A Flight-Path-Overshoot Flying Qualities Metric for the Landing Task

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An analysis was conducted of the attitude and flight-path-angle response of configurations used in the total in-flight simulator pitch rate command systems program. The results showed poor correlation between the pilot ratings and attitude response and indicate that attitude was not a major influence in the results. A strong correlation was found to exist, however, between the amount of flight-path-angle peak overshoot and the pilot ratings. This correlation is similar to the best correlations that have been obtained in recent closed-loop and time-domain analyses, but has the advantage of greatly simplified implementation and interpretation.

Nomenclature

DB	= attitude dropback, deg (Fig. 1)
h	= altitude
q	= pitch rate, deg/s
q_m	= maximum pitch rate, deg/s
PR	= pilot rating
$T\theta_2$	= pitch attitude numerator time constant, s
TIFS	= total in-flight simulator
α	= angle of attack, deg
γ	= flight-path angle, deg
γ_P	= flight-path angle at peak overshoot, deg
γ_R	= flight-path angle at control release, deg
θ	= pitch attitude, deg
θ_R	= pitch attitude at control release, deg
θ_{SS}	= pitch attitude during steady state, deg
τ	= time constant, s
ω_n	= short-period dominant mode natural frequency, rad/s

Introduction

IN recent years, virtually all advanced aircraft have utilized pitch rate command flight control systems. It is well known in the flying qualities community that pilots newly introduced to pitch rate command flight control systems have a strong tendency to float or balloon on landing. Some analysts believe this is caused by the attitude-hold tendency of these systems and is thus only a familiarization problem that can be overcome with modest training. Others think that these systems have a basic flying qualities deficiency and should be designed to have characteristics more like conventional aircraft. In most cases, problems of this nature are not adequately resolved in ground-based simulators because of the complex interaction of the visual and motion cues and any pilot stress in an actual landing environment.

Because of the paucity of flight data taken under controlled conditions applicable to these situations, a total in-flight simulator (TIFS) program was undertaken to enlarge the flight data base.[1] Analysis of the results of Ref. 1 did not correlate well with established flying qualities criteria. However, time history analyses based on angle of attack α and normal acceleration at the pilot location *NZP* and analyses based on altitude and altitude rate pilot loop closures did provide promising results.[1,2]

Despite the success of the altitude and altitude rate pilot loop closures, a time-history approach has much appeal because the data can be analyzed directly from simulator or flight responses. It is especially adaptable to specification and evaluation criteria requirements. It also provides flexible guidelines for flight control system design. Although the α-*NZP* time history criterion proposed in Ref. 1 provided good correlation, it relies on a somewhat complex equation that consists of several terms involving the initial angle-of-attack slope, intermediate angle-of-attack slope, first *NZP* peak value, second *NZP* peak value, and a weighted value of the time to reach steady-state angle of attack. In addition, it is not directly pilot-centered in that angle of attack is not visible to the pilot and cannot be used as a direct cue. It would seem that attitude and altitude rate or flightpath angle would be better time history parameters because the pilot can perceive these. Reference 1 acknowledges this by pointing out that angle of attack may be a surrogate for the flight path. However, it would seem better to use the primary variable rather than a surrogate.

This study was undertaken, therefore, to determine if pilot-centered time-domain variables provide good correlation with the data base of Ref. 1. A summary of the Ref. 1 configurations and results is presented in Table 1.

Procedure

At the outset, an attempt was made to use heuristic reasoning to choose the most promising time-domain variables for a preliminary analysis of the data. Pilots most frequently use the terms attitude, altitude, rate of descent, and flight-path angle when describing their cues in approach and landing tasks. However, these terms are used in a piloting sense and cannot always be interpreted in terms of strict engineering definitions. The use of attitude by the pilot during landing approaches has been well established analytically, but its role during flare and touchdown is less well understood. During flare and touchdown, pitch rate command systems typically evoke comments on float tendencies, which suggests a perception of the rate of descent, flight-path angle, and height above the runway (altitude). Rate of descent, flight-path angle, and altitude are directly related; hence, considering any one of them is probably adequate for a first analysis. Flight-path angle is generally considered more fundamental by most analysts and, therefore, in addition to attitude, is a reasonable choice for

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analysis. Consequently, attitude and flight-path angle were chosen for initial analysis.

