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Systems Technology, Inc.
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SECTION I

INTRODUCTION

A. BACKGROUND

The NASA Space Shuttle Orbiter Approach and Landing Test (ALT) Programs (Refs. 1 and 2) included five free flights during which the Orbiter separated from the carrier aircraft and landed at the Edwards Air Force Base complex. On the last two flights, the Orbiter tail cone was replaced by dummy main engines to simulate the actual orbital configuration. Free Flight 4 (FF4) and the first three flights landed on Rogers Dry Lake Bed (Runway 17). Free Flight 5 (FF5), flown on 26 October 1977, landed on concrete Runway 04. On ALT-FF5, a pilot-induced oscillation (PIO) occurred just prior to touchdown. As described in Ref. 1:

> "The Orbiter approach and landing were controlled manually in the control stick steering flight control mode through the entire free flight until touchdown. For the last 8 seconds prior to touchdown, there was a pitch oscillation caused by control stick inputs to control sink rate."

The pitch problem, of prime concern herein, led to additional lateral control complications. Continuing from Ref. 1:

> "The inputs kept the elevons rate limited and the flight control system did not respond to some roll inputs. This appears to have triggered very large roll commands just at touchdown. The vehicle touched down softly with wings level, but skipped back into the air rolling right. A pilot-induced oscillation in roll then occurred for 4 seconds. The pilot ceased roll input momentarily and the motion damped quickly just prior to second touchdown which occurred 6 seconds after the first. The left wheel lifted off slightly on the rebound but the vehicle stayed on the ground and completed a normal rollout."

Although not of the severity or duration as occurred on FF5, flight data from FF4 (e.g., Fig. 62, Ref. 2) also clearly show pitch oscillations just prior to touchdown.

Based on the ALT flight test results, modifications were made for the Orbital Flight Test (OFT) configuration. These included: changes to the rotational hand controller signal shaping; increased flight control system sampling rates; pitch axis flight control system equalization and gain changes; and revisions to the elevon rate limiting logic.

A simulated in-flight evaluation of the Orbiter was carried out during June-July 1978 in the USAF/Calspan Total Inflight Simulator (TIFS). Reference 3 concluded:

> "Preliminary results indicate that the nominal ALT and OFT configurations are prone to pilot induced pitch oscillations when the pilot attempts tight flight path control near touchdown."

B. STI CHARTER AND TECHNICAL APPROACH

In November 1978, Systems Technology, Inc. (STI) started an 8 month study program with the charter to:

> Conduct independent analyses of the Shuttle Orbiter approach and landing conditions to ascertain possible causes and potential cures for observed PIO-like flight deficiencies.

A formal briefing covering the work accomplished under this study was presented at the Shuttle Landing Workshop held at Johnson Space Center, Houston, Texas, in March 1979. This report summarizes the work accomplished and the results presented at the Workshop.

The phases of the technical approach used in our study were as follows.

1. Identification and Quantification of the PIO Cause

This was accomplished by examination of the PIO flight evidence and application of closed-loop pilot/vehicle analyses. Critical quantitative features of the PIO were identified and approximately reproduced analytically. Definition of Closed-Loop Path/Attitude Stability Boundaries was determined to be a valuable technique for delineating and illustrating the basic causes of this particular PIO. This study phase is described in Section II.

2. Comparison of Pilot Control Characteristics of the Orbiter with a "Good" Aircraft

The same analytic techniques used for the Orbiter were applied to the YF-12. This aircraft has flown the Orbiter approach and landing task without problems. Comparison of the control characteristics of the Orbiter with the YF-12 allowed the identification of critical characteristics. A limited manned real-time simulation was used to confirm that the analytically exposed differences did correlate with overall path/attitude control qualities. Simulation of a known "good" aircraft also confirmed the ability of our limited simulation to discriminate control capability differences. Section III discusses this program phase.

3. Delineation and Examination of Potential Improvements

Flight control system modifications which could improve critical Orbiter control characteristics were examined and analytically evaluated. The limited manned simulation developed in Phase 2 was used to evaluate the effectiveness of the poential control system modifications. A preliminary assessment of the effects of surface rate limiting and attempts to minimize them through the use of a nonlinear stick filter were also accomplished. This the the subject of Section IV.

Section V presents our conclusions. A number of appendices present various details of the study.

SECTION II

IDENTIFICATION AND QUANTIFICATION OF THE PIO CAUSE

In Article A time histories from ALT-FF5 are presented and critical features of the PIO noted. The application of pilot/vehicle analyses to the ALT-FF5 configuration allowed the approximate reproduction of the FF5 phenomenon. These are described and the results presented in Article B.

A. FREE FLIGHT 5; FLIGHT EVIDENCE OF THE PIO

Pertinent time histories from FF5 for approximately 12 sec prior to first touchdown are shown in Fig. 1. The figure includes the pilot's input, i.e., the Rotational Hand Controller (RHC) pitch deflection, "elevator," pitch rate, and altitude signals.

Examination of the time histories indicates that two modes were involved in the PIO. A higher-frequency mode, which has been designated as $\omega''_{sp} = 3.4$ rad/sec, is clearly evident in the pitch rate, elevator, and RHC responses. A lower-frequency mode, designated as $\omega''_{h} = 1.9$ rad/sec, shows up in the altitude response. Both modes were approximately neutrally stable for the last 8-10 sec prior to first touchdown.

There is evidence of some elevon surface rate limiting in the responses shown in Fig. 1 and also in other flight test data not presented. The analyses presented below and the simulation described in Sections III and IV are consistent with the conclusion that rate limiting played a small role, if any, in the ALT-FF5 pitch PIO. However, the effectiveness of proposed Orbiter improvements was found to be significantly dependent on increased surface rate capability. This is discussed in Section IV.

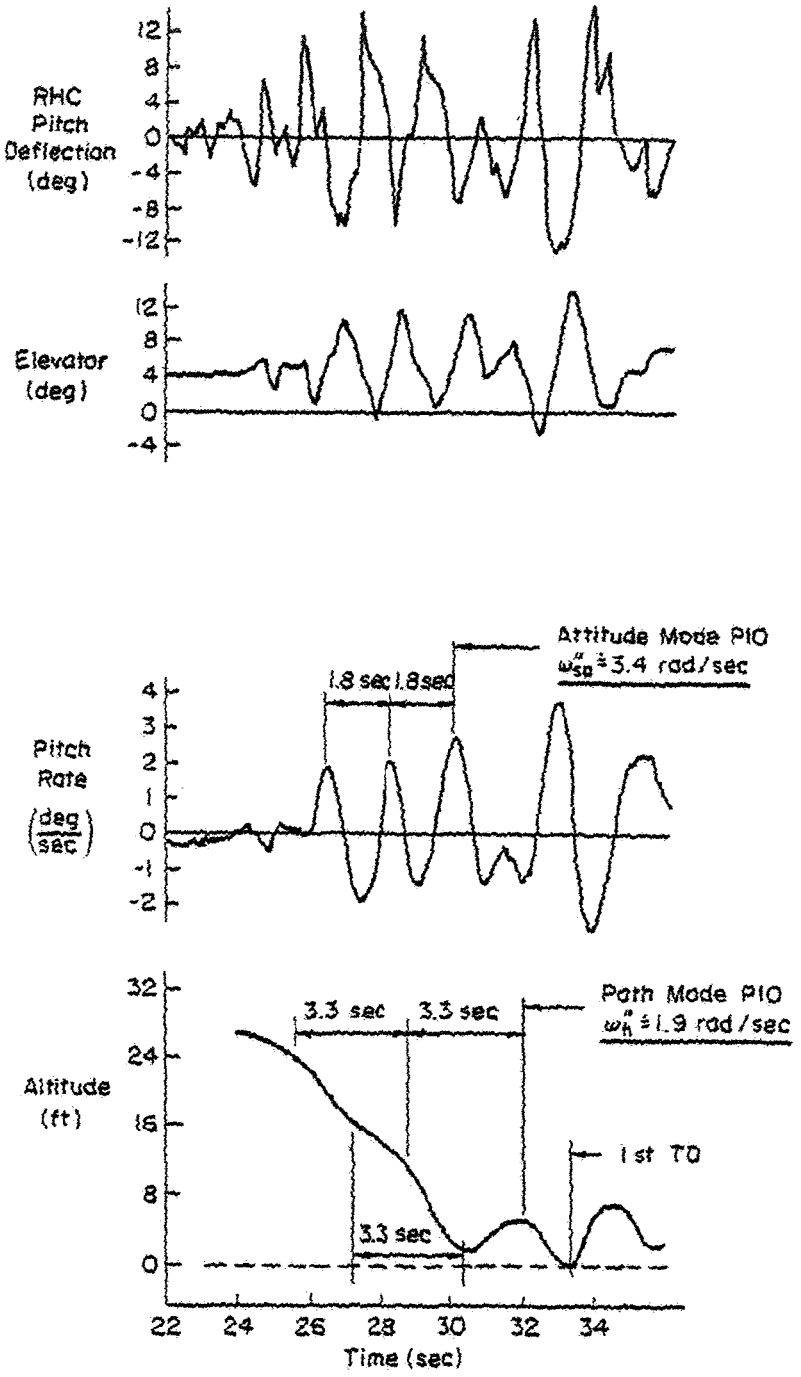

Figure 1. FF5 Flight Evidence of PIO

B. APPROACH AND LANDING CONDITION

Mathematical models of the human pilot have been successfully used for over 20 years in the analysis of pilot/vehicle systems (see Ref. 4). The classical, quasi-linear model described in Ref. 4 has been applied to the ALT-FF5 approach and landing flight condition. The control structure, pilot model form, and pilot model parameter values used are based on a vast store of flight test and simulator results (Refs. 4 and 5).

1. Control Structure

The control structure is presented in the block diagram of Fig. 2. The primary guidance requirement in the landing approach task is to maintain the desired path, i.e., altitude. In a visual approach, the cues available are as perceived from the pilot's location. The control structure shown in Fig. 2 reflects a pilot technique of making altitude corrections by biasing aircraft attitude up or down in proportion to altitude errors, i.e., the difference between his desired altitude, h_{p_c}, and the perceived altitude, h_p. Direct control of altitude with elevator is usually not practical as excessive pilot anticipation would be required to overcome the response lag in aircraft flight path for elevator inputs. The inner attitude loop shown in Fig. 2 provides

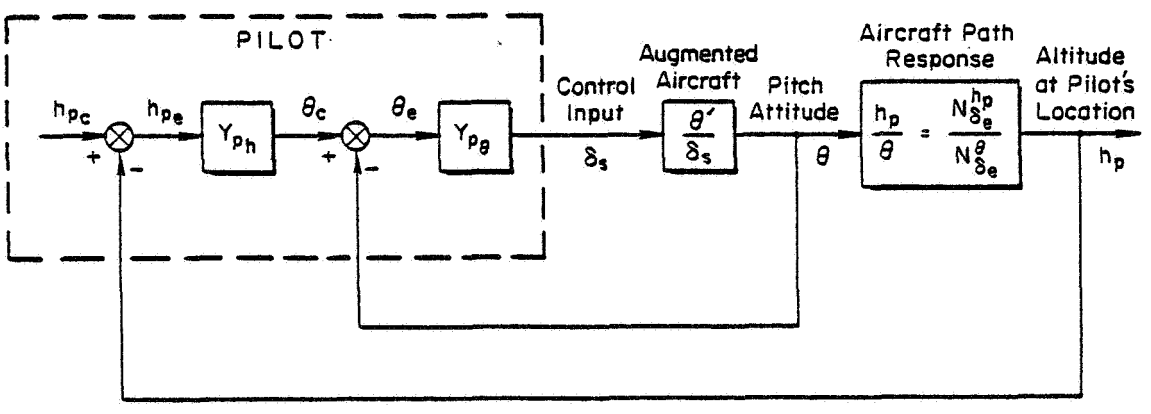

Figure 2. Control Structure for Pilot/Vehicle Analyses

equalization (i.e., lead) for the outer path loop; it also recognizes the additional task requirement of maintaining attitude control, per se.

2. Aircraft Characteristics

The pertinent aircraft characteristics are represented by the two right-hand blocks in Fig. 2, i.e.,

θ'/δ_s	The augmented pitch attitude transfer function for control inputs
h_p/θ	The aircraft's path response to attitude changes for pilot control inputs

This representation of the aircraft dynamics as a two block series is adequate, as the Orbiter has a single control point. As will be discussed further below and in Sections III and IV, it is also very useful, as it delineates and emphasizes the only relevant aircraft characteristics.

The ALT-FF5 pitch attitude transfer function and frequency response are given in Fig. 3. Also given in the figure are the transfer function and frequency response of a low-order "equivalent" system model of the form:

$$\left.\frac{\theta}{\delta_s}\right]'_{eq} = \frac{K e^{-\tau_e s}}{s(T_E s + 1)}$$

The parameter values of the latter ($K = 0.4$ deg/sec/deg, $1/T_E = 3.5$ rad/sec, and $\tau_e = 0.264$ sec) were obtained by making a best fit with the complete frequency response of the ALT. As discussed below, the equivalent system is useful for pilot model parameter value adjustment and for making comparisons with other aircraft. All analysis was done using the complete ALT transfer function as given in Fig. 3. The effects of surface rate limiting are <u>not</u> included.

The Orbiter path response to attitude transfer function and frequency response for elevator inputs is presented in Fig. 4. It should

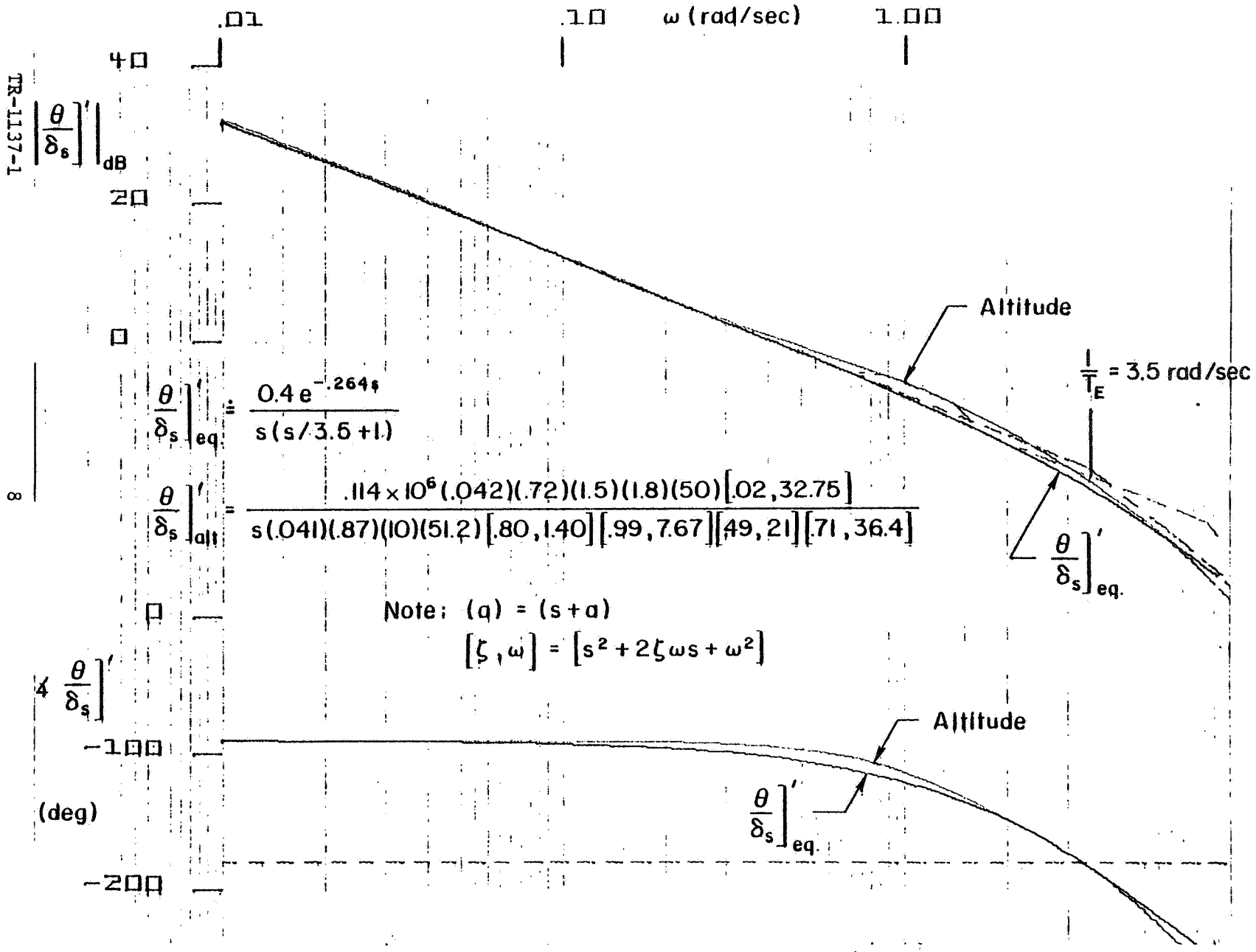

Figure 3. Orbiter Attitude Response; ALT-FF5 PIO Condition

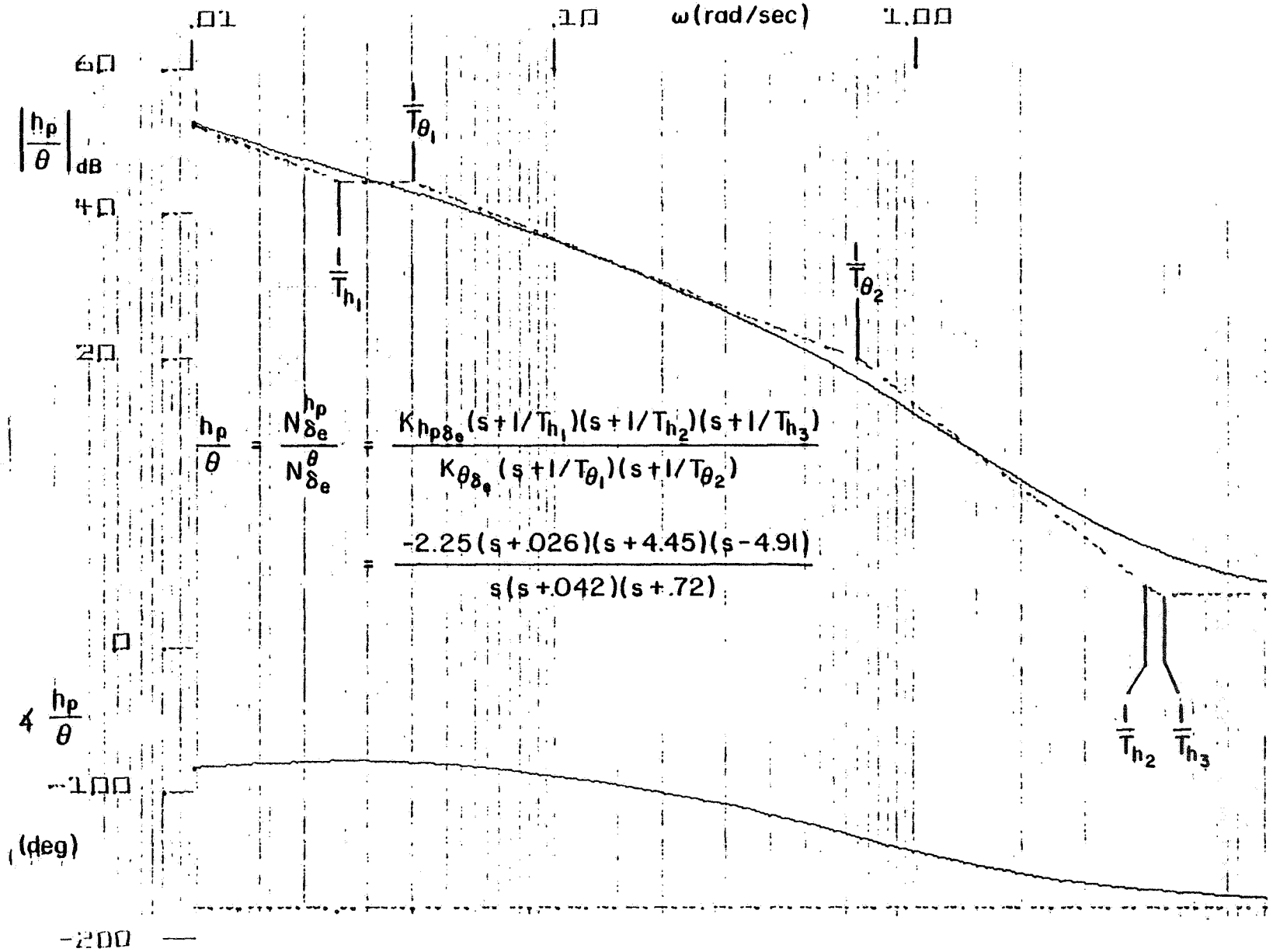

Figure 4. Orbiter Path Response, h_p/θ; ALT-FF5 PIO Condition

be noted that these characteristics are identical to the unaugmented airframe. Without exception, response ratios for elevator inputs can not be modified by feedbacks or feedforwards to the elevator. These characteristics of the Orbiter are invariant as long as augmentation via the elevator is the only practical means.

