SUMMARY OF RECENT HANDLING QUALITY RESULTS AT STI PERTINENT TO REVISION OF MIL-F-8785B

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INTRODUCTION

The results of a number of handling quality programs which include analysis simulation and flight test are presented. Lessons learned from a series of moving base simulations involving approach and landing of STOL airplanes are summarized. This is followed by a review of the effects of large windshears. The importance of including such effects in the specification requirements is discussed. A method for predicting an overall pilot rating given separate ratings for each individual axis of control is presented. Finally some pilot describing function results which have application for defining equivalent system for path control are presented.

SOME CONSIDERATIONS FOR IDENTIFYING LONGITUDINAL PATH CONTROL DEFICIENCIES DURING APPROACH AND LANDING

A series of simulations were conducted to obtain the technical data required to assist the FAA in establishing certification criteria for STOL aircraft. For the most part these were conducted on the NASA Ames FSAA simulator.

A summary of the factors which tended to reveal vehicle deficiencies related to piloted control of flight path is given as follows:

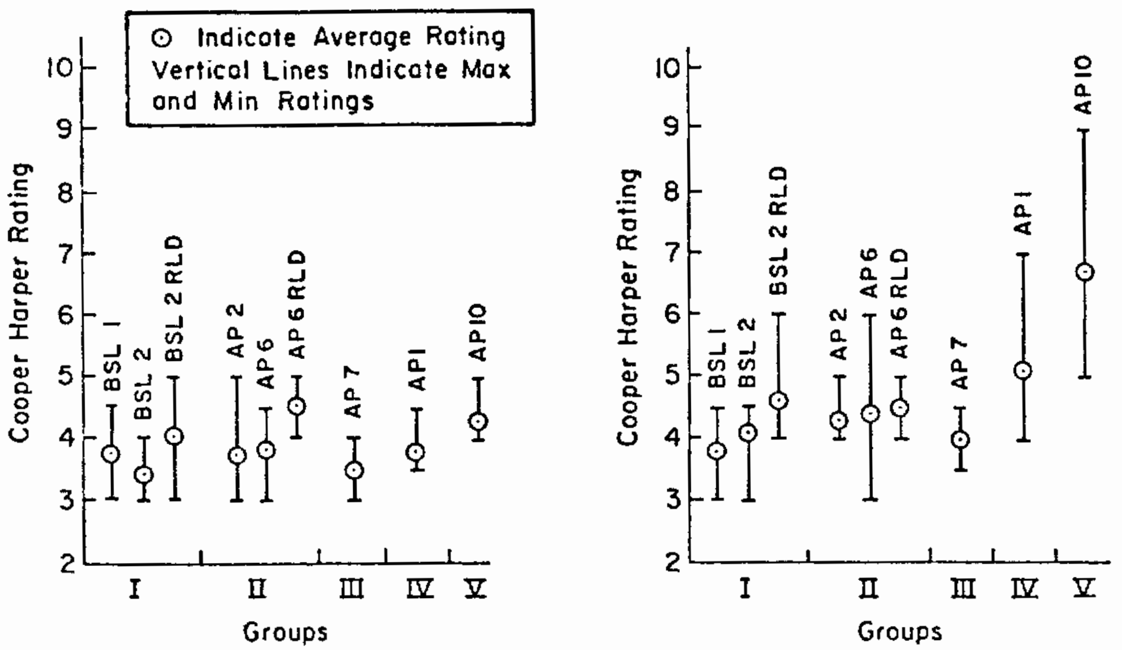
1. Tracking the ILS glideslope in IMC conditions did not prove to be a useful task for identifying path control problems. The portion of the approach from breakout to flare initiation (short final) was found to be most critical.

2. Even on short final, path control deficiencies were not always apparent in calm air. The addition of random turbulence (σ_{u_g} = 4.5 ft/sec) was found to be a key factor in separating out vehicles with severe path control deficiencies.

3. Vehicles with more subtle path control deficiencies were identified by introducing large discrete wind-shears just prior to touchdown.

4. Investigation of different random turbulence models revealed that in the critical region (short final), the dominant features of the turbulence are essentially identical. Hence, the identified vehicle deficiencies were not dependent on the turbulence model used.

An illustration which supports the first of the above conclusions is presented in Fig. 1. These data are taken from Ref. 1 which was a study to identify minimum acceptable manual STOL flight path control characteristics. The configurations range from fair to very bad. The data in Fig. 1a are for ILS tracking only (σ_{ug} = 4.5 ft/sec) with the runs being terminated at breakout (300 feet altitude). The pilot ratings show that this task did <u>not</u> highlight path control deficiences in any of the configurations. Figure 1b illustrates that when the task was expanded to include



a) Pilot Rating for Glideslope Tracking Task (IFR Only)

b) Pilot Ratings for Path Control Part of Composite Task (IFR and VFR Path Control)

Figure 1. Pilot Ratings for Path Control

visual lineup, flare and touchdown, certain of the configurations were found to be unacceptable. The pilot commentary, summarized in Table 1, verifies that path control deficiencies with the poor configurations became apparent when attempting to get set up for the flare in the presence of turbulence. Based on the pilot commentary (Table 1), the poor configurations are identified as much by the rating variability (5 to 9, 4 to 7, etc.) as by the absolute rating, itself. The rating variability appears to occur because of real changes in landing performance or pilot effort due to critical but random combinations of particular turbulence inputs and off-nominal flight; i.e., the same configuration can be very bad on some trials and acceptable on others. Unfortunately, the bad cases often look like pilot error and may not always be accounted for in the ratings.

EFFECT OF DIFFERENT TURBULENCE MODELS

Because, as just discussed, turbulence on short final is a critical factor in identifying vehicle deficiencies, the sensitivity of pilot opinion to the turbulence model deserves consideration and clarification. To this end, an analysis and simulation study was undertaken (Ref. 2) to identify the effect of different turbulence models on the critical last few hundred feet of the approach.