Attitude Analysis and Discussion

The data base was first analyzed from the point of view of attitude dropback (DB) and overshoot of pitch attitude as defined by Ref. 3 (Fig. 1). These concepts could be applied in a straightforward manner to most of the pitch attitude responses (Fig. 2). However, a few of the attitude responses had no steady-state value. Instead, they exhibited a continuously increasing dropback after the peak value was attained (Fig. 3). Consequently, the values of dropback and overshoot were normalized by dividing by the value at control release. The configurations that had no steady state tended toward a pitch attitude value of zero. Therefore, they were arbitrarily assigned a normalized value of 1 and flagged when plotted (See Fig. 4).

Results of the attitude dropback analysis (Fig. 4) show that most of the configurations had very little overshoot (negative dropback) or dropback. Only the washout and conventional configurations had dropback greater than 0.25. The configurations with continuously increasing dropback are plotted on the left-hand axis and flagged. Reference 3 indicates that attitude dynamics are satisfactory if there is no overshoot and if the dropback is not excessive. This is true if the configurations meet the requirements on frequency and damping, which these data do.[1] To achieve satisfactory attitude dynamics, some pitch rate overshoot is required, but not necessarily very much. Pitch rate, of course, transforms into pitch attitude by way of integration. All of the configurations had some pitch rate overshoot.

The correlation between pilot rating (PR) and the amount of attitude dropback was poor—54% of the data were within a ±1.0 PR band and 86% within a ±1.5 PR band. There is a tendency for the ratings to degrade as dropback becomes negative (overshoot), as predicted in Ref. 3. However, the large spread in pilot ratings, particularly in the zero dropback region, indicates that attitude response was not a major factor in the pilot ratings. This result is in agreement with Ref. 1, which showed poor correlation between the results and classical attitude criteria such as Neal-Smith[4] and equivalent systems.

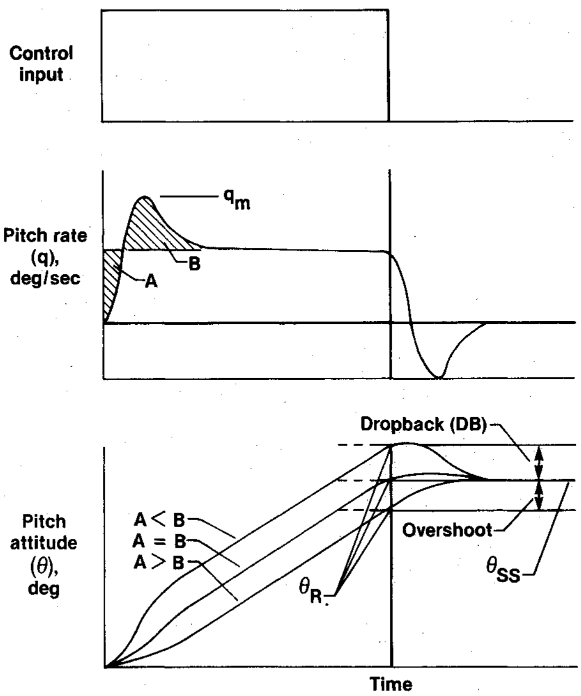
Flight-Path Analysis and Discussion

None of the flight-path-angle responses had a steady-state value, because all configurations had a gradual decrease in flight-path angle γ after the peak value γ_P was attained (Figs. 2 and 3). Therefore, it was decided to use the value at control release γ_R and the peak value as parameters for the flight-path angle response (Fig. 5). This is convenient both from an analytical and a pilot-centered point of view. It is easily determined from a boxcar command input and is a reasonable pilot-control strategy (pull on the stick to achieve a comfortable pitch rate and then release it when the desired flight-path angle is achieved). A 5 s boxcar command was used because Ref. 1 documents the configurations with this input. The difference between the peak and release values was proportioned to the release value and expressed as a percent peak overshoot in flight-path angle (Fig. 5). Hence

$$\gamma \text{ peak overshoot, } \% = \frac{\gamma_P - \gamma_R}{\gamma_R} 100$$

Because all of the pitch attitude peak responses were only slightly larger than the values at the control release, it was clear that this technique should not be applied to pitch attitude.