Only the higher-frequency roots shown in Fig. 4 (i.e., $1/T_{\theta_2}$, $1/T_{h_2}$, and $1/T_{h_3}$) are of concern to the PIO problem. The values of these roots are dictated by basic airframe characteristics. T_{θ_2}, the flight path lag, is dominated by basic airframe characteristics. T_{h_2} and T_{h_3} are set primarily by the pilot's location relative to the center of instantaneous rotation (CIR) for elevator iputs. For a pilot location aft of the CIR, as in the Orbiter, $1/T_{h_2}$ and $1/T_{h_3}$ will be two distinct first-order roots. They will be of approximately the same magnitude but of opposite sign. In aircraft where the pilot is located forward of the CIR, the more common case, these two roots will couple into a second--order, ω_h, pair. This will be illustrated in Section III, where the Orbiter characteristics are compared to other aircraft. For a more complete discussion of these transfer functions and approximations for the values of their roots, see Ref. 6.

3. Pilot Characteristics

The other half of the control structure block diagram of Fig. 2 represents the pilot's characteristics. These are shown by the two left-hand blocks enclosed within the dashed box. Y_{p_θ} accounts for the pilot's action in closing the inner attitude-to-elevator loop; Y_{p_h} accounts for his closure of the outer path-to-attitude loop. The pilot model forms used in the analysis are given by:

$$Y_{p_\theta} = K_{p_\theta}(T_{L_\theta}s + 1)e^{-\tau_\theta s}$$

$$Y_{p_h} = K_{p_h}$$

The inner-loop pilot model decribing function, Y_{p_θ}, accounts for the pilot's gain (K_{p_θ}), lead (T_{L_θ}), and time delay (τ_e) in controlling attitude with elevator. The pilot will adjust his control characteristics for the particular vehicle and task at hand. As decribed in Ref. 4, the cardinal adjustment will be to create a "K/s region" in the frequency domain around "crossover." By doing this the pilot obtains an aircraft pitch rate response proportional to those attitude errors (with frequency content) which would be detrimental to overall task performance. For attitude control, the important frequency region is typically from 0.5 to, say, 6.0 rad/sec. Closed-loop performance, both in terms of average errors and time to make a steady-state correction, is improved by higher crossover frequencies. When attitude control alone is the task and tight regulation is not required, the pilot can operate at the lower end of the above frequency region. As the task requires more stringent attitude regulation and/or an outer-loop requirement, such as altitude control, is added, he will have to operate at a higher crossover, say, 3.0 rad/sec. If tight control of outer-loop altitude errors is demanded or quick corrections required, the equalization function of the inner loop will push attitude crossover to the higher end of the frequency region.

The lead term, T_{L_θ}, in the pilot model form is the means by which the model can reflect the pilot's adjustment to create a K/s region, i.e., a rate response. By setting the lead equal to the Fig. 3 equivalent system lag, the desired result is obtained. This is shown in the open-loop pilot/vehicle frequency response plot of Fig. 5b. By comparing this plot with the vehicle-alone characteristics shown in Fig. 3, it can be seen that the pilot's equalization has stretched the high end of the K/s region, (i.e., the frequency region in which the amplitude response is well approximated by a straight line with slope of -20 dB/decade) from about 1.0 rad/sec to, say, 4.0 rad/sec.

The pilot's time delay, τ_e, has also been included in the Fig. 5 system survey. It has been shown (Ref. 4) that pilot lag is a function of the lead adopted and the relationship used herein is given in Fig. 6.

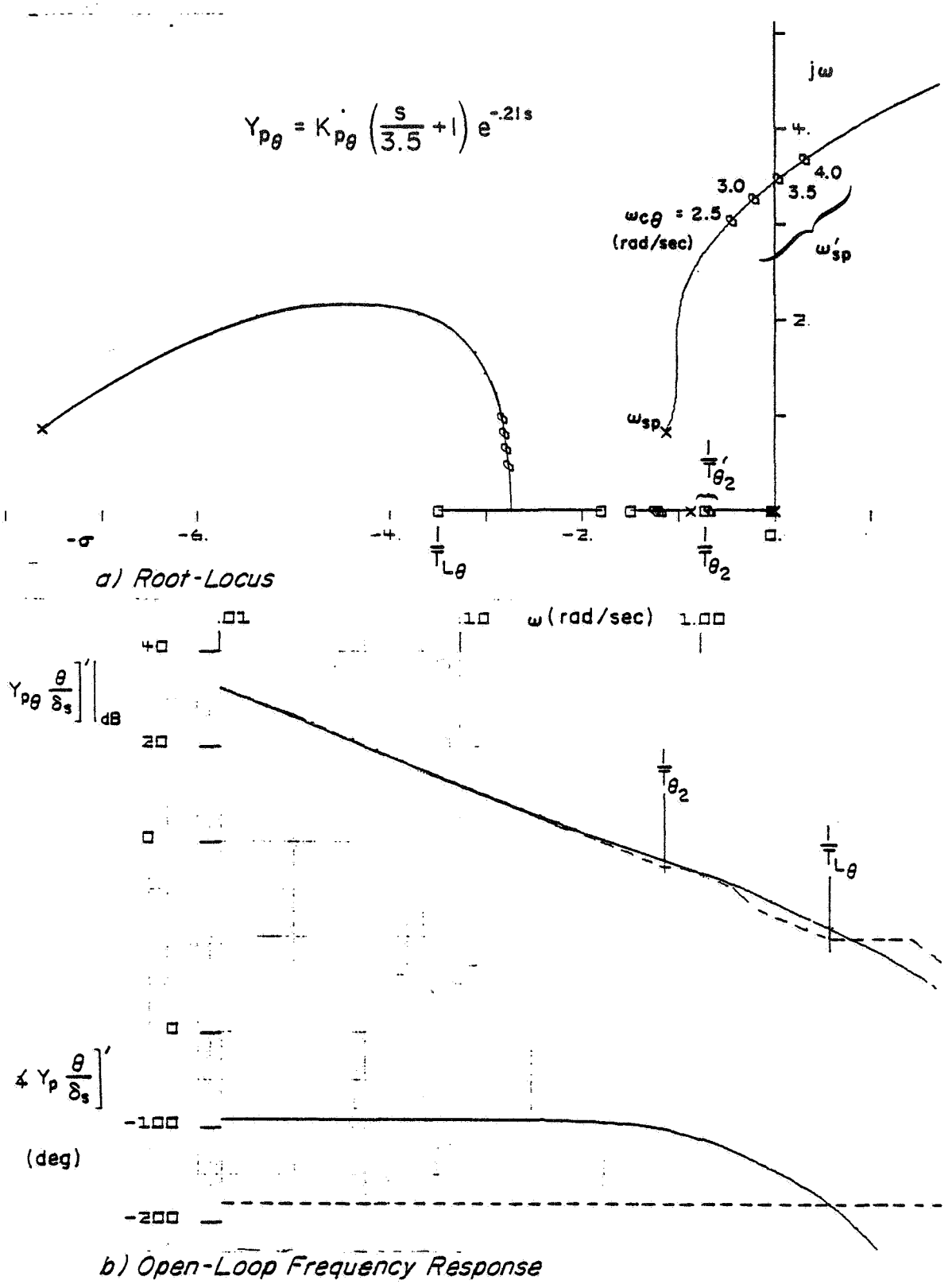

Figure 5. System Survey for Pilot Closure of Attitude Loop; Orbiter ALT Configuration

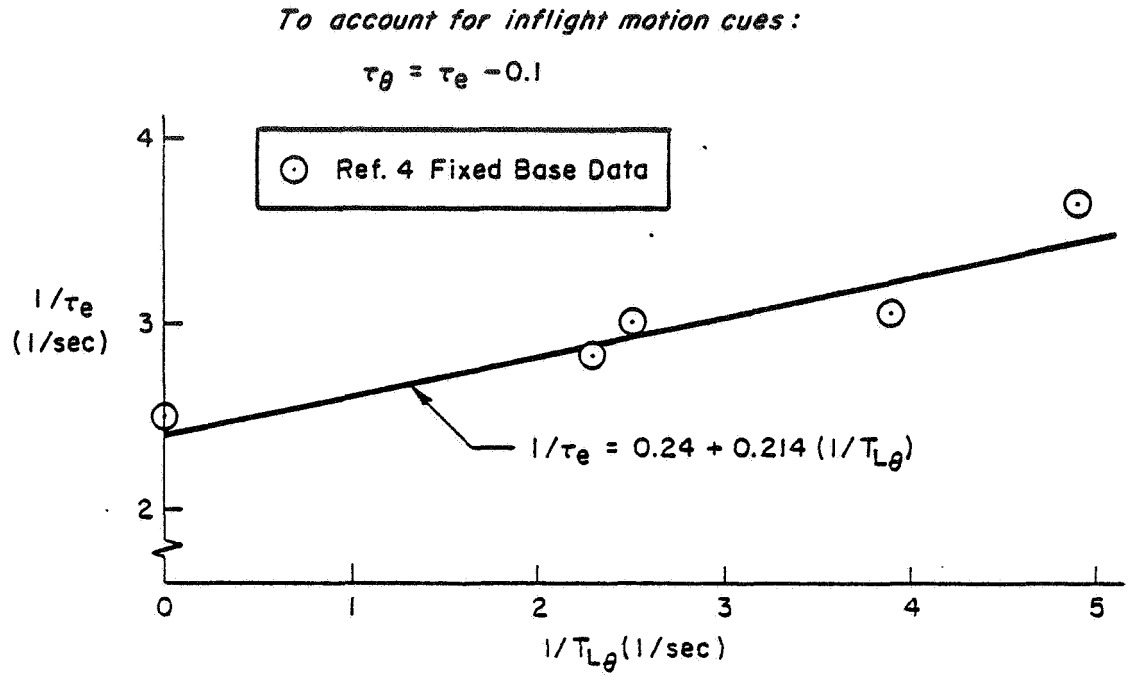

Figure 6. Pilot's Effective Time Delay, τ_e, as a Function of Pilot Lead, T_{L_θ}, Required

4. Pilot/Vehicle Closed-Loop Characteristics

For pilot attitude gains corresponding to crossover frequencies from 2.5 to 4.0 rad/sec, the location of the closed-loop attitude mode, ω''_{sp}, is shown (as diamonds) in the root locus plot of Fig. 5a. As can be seen, the maximum stable crossover frequency is slightly less than 3.5 rad/sec. The other critical mode shown in this plot is the path mode, $1/T'_{\theta_2}$. For the above range of pilot gains, this mode will be very close to the basic aircraft flight path lag, $1/T_{\theta_2}$.

These two modes, the attitude mode, (ω'_{sp}) and the path mode ($1/T'_{\theta_2}$), limit outer-loop performance. This is illustrated by root locus plots for pilot closure of the path loop. Figure 7 shows these plots for three levels of inner-loop crossover frequency. The top plot is for modest inner-loop gain and shows the stable attitude mode, ω'_{sp}, being further stabilized with increasing outer-loop gain resulting in the final closed-loop attitude mode designated by ω''_{sp}. The closed-loop path mode, ω''_h emerges from the coupling of the $1/T'_{\theta_2}$ path mode and the

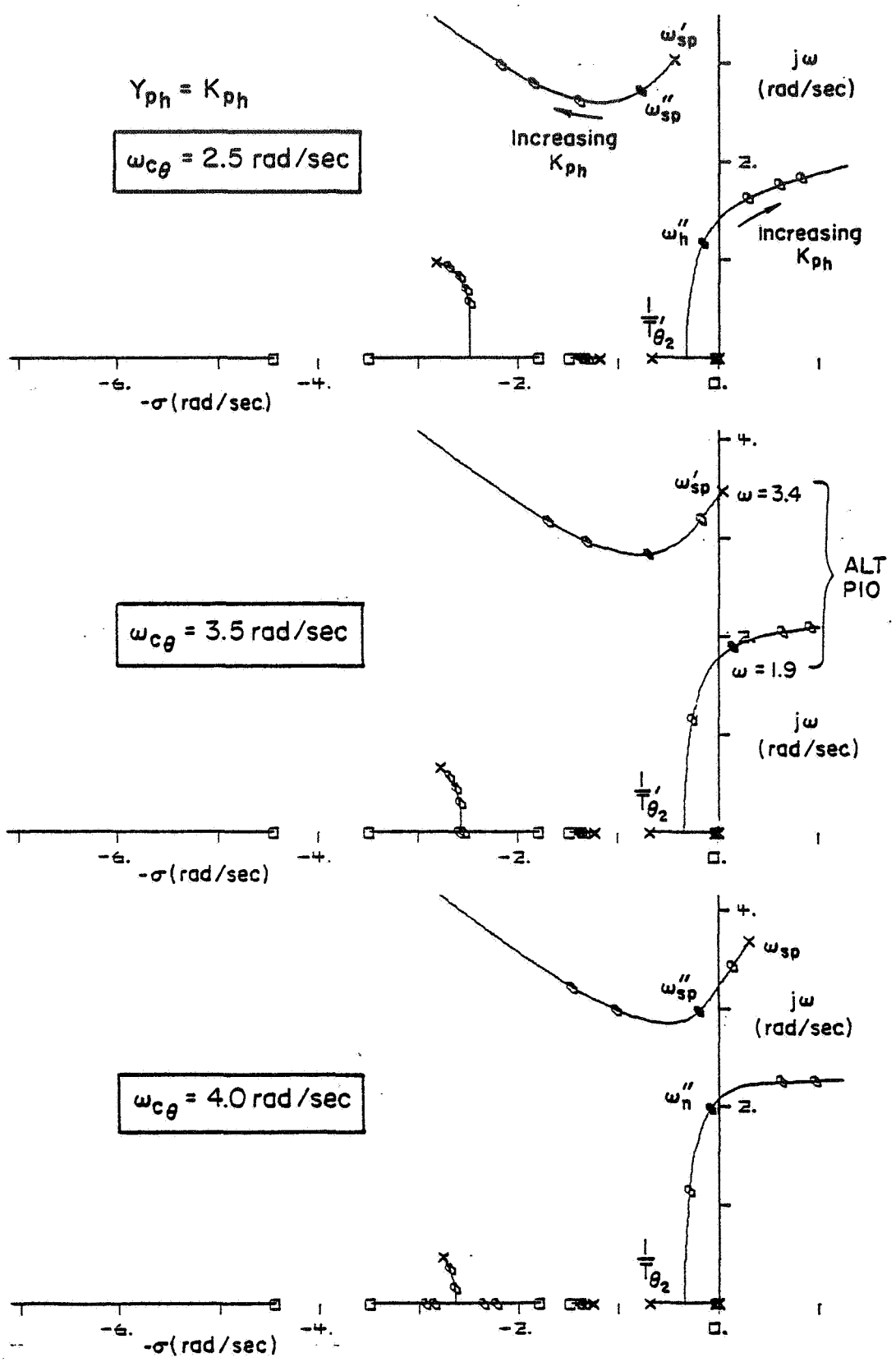

Figure 7. Pilot Closure of Path Loop: Orbiter ALT Configuration

kinematic altitude integration. The top plot also shows that with modest inner-loop gain, the maximum stable path mode frequency is limited to about 1.4 rad/sec. To achieve better path control, i.e., higher closed-loop bandwidth, the pilot must exercise tighter attitude control. The center root locus of Fig. 7 shows that for inner-loop crossover corresponding to about neutral stability of the attitude mode (without the outer loop), the achievable, stable path mode frequency has been increased to about 1.8 rad/sec. For reference, the observed ALT-FF5 PIO frequencies are noted in the center plot. The bottom plot illustrates that higher inner-loop gain results in a situation where attitude mode stability is critically dependent on the outer loop but the potential improvement in path bandwidth is minimal.

The tradeoff between performance and stability is illustrated by the Closed-Loop Path/Attitude Stability Boundaries shown in Fig. 8. The figure shows the closed-loop stability limits as a function of combinations of attitude and path gain. Within the stable region, lines of constant closed-loop mode frequency are also shown. At lower attitude gains a path mode instability will result at the limiting path gain. Since the (right-hand) path mode boundary is sloping upwards to the right, higher path gains resulting in better performance can be achieved

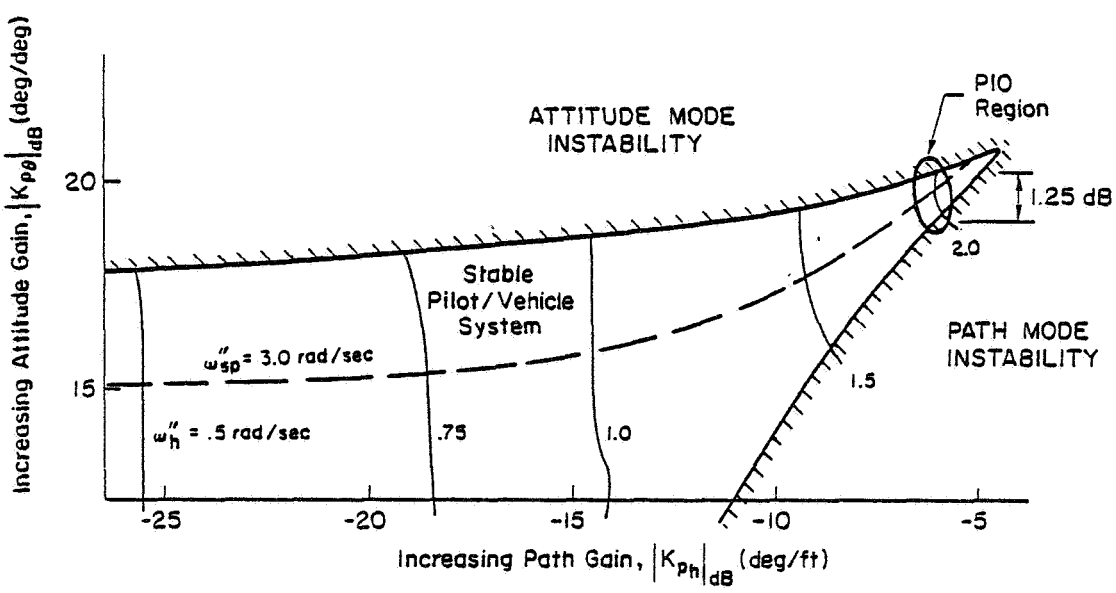

Figure 8. Closed-Loop Path/Attitude Stability Boundaries; Pilot/ALT System

by increasing inner-loop attitude gain. This is true for attitude gains up to about 18 dB, which corresponds to an inner-loop crossover frequency of $\omega_{c_\theta} = 3.5$ rad/sec. At higher attitude gains, a finite level of path gain is required to stabilize the attitude mode.

