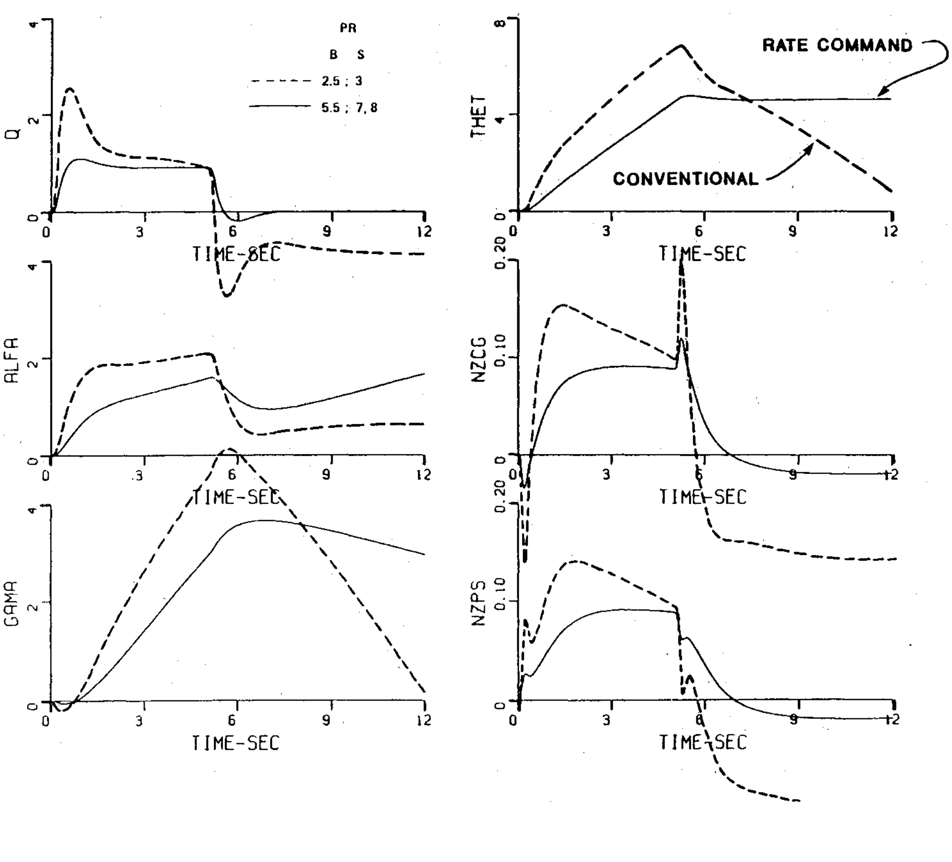

Fig. 5 Time history comparison.

renders the most easily observable airplane response devoid of information about several of the dynamic modes of the augmented airplane that he is trying to control; i.e., observing the pitch attitude does not give any information about variations in the angle of attack, airspeed, or flight path that may be occurring as a result of previous control actions.

For "conventional" airplane dynamics, pitch attitude provides surrogate cues for control of the angle of attack, flight path, and airspeed. For conventional dynamics, the stick commands the angle of attack at all frequencies below the short-period frequency (assuming the phugoid roots have low residue in the angle of attack). In this situation, abrupt stick inputs command the angle of attack to change, which is reflected by a corresponding pitch attitude change that is observable by the pilot. If the stick input is held constant, the angle of attack will remain constant and any change in pitch attitude can be interpreted as a change in the flight path angle. These features can be observed in the time histories for the conventional airplane shown in Fig. 5. If the airplane is initially in equilibrium and the power is changed, the conventional airplane will tend to maintain the angle of attack and as the change in airspeed causes the flight path to change, the pilot can be alerted to these deviations from equilibrium by the change in the pitch attitude. Thus, it is hypothesized that pitch attitude is important to pilots for control of conventional airplanes not because it is an end in itself, but because it provides surrogate cues for the other less observable airplane responses.

The pitch rate command system exhibits infinite static gain in pitch attitude, angle of attack, airspeed, and flight path angle. This characteristic prohibits pilot-in-the-loop continuous control and forces the pilot to use pulse-type stick commands. A consequence of this altered control technique is that piloting cues derived from stick force and stick deflection

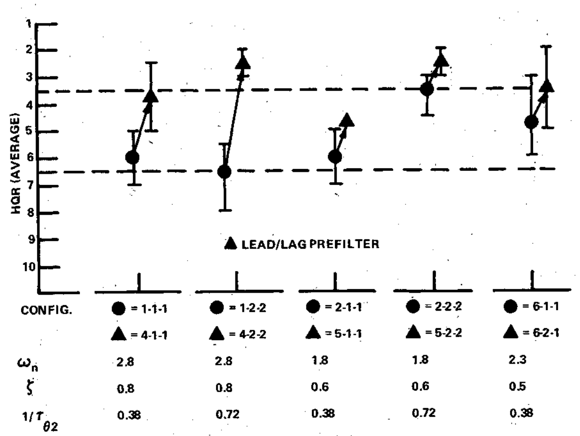

Fig. 6 Effect of lead/lag prefilter.

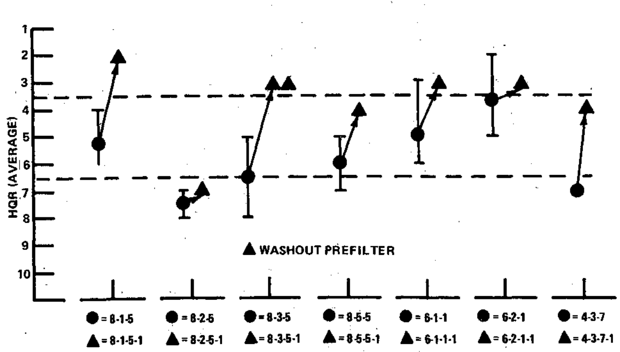

Fig. 7 Effect of washout prefilter.

are diminished or removed. The effect of the washout prefilter is to change the response to stick at low frequency from rate ordering to position ordering in the attitude, angle of attack, and flight path. This alteration in the response character permits continuous pilot-in-the-loop control to be used and restores the pilot's capability to use stick-feel cues.

Conclusions

1) The experiment of Ref. 6 has demonstrated that pitch rate command/attitude hold control systems provide only mediocre flying qualities for landing in stressful conditions, i.e., poor initial conditions, turbulence, and crosswind.

2) Through pole-zero cancellation, the pitch attitude response of a pitch rate command/attitude hold flight control system is made essentially independent of the low-frequency roots of the characteristic equation. Dynamic modes near $1/T_{\theta_1}$ and $1/T_{\theta_2}$, which must be controlled by the pilot in landing, are rendered unobservable in the pitch attitude response.

3) The closed-loop pole at $1/T_{\theta_2}$ tends to decrease the bandwidth of control of the angle of attack and flight path rate.

4) Use of the series pilot model and design criteria that focus on the inner loop control of pitch attitude did not lead to good flying qualities for landing.

5) The flying qualities of pitch rate command/attitude hold control systems for landing can be improved by use of properly designed lead/lag and/or washout prefilters.

6) It is hypothesized that the flying qualities of pitch rate command/attitude hold flight control systems may be improved for the landing task by addition of explicit displays of flight path angle deviations and angle of attack status relative to reference values.

Recommendations

1) Improved conceptual models of the role of the pilot in the landing task are required, together with design criteria specifically directed at flying qualities for landing.

2) Pilot models should be extended to account for the role that stick force and stick deflection play in the pilot's control actions and impression of the flying qualities.

3) Research experiments should be performed to determine what command/response type is best suited for pilot control in landing.

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