Figure 2 presents the calculated effect of the horizontal and vertical components of the MIL-F-8785B Dryden model on the RMS sink rate of a DHC-6 Twin Otter aircraft if attitude and throttle are fixed. Sink rate excursions due to the vertical component are seen to approach zero near touchdown. This is a consequence of the fact that scale length, L_w, and altitude approach zero simultaneously ($L_w = h$). The key implication of Fig. 2 is that the important variable for comparisons of different gust models is the variation of the horizontal component at speeds and altitudes consistent with short final. Figure 3 presents the normalized RMS sink rate excursions vs. the breakpoint of the horizontal gust filter for a simulated DHC-6 Twin Otter with altitude and throttle fixed. It shows that 1) maximum path disturbance occurs for values of V/L_u between $1/T_{\theta_1}$ and $1/T_{\theta_2}$, and 2) the sink rate disturbances for these values of V/L_u are relatively constant. Investigation of four

TABLE 1. PILOT COMMENTARY WHERE FLIGHT PATH CONTROL PROBLEMS ON SHORT FINAL WERE SPECIFICALLY NOTED (TASKS 2.1 AND 3.1)

	PILOT 1	PILOT 2	PILOT 5	PILOT 7	PILOT 8	PILOT 9
BSL1	None	Poor vertical speed response makes it easy to overcontrol Put on too much power to correct for a low condition and then don't get it off in time, etc.		None	None	Am flying glide slope (ILS) to get to window for flare
BSL2	None	None		I am having quite a bit of problems with the turbulence particularly during the final glide slope tracking and the flare	None	None
BSL2RLD	Requires moderate compensation on throttles to set up for flare			None		Poor sink rate to throttle response is responsible for problems in getting set up at flare point Flying IVSI to throttles even in close
AP1	The primary deficiency is a very sluggish sink rate to throttle response. The major problem is the inability to recover from off nominal vertical position in time to set up for landing on this short runway		Pilot rating is a 3 down to breakout and then a 7 on short final	The workload gets too high trying to get the power set for your flare, particularly with these last minute flight path corrections where the power can be going up and down	... real dicey to get a good sink rate and a good aim point on the runway	Primary difficulty was the considerable lag in the throttle and if your effecting a change on glide path the resulting change in sink rate late in the approach will give you real problems
AP2	The primary problem in landing is setting up for the flare with power in the presence of these fairly large gust disturbances	Recovery from turbulence effects coming into the flare was difficult		Turbulence is not a problem and getting set up for flare is also not a problem with this configuration		
AP6	None	None		None		
AP6RLD	Moderate compensation on sink rate control with power is required to set up the flare point			Sink rate response to attitude and power are good		None
AP7	None			None		None
AP10	The sluggish sink rate to throttle makes it difficult to get set up. My primary objection to this configuration lies in the inability to control sink rate during the last several hundred feet of the approach			The main problem with flight path control is that flight path angle washes out after a throttle input. This problem is especially noticeable as you approach the flare point and even during the flare	Got low and slow, a bear to correct	Seems very sensitive to throttle making it difficult to set up for flares. Extremely hard to get into proper flare window

Notes: Blank space means pilot did not fly the configuration.
"None" means that no specific comments relative to flight path control on short final were recorded.

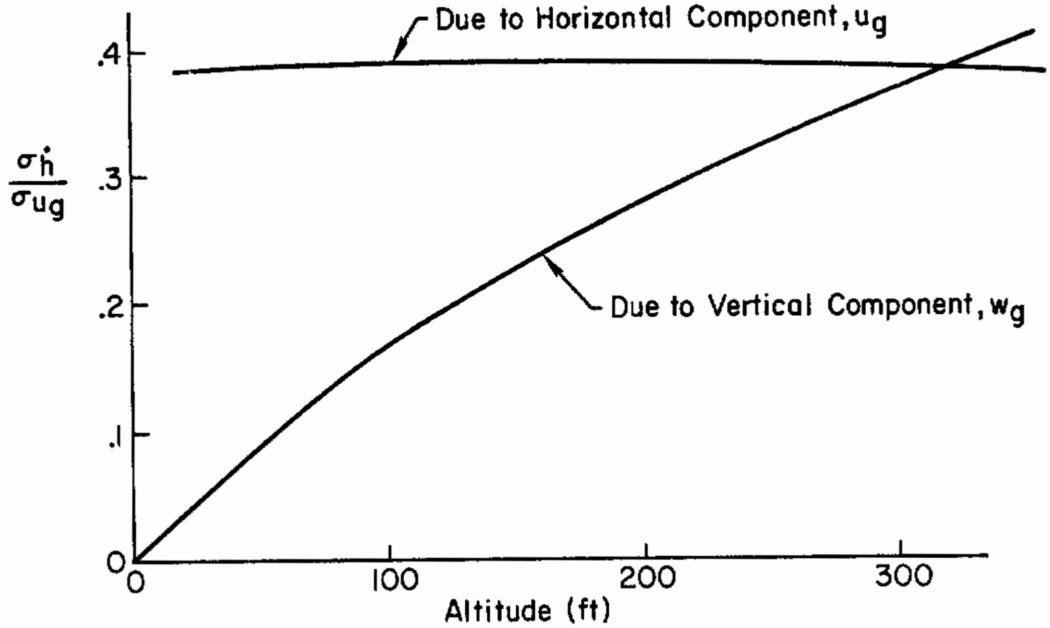


Figure 2. Effect of Horizontal and Vertical Gusts for Varying Altitude (Attitude and Throttle Fixed)

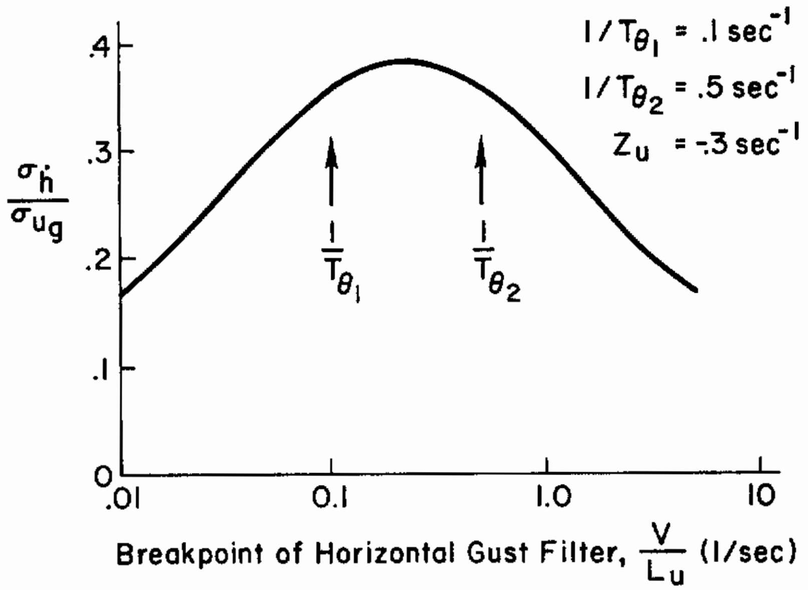


Figure 3. Effect of Horizontal Gust Filter Breakpoint on Altitude Rate Dispersion

competing models was conducted. These consisted of the MIL-F-8785B Dryden and Von Karman forms, the Boeing model (Ref. 3), and the Etkin model (Ref. 4). The values of V/L_u between 50 and 200 feet altitude were found to be bounded by the usual values of $1/T_{\theta_1}$ and $1/T_{\theta_2}$ for CTOL and STOL aircraft for all of the above turbulence models. It was, therefore, not surprising that piloted simulator evaluations of path control showed that the effect of using different turbulence models was negligible (Ref. 5).