Figure 6 shows pilot ratings as a function of flight-path-angle peak overshoot—77% of the ratings were within a ±1 PR band and 95% within a ±1.5 PR band. This correlation is quite remarkable when one considers the simplicity and ease of applying the metric. The reason for this correlation may be that the flight-path-angle peak overshoot is an indication of



$$\text{Normalized dropback} = \frac{\theta_R - \theta_{SS}}{\theta_R} = \frac{DB}{\theta_R}$$

θ_R = Pitch attitude at control release

θ_{SS} = Pitch attitude during steady state

Fig. 1 Attitude response analysis features.

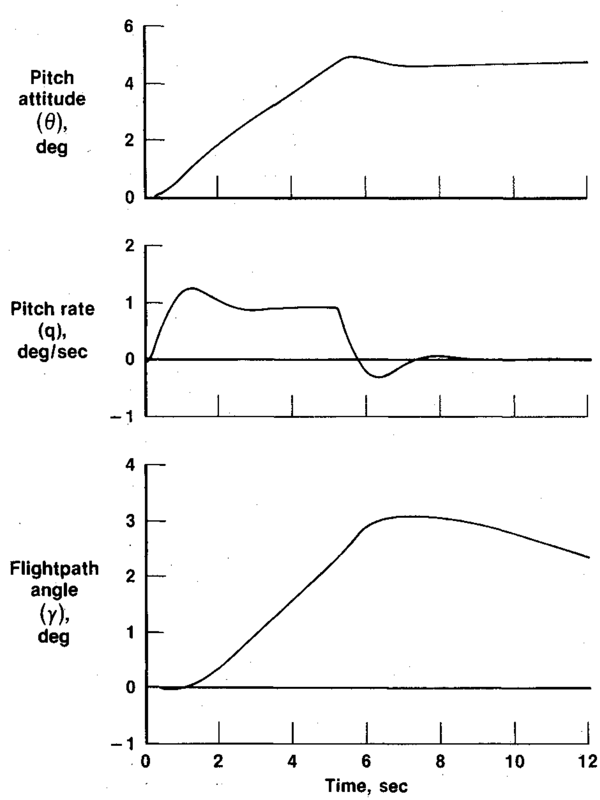


Fig. 2 Typical response for pitch rate command system,[1] 5 s boxcar command input.

the predictability of the flight-path response. This is very important to the pilot in the landing task. If the aircraft acquires (with little or no overshoot) the flight path that the pilot sees on neutralizing the controls, he can readily predict the response. On the other hand, if the aircraft significantly overshoots the flight-path angle that the pilot sees when he releases the controls, it is difficult for him to anticipate the response.

The characteristics of flight-path response after the peak overshoot value were also examined. As previously mentioned, all configurations exhibited a gradual change or settling in flight-path angle after the peak value was attained. This is because a change in angle of attack was brought about by the speed bleed-off during the pull-up command. The settling is an indication of the amount of aft stick that the pilot needs during the landing maneuver. Reference 1 indicates that, because conventional aircraft require a noticeable amount of aft stick during the landing maneuver, aft stick is an important factor in the handling qualities.

The settling in flight-path angle was minimal for the typical pitch rate command configurations (Fig. 2), but was more pronounced for the conventional aircraft configuration (Fig.3) and the washout configurations (Fig. 7). In the case of the pitch rate command systems, the settling was minimized by their attitude-hold tendencies. It was noted that prefilters (Fig. 8), as well as washout (Fig. 7), reduced the flight-path peak overshoot ratio when applied to a typical pitch rate command system (Fig. 2). However, prefilters (Fig. 8) did not increase the amount of flight-path settling, whereas washout (Fig. 7) did.