For maximum performance, the pilot is drawn into the tip of the plot where the PIO region has been noted. At a stable operating point within this region, the system is very sensitive to both attitude and path gains. At a fixed attitude gain, lower path gain will result in an attitude mode instability, while a higher path gain results in a path mode instability. The range of stable path gains is only about 1.2 dB. A similar situation exists for fixed path gain. A higher attitude gain will result in an attitude mode instability and a lower attitude gain results in an unstable path mode. The only way to back out of this region in a stable manner is by a judicious, simultaneous reduction in both attitude and path gains. This extreme sensitivity to small changes in pilot control characteristics indicates that the configuration is PIO prone. The existence in the ALT-FF5 flight test data of both neutrally stable modes at very near the same frequencies indicated by the analyses is strong evidence that we have analytically reproduced the PIO condition.

SECTION III

COMPARISONS WITH A "GOOD" AIRCRAFT

The YF-12 has flown the Orbiter approach and landing task without problems. YF-12 aircraft data were provided by the Dryden Flight Research Center and the analytic procedure described in the previous section applied. The results of the YF-12 analyses are presented in this section and comparisons made with the Orbiter.

A. AIRCRAFT CHARACTERISTICS

As indicated in the previous section, the critical aircraft characteristics can be investigated in terms of the augmented attitude response to control inputs and the basic airframe path response to attitude changes. A comparison of the YF-12 and Orbiter attitude response is shown in Fig. 9. The frequency response curves shown are for the complete aircraft. The amplitude characteristics of the Orbiter have been shifted by about 6 dB to take out the difference in stick gearing in the two aircraft. This more clearly illustrates that the amplitude responses as a function of frequency are nearly identical out to a frequency of about 5.0 rad/sec. This is borne out by the equivalent system comparison made in the inset of Fig. 9. This shows that, aside from the steady-state gearing, the difference in attitude response of the two vehicles is the significantly longer effective time delay in the Orbiter; τ_e for the Orbiter is 0.264, while for the YF-12, τ_e is only 0.093 sec. This clearly shows up in the phase responses of the two vehicles. The phase lag of the Orbiter starts rolling off at a much lower frequency than for the YF-12 and at 4.0 rad/sec has about 50 deg more phase lag.

A comparison of the flight path response to attitude changes of the two vehicles is shown in Fig. 10. The responses are nearly identical out to about 2.0 rad/sec. The basic flight path lag, T_{θ_2}, of the vehicles (not noted in the figure) are similar. The differences in the

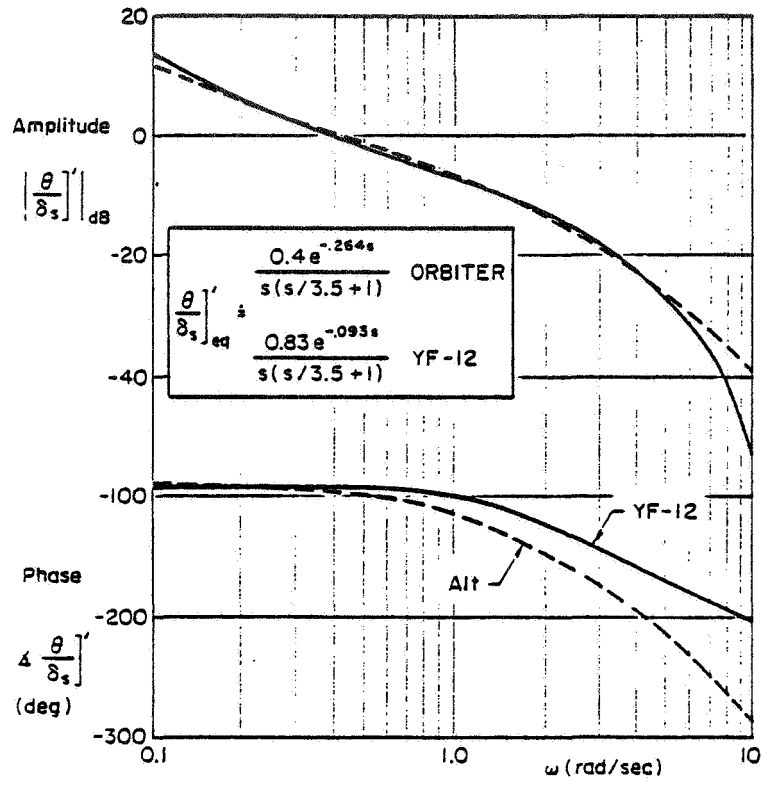

Figure 9. Comparison of YF-12 and Orbiter Attitude Response, $\theta/\delta_s]'$

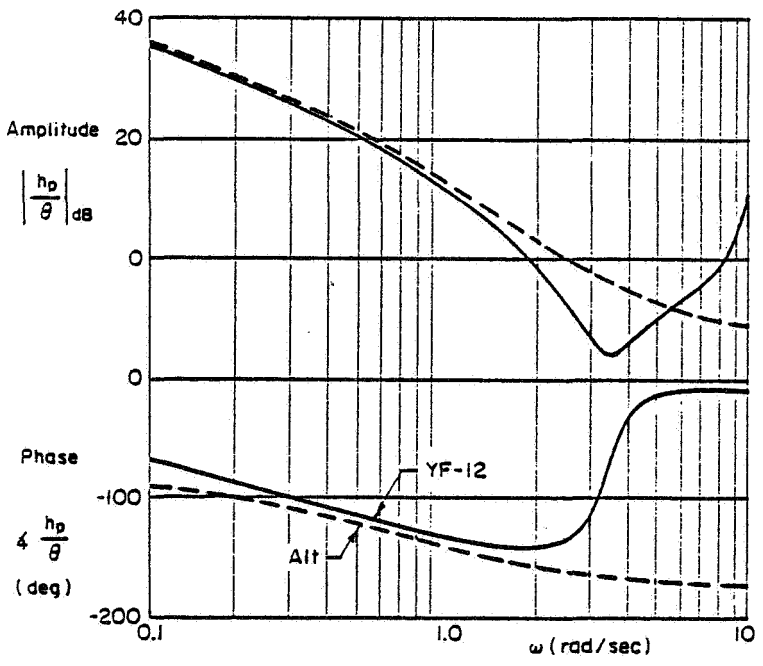

Figure 10. Comparison of YF-12 and Orbiter Path Response, h_p/θ

higher-frequency region are, as discussed in Section II, associated with the pilot's location relative to the center of instantaneous rotation (CIR) for control inputs. In the Orbiter, the pilot is aft of the CIR, giving rise to two first-order roots in the altitude response numerator. These roots, being of opposite sign and about equal magnitude, make no net phase contribution to the Orbiter response and tend to hold up the amplitude response for frequencies above 2.0 rad/sec. The YF-12 pilot is forward of the CIR. The resulting roots are a lightly damped second-order pair. They are responsible for the amplitude dip and abrupt phase lead shown in the Fig. 10 YF-12 frequency response.

B. PILOT/VEHICLE CLOSED-LOOP CONTROL ANALYSES

The control structure of Fig. 2 was used to analyze the YF-12 closed-loop characteristics. The pilot model forms and adjustments for the YF-12 were the same as those used for the Orbiter (see SectionII).

The root locus for the pilot's closure of the YF-12 attitude loop is shown in Fig. 11. The analogous plot for the Orbiter was shown in Fig. 5a. The diamonds in Fig. 11 indicate the location of the closed-loop attitude mode for pilot gains corresponding to crossover frequencies in the range from 2.5 to 4.0 rad/sec. A comparison of Figs. 5 and 11 shows that the YF-12 pilot has significantly higher attitude bandwidth capability. The neutral stability frequency in the YF-12 is about 5.5 rad/sec, while in the Orbiter it is slightly below 3.5 rad/sec. Piloted control at a closed-loop bandwidth which corresponds to a neutrally stable Orbiter would result in attitude responses in the YF-12 with adequate damping. The closed-loop path mode, $1/T'_{\theta_2}$, for the YF-12 (as with the Orbiter) lies very close to the bare airframe flight path lag, $1/T_{\theta_2}$.

Pilot closure for the YF-12 outer path loop is illustrated by the root loci of Fig. 12 for three levels of inner-loop crossover frequency. The analogous plots for the Orbiter were shown in Fig. 7. The pilot location zeros, ω_h, show up clearly for the YF-12. The top plot in Fig. 12 shows that a path bandwidth of nearly 2.0 rad/sec is available in the YF-12 with only modest inner-loop gain. This is about the

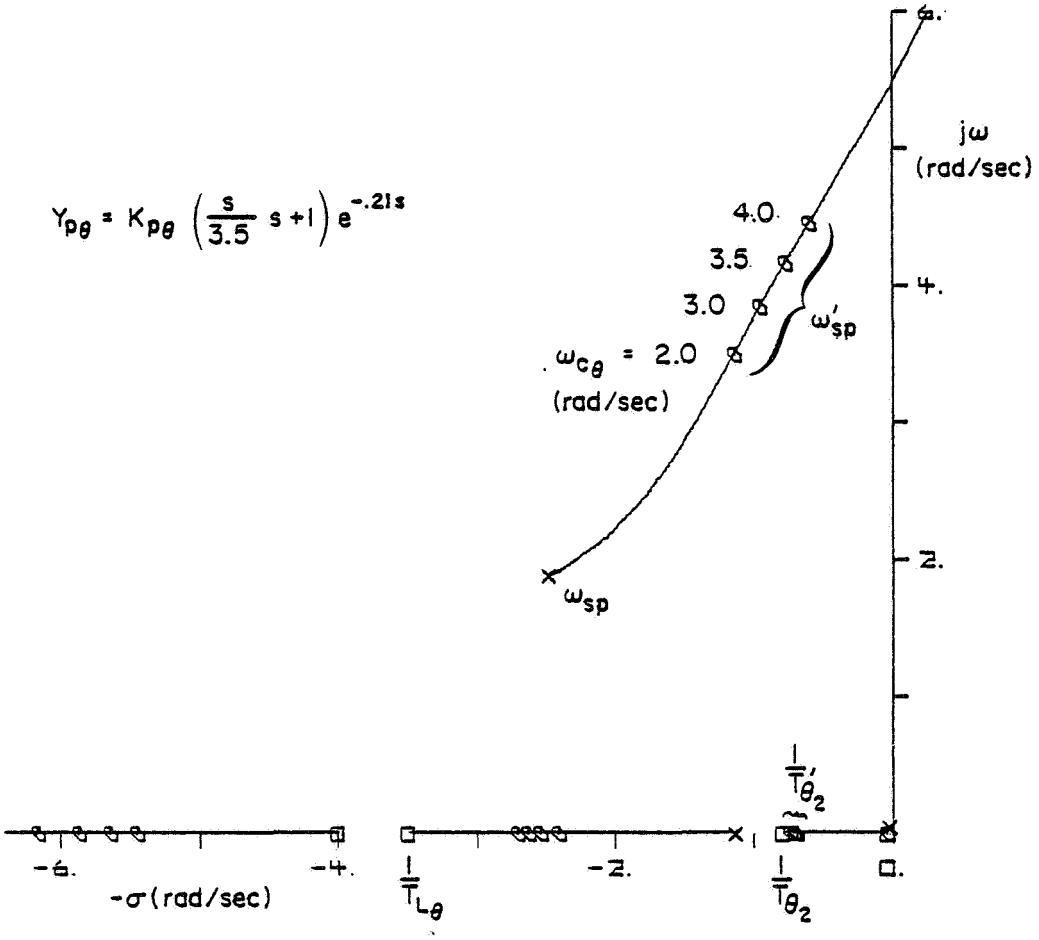

Figure 11. Pilot Closure of YF-12 Attitude Loop: $\theta \rightarrow \delta_s$

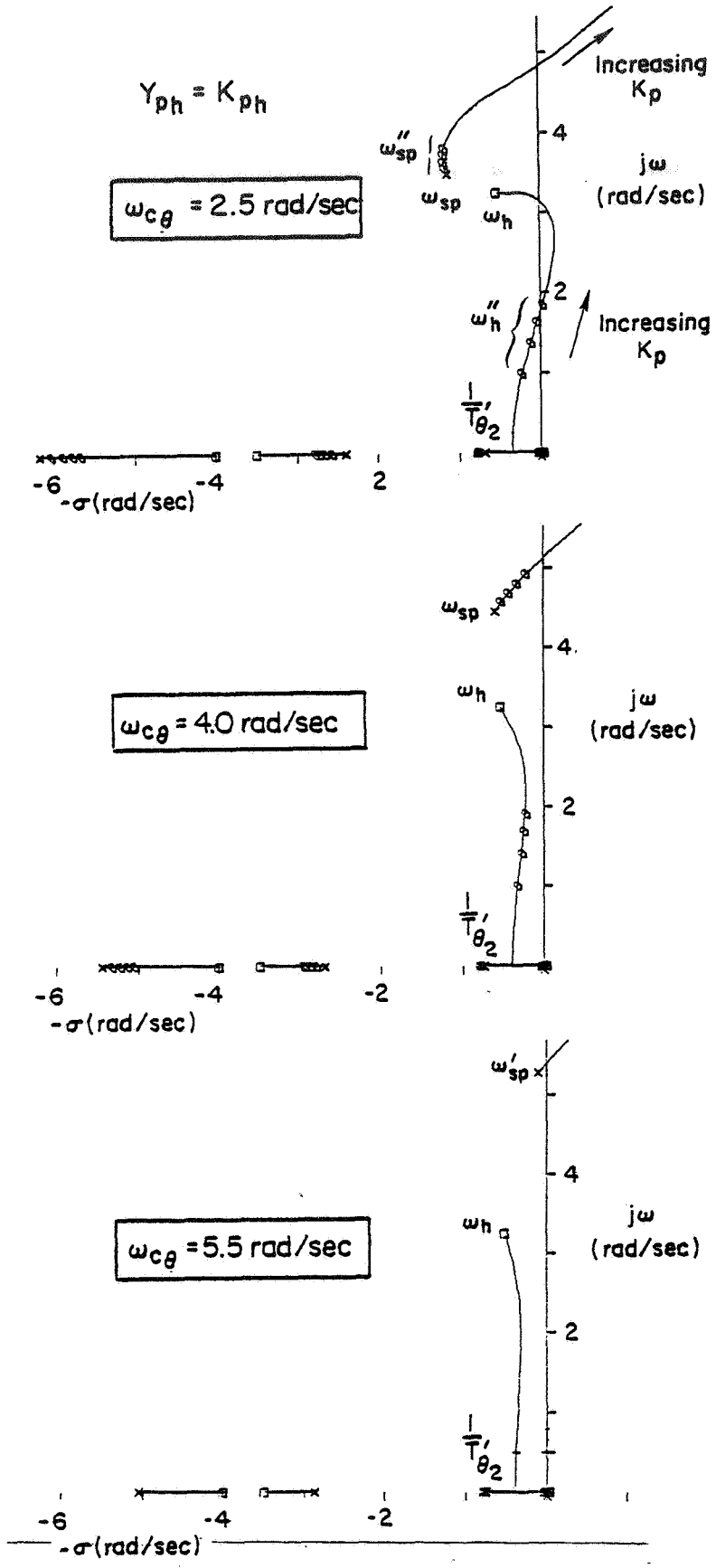

Figure 12. Pilot Closure of YF-12 Path Loop: $h_p \rightarrow \theta_c$

maximum available in the Orbiter, and was only achievable with the higher inner-loop gains associated with the PIO-prone region. Examination of the lower two root loci in Fig. 12 indicates that for a tighter attitude control, the potential for a path mode instability disappears. The closed-loop path mode frequency is limited only by the ω_h zeros to about 3.0 rad/sec. System stability is determined only by the attitude mode.

The tradeoff between performance and stability is somewhat different in the YF-12 than was the case in the Orbiter. Closed-loop path/attitude boundaries for the YF-12 are shown in Fig. 13. For comparison, the boundaries for the Orbiter have been superimposed in the same figure. For path bandwidths in the YF-12 lower than, say, 1.5 rad/sec sec, there is no minimum attitude gain required. The YF-12 pilot can operate with modest inner-loop crossover frequencies in the range of ω_{c_θ} = 3.0 to 4.0 rad/sec (which corresponds to attitude gains of 15-20 dB in Fig. 13) and achieve path bandwidths of 2.0 rad/sec and beyond — and still retain reasonable stabilty margin. Tighter attitude gain will not buy him higher path bandwidth, and it is not likely that he will be drawn into the tip of the stability boundary plot as is the case with the Orbiter. The higher path gains in the YF-12 associated with higher-frequency closed-loop path modes indicate a significantly greater capability to minimize path errors below the outer-loop crossover frequency. To back away from the maximum performance conditions, the pilot only needs to reduce his path gain while retaining control of attitude within reasonably wide margins.

C. SIMULATION

A limited fixed-base piloted simulation was carried out to confirm that the analytically exposed differences did correlate with overall path/attitude control qualities. The simulation was also later used to evaluate potential improvements. These are discussed in Section IV, and the simulation is described more fully therein and in Appendix B. A brief description is given here to provide background for the results to be presented below.