EFFECT OF LARGE WINDSHEARS ON PATH CONTROL

This section presents the results of a combined analysis and manned simulation program directed towards determination of the effects of wind shear on powered-lift STOL airplanes in the landing configuration. The powered-lift concepts considered were the externally blown flap (EBF), upper surface blowing (USB), and the Augmentor Wing. Descriptions of these powered-lift STOL concepts may be found in Refs. 6-8, respectively. A non-powered-lift shorthaul concept was also considered in order to provide a basis for comparison for evaluation of accident potential. The De Havilland DHC-6 Twin Otter was picked as the representative non-powered-lift STOL.

Several stability command augmentation systems (SCAS) were evaluated to investigate their effectiveness for regulating against large shears. These systems ranged in complexity from simple direct-lift control (DLC) to a SCAS which allowed an inherently backside aircraft to be flown using the conventional frontside piloting technique.

The objectives of the program were to: 1) determine whether limiting characteristics were set by aircraft performance limits or by closed-loop pilot/vehicle deficiencies; and 2) make comparisons of fundamental STOL augmentation concepts.

Effect of Wind Shear on Performance Margins

The primary effect of wind shear is to change airspeed. This results in excursions from the flight path due to the corresponding change in lift. Hence regulation against wind shear can be accomplished by changing the lift or by accelerating the aircraft so that the net airspeed change is minimized. Physical interpretation of the acceleration required to cancel the effect of wind shear is simplified if it is treated as an "effective flight path angle," e.g., $a_x = g\gamma_{eff}$. The condition for maintaining constant airspeed in a wind shear is expressed in terms of γ_{eff} as follows:

$$\gamma_{eff} = \gamma_i \left(1 + \frac{V_w}{V_a}\right) + \frac{1}{g} \dot{V}_w \tag{1}$$

where γ_i = inertial flight path angle (glide slope angle), and $\sin \gamma \doteq \gamma$ and $\gamma_a \doteq \gamma_i[1 + (V_w/V_a)]$. In order to keep the sign convention for winds consistent with the usual formulation of the equations of motion, a positive wind has been defined as a tailwind.

γ_{eff} is a fictitious flight path angle used to define a speed/power equilibrium point on the usual γ-V representation. This point represents the required acceleration/deceleration capability to regulate against wind and wind shear in terms of flight path angle capability in calm air.

The aircraft performance capability may be compared to the performance required to maintain zero glide slope error in wind and wind shear by comparing γ_{eff} with the maximum or minimum achievable γ on a γ-V plot. This is illustrated in the generic sketch shown in Fig. 4 (γ-V shapes typical of an EBF or USB STOL concept). This sketch is indicative of the effects of a large steady headwind which is shearing towards zero (effects of negative wind and positive wind shear are additive). The effective flight path angle is a function of the wind speed, V_w, and therefore changes during the time the airplane is in the wind shear as follows:

$$\gamma_{eff} = \gamma_i \left(1 + \frac{V_w}{V_a}\right) + \frac{\dot{V}_w}{g} + \gamma_i \frac{\dot{V}_w}{V_a} t \tag{2}$$

Thus, for the usual case where wind is decreasing during the approach, a given wind shear may initially exceed the aircraft control power ($\gamma_{max} < \gamma_{eff}$) until the steady component of wind decreases sufficiently to allow control, as illustrated in Fig. 5. It therefore seems logical to define the limiting combinations of steady wind and wind shear when $\gamma_{eff} = \gamma_{max}$ at $t = 0$, e.g., flight path control margin equals zero at the beginning of the shear. This

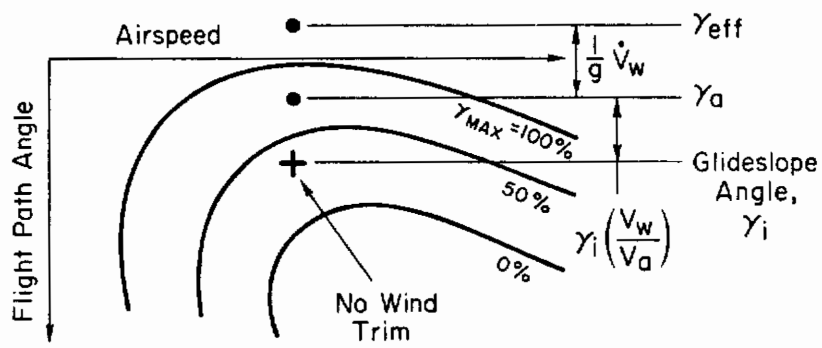


Figure 4. Effect of Wind and Wind Shear on Performance Margins

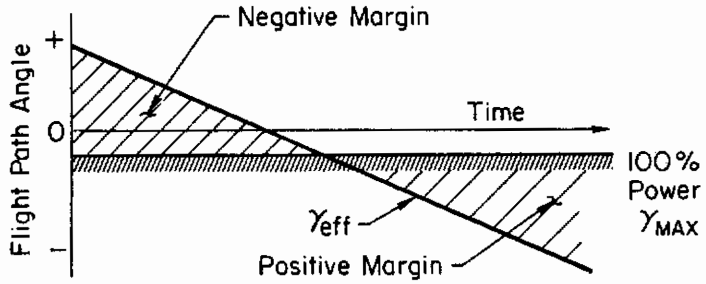


Figure 5. Illustration of Change in γ_{eff} with Time in a Decreasing Headwind Shear

is done by substituting γ_{max} and γ_{min} for γ_{eff} in Eq. (1) and solving for limiting values of wind shear, $\dot{V}_w$, e.g.,

$$\dot{V}_w = g\left[\gamma_{\substack{max \\ (min)}} - \gamma_i\left(1 + \frac{V_w}{V_a}\right)\right] = g\left[\gamma_{\substack{max \\ (min)}} - \gamma_a\right] \qquad (3)$$

The boundaries which derive from Eq. (3) are plotted in Fig. 6 where γ_{max} was taken as zero and γ_{min} as −10 deg. These numbers were picked as a consequence of the tentative STOL airworthiness requirements which dictate a capability of 4 deg below the glide path and level flight in the up direction. For decreasing winds (second and fourt quadrant) the path control