A comparison of data from configurations with prefilter added and with washout added is presented in Fig. 9. Conventional and canard configurations are included for reference. The trend line from Fig. 6 is superimposed on these data. All of the basic configurations (circles), basic configuations plus lead/lag (squares), and basic configuration plus lead/lag plus canard (quarter-circle) had a minimum of flight-path settling, which is typical of pitch rate command systems. All of the washout configurations (diamonds and triangles) had flight-path settling representative of a conventional aircraft (elongated diamond). Nevertheless, it can be seen that all the data follow the same trend line and flight-path peak overshoot is clearly the dominant influence. This indicates that the decrease in flight-path peak overshoot, and not the increase in

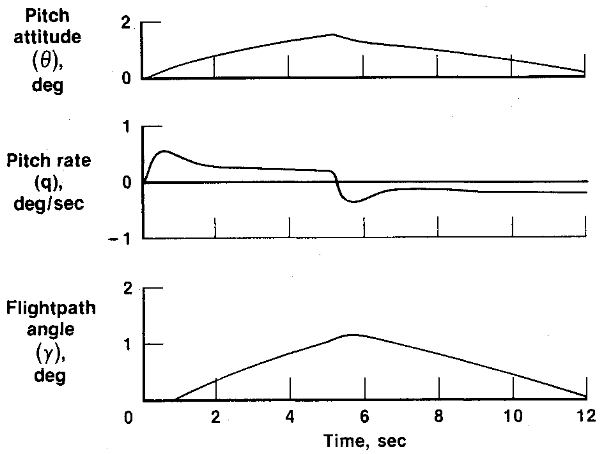


Fig. 3 Typical response for conventional aircraft,[1] 5 s boxcar command input.

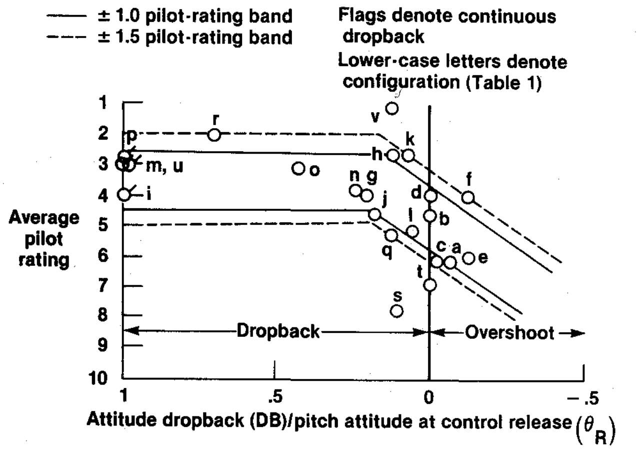


Fig. 4 Pilot ratings as a function of normalized attitude dropback.

Table 1 Description of configurations[a]

Configuration	ω_n, rad/s	$1/T_{\theta_2}$, s^{-1}	Description	Pilot rating (average)	Ref. 3 configuration no.
a	2.8	0.38	Rate command	6.0	1-1-1
b	2.7	1.00	Rate command	4.5	1-3-7
c	1.8	0.38	Rate command	6.0	2-1-1
d	1.8	0.72	Rate command	3.8	2-2-2
e	$\tau=0.4$ s	0.38	Neutral static	5.8	3-1-3
f	$\tau=0.4$ s	0.72	Neutral static	3.8	3-2-4
g	2.8	0.38	Rate command (a) plus lead/lag	3.8	4-1-1
h	2.8	0.72	Rate command plus lead/lag	2.5	4-2-2
i	2.7	1.00	Rate command (b) plus lead/lag plus washout	4.0	4-3-7-1
j	1.8	0.38	Rate command (c) plus lead/lag	4.5	5-1-1
k	1.8	0.72	Rate command (d) plus lead/lay	2.5	5-2-2
l	2.3	0.38	Superaugmented	5.0	6-1-1
m	2.3	0.38	Superaugmented (1) plus washout	3.0	6-1-1-1
n	2.3	0.38	Superaugmented (1) plus lead/lag	3.7	6-2-1
o	2.3	0.38	Superaugmented (1) plus lead/lag plus washout	3.0	6-2-1-1
p	2.8	0.72	Conventional aircraft	2.8	7-1-4
q	1.5	0.40	t' plus lead/lag	5.2	8-1-5
r	1.5	0.40	t' plus lead/lag plus washout	2.0	8-1-5-1
s	1.1	0.40	Modified shuttle	7.7	8-2-5
t	1.5	0.40	Shuttle-like	6.7	8-3-5
u	1.5	0.40	Shuttle-like t plus sashout	3.0	8-3-5-1
v	1.5	0.40	t' plus lead/lag plus canard	1.0	8-4-6

[a]The term ω_n is the short-period dominant mode natural frequency, T_{θ_2} the pitch attitude numerator time constant, τ the time constant. The t' configuration is the Shuttle-like t configuration minus 47 ms time delay.