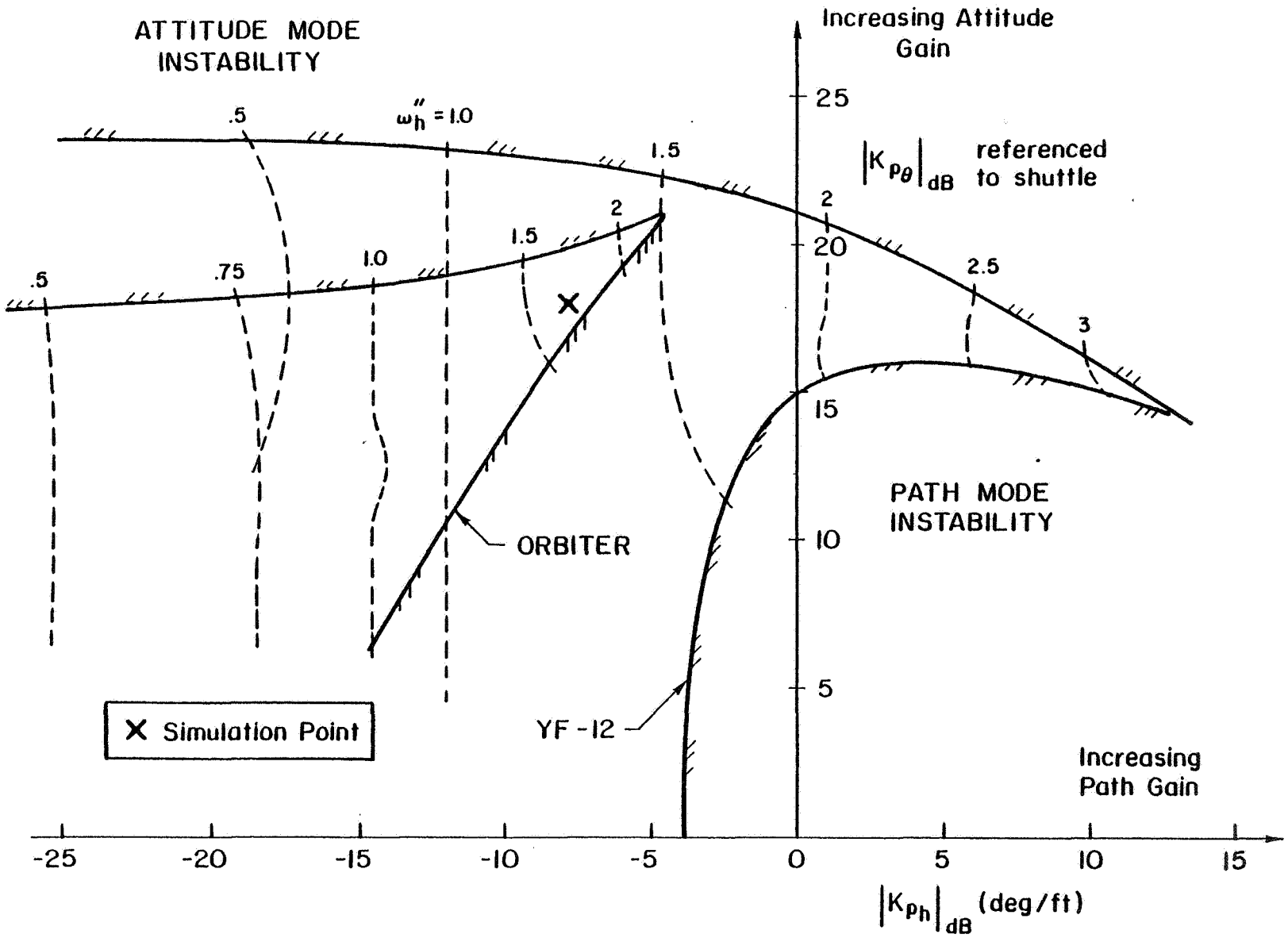

Figure 13. Closed-Loop Path/Attitude Stability Boundary Comparison of YF-12 and Orbiter ALT Configurations

The problem was to develop a fixed-base task using the (Contractor's) limited available display capability (a two-gun CRT) which would drive the pilot into sensitive control regions. It was also desired to maintain a reasonable relationship to a real-world approach and landing. The display used is shown in Fig. 14. Attitude information is provided by a moving horizon relative to a fixed reference —— a conventional inside-out display. Path information was provided by a "ground plane" line which was displaced from the same reference in proportion to altitude at the pilot location. The task was started with the ground plane at the bottom of the CRT screen corresponding to an altitude of about 18 ft. Initial conditions also included a slightly nose-down pitch attitude with corresponding positive sink rate. Once the task started, the ground plane would move up the screen and its length would shrink such that at the end of 9 sec it became a dot. The pilot's task was to stop the ground plane on the fixed reference as smoothly as possible without overshoot before the length of the line became zero. If the pilot moved

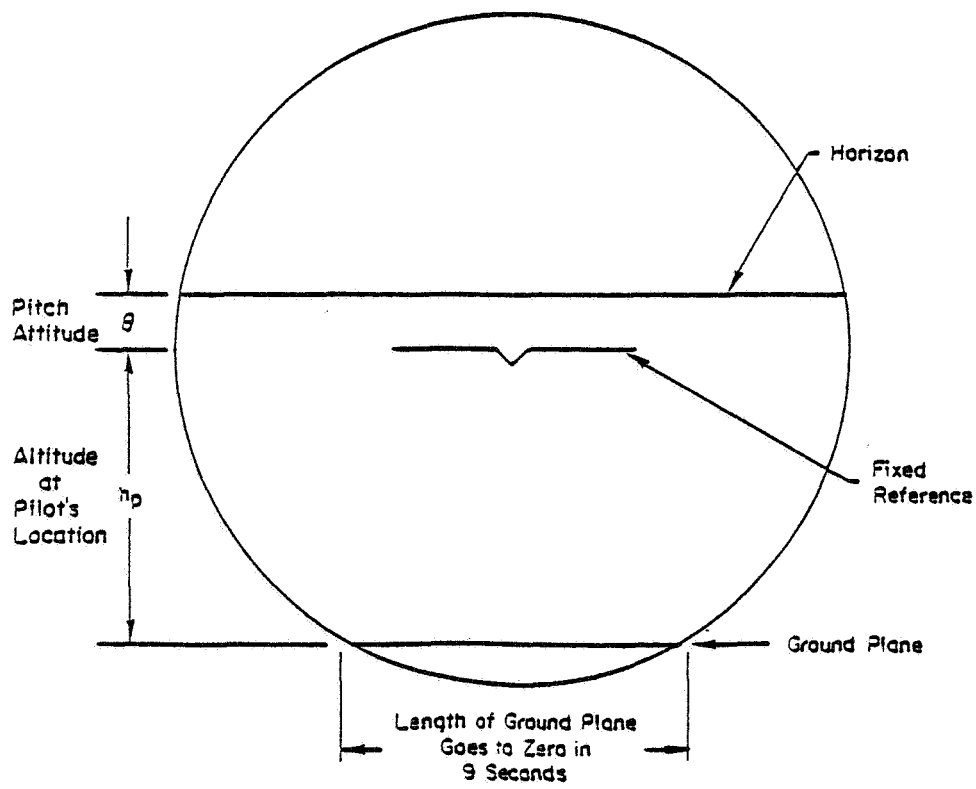

Figure 14. Simulation Display

the ground plane to the reference line before the allotted time, the task was to maintain the ground contact (i.e., "h_p = 0"). If the length of the line went to zero before achieving the desired steady altitude it was considered analogous to stalling above the runway.

Typical responses from the Orbiter and the YF-12 simulation are shown in Fig. 15. The nature of the responses are quite different for the two aircraft. In the YF-12 the pilot was able to make the desired path correction quite quickly and smoothly and had no problem in maintaining the desired altitude. Only small attitude corrections were required. He was able to accomplish this repeatably with this aircraft.

With the Orbiter, oscillations in both attitude and altitude are evident. Repeated trials with this aircraft resulted in similar results. Although the measurement of closed-loop frequencies from these time responses is quite crude, it does tend to confirm that the task provoked tight control close to that corresponding to the analytically derived PIO region. The location of this control point derived from the simulation results is shown as an X on the stability boundary plot given in Fig. 13.

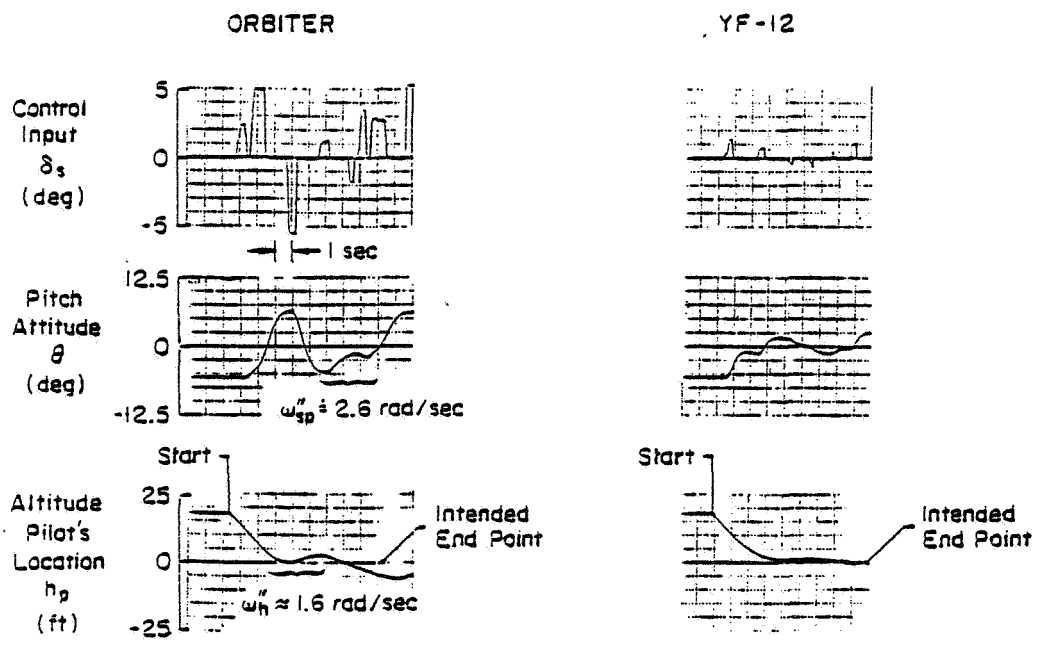

Figure 15. Comparison of Orbiter and YF-12 Simulation Responses

D. SUMMARY

The results of the closed-loop pilot/vehicle analysis of the Orbiter and a "good" aircraft, i.e., the YF-12, have been shown to be consistent with flight test and a limited fixed-base simulation. The simulation demonstrated the ability to discriminate control capability differences.

By comparing the pertinent characteristics of the two vehicles, the critical Orbiter/DFCS characteristics have been identified as:

- Excessive time delay in the attitude response to pilot control inputs, and
- Degraded path response to attitude changes associated with the unfavorable Orbiter pilot location.

SECTION IV.

DELINEATION AND EXAMINATION OF POTENTIAL IMPROVEMENTS

The control structure block diagram used in previous sections is examined to delineate potential improvements. The excessive time delay in the Orbiter pitch response was determined to be the most likely candidate for practical modifications. Several configurations made up of combinations of DFCS (digital flight control system) modifications were identified and these are described. These configurations were evaluated using a piloted simulation and the results are presented.

A. DELINEATION OF POSSIBLE IMPROVEMENTS

The control structure block diagram of Fig. 2 has been used to expose the Orbiter deficiencies. That block diagram presumed that only information from outside the aircraft was available. The control structure diagram of Fig. 16 allows the possibility of other displays. As the use of a head-up display (HUD) in the Orbiter was the subject of a concurrent Johnson Space Center study, additional displays were not considered during our program. Although it is possible that a HUD would be of great value in aiding the pilot to more closely follow the desired approch trajectory, conflicting cues between the display and the real world may be a problem. If the pilot requires a correction near

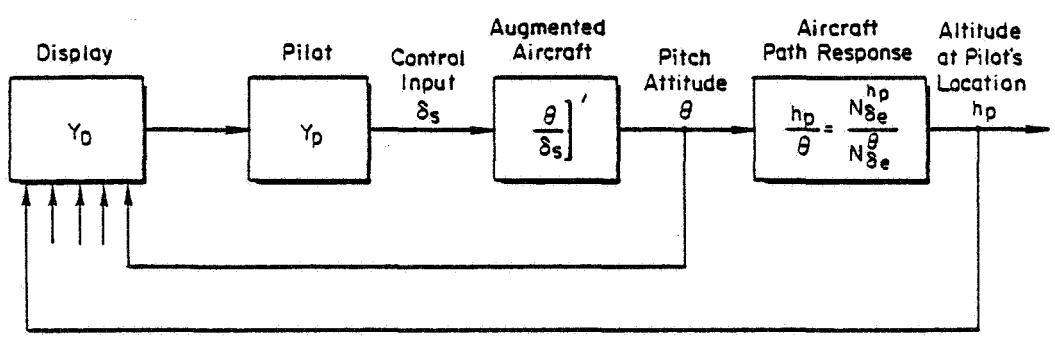

Figure 16. Control Structure for Pilot/Vehicle/Display Analyses

(perhaps due to a gust disturbance), it is possible that he rt to using only real-world cues. If tight control is re- ıe ALT-FF5 PIO situation could reoccur.

ther elements in the control structure are the pilot and the characteristics. The pilot might be trained to better under- cope with the Orbiter's peculiar control characteristics. tely, the cues, at the pilot's location, are not good for ng the situation. References 1 and 2 indicate that the ALT-FF5 unaware of a pitch control problem. It is possible that tech- or recognition and correction of an impending PIO could be d through ground-based and in-flight simulation. Exposure of tter pilot to the vehicle's limiting characteristics (even if odifictions are made) through simulation could be beneficial.

study concentrated on possible modifications to the aircraft characteristics. As has been pointed out previously, the aircraft's pat[illegible]se characteristics cannot be modified by augmentation via the elev Forable modification of these characteristics could poss- ibly [illegible]lished by augmentation via either the speed brake or the body Nither was deemed practical for an augmentation role.

biter's pitch response characteristics were found to be defi- cie[illegible]ion III), and these may be modified by DFCS changes. This is th[illegible] of the following section.

lysis presented previously was accomplished using the ALT DFteristics. The OFT configuration (defined in Appendix A) was fofer no relief relative to the ALT. The OFT configuration was us Baseline in our subsequent analysis and simulation.

B. PITCH RESPONSE IMPROVEMENTS

d be expected that an improved Orbiter pitch response would r[illegible]only in better attitude control, per se, but in better path co. As noted in Section II, a key function of the attitude lat control situations is to provide equalization of the outer l is demonstrated by the stability boundary plots in Fig. 17.

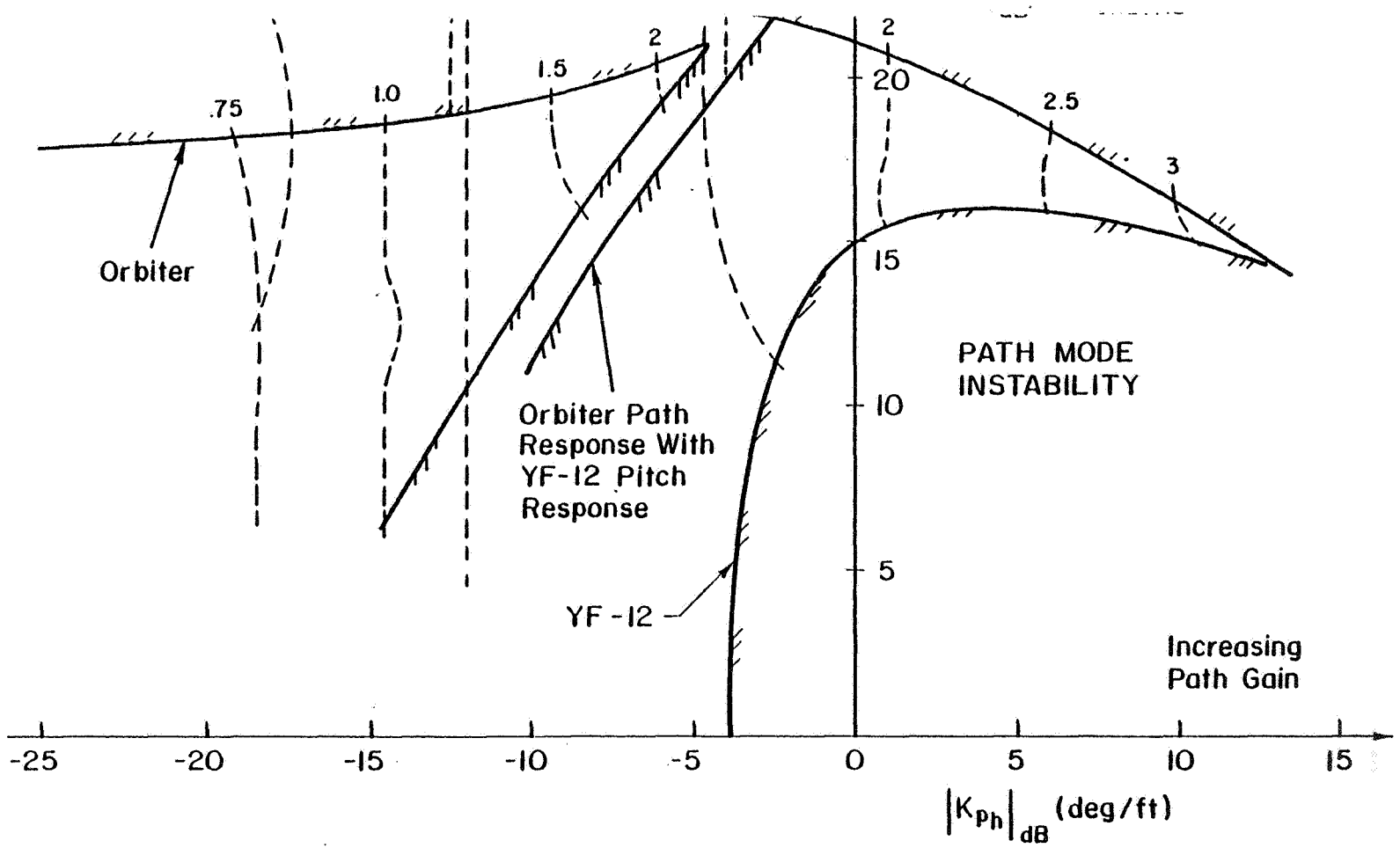

Figure 17. Closed-Loop Path/Attitude Stability Boundary Comparisons of YF-12 and Orbiter Configurations

Here, in addition to the characteristics of the Orbiter and YF-12, we have superimposed the characteristics of a halfbreed aircraft. For this third configuration we used the path response of the Orbiter and the attitude response of the YF-12. This gives some indication of the benefits which could result from Orbiter pitch response improvements. Although the shape of the boundaries are the same for the nominal Orbiter and the halfbreed, considerably higher gain margins are available in the latter for closed-loop path modes in the region of 2.0 rad/sec. The tip of the improved Orbiter boundaries is still considered PIO prone, but the significantly higher frequencies in this region may not be of interest to the pilot.

The Orbiter DFCS was investigated for modifications which would result in a less sluggish pitch response of the augmented Orbiter. These modifications (used in various combinations) were selected for further evaluation by simulation. The simplified OFT Orbiter/DFCS pitch channel block diagram of Fig. 18 will be used to define the modifications. (A more complete block diagram is given in Appendix A). The three modifications used and the corresponding estimated improvement are given in Table 1. Modification a) tightens up the basic pitch rate loop

TABLE 1

POSSIBLE IMPROVEMENTS OF ORBITER PITCH RESPONSE

MODIFICATION	CUMULATIVE ESTIMATED IMPROVEMENT
a) Move elevator feedback lag from 1.5 to 0.5 rad/sec and increase loop gain (GDQ) by approximately 1.5.	Increase in pilot's available attitude control bandwidth from 2.35 to 3.85 rad/sec.
b) Add washed-out analog feedforward from stick to actuator	Reduction in initial time delay in pitch rate response to step inputs from approximately 0.20 sec to 0.10 sec. Further increase in available bandwidth to 5.5 rad/sec.
c) Move bending mode filter from forward path to pitch rate gyro feedback path.	Additional reduction in initial time delay. Increase in available bandwidth.