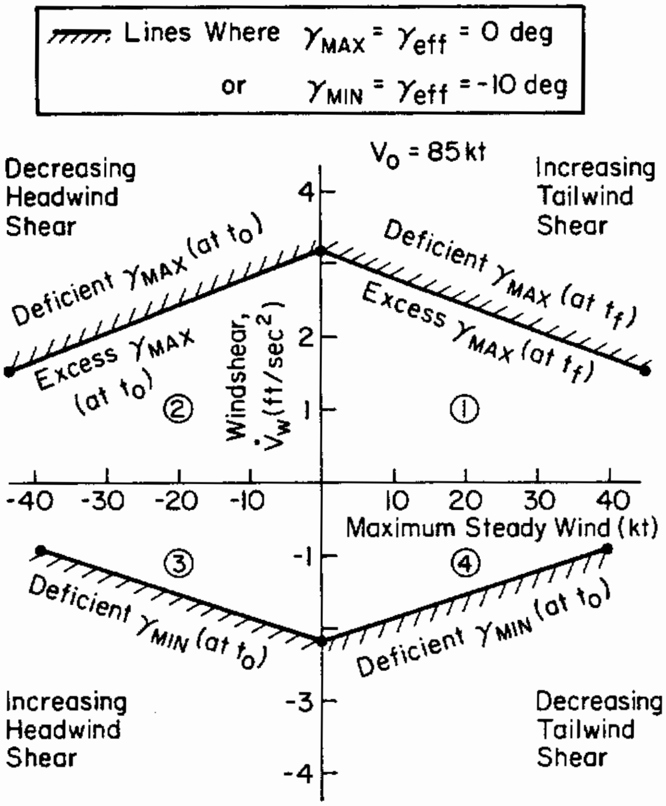


Figure 6. Boundaries Where Flight Path Control Margin Equals Zero ($\gamma_{max\,(min)} = \gamma_{eff}$)

margin is zero ($\gamma_{eff} = \gamma_{max}$) when the shear starts and is positive ($\gamma_{eff} < \gamma_{max}$) for the remainder of the shear. For increasing winds the path control margin is initially positive ($\gamma_{eff} > \gamma_{max}$) and degrades to zero when the shear ends ($t = t_f$).

Simulation Test Matrix

The matrix of discrete wind shears used in the simulation program was developed to include combinations of steady wind and wind shear on both sides of the theoretical performance boundaries developed in Eq. (3) and plotted in Fig. 6. The test matrix primarily concentrated on Quadrants 2 and 4 with some runs in Quadrant 3. Quadrant 3 proved to be less critical because of the low groundspeed and favorable effect on lift in the flare of an increasing headwing shear. Quadrant 1 is not practical because it implies a tailwind at touchdown.

Initial simulator experiments (NASA Ames FSAA) showed that the most critical type of shear is one that terminates just as the pilot is coming into the flare due to a sudden change in the required effective flight path angle ($\Delta\gamma_{eff} = \dot{V}_w/g$). The shears in the remainder of the experiment were terminated between 50 and 100 ft to maximize this effect.

The wind variation which makes up a shear may be due to changes in altitude, position, time, or a combination of these variables. It was decided to use time as the independent variable because:

- The ensuing aircraft motions do not affect the shear gradient, e.g., a uniform shear is assumed.
- Any shear occurring in real life can be converted to a time-dependent form.

The simulation scenario consisted of starting on the glide slope and localizer in IFR conditions at 1500 ft altitude with a breakout to VFR at 300 ft at which point the pilot visually acquired the runway and continued the approach to a landing.

Experimental Results

A comparison of the pilot commentary with the accident potential rating scale from Ref. 9 was made to determine if a number could be associated with the pilots' opinion of unacceptable hazard. A reasonably consistent trend was identified which correlated commentary relating to unacceptable hazard and an accident potential rating of 4.

The results of the piloted simulator program are summarized in Fig. 7 by fairing approximate pilot rating boundaries where the accident potential rating was equal to 4 on a grid of steady wind vs. wind shear. The separation between these pilot rating boundaries and the theoretical boundaries [defined by Eq. (3) and plotted in Fig. 6] is a measure of shear vulnerability. That is, when the pilot rating boundary lies below the theoretical boundary in Fig. 7, the configuration tends to be highly vulnerable to decreasing headwind shears.

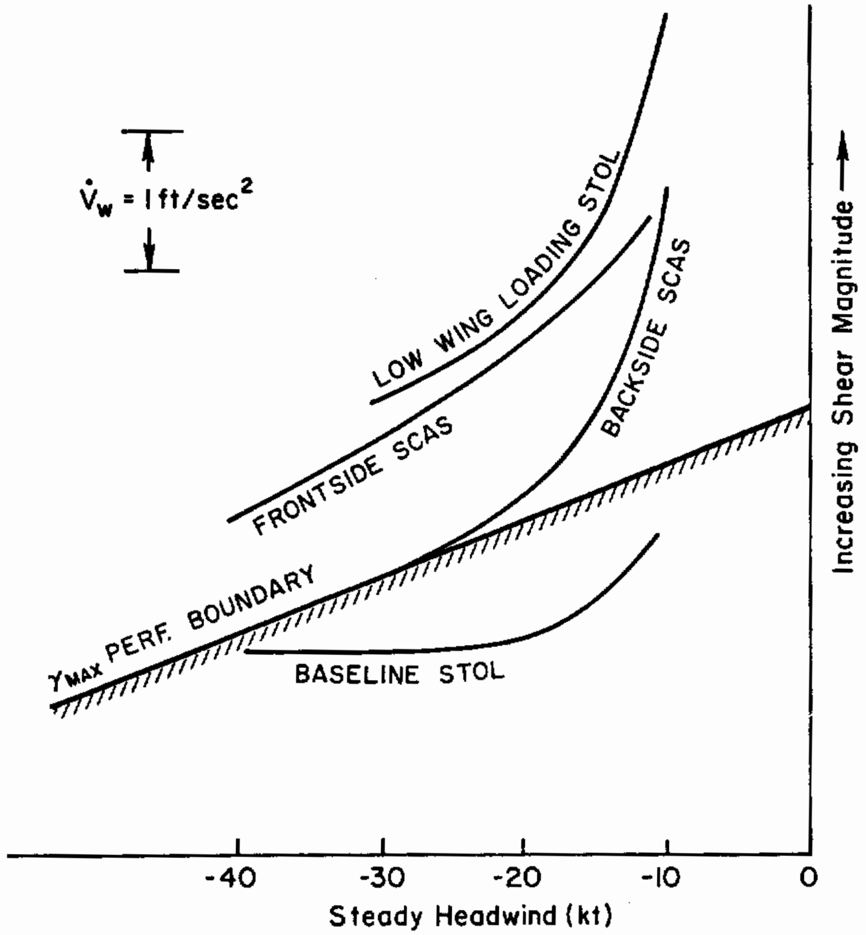


Figure 7. Comparison of Unacceptable Accident Potential Rating with γ_{max} Performance Boundary (Decreasing Headwind Shear)

Each of the configurations in Fig. 7 are discussed in detail in Ref. 10 along with an analysis of vehicle deficiencies which relate to flight path control in windshear. The point of emphasis in the present paper, however, is that the use of a critically timed discrete windshear separates out the more subtle path control deficiencies. This is well illustrated by comparison of the hazard boundaries in Fig. 7 and the Cooper Harper Ratings for these same configurations with a 4.5 ft/sec RMS random turbulence level in Fig. 8.