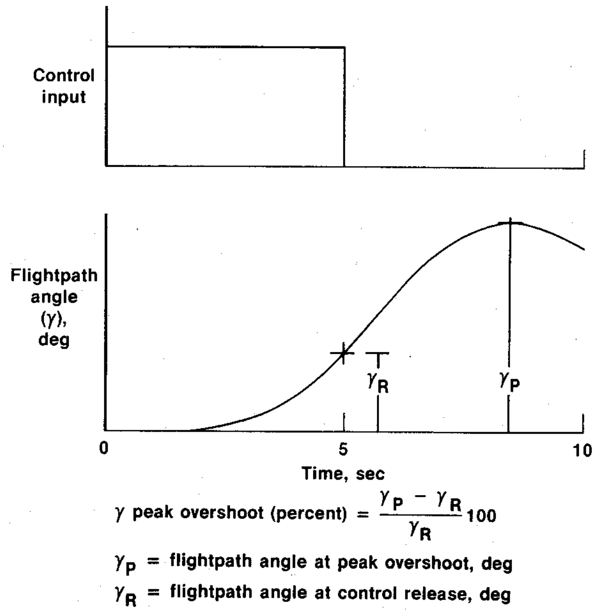


Fig. 5 Flight-path angle response features.

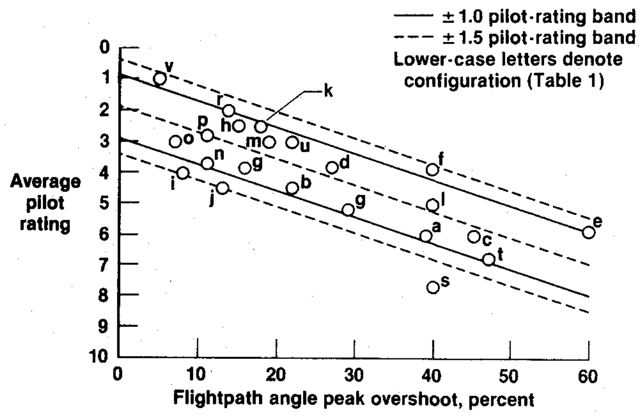


Fig. 6 Pilot ratings as a function of flight-path angle peak overshoot.

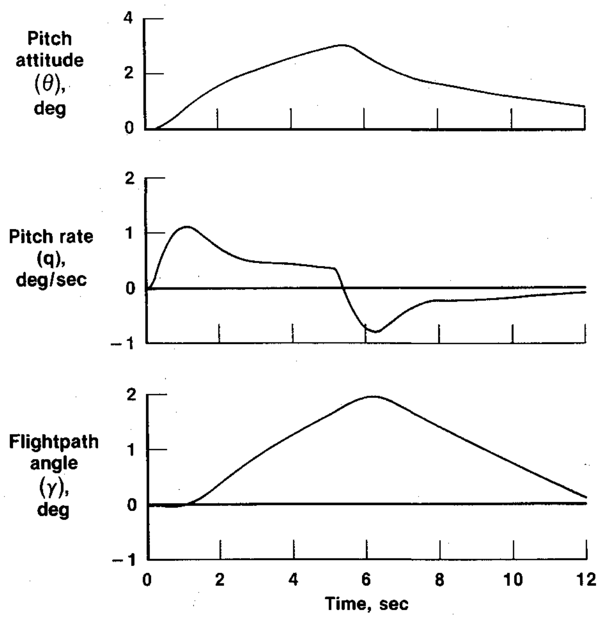


Fig. 7 Typical response for pitch rate command with washout filter,[1] 5 s boxcar command input.