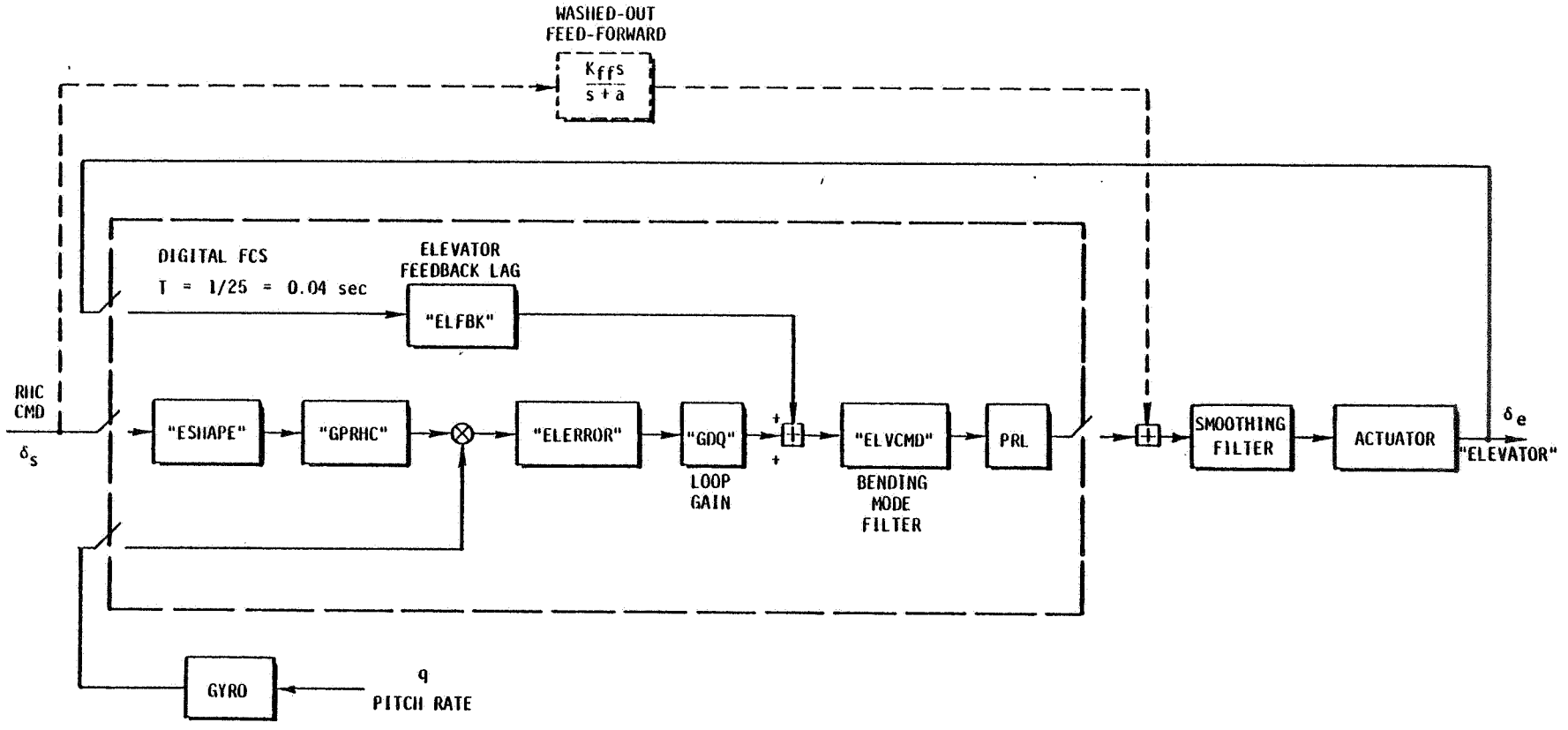

Figure 18. Simplified OFT Orbiter/DFCS Pitch Channel Block Diagram

simultaneously moving the equalization and increasing the loop gain. Modification b) attempts to overcome the initial digital delays by adding an analog path directly from the controller to the existing analog smoothing filter. This is shown by the dashed lines in Fig. 18. The practicality of this mechanization was not determined. Relocating the digital bending mode filter, Modification c), could also quicken the augmented response.

The configurations simulated, made up of combinations of the above modifications, are given in Table 2. Also simulated was an Orbiter control system redesign accomplished by Dryden Flight Research Center. This system makes use of normal acceleration feedback in addition to pitch rate. It is described further in Appendix B.

Pitch attitude frequency responses for the above configurations are given in Fig. 19. In addition, pitch rate time responses for RHC inputs are shown in Fig. 20. The effectiveness of these modifications in reducing the sluggishness of the nominal OFT pitch response can be seen both in the time responses and the phase characteristics of the frequency responses. In subsequent sections we will categorize these systems by their "unstable frequency," ω_u. This is defined as the frequency at which the phase response equals 180 deg (e.g., see Fig. 19).

TABLE 2

ORBITER CONFIGURATIONS SIMULATED

CONFIGURATION	MODIFICATIONS
OFT	None
1	Mod. a)
2	Mods. a), b)
3	Mods. a), b), c)
4	Mods. a), c)
5	DFRC, see App.B

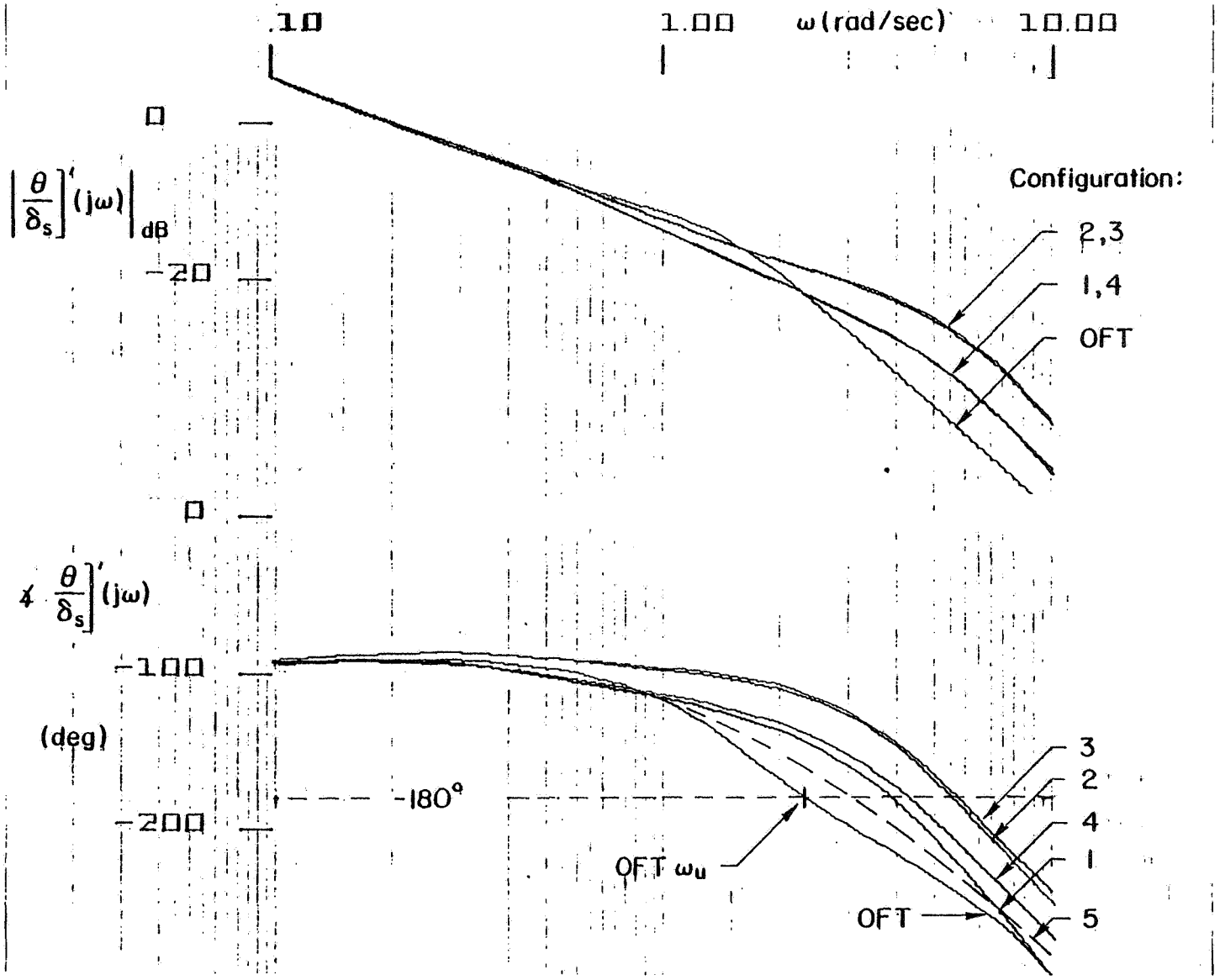

Figure 19. Comparison of Nominal and Modified Orbiter/DFCS Pitch Attitude Frequency Responses for Small RHC Inputs ($|\delta_s| \leq 5$ deg)

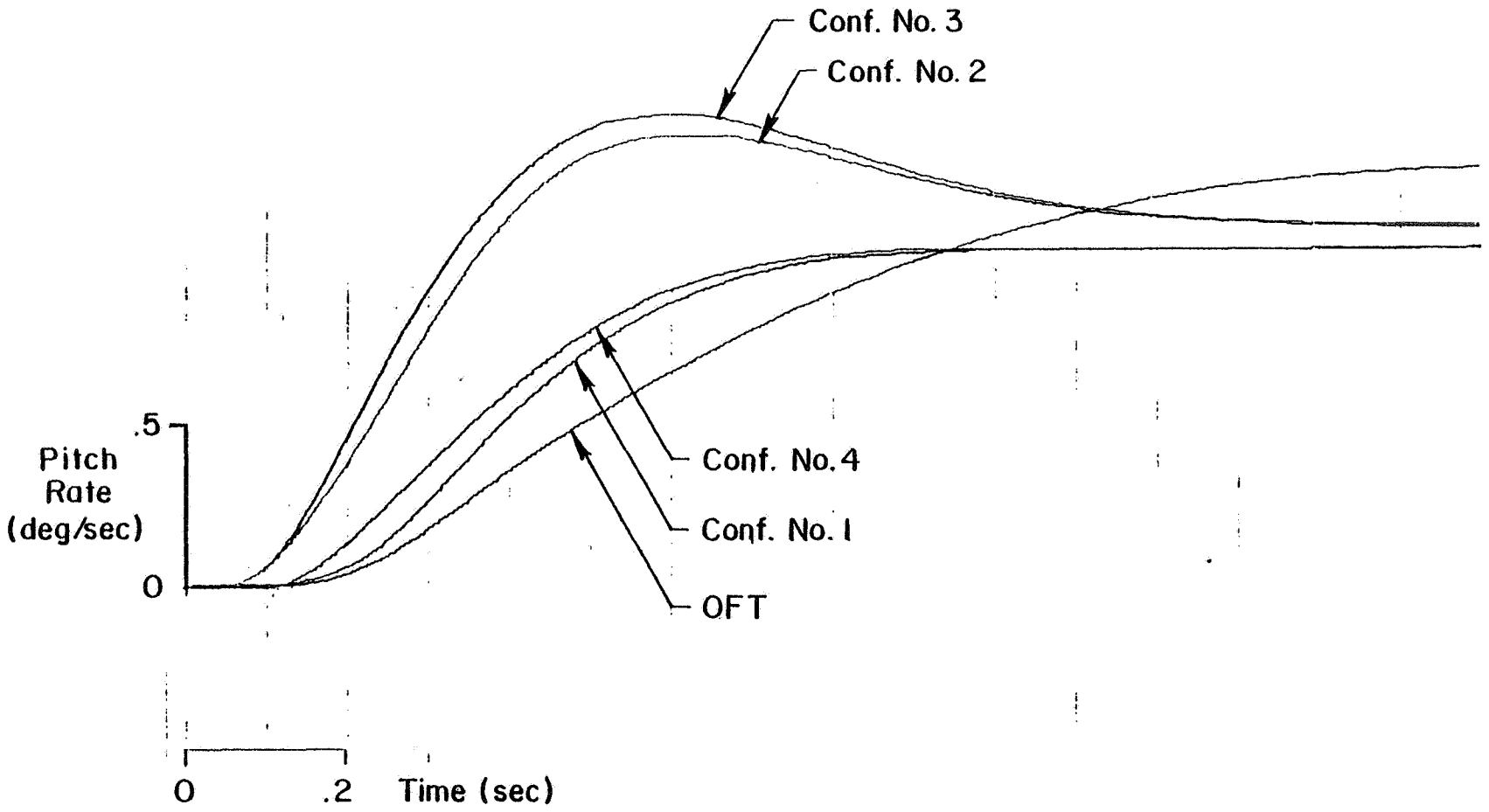

Figure 20. Comparison of Nominal and Modified Orbiter/DFCS Pitch Rate Responses to 5 deg Step Inputs

Although this single parameter is by no means an all-inclusive criterion for pitch response, it is a useful categorization for subsequent comparisons.

C. SIMULATION RESULTS

The simulation was briefly described in Section III. A more complete description, along with the configurations tested, task variations, and more detailed evaluation of the results, is presented in Appendices B, C, and D. Only the highlights of the results are presented here.

The Cooper-Harper rating plot in Fig. 21 summarizes the main simulation results. The trend lines shown in the figure are supported by pilot commentary and further data anlysis presented in Appendix B. The ratings are plotted versus the unstable frequency, ω_u, as defined above. It is used here to categorize pitch responsiveness. The configurations noted correspond to those given in Table 2. The no-rate-limit data (solid trend lines in Fig. 21) for both the experienced and inexperienced pilot are consistent with analytic expectations, i.e., increasing attitude bandwidth capability allowed improved task rating (and performance).

The data with rate limits (the dashed trend lines) also show a consistent effect. To a certain extent, the potential improvement is obviated by the existence of surface rate limits in the range of 20-26 deg/sec. This is particularly true for the most responsive configurations which show the highest potential improvement. Configurations 1 and 5 do show some improvement over the nominal Orbiter even with 26 deg/sec surface rate limits.

The level of experience of the pilot with a given configuration was found to have an important effect. The simulation program was run in seven sessions which spanned a two-month time period. Tests with the same configuration were repeated in various sessions. Typically, after the third exposure to a given configurationn, the pilot's rating data became consistent from session to session. To what extent this learning

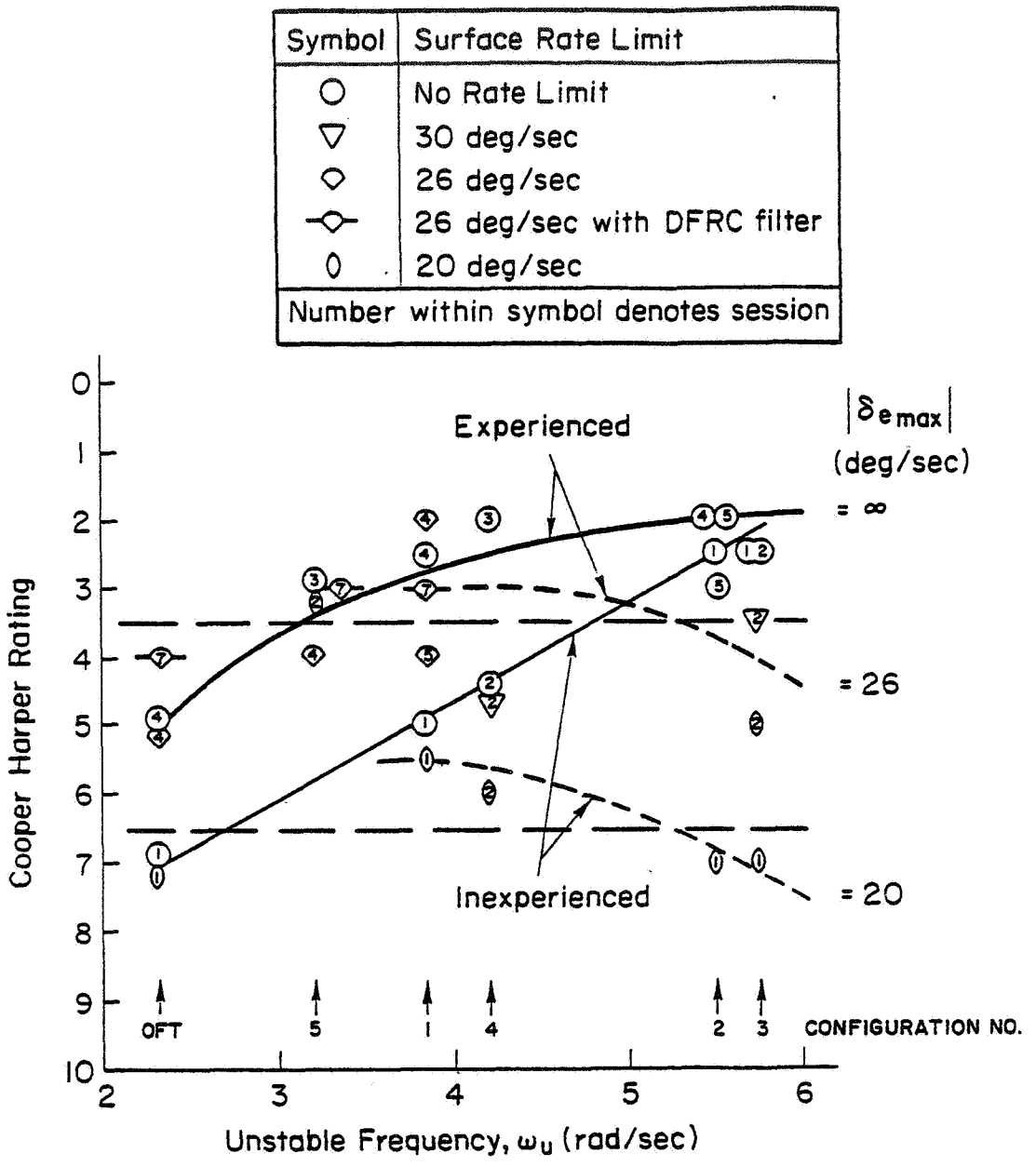

Figure 21. Effects of Orbiter Control System Modifications on Pilot Rating

effect was influenced by simulation and task artifacts was not determined. The number of exposures to a given configuration dictated the separation of data in Fig. 21 by experience. This experience factor, which might have some implications insofar as maintaining pilot proficiency, is clearly a strong effect in the data shown in Fig. 21, except in the case of the more responsive configurations.

A "PIO suppression filter" was designed by Dryden Flight Research Center and received a limited evaluation at the end of our simulation program. The filter mechanization is described in Appendix B. The nonlinear filter acts directly on the RHC output and is intended to reduce the amplitude of high-frequency RHC inputs without introducing additional phase lag. The filter was used with the nominal OFT and Configurations 1 and 5 with surface rate limits of 26.0 rad/sec. In all cases, the filter improved pilot ratings. These are shown by the "winged" symbols in Fig. 21.

All the data shown in Fig. 21 are for the defined task without additional disturbances. As described in Appendix B, random shears were introduced to further test the configurations. The general conclusion from the trials with the shear was the obvious —— task difficulty increased with the introduction and increased magnitude of the shear. The pilot commentary with the suppression filter in the presence of shears did indicate some reservations as to the desirability of the filter. Unfavorable effects were not clearly defined.

SECTION V

CONCLUSIONS

- Analysis of the ALT-FF5 PIO indicates that when the pilot needs moderately tight attitude and path control the closed-loop system is PIO-prone.

- Analysis of the OFT configuration indicate no relief relative to ALT.

- By comparison, a "good" aircraft (YF-12) does not show PIO-proneness for similar closed-loop bandwidths, and

- The critical Orbiter/DFCS characteristics are:
  - Sluggish attitude response to stick.
  - Degraded path response to attitude associated with unfavorable pilot location.

- Improved attitude response alone will improve the attitude/path closed-loop stability characteristics.

- A simple fixed-base simulation of improved systems proved consistent with analytic results; i.e., significant improvement in pilot's ability to consistently control attitude and sink rate.

- The piloted simulation was strongly sensitive to imposition of 20-26 deg/sec surface rate limits. Nevertheless, two of the configurations show some promise of improvement over the nominal (non-limited surface rate) OFT Orbiter even with 26 deg/sec.

- The "PIO suppression filter" designed by Dryden Flight Research Center counteracted the rate limit effect when the task was flown without disturbances. Limited tests indicated that its desirability should be further evaluated in the presence of disturbances.

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APPENDIX A

LINEARIZED MODEL OF OFT ORBITER

This appendix develops the linearized model of the OFT Orbiter/Digital Flight Control System (DFCS) used in the pilot/vehicle analyses. Data for the airframe alone are presented first. This is followed by the characteristics of the augmented, closed-loop Orbiter/DFCS.