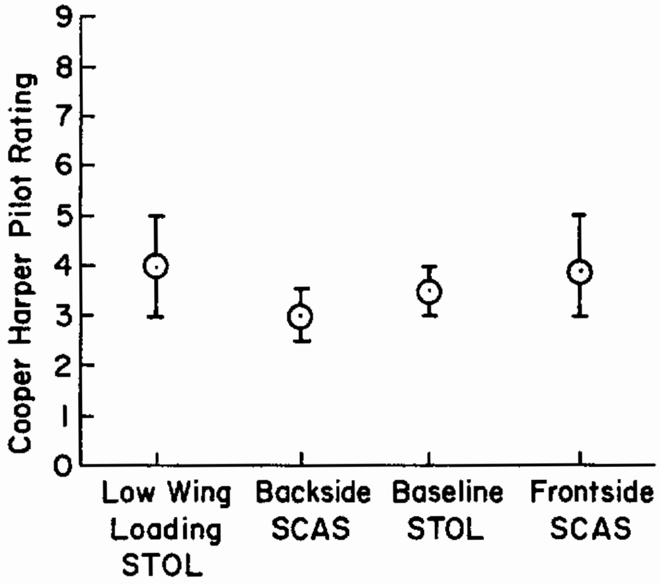


Figure 8. Cooper Harper Ratings in Random Turbulence
(σ_{ug} = 4.5 ft/sec - 8785B Dryden Model)
Task - Flightpath control on short
final - 300 ft to flare initiation

The Fig. 8 data illustrate that performing the critical set-up-for-flare maneuver in moderate random turbulence did not reveal any significant differences between path regulation among the tested vehicles. Figure 7, however, shows the Baseline STOL to be highly vulnerable to decreasing headwind shears. Some improvement is shown when the Baseline STOL is augmented with a washed out throttle to spoiler crossfeed (Backside SCAS). The Frontside SCAS and Low Wing Loading STOL are seen to be the least vulnerable to large discrete shears.

Conclusion

The use of a random turbulence model does not generally allow detection of path control deficiencies that may be critical to safety in a large win-shear on short final. There should be some provision in the MIL-F-8785B standard that will insure adequate performance in a critically timed discrete shear. The exact form that such a requirement should take is not clear at this time. Some research is required to consolidate the data from the windshear programs that have been completed to date and to develop a tentative criterion.

PREDICTION OF OVERALL PILOT RATINGS FROM SINGLE AXIS RATING DATA

An empirical formula for estimating the combined effect of pilot ratings for m individual control axes was developed in Ref. 11 and is presented below:

$$R_m = 10 + \frac{1}{(8.3)^{m-1}} \prod^{m} (R_i - 10) \qquad (4)$$

Where R_i is the rating for each individual axis.

Correlations obtained between actual and predicted pilot rating data are given in Fig. 9. Here the ordinate is the multiple-axis rating computed, from the observed single-axis ratings, R_i, using Eq. 4. The abscissa, of course, is the actual multiple-axis rating for the same set of individual axis ratings. The spread in the individual points is due to the uncertainties in either or both the single-axis and multi-axis rating data (e.g., rating = 4-1/2 to 5). The Ref. 12 data are most pronounced in this respect, the spread here reflecting the differences in single-axis ratings delivered before and after the 3-axis runs, and also differences between the first and second series of 3-axis runs, themselves; the center point is based on the overall averaging of the single and 3-axis data given in Ref. 12.

The correlation shown is on the whole quite good for the region of most interest, i.e., ratings between 2 and 7. In fact for this region, and neglecting the spreads shown for the Ref. 12 data, the computed rating agrees with the observed rating within about half a point.

Implications for MIL-F-8785B(ASG) Revision

The impact of the foregoing on the single-axis requirement to achieve various levels of multiple-axis (i.e., whole task) flying qualities is potentially quite drastic. That is, for Level 1 whole task flying qualities

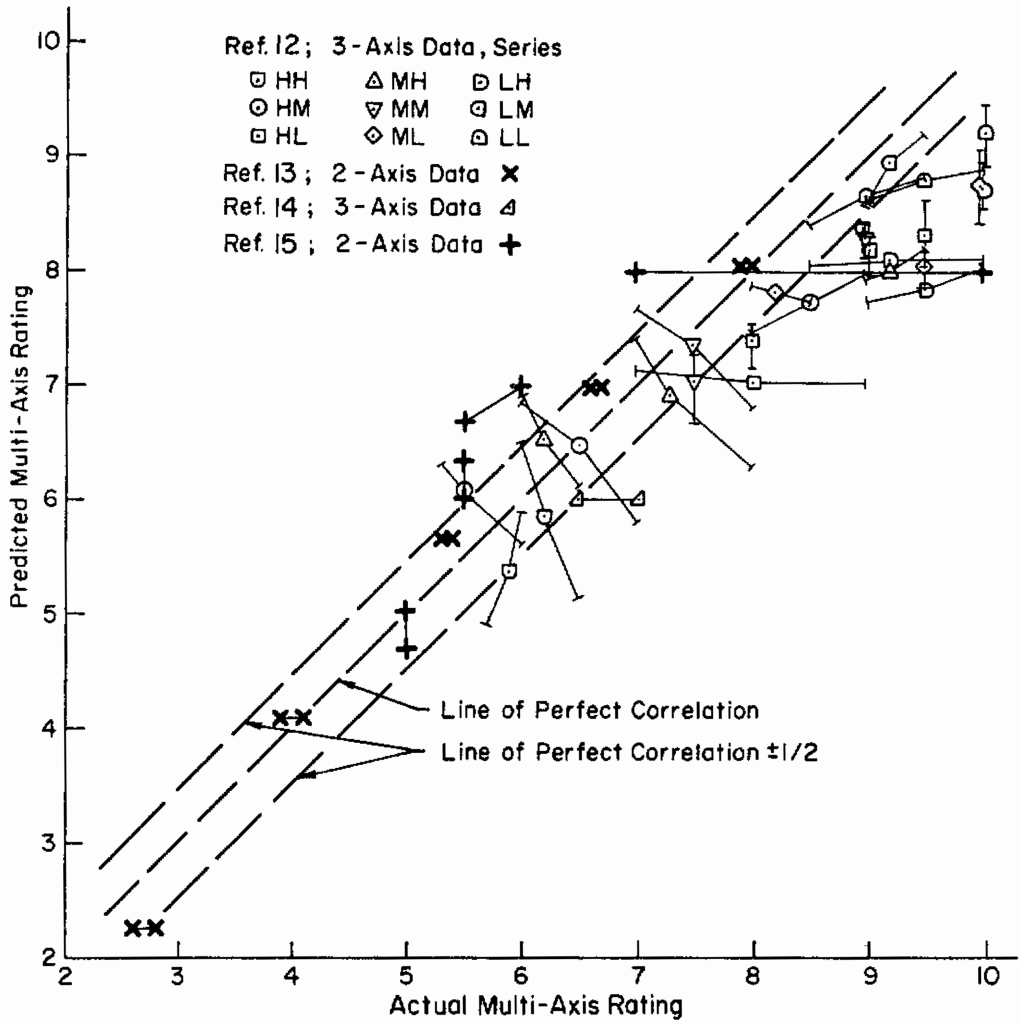


Figure 9. Correlations Obtained Using Equation 4.