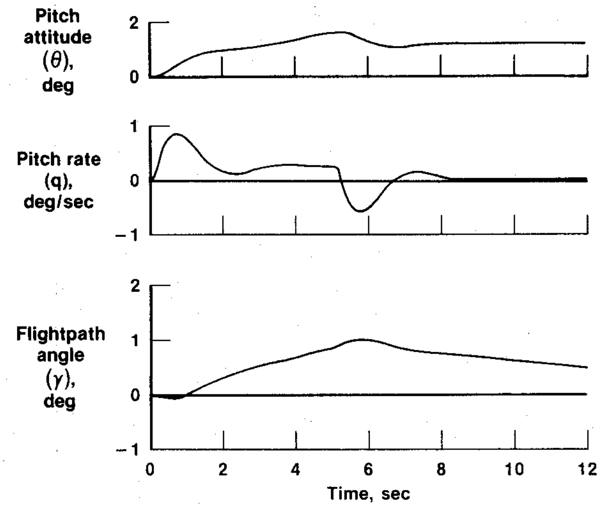


Fig. 8 Typical prefilter pitch rate command aircraft response,[1] 5 s boxcar command input.

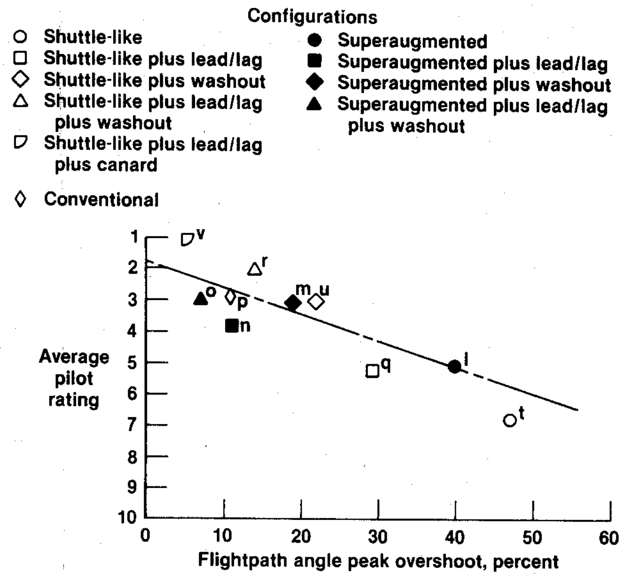


Fig. 9 Pilot ratings for selected configurations.

flight-path settling, is responsible for the improvement in the pilot ratings. It appears that flight-path settling and the associated monotonic stick forces are much less important factors than proposed in Ref. 1.

Figure 9 also illustrates how well the flight-path peak overshoot parameter correlates what seem to be a variety of unrelated configuration effects. Conventional aircraft, superaugmented aircraft, Space Shuttle-like aircraft, various combinations of lead/lag and washout filters, and even the canard configuration can be explained in terms of flight-path peak overshoot. The canard configuration has been thought to be influenced by *NZP* effects associated with the change in the center of rotation. Figure 9 indicates that these influences are small in comparison to flight-path peak overshoot.

Figure 10 shows a direct comparison between the flight results of Ref. 1, the ratings predicted by the $\alpha - NZP$ time-domain technique of Ref. 1, the ratings predicted by the altitude h closure technique of Ref. 2 that used an altitude outer-loop closure and an attitude inner-loop closure, and the ratings predicted by the results of this analysis. (Rating predictions from the results of this analysis were obtained using the central trend line from Fig. 6.) It can be seen that the rating predictions are in general agreement and, in most cases, that