AIRFRAME CHARACTERISTICS

OFT Inertia and Geometry

The following parameters were taken from Ref. 3, page 21:

W	Total weight	184,000 lb
S	Reference wing area	2,690 ft^2
$\bar{c}$	Reference chord	39.57 ft
L_B	Reference body length	107.5 ft
X_{CG}	Center-of-gravity position	66.7% L_B
I_y	Pitch moment of inertia	6,380,000 slug-ft^2

The geometry of Fig. A-1 was taken from Ref. 8.

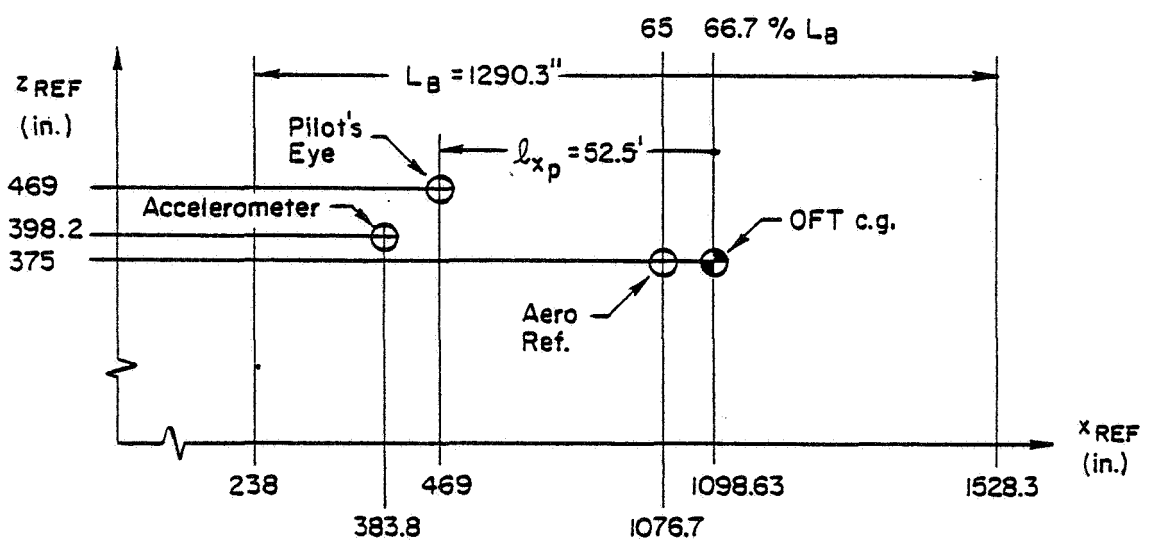


Figure A-1. Pertinent Geometry

Orbiter Nondimensional Aerodynamic Coefficients

The following equations for lift, drag, and pitching moment coefficients are taken from Ref. 3, with minor modifications based on information received from DFRC. . Gear down, out of ground effect, and no-speed-brake ($\delta_{SB_0} = 0$) conditions have been assumed.

$$C_L = -0.0361 + 0.0476\alpha + 0.0186\delta_e$$

$$C_D = 0.0627 - 0.00205\alpha + 0.000495\alpha^2 + [0.000215 + 0.00028\alpha]\delta_e + 0.000095\delta_e^2$$

$$C_{m_{cg}} = 0.0251 - 0.0005\alpha - 0.0087\delta_e + C_{m_q}\, q\, \frac{\bar{c}}{2V} + \left(X_{cg} - .65\right) \frac{L_B}{\bar{c}}\, C_L$$

where

$$C_{m_q} = -0.047 \text{ 1/deg} \quad \text{for } \alpha < 6 \text{ deg}$$

$$= -0.041 \text{ 1/deg} \quad \text{for } \alpha > 6 \text{ deg}$$

All angular units are in terms of degrees. For the OFT c.g. position of 66.7% L_B the pitching moment coefficient referenced to the c.g. is given by:

$$C_{m_{cg}} = 0.0234 + 0.00170\alpha - 0.00784\delta_e + C_{m_q}\, q\, \frac{\bar{c}}{2V}$$

OFT Landing Approach "Trim" Condition

The nominal flight condition is:

$$h = 2420 \text{ ft}, \quad V_E = 190. \text{ KTEAS}, \quad \gamma = 0 \text{ deg}$$

which corresponds to:

$$V_T = 333.1 \text{ fps} \quad , \quad q = 122.9 \text{ psf}$$

The Orbiter is decelerating at about 6 ft/sec^2 at this condition, and perturbation equations are computed for $\dot{q} = \dot{\gamma} = \dot{\alpha} = q = 0$. For $\dot{q} = q = 0$, the pitching moment coefficient must equal zero and the relation between "trim" angle of attack and elevator is given by:

$$\delta_{e_o} = 2.985 + 0.2166\alpha_o$$

"Trim" lift and drag coefficients are given by:

$$C_{L_o} = 0.0194 + 0.0516\alpha_o$$

$$C_{D_o} = 0.0642 - 0.00104\alpha_o + 0.000560\alpha_o^2$$

For $\dot{\gamma} = 0$ the required lift coefficient is given by:

$$C_{L_o} = \frac{W}{S\bar{q}} = \frac{184,000.}{(2690.)(122.9)} = 0.556$$

and the trim angle of attack is:

$$\alpha_o = \frac{(C_{L_o} - .0194)}{.0516} = 10.4 \text{ deg}$$

The trim drag coefficient is:

$$C_{D_o} = 0.0642 - 0.00104(10.4) + 0.000560(10.4)^2$$

$$C_{D_o} = 0.114$$

The trim elevator position is given by:

$$\delta_{e_o} = 2.985 + 0.2166(10.4) = 5.24 \text{ deg}$$

Perturbation aerodynamic coefficients for this condition are:

$$C_{L_\alpha} = 0.0476 \text{ 1/deg} = 2.73 \text{ 1/rad}$$

$$C_{D_\alpha} = 0.00971 \text{ 1/deg} = 0.557 \text{ 1/rad}$$

$$C_{m_\alpha} = 0.00170 \text{ 1/deg} = 0.0974 \text{ 1/rad}$$

$$C_{m_q} = -0.041 \text{ 1/deg} = -2.35 \text{ 1/rad}$$

$$C_{L_{\delta_e}} = 0.0186 \text{ 1/deg}$$

$$C_{D_{\delta_e}} = 0.00412 \text{ 1/deg}$$

$$C_{m_{\delta_e}} = -0.00784 \text{ 1/deg}$$

Bare Airframe Transfer Functions

The dimensional derivatives and transfer functions presented in Fig. A-2 are based on the definitions and conventional, longitudinal stability axis equations of motion given in Ref. 6. Angular units of radians are used for all airframe states in Fig. A-2; elevator inputs are in terms of degrees.

```
OFT 190 KTEAS APPROACH

 GEOMETRY:
        VT          ALPHA       GAMMA       LX A        LX H      LX D
      333.1          0.0         0.0         0.0        52.50      0.0
        A           RHO         MACH        XIO         ZJ
     1107.2       .002213      .3009        0.0         0.0
        S           C         WEIGHT        IY       ALTITUDE
      2690.        39.57      184010.    .6380E+7      2420.

 NON-DIMENSIONAL DERIVATIVES:
        CL          CLA         CLAD        CLM
      .5560        2.730        0.0         0.0
       CMA         CMAD        CMQ         CMM
     .09740         0.0       -2.350        0.0
        CD          CDA         CDM         TM          TDTH
     .11400        .3570        0.0         0.0         0.0
       CDDE        CLDE        CMDE
     .004100      .013600    -.007840

 DIMENSIONAL DERIVATIVES:
        XU          XU *        XW          TU
    -.03953      -.03953   -.00017338       0.0
        ZU          ZU *        ZWD         ZW
    -.19279      -.19279       0.0       -.4931
        MU          MU *        MWD         MW
       0.0          0.0         0.0      .0005990
       MAD          MA          MQ
       0.0         .1995      -.2859
       XDE         ZDE         MDE
    -.2368       -1.0742    -.016060

OFT 190 KTEAS APPROACH

     DENOMINATOR:   (-.1707)(.854)[.424;.1597  .0677;.14461 <-.00372>

OFT 190 KTEAS APPROACH

  DE  NUMERATORS:

            N(U-DE)  -.237(.488)(-1.407)(1.698) <.276>

            N(W-DE)  -1.074(5.23)[.1279;.1332  .01705;.13211 <-.0997>

          N(THE-DE)  -.01606(.0360)(.537) <-.000311>

AT CG       N(DD-DE)   1.074(.001316)(-1.495)(1.777) <-.00376>

AT CG       N(AZ-DE)  -1.074(0.0)(.001316)(-1.495)(1.777) <.00376>

AT PILOT    N(HD-DE)   .231(.001309)(3.16)(-3.93) <-.00376>
```

Note:

(a) = (s + a)

$[\zeta;\omega_n \quad \sigma,\omega] = [s^2 + 2\zeta\omega_n s + \omega_n^2] \qquad \sigma = \zeta\omega_n, \quad \omega_n = \omega\sqrt{1-\zeta^2}$

<c> = Lowest order (non-zero) coefficient of polynomial

Figure A-2. OFT Dimensional Derivatives and Transfer Functions

DIGITAL FLIGHT CONTROL SYSTEM (DFCS)

The linearized OFT Orbiter pitch channel flight control system is shown in Fig. A-3. Data on the DFCS were taken from Refs. 2 and 7. As shown in the figure, a single time delay, $e^{-\tau_1 s}$, was used to represent all the effects of the digital implementation. τ_1 was adjusted to obtain a best fit with pitch attitude frequency response data provided by Dryden Flight Research Center. A comparison of the linearized model using $\tau_1 = 0.0455$ sec with the data is shown in Fig. A-4.

AUGMENTED, CLOSED-LOOP OFT ORBITER/ DFCS TRANSFER FUNCTIONS

The closed-loop pitch attitude to RHC command input transfer function is:

$$\left.\frac{\theta}{\delta_s}\right]'_{\theta\to\delta_e} = \frac{1.50 \times 10^5(.036)(.537)(.590)(1.50)(-43.9)[.02,32.75]}{(0)(.031)(14.2)[.97,.620][.63,1.59][.39,20.6][.68,37.1][.99,50.2]}$$

where

$$(a) = (s + a); \qquad [\zeta,\omega_n] = \left[s^2 + 2\zeta\omega_n s + \omega_n^2\right]$$

Other closed-loop airframe responses can be obtained by using ratios of bare airframe numerators (Fig. A-1). These are not changed by the DFCS.

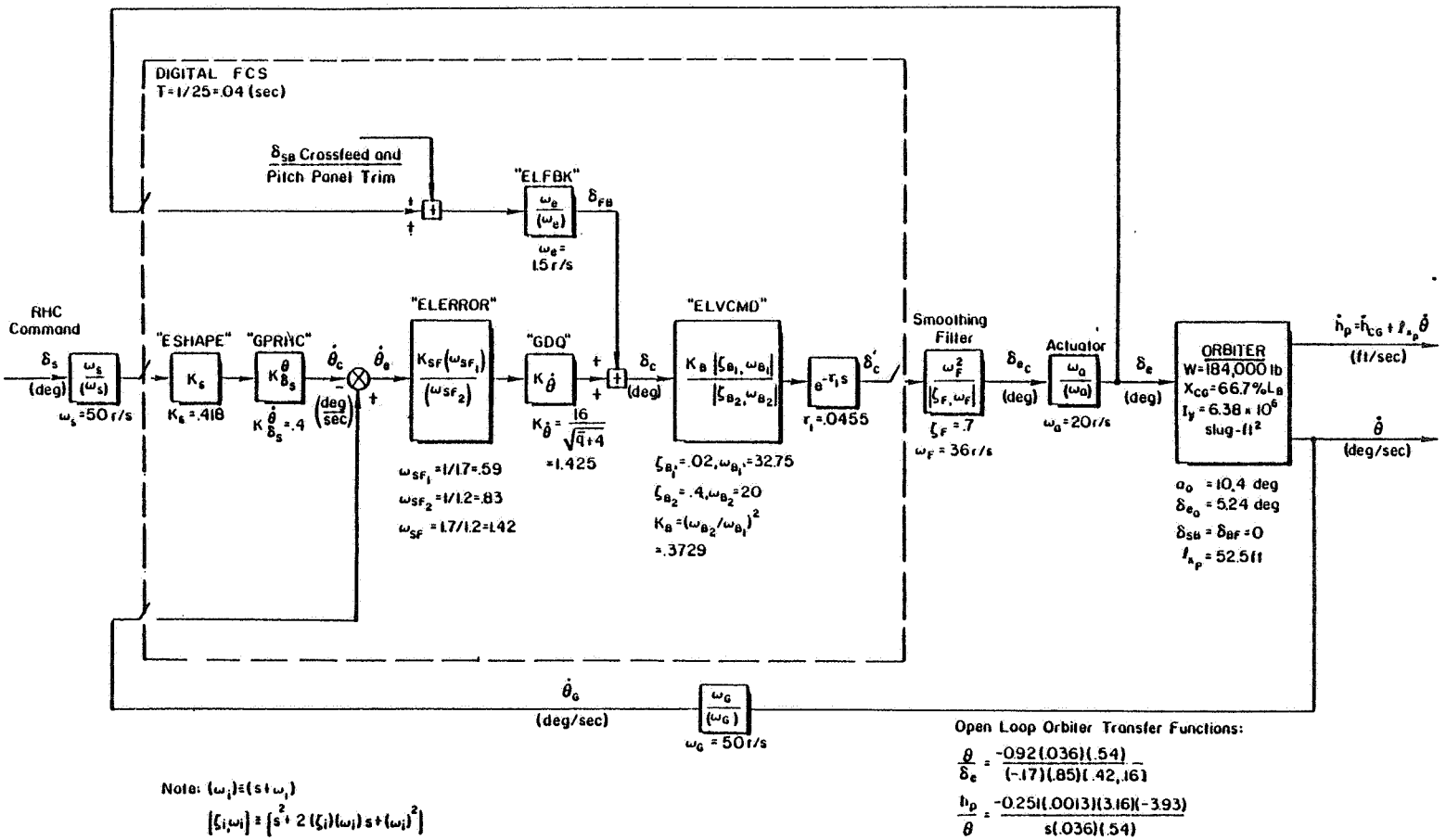


Figure A-3. Linearized OFT Orbiter/DFCS Pitch Channel Landing Approach
Condition: h = 2420 ft, V = 190 kt EAS, $\bar{q}$ = 122 psf
Small Inputs: $|\delta_s| \leq 5$ deg

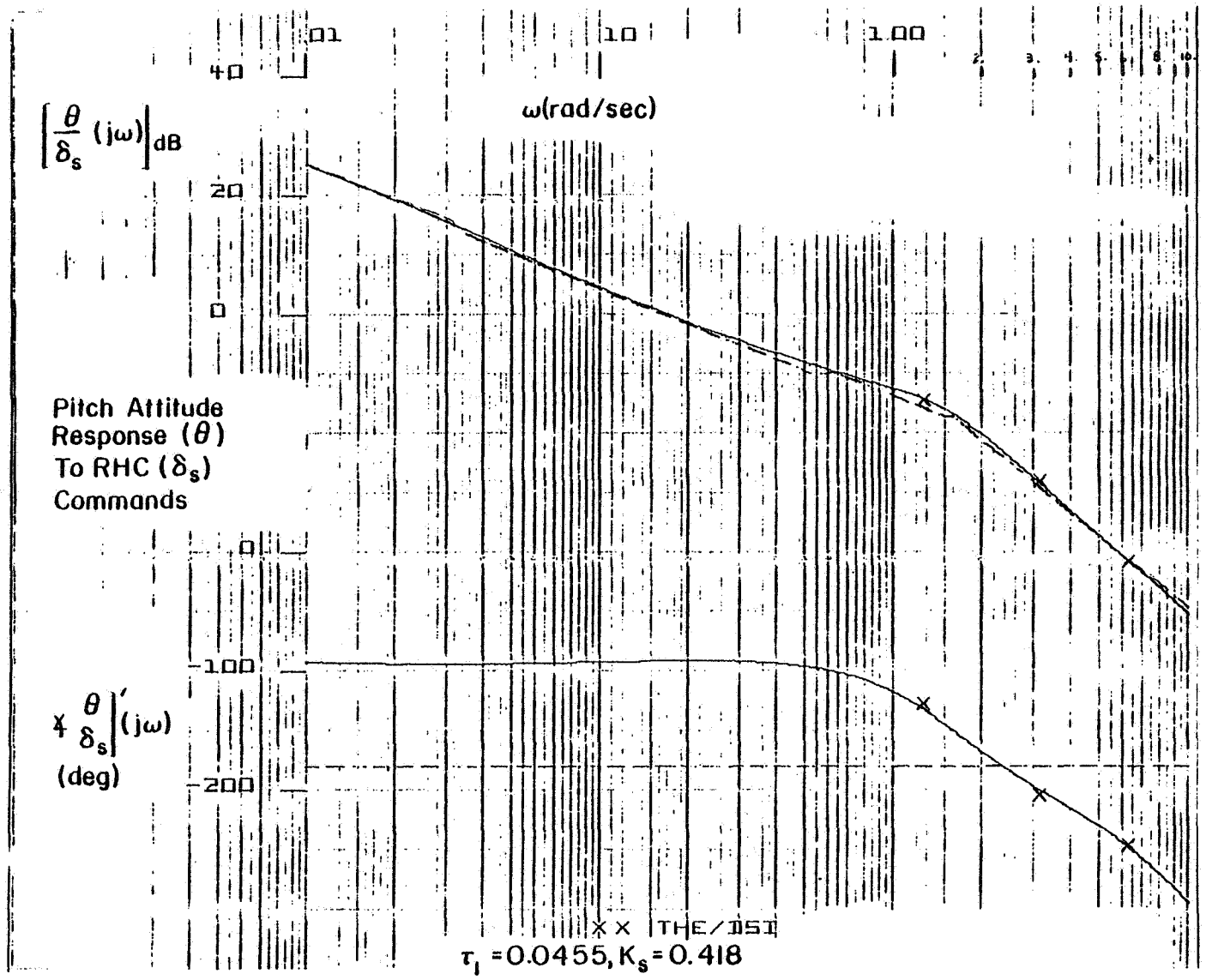


Figure A-4. Comparison of Linearized Model of OFT Orbiter/DFCS Pitch Channel with Complete Nonlinear Model (X) Frequency Response for for Small ($\delta_s \leq 5$ deg) Inputs

APPENDIX B

SIMULATION DETAILS

SIMULATION DESCRIPTION

The simulation consisted of the following components:

- A chair-mounted (two-axis) control stick
- AN EAI 1631-R analog computer
- PDP-11 minicomputer
- Dual-beam oscilloscope display

The interfacing for these components is shown in Fig. B-1, which also defines the function of each component.