corresponding to a multiple-axis rating of 3.5 or better (Ref. 16), the required longitudinal and lateral-directional flying qualities must be better, according to Eq. 4, than about $2.65 + \Delta$ for one and $2.65 - \Delta$ for the other (where $2.65 + \Delta < 3.5$). Taking the most beneficial view of the 1/2 rating point "inaccuracy" (Fig. 9) of Eq. 4 increases these values to $2.95 + \Delta$ and $2.95 - \Delta$ (where $2.95 + \Delta < 4$). Such an explicit requirement for longitudinal and lateral-directional flying qualities, which are each a little better than the Level 1 (3.5) boundary is somewhat in keeping with vague undocumented "stories" of aircraft which were not satisfactory because too many of their parameters, while each individually satisfactory, were very near the boundary value (a possibility mentioned also in Ref. 16, Item 1.5).

On the other hand, it must be recognized that the data used (Ref. 16) to establish the various level boundaries were, wherever possible, based on the results of flight-test investigations where tasks other than those being rated were necessarily present. Since such other tasks (or parameters) were supposedly in the "good" (Level 1) region, it seems pertinent to consider that for a configuration rated 3-4 the pilot may have been flying longitudinal and lateral axes each rated about 3. Past experience with preceding versions of the MIL Spec tend to further support the above observation; that is, airplanes near but within the satisfactory boundary values in both longitudinal and lateral-directional handling are generally satisfactory overall.

Because of the above considerations and the lack of definitive in-flight data on multiple-axis effects, it seems inadvisable to alter the Level 1 definition. However it is still appropriate considering the evidence herein, to issue a warning requiring further explicit study of those situations where both longitudinal and lateral-directional flying qualities approach very near the Level 1 boundaries.

The Level 2 boundaries are also based on the practice of "good" (i.e., Level 1) remaining parameters. This means that if one axis of the airplane is worse than Level 1 but better than, or equal to, the Level 2 boundary the other axis must be better than or equal to the Level 1 boundary. This interpretation of the actual data used to establish the Level 2 boundaries is hinted at in Ref. 16, where it is noted that some of the Level 2 boundaries were somewhat arbitrarily "stiffened" so that two axes in the Level 2 region might still represent Level 2 conditions. The actual "stiffening" required to produce this state of affairs is quite extreme, based on the present findings, and it seems doubtful that such extreme stiffening was actually or uniformly applied to the data.

Analysis in Ref. 11 suggests that, neglecting whatever "stiffening" was applied to "some" requirements (Ref. 16), a proper Level 2 definition reflects conditions where:

a. either the longitudinal or lateral-directional axis is better than, or equal to, Level 1; and the other axis is worse than Level 1 but no worse than the Level 2 boundary, or

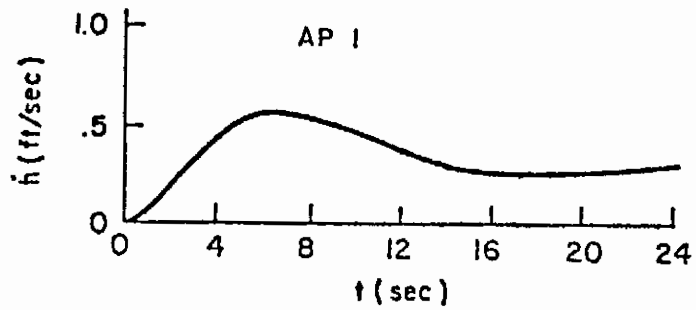
b. both the longitudinal and lateral-directional axes are worse than Level 1 but no worse than a boundary halfway between the Level 1 and Level 2 boundaries.

SOME EXPERIMENTAL DATA ON EQUIVALENT SYSTEM FORMS FOR PATH CONTROL

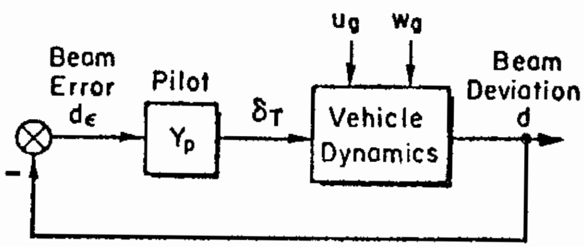
The equivalent system approach to the specification of handling qualities has shown considerable promise (For example, see Ref. 17). However, all the work accomplished to date has involved attitude control. This section presents some moving base simulator data which suggests an equivalent system form for path control when operating on the backside of the power required curve e.g., pilot controls airspeed with pitch attitude and sink rate with power.

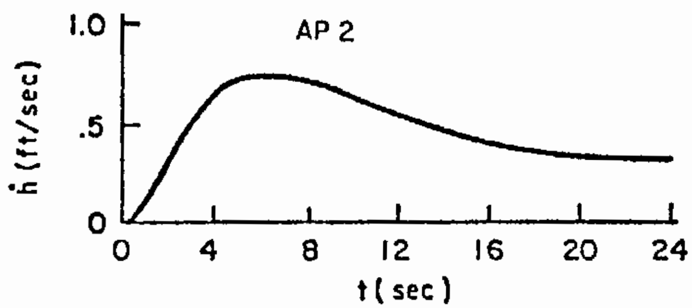
A review of the comments for AP1 and AP10 in Table 1 reveals that the pilots had a very difficult time trying to sort out what the actual problem was. Some said that the response was sluggish, probably referring to the fact that the longer-term flight path correction was a lot less than indicated from the initial response. The engine lag was decreased from the nominal 1.5 sec to 0.5 sec for several pilots. All indicated that they could see the effect, but it was of no help in controlling flight path for these two configurations. (There was no change in pilot rating.) This served as evidence that the pilots were not referring to engine lag effects when commenting on the excessively "sluggish" response of AP1 and AP10.