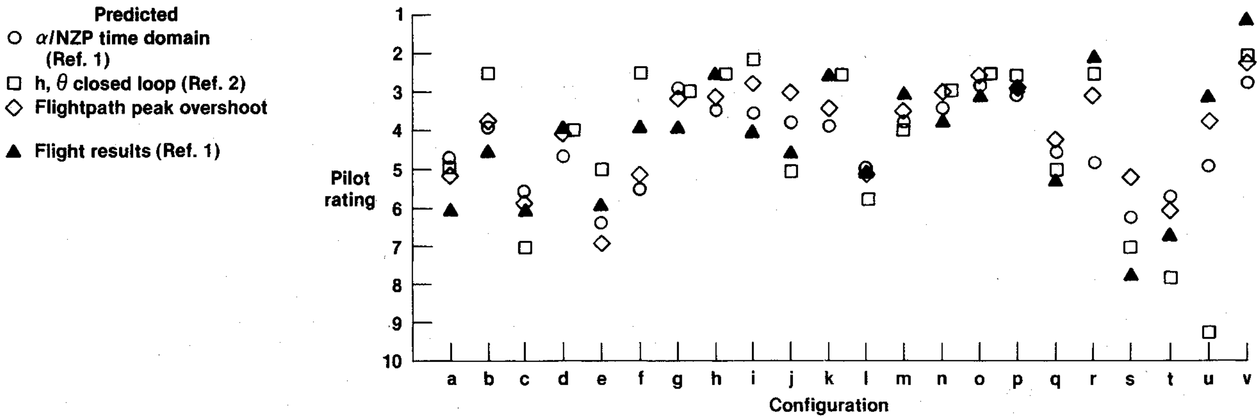


Fig. 10 Comparison of flight results and predictions (see Table 1).

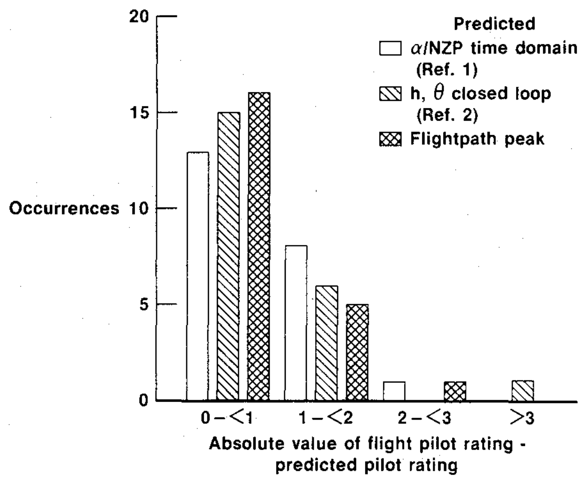


Fig. 11 Pilot rating prediction error histogram.

they track the flight data fairly well. The largest disagreement between the flight results and the flight-path criterion is configuration s, where a 2.5 PR error exists. The worst comparison for the $-NZP$ criterion is configuation r, where the discrepancy is a PR of 2.75. The worst case for the altitude closure analysis is configuration u, where a Δ PR of 6 exists. Figure 11 presents this information in histogram form. It can be seen that the flight-path criterion gives somewhat better overall results, despite the fact that it is considerably easier to implement and interpret than the other techniques.

With regard to Fig. 6, it is worth noting that the study of Ref. 1 was essentially eight subexperiments. The study considered the influence of several different parameters in the landing task: $1/T_{\theta_2}$ (where T_{θ_2} is the pitch attitude numerator time constant), dominant mode frequency, conventional response, superaugmentation, Shuttle dynamics, rate command, prefilters, washout, static stability, and canards. This wide diversity of influences can be explained in terms of one relatively simple unifying parameter. Of course, until other data bases are analyzed, these conclusions must be limited to the range of parameters considered in Ref. 1. Nevertheless, the general conclusions reached here seem very convincing and should aid in the analysis of other landing data.

If the metric is used as a flight test specification, care must be taken that the test input closely approximates a 5 s block because the flight-path peak overshoot changes as the duration of the block changes. This should not pose a problem, however, because many techniques are available to produce precise test inputs. For example, the test input can be computer generated or the pilot can generate it with the aid of stick stops and a timer.

Conclusions

An analysis was made of the attitude and flight-path angle response of configurations used in the total in-flight simulator pitch rate command study. Results indicate that the attitude response was generally satisfactory for all configurations and therefore not a factor in the pilot-rating results. A strong correlation was found to exist between the amount of flight-path angle peak overshoot and the pilot ratings. The correlation was valid for all configurations despite a diversity of configurations that included conventional aircraft, Space Shuttle dynamics, superaugmented aircraft, neutral static stability, prefilters, and canards. In comparison to the influence of flight-path angle peak overshoot, expected influences such as monotonic stick forces and initial acceleration at the pilot station were negligible. The correlation was similar to the best correlations that have been obtained in recent closed-loop and time-domain analyses, but has the advantage of greatly simplified implementation and interpretation.

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