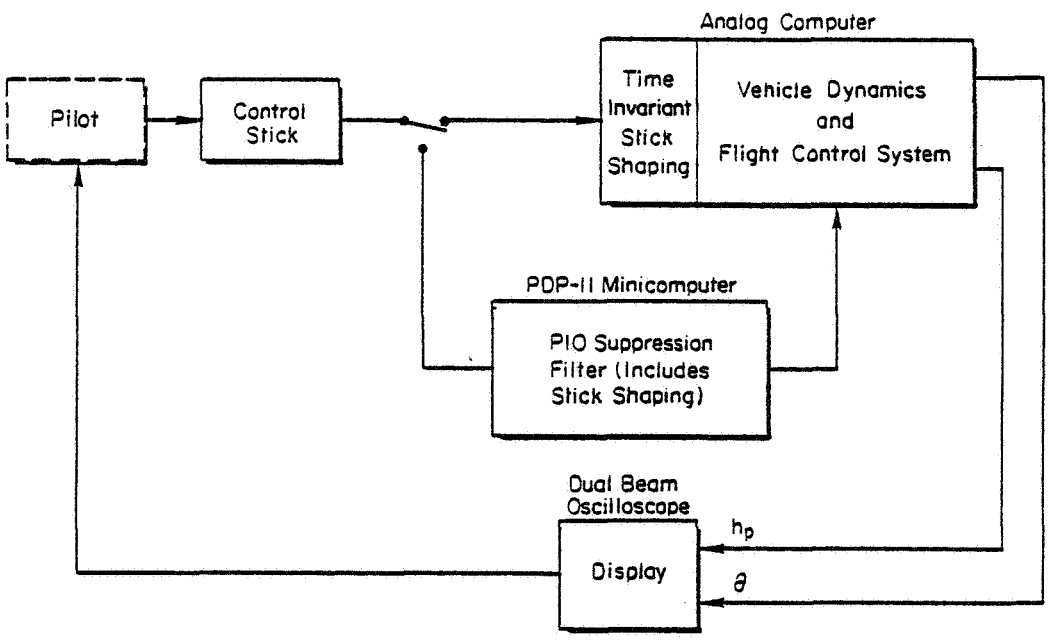


Figure B-1. Simulator Component Interface Diagram

Control Stick

A conventional two-axis fighter control stick was used. The control stick was mounted between the legs of the steel-frame chair on which the pilot sat. Figure B-2 shows the control stick, close up and mounted on the chair.

Only the longitudinal control stick axis was used in this simulation. Longitudinal stick force characteristics are given in Fig. B-3. The stick had a throw of 22.7 deg forward and 19.5 deg aft of the stick neutral position. Stick position was sensed by a potentiometer which was mounted at the base of the handgrip support. The potentiometer had about ±1 deg of deadband about the stick neutral position and was otherwise vertically linear with stick angular displacement.

Stick Shaping and Filtering

For all Orbiter configurations, the OFT stick shaping was used. This consisted of a ±1.15 deg deadband about the neutral stick position with a parabolic characteristic outside the deadband. The deadband was well approximated by the stick sensing potentiometer deadband previously mentioned. The parabolic characteristic was mechanized on the analog computer as

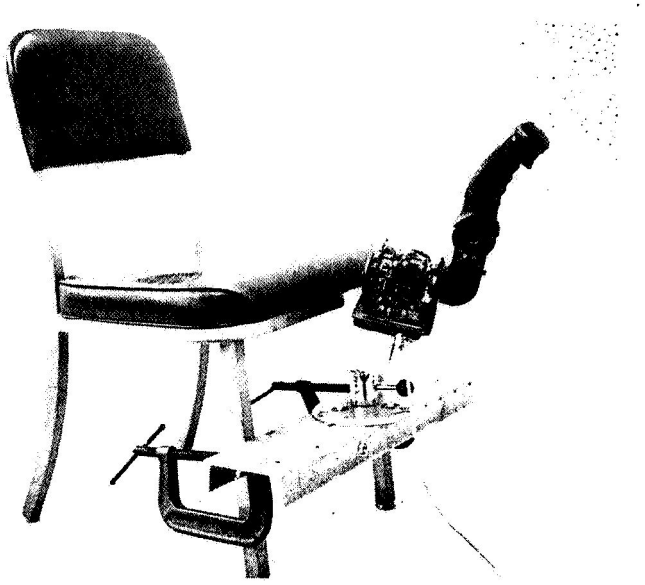
$$\delta_{ss} = \left(.36 + .04837|\hat{\delta}_s|\right)\hat{\delta}_s$$

where

δ_{ss} = Shaped stick

$\hat{\delta}_s$ = Sensed stick position

For the evaluation of the DFRC PIO suppression filter, the integrated stick shaping and filtering were mechanized on the PDP 11 minicomputer. The block diagram of the suppression filter and a listing of the digital program used to model it are provided in Figure B-4 and Appendix D, respectively.



a) Mounted

b) Close-Up

Figure B-2. Control Stick

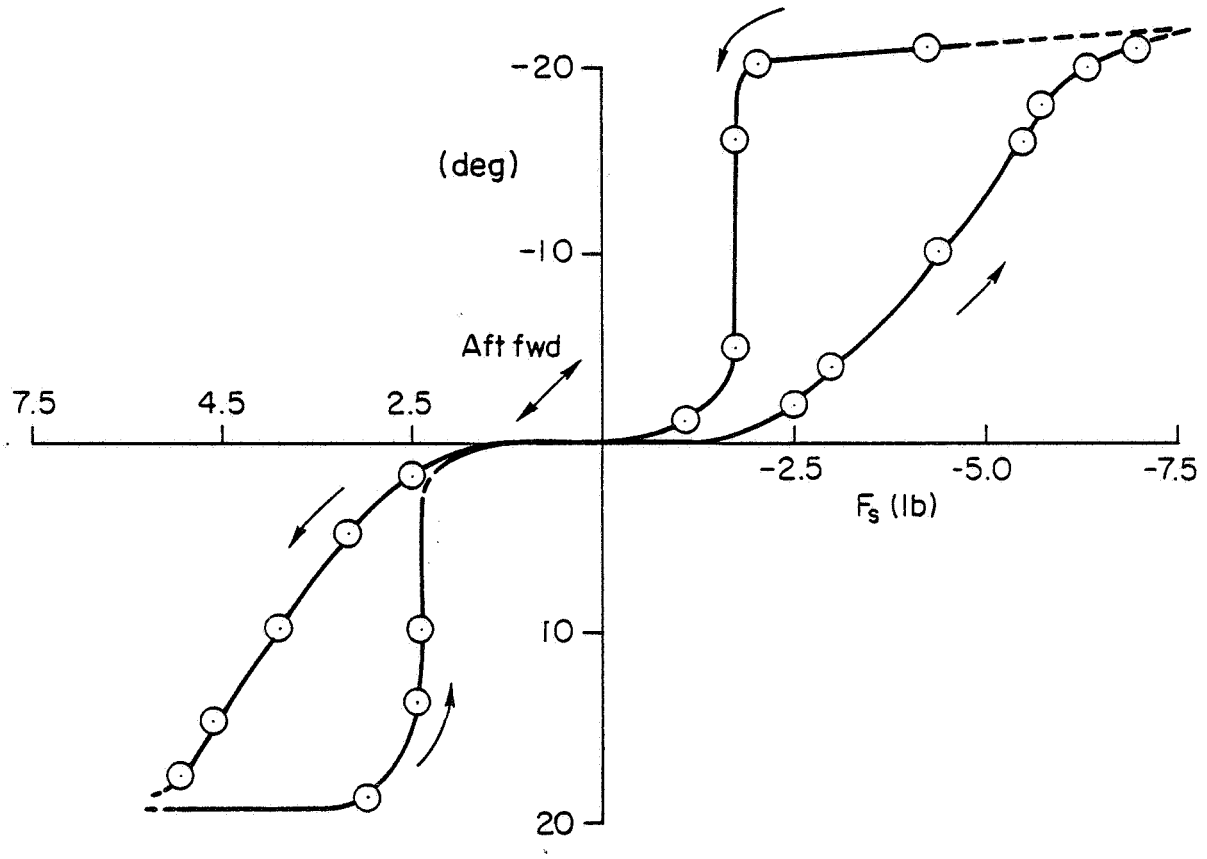


Figure B-3. Longitudinal Stick Force Characteristics

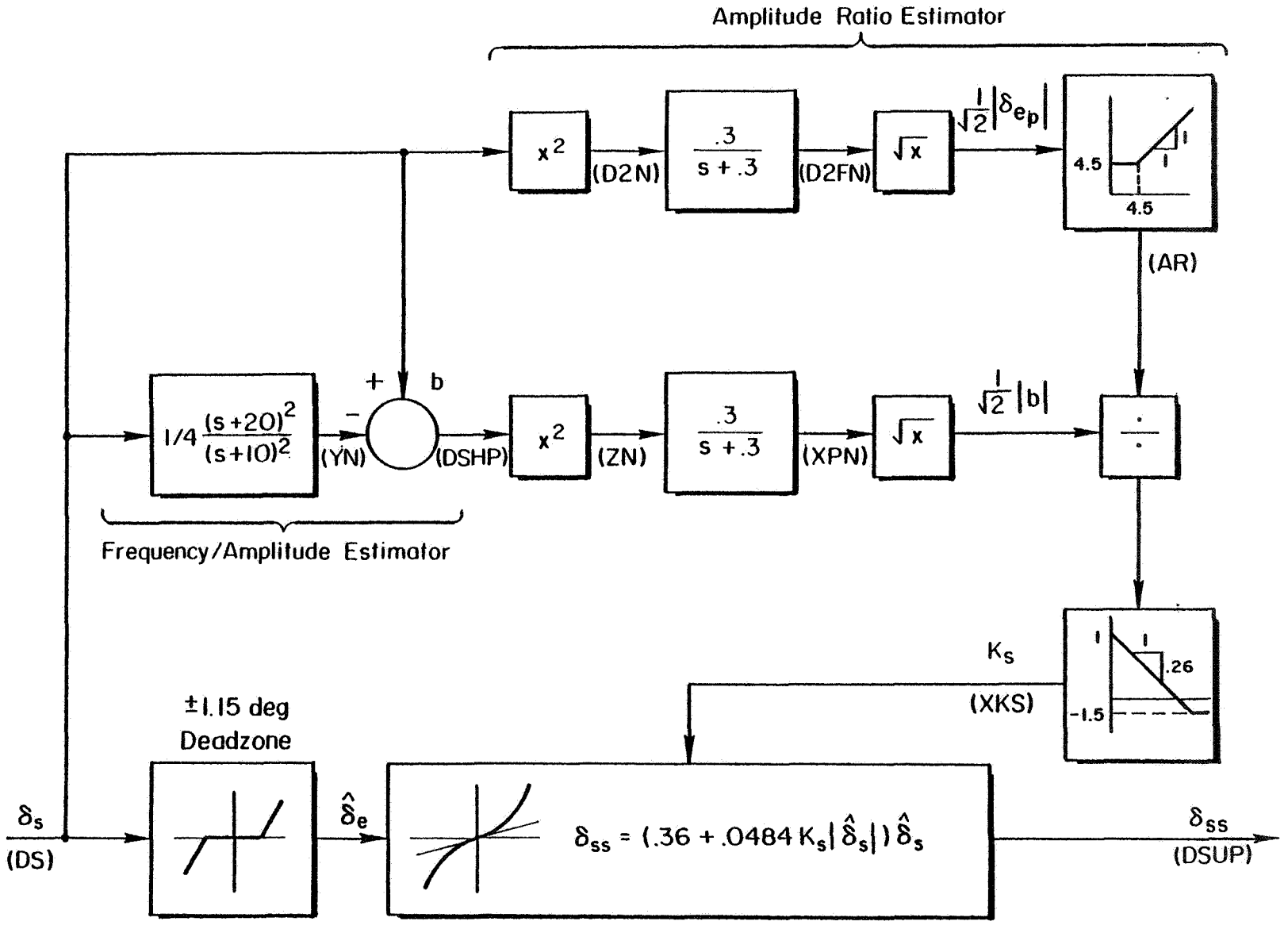


Figure B-4. DFRC PIO-Suppression Filter

For the YF-12 and 747 configurations simulated, no shaping or filtering were applied to the sensed stick position.

System Dynamics

Vehicle dynamics consisted of two-degree-of-freedom aerodynamic equations of motion plus the kinematics equation for the pilot location altitude, h_p:

$$\dot{\alpha} - Z_w\alpha - \dot{\theta} = (Z_{\delta_e}/U_o)\delta_e$$

$$-M_\alpha\alpha + \ddot{\theta} - M_q\dot{\theta} = M_{\delta_e}\delta_e$$

$$\dot{h}_p = U_o(\theta - \alpha) + \ell_{x_p}\dot{\theta}$$

These equations were mechanized on the analog computer.

Aerodynamic derivative data and the resulting h_p/θ transfer function for the simulated aircraft are provided in Table B-1.

Control Systems)

The control system models for the Orbiter are defined in the block diagram of Fig. B-5. These models represent the OFT control system and the variations on it, previously discussed in Section IV.

The YF-12 control system model is shown in Fig. B-6.

The 747 bare airframe dynamics were not augmented. The elevator actuator was modeled as a 20 rad/sec first-order lag.

The elevator actuator model for all three aircraft was mechanized with an adjustable rate limit. Table B-2 provides a summary of the configurations tested. In addition to defining the control system for each configuration, Table B-2 lists the resulting closed-loop controlled element, q/δ_s, for each. Note that this transfer is the three-degree-of-freedom result; it differs negligibly from the two-degree-of-freedom

TABLE B-1

VEHICLE DYNAMICS USED IN SIMULATION

AIRCRAFT	AERODYNAMIC DIMENSIONAL DERIVATIVE DATA							h_p/θ [a]
	U_o (ft/sec)	Z_w (1/sec)	Z_{δ_e} (ft/sec^2-rad)	M_α (1/sec^2)	M_q (1/sec)	M_{δ_e} (1/sec^2)	ℓ_{x_p} (ft)	(ft/rad)
Orbiter	333.	-.493	-61.55	.1995	-.286	-0.9202	52.5 83.0	$\frac{14.4(3.15)(-3.93)}{(0)(.533)}$ $\frac{-16.1[.237,\ 3.3]}{(0)(.533)}$
YF-12	354.	-.854	-60.16	-.6256	-.531	-2.532	49.9 0.54	$\frac{26.1[.160,\ 3.32]}{(0)(.812)}$ $\frac{-23,2(-3.27)(3.79)}{(0)(.812)}$
747	278.	-.613	-9.73	-.539	-.437	-.574	86.0	$\frac{70.[.210,\ 1.53]}{(0)(.58)}$

[a]The pilot location altitude-to-pitch-attitude transfer function for an elevator input.

Note: For all three aircraft, the vehicle dynamics are for approach-landing flight conditions, as described or referenced below:

Orbiter: See Appendix A

YF-12: Unpublished data received from DFRC

747: Heffley, R. K., and W. J. Jewell, Aircraft Handling Qualities Data, NASA CR-2133, Dec. 1972.

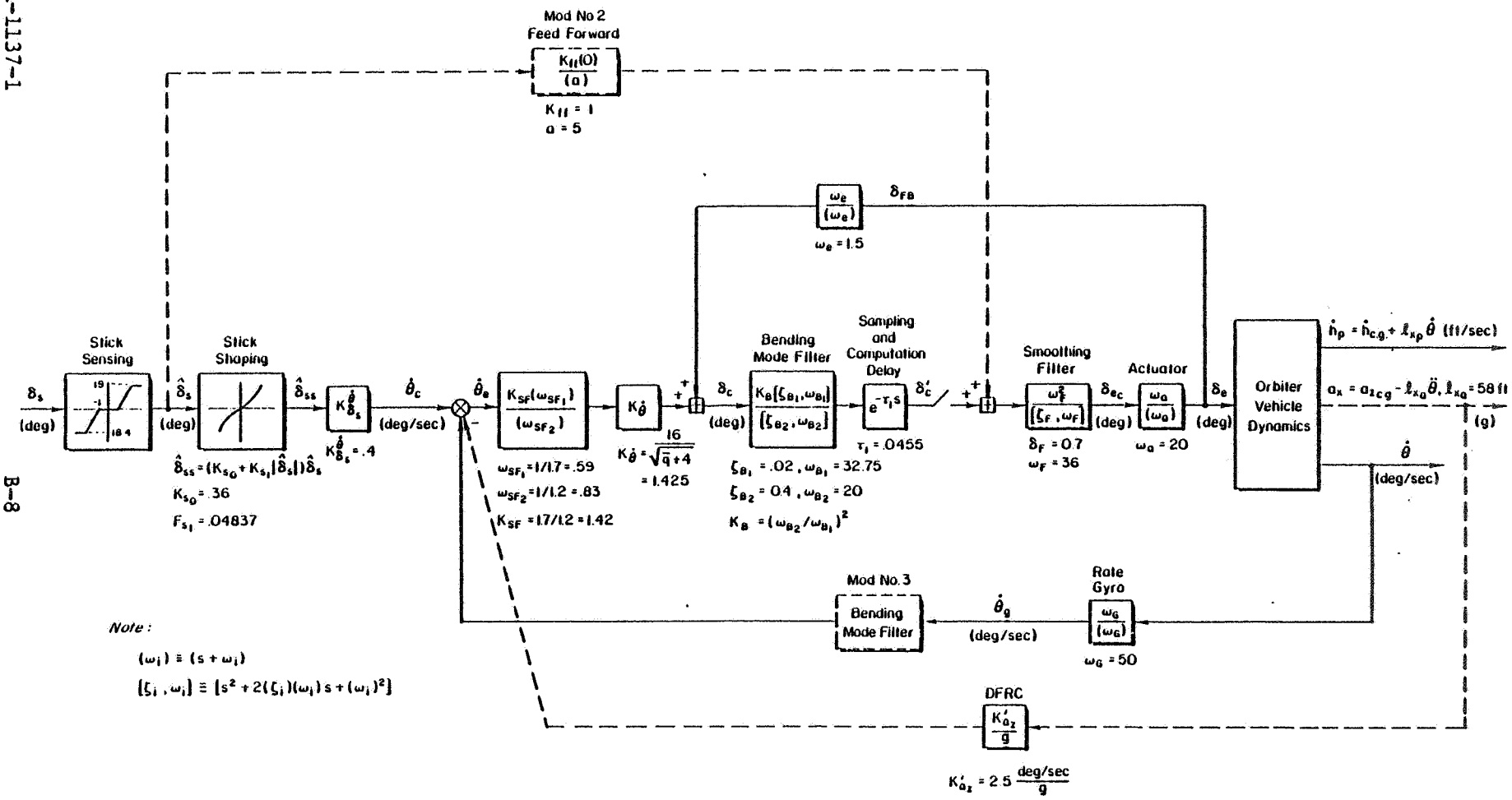


Figure B-5. Simulation Model of Orbiter OFT and Variant Control Systems

TABLE B-2. TESTED CONFIGURATIONS

CONFIGURATION DESIGNATION	AIRCRAFT	CONTROL SYSTEM[a]	CLOSED-LOOP CONTROLLED ELEMENT[b,c] q/δ_s (1/sec)
OFT	Orbiter	Nominal	$\frac{-1.49 \times 10^5(.036)(.537)(.59)(1.5)(-43.9)[.02;32.75]}{(.0313)(14.2)[.973;.62][.628;1.59][.39;20.6][.683;37.][.988;50.2]}$
1		Mod. a	$\frac{-2.25 \times 10^5(.036)(.5)(.537)(.59)(-43.9)[.02;32.75]}{(.0276)(.702)[.849;.479][.755;5.92][.408;21.8][.688;38.2][.986;51.6]}$
2		Mods. b, c	$\frac{8.11 \times 10^5(.036)(.5)(.532)(.537)(2.75)(77.5)[.190;20.4]}{(.0276)(.702)(5.)[.849;.479][.755;5.92][.408;21.8][.688;38.2][.986;51.6]}$
3		Mods. a, b, c	$\frac{-6.00 \times 10^5(.036)(.5)(.53)(.537)(2.15)(156.)[.4;20.]}{(.0276][.701)(5.)[.851;.479][.735;5.85][.414;22.1][.692;38.0][.986;51.5]}$
4		Mods. a, c	$\frac{4.39 \times 10^5(.036)(.5)(.537)(.59)(-44.)[.4;20.]}{(.0276)(.701)[.851;.479][.735;5.85][.414;22.1][.692;38.0][.986;51.5]}$
5		DFRC	$\frac{-222650.[.036)(.537)(.59)(1.)(-44.)[.02;32.75]}{(.0591)(1.07)(2.98)(9.77)[.967;.431][.414;20.9][.688;37.1][.986;50.8]}$
6		DFRC + Mod. 3	Not analyzed
YF-12	YF-12	See App. B, Fig. B-4	$\frac{7726.(0)(.0376)(.79)(4.)[.047;9.65][.7;50.5]}{(1.13)(28.6][38.3)[.28;.054][.796;3.10][.05;20.][.644;39.6]}$ [d]
747	747	20 rad/sec actuator	$\frac{11.48(.58)}{(20.)[.584;.898]}$

[a]The nominal Orbiter control system and the various modifications called out in this table are shown in Fig. B-5. For convenience, these modifications are also identified here:

Mod. a $K_\theta = 1.5K_{\theta_{nom}} = 2.138$; $\omega_e = 0.5$ rad/sec

Mod. b Addition of analog stick feedforward to smoothing filter input

Mod. c Moving of bending mode filter to feedback path

DFRC Addition of vertical accelerometer feedback and $K_\theta = 1.3K_{\theta_{nom}}$; $\omega_e = 1$ rad/sec

[b]Transfer functions are for 3 degree of freedom equations of motion. $(\omega_i) = (s + \omega_i)$; $[\zeta_i;\omega_i] = [s^2 + 2\zeta_i\omega_i s + \omega_i^2]$

[c]Transfer function gain is for effective stick gain, K_s, of 0.418.