The fundamental closed-loop piloting problem was analyzed using the frequency response characteristics of the sink rate, $\dot{h}$, to throttle, δ_T, transfer functions (for constrained attitude) plotted in Fig. 10 for AP1 (a bad configuration) and AP2 (a good configuration). Utilizing experimental and theoretical results from the theory of manual control (for example, see Ref. 18), it can be shown that the flat region in the frequency response (for AP1) represents a fundamental limitation on closed-loop control. This stems from the fact that the human operator always tries to adjust his control inputs so as to equalize the vehicle frequency

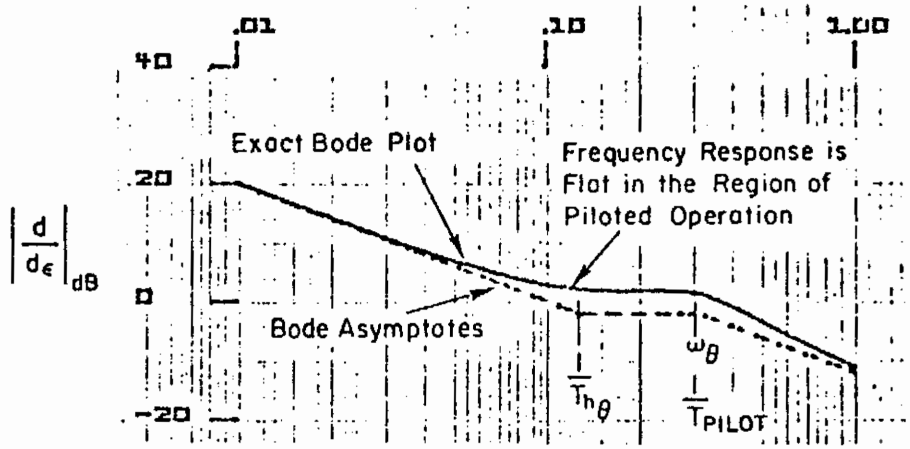


Time Response to I Percent Step Throttle For AP I



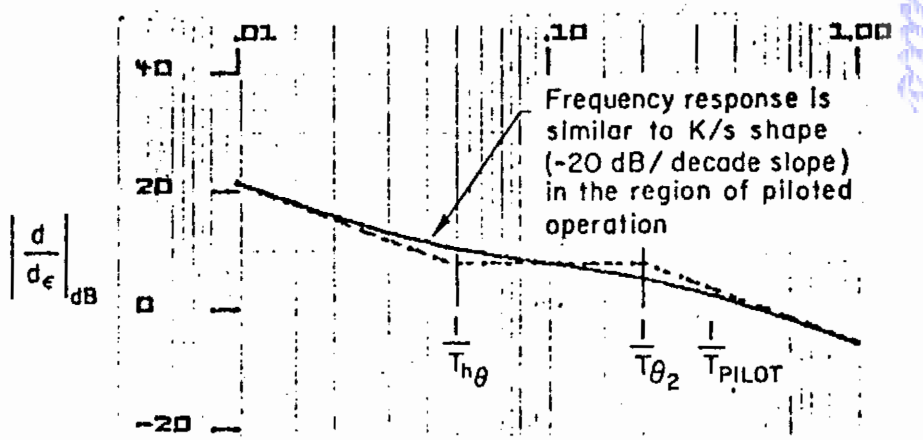


Time Response For I Percent Step Throttle For AP 2



Beam to Beam Error Frequency Response for AP I (Unacceptable Configuration)

Note: T_{PILOT} is pilot compensation obtained from describing function runs during simulation



Beam to Beam Error Frequency Response for AP 2 (Acceptable Configuration)

Figure 10. Time and Frequency Response Characteristics of an Acceptable and an Unacceptable Configuration

response to a −20 dB/decade slope (or K/s shape). With mid-frequency droop, this was not possible.* Faced with undesirable and nonequalizable response characteristics, the pilots rated these configurations very poorly. Physically this was manifested in a path response to throttle that initially looked very good, but never seemed to settle down. As a result, the pilots were "constantly hunting for the proper throttle setting as they came into the flare."

The primary purpose of this program was to identify vehicle characteristics which result in unacceptable path control. Comparison of the time response and frequency response characteristics of AP1 and AP2 in Fig. 10 reveals the following:

- The shape of the time responses is about the same.
- The shape of the frequency responses (including pilot lead) is noticeably different. AP2 is almost a pure −20 dB/decade slope (desirable K/s feature) whereas AP1 has a significant mid-frequency droop (undesirable and unequalizable by the pilot).

The pilot ratings (Fig. 1b) and commentary (Table 1) strongly indicate that AP1 is unacceptable and AP2 is acceptable. Therefore, it appears that the frequency response characteristics are more discriminatory in terms of identifying limiting path control deficiencies and represent the most promising equivalent system form.

Describing Function Analysis

Based on the classical pilot modeling rules (Ref. 19) the frequency response for AP1 is nonequalizable to K/s since a low frequency <u>double</u> lead would be required at ω_θ (in addition to a lag at $1/T_{h_\theta}$). In order to determine exactly what the pilot equalization characteristics were when faced with this situation, a special experiment was set up to take describing function measurements. The details of this experiment are presented in Ref. 20. A summary of the data is given in Fig. 11. Using the following form for the pilot plus vehicle these data were fit by the solid and dashed lines in Fig. 11

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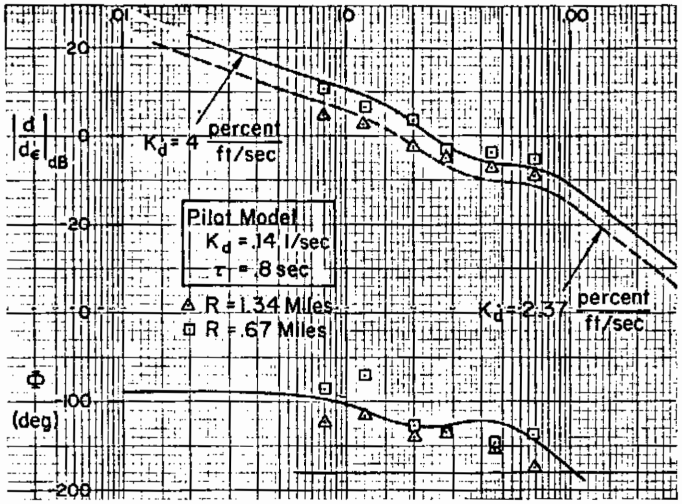
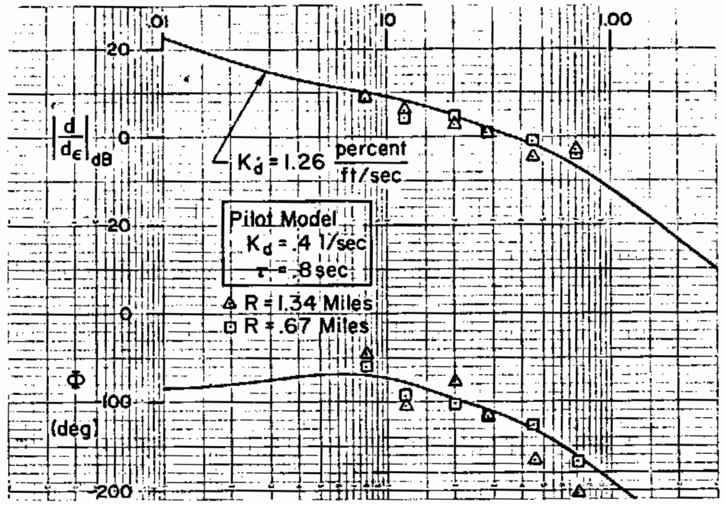
*It should be noted that an automatic system could be developed with complex equalization to get an acceptable response but that this is beyond the capability of the human pilot.



a) Group I (BSL 2)

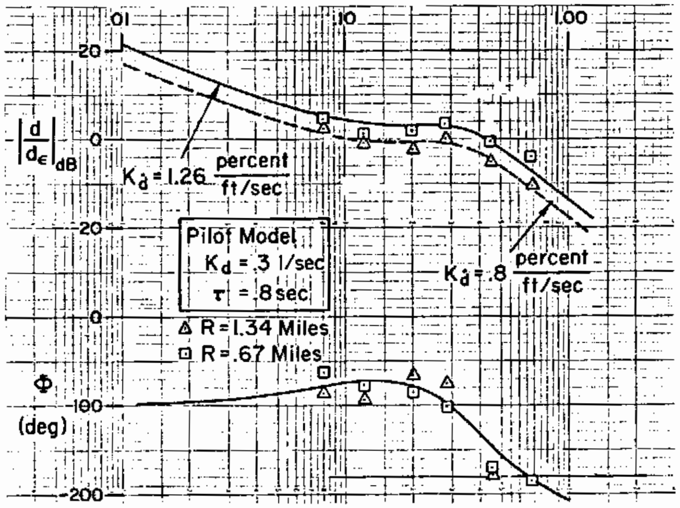
Pilot Rating 3-4 $\frac{1}{2}$*



b) Group II (AP 6)

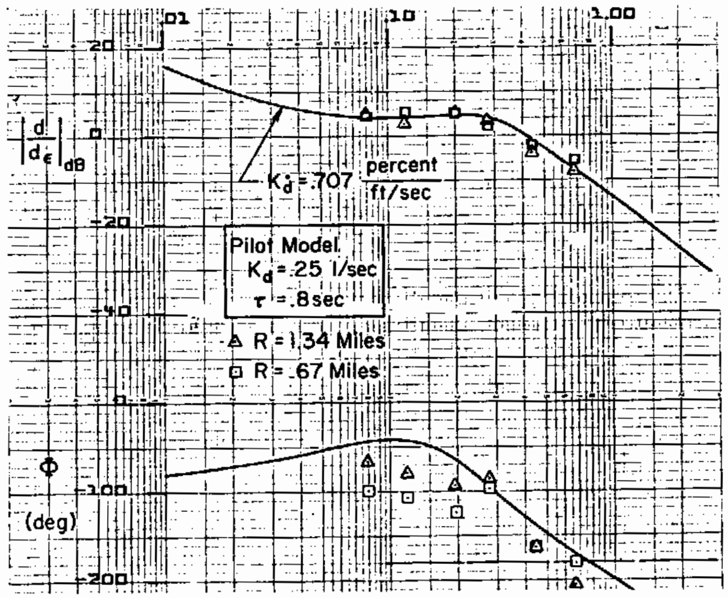
Pilot Rating 3-6

*Pilot ratings are for path control segment of composite task.



c) Group IV (AP 1)

Pilot Rating 4-7



d) Group V (AP 10)

Pilot Rating 5-9

Figure 11. Experimental-Analytical Pilot/Vehicle Model Correlations

$$\frac{d}{d_\epsilon} = Y_p Y_c \doteq \frac{Y_p N^{\theta}_{\delta_e} \delta^{d}_{T}}{N^{\theta}_{\delta_e}}$$

$$\doteq \underbrace{K_{\dot{d}}(s + K_d)e^{-\tau s}}_{\text{Pilot}} \; \underbrace{\frac{M_{\delta_e} Z_{\delta_T}\left(s + \frac{1}{T_{d\theta}}\right)}{s N^{\theta}_{\delta_e}(T_e s + 1)}}_{\text{Augmented Airframe}} \qquad (6)$$

where

$$N^{\theta}_{\delta_e} = M_{\delta_e}\left(s + \frac{1}{T_{\theta_1}}\right)\left(s + \frac{1}{T_{\theta_2}}\right) \qquad (7)$$

or

$$M_{\delta_e}(s^2 + 2\zeta_\theta \omega_\theta s + \omega^2_\theta) \qquad (8)$$

K_d represents the pilot's internally derived sink rate command based on a beam error. $K_{\dot{d}}$ represents the amount of throttle response that was used for a perceived error between the target sink rate and actual sink rate on the IVSI instrument or from the visual display during the final approach segment. τ represents the overall pilot lag that arises from several sources such as neuromuscular and scanning lags.

The pilot model parameters (K_d, $K_{\dot{d}}$, τ) were varied to obtain the experimental data fits in Fig. 11. Each data point in the figure represents the average experimental value across all the pilots who flew each of the configurations. Two glide slope sensitivities were run for each configuration to help quantify the effect of the pilot's "tightening up" as glide slope sensitivity increases near decision height. The implications of these data for STOL path control are covered in detail in Ref. 20. The important points to be made here are that: the pilots were not able to equalize the mid frequency shelf to a K/s form; and the path control pilot ratings (shown below each plot in Fig. 11) are significantly degraded for those cases where the pilots were unable to equalize the effective controlled element to a K/s shape (AP1 and AP10).

QUESTIONS AND ANSWERS

1. Wayne Thor, ASD; What were magnitudes of shear? How about combinations of wind magnitude/shear?

   Wind shears varied from 1 ft/sec^2 to 6 ft/sec^2. The maximum steady wind was 40 kt (see Ref. 9 for more detailed answer).

2. D. Moorhouse: In the accidents at Logan and the 727 at Kennedy, the aircraft had the capability to survive the shears. Would a specification have helped this?

   It is difficult to answer this with any confidence, but I would suspect that a specification would at least make the vulnerability of these aircraft to windshears more apparent.

3. Bill Levison, BBN: Are factors that deal with the pilot's ability to detect and identify shears being considered in proposed revisions dealing with performance in shears?

   They were not considered in the work reported here. It was noted, however, that a sudden large change in airspeed was used as a cue.

4. Don West, Boeing: Was engine response time modeled?

   Yes. In fact the throttle spoiler crossfeed washout was set to inverse model the engine lag in the augmented configurations.

5. Dwight Schaeffer, Boeing: Was there any difference in the tailwinds?

   Not really. We also looked at decreasing tailwind shears which showed up as overshoots. The shear vulnerability remained about the same as shown on Fig. 7. These data are given in more detail in Refs. 9 and 10.

6. Chick Chalk, CALSPAN: Was the turbulence model really 8785B or modified?

   It was the 8785B model.

7. Bill Levison, BBN: Did you use any non-Gaussian turbulence models?

   No.

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