[d]For cockpit pitch velocity, which is different from that at c.g. due to bending mode.

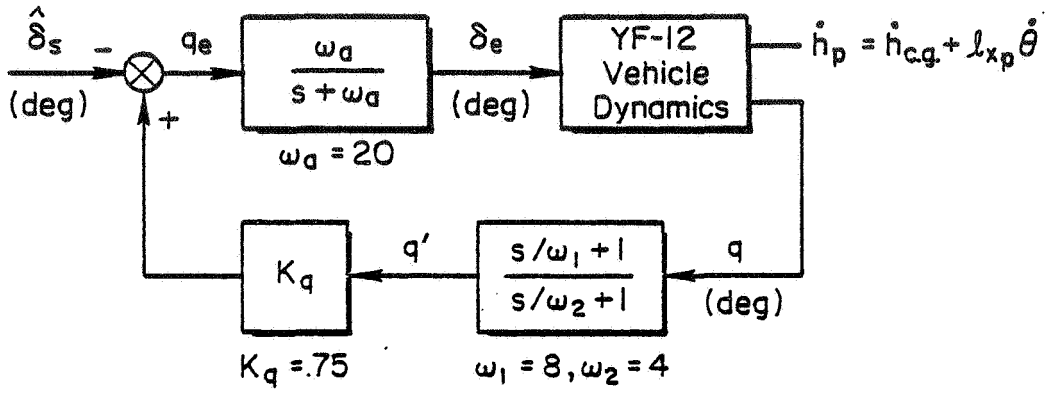


Figure B-6. YF-12 Control System Model

differs negligibly from the two-degree-of-freedom transfer function only in the very low frequency range.

Display

The display is illustrated in Fig. B-7. The usual horizontal line symbol —— representing the aircraft with wings level —— was marked in the center of the CRT. The horizon was represented by a horizontal line extending across the entire CRT face. Changes in pitch attitude were presented in the usual inside-out sense, the horizon moving down to indicate pitch up. The third horizontal line represented the ground-plane. In addition to moving up and down proportional to the decrease and increase, respectively, in pilot location altitude, this line also decreased in length at a constant rate, converging to a dot, a preset length of time after the start of each run (see task description).

Pilot

The pilot was an STI senior research engineer whose qualifications included:

- Commercial license for single-engine and multi-engine fixed-wing aircraft and for rotorcraft, with instrument and instrument instructor ratings.

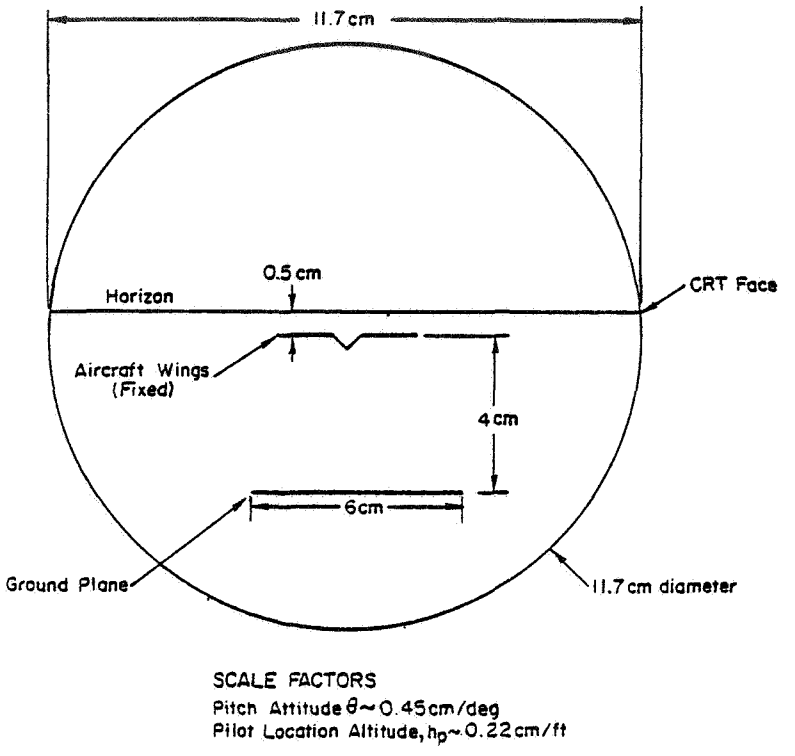


Figure B-7. Simulator Display (with Nominal Task Initial Conditions)

- Approximately 4000 hours in light aircraft.
- Test pilot in flight tests involving:
  - Princeton Variable Stability Navion
  - Light aircraft handling qualities and spoiler development
- Test pilot in a number of fixed- and moving-based simulations.

TEST FORMAT

Task

The task was designed to present the pilot with the same dynamics and kinematics, and with similar constraints, as he would experience in an actual landing. Each run began with the aircraft trimmed at a nose

down attitude above the groundplane. Thus, the pilot started each with a positive sink rate. The task was to arrest this sink rate and bring the groundplane to rest as smoothly as possible on the aircraft wings at or before the end of a fixed time interval. The time-to-go was indicated by the instantaneous length of the groundplane line; the task ended when the line converged to a dot. If the groundplane got up to the aircraft wings before the task time expired, then the remaining time was to be spent holding the altitude (groundplane) constant at zero (on the wings).

Thus, this task bears a good deal of similarity to an actual landing flare. The time limit provides a constraint similar to that posed by the runway aimpoint. Having the time run out before the groundplane reaches the aircraft wings is analogous to floating past the aimpoint and using up runway. Having the groundplane overshoot the aircraft wings is analogous to a hard landing.

It must be emphasized that this task does not — and is not intended to — simulate an actual landing. It does, however, bear enough similarity to that task that it might reasonably be expected to expose deficiencies in aircraft handling qualities which would affect landing performance and to allow various alternative systems to be evaluated relative to one another. The simplicity and brevity of this task, on the other hand, made it an effective tool for exploring a large number of variations in a relatively short time.

Task time, T, was picked to be 9 sec. This allowed sufficient time for the pilot to close the loop and excite a PIO if the system were PIO-susceptible. On the other hand, it was short enough to allow a high task repetition rate. In one of the later test sessions the effects of longer task time — up to 25 sec — were examined.

A "random wind shear" was also added to the task in later test sessions. The nominal wind shear was 0.5 kt/sec for the last 5 sec of the task. Variations of the wind shear magnitude, $|u_g|$, and duration, ΔT_g, were also tested in later sessions.

Protocol

Before random wind shear was added, the following protocol was used. The pilot was allowed to familiarize himself with each new configuration by "flying" the aircraft and then performing the prescribed task repeatedly until he felt his performance was "stable." After this "warmup" he made at least ten "formal" runs at the tested condition (task/configuration). Then he rated the condition on the Cooper-Harper scale (Appendix C, Fig. C-1) and tape recorded any explanatory comments.

The protocol for conditions run with random wind shear was similar to the above. The pilot did his warmup without any wind shear. He then rated and commented on the system "with no disturbance." Then he did ten formal runs, four of which, selected "at random" by the test conductor without the pilot's knowledge, include wind shear —— two runs with one sign of u_g and two with the other. After this he rated and commented on the condition "with random shear."

RESULTS

Summary

Seven "test sessions" were conducted in all. The first two sessions provided a comparison of the Orbiter OFT with the YF-12 and the 747, two aircraft known to have good flying qualities; and a survey of the effects of various modifications to the Orbiter OFT flight control system and of elevator rate limitng. Another Orbiter control system variant, this one designed by DFRC and featuring a heave acceleration feedback, was evaluated in Session 3.

Based on the experience gained in the first three sessions, it was felt that some random disturbance was needed to keep the pilot "honest." Even a poor system can be made to perform well in a discrete task if the pilot can learn the appropriate input pattern. So, "random shear" was introduced in Session 4, and its effects on various Orbiter control systems were surveyed in Sessions 4 and 5. Thereafter, random shear was made a routine part of the formal runs.

Another question which arose concerning the task definition was how much effect the severity of the selected task had on the handling qualities evaluation. Session 6 was therefore devoted to examining these effects. The variations tried included:

- Reducing initial pitch attitude and thus sink rate.
- Increasing task duration.
- Varying wind shear magnitude.
- Increasing the duration of the wind shear so it would come in earlier, allowing the pilot more time to respond to it.

The last session was devoted to an evaluation of the DFRC PIO suppression filter.

Raw simulation results are contained in Appendix C, which includes:

- A copy of the Cooper-Harper scale used for the pilot rating evaluations (Fig. C-1).
- A summary run log which catalogs all conditions run and the pilot's ratings given for each, in chronological order (Fig. C-2).
- A transcript of the pilot's comments.

Most of the runs made during the warmup period and all formal runs were recorded on a strip chart. Figure B-8 provides example strip chart recordings. It shows four consecutive formal runs for the Orbiter OFT configuration with no elevator rate limit. Other time histories are used in the next article to illustrate specific simulation results.

Specific Results

The results presented below rely primarily on the pilot ratings and comments obtained in the simulation. These results are presented in the following fashion. For each factor discussed, a pilot rating plot for a subset of related conditions (task/configuration) is given. This is usually accompanied by a summary table of pilot comments for all conditions presented in the plot. In some cases, illustrative time histories are also included.

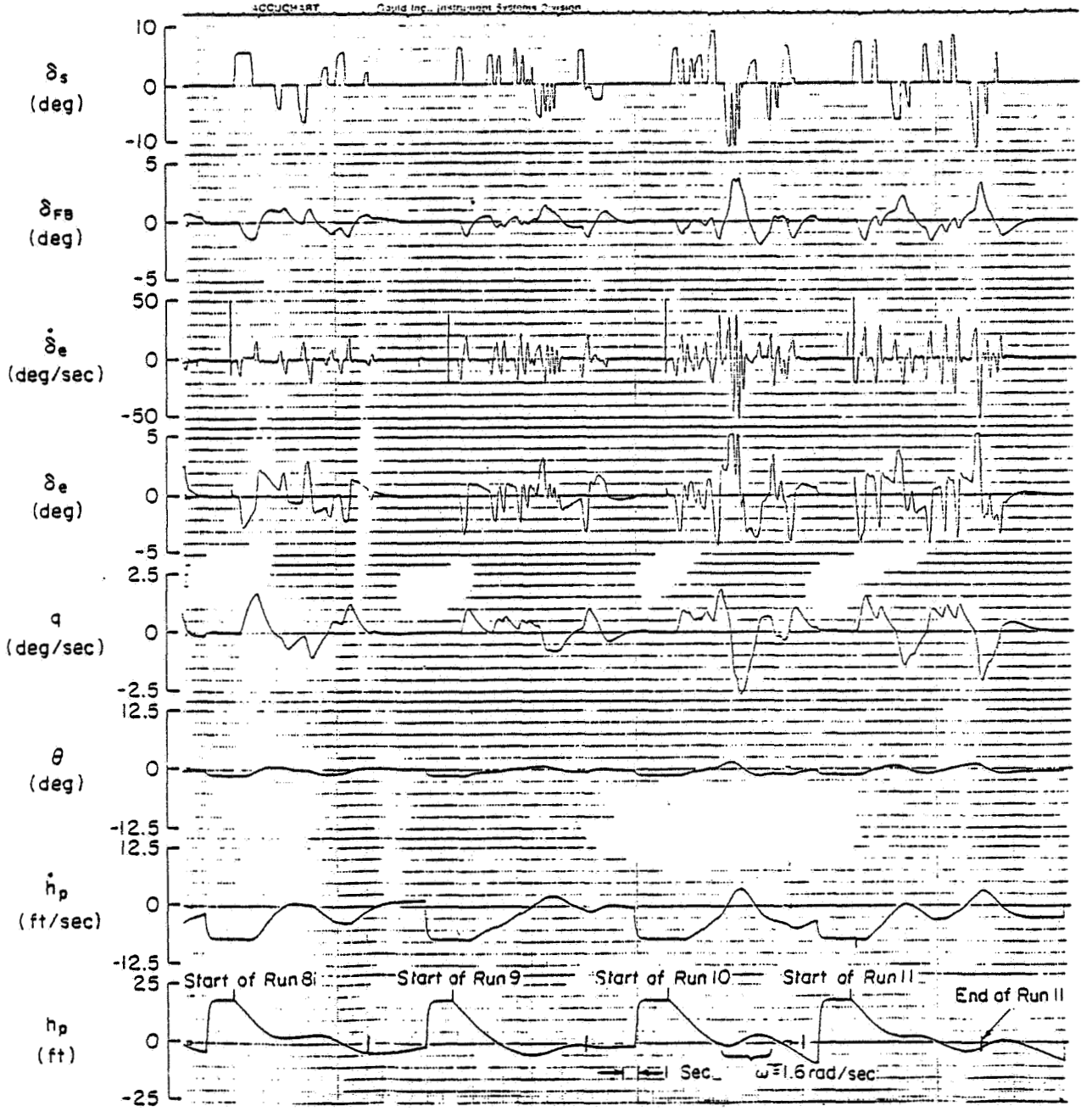


Figure B-8. Orbiter OFT Time Histories (Session No. 1)

Consistency of Pilot Ratings, OFT Configuration. One of the first concerns in a study that relies heavily on pilot opinion to determine system merit is: how consistent is that opinion? Pilot ratings, and performance as well, are subject to random variability due to a number of pilot-related factors —— fatigue, stress, etc. Systematic variations, due to becoming familiar with the task and the configuration, also help confound the evaluation of system merit.

Figure B-9 shows the variations in pilot ratings for the Orbiter OFT configuration over the course of the simulation test period. Since it is the current Orbiter configuration, the OFT was the configuration tested most often. It was run on all the later (after No. 3) sessions to provide a baseline against which to evaluate the effects of task/configuration changes. A summary of pilot comments of the Fig. B-9 conditions is provided in Table B-3.

Note the following about the Fig. B-9 ratings:

- They include both "no disturbance" and "random shear" ratings.
- The "no disturbance" data include pilot ratings with no elevator rate limit, with a 20 deg/sec limit, and with a 26 deg/sec limit, the latter applying to the majority of the plotted data.

The figure indicates:

- The "learning" trend over the first two sessions with asymptotic behavior thereafter.
- Excellent repeatability (for the no disturbance condition).
- No effects of rate limit on pilot ratings. This result corresponds to the observation that elevator rates of 21 deg/sec and even 20 deg/sec were not exceeded very frequently when the OFT configuration was run with no rate limits, and that performance did not appear to be affected by the imposition of those limits.

The comments tend to bear out the observed consistency in the pilot ratings. The following factors are noted again and again:

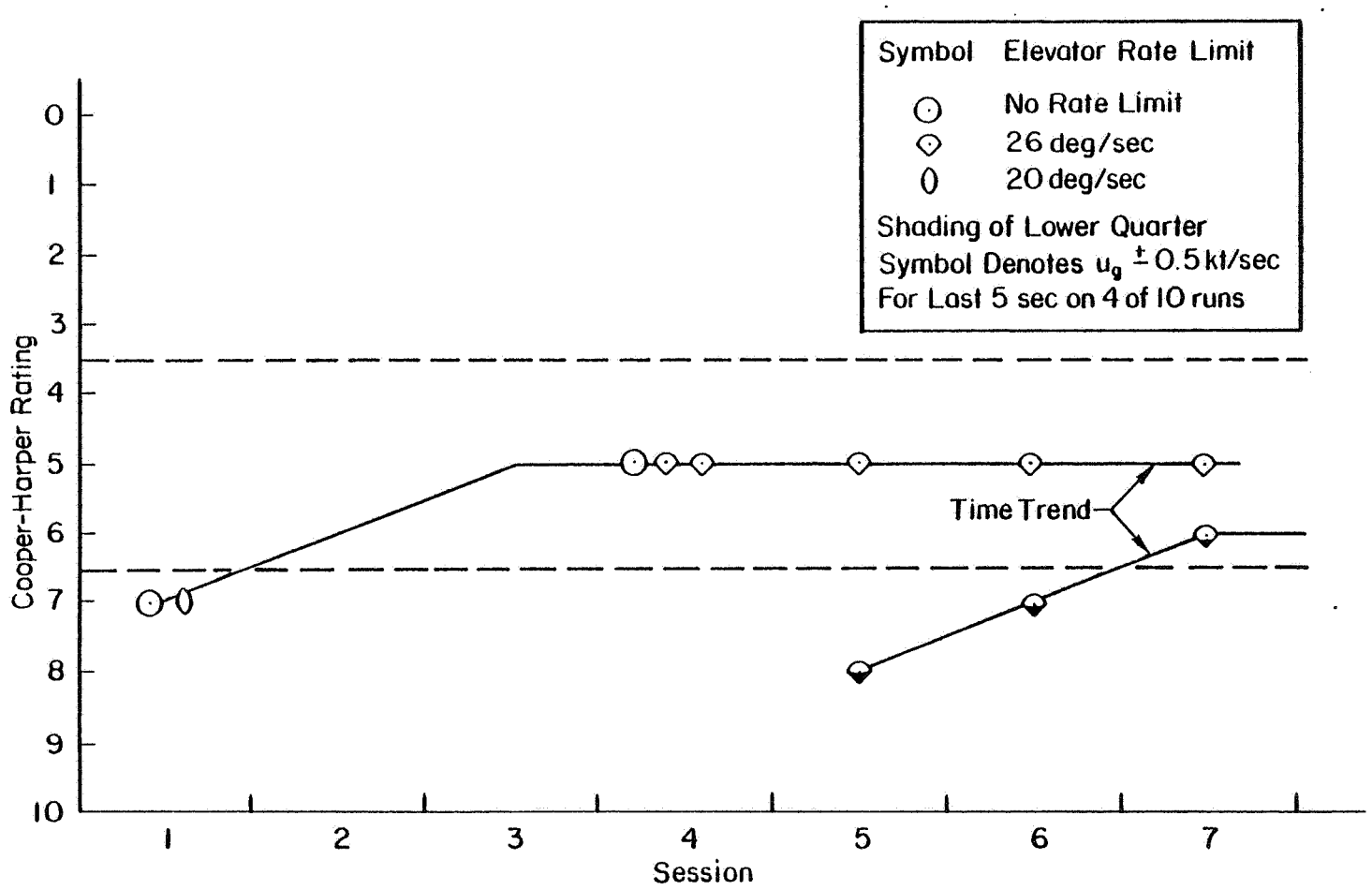


Figure B-9. Pilot Rating Variations with Time (OFT Configuration)

TABLE B-3

SUMMARY OF PILOT COMMENTS FOR OFT CONFIGURATION

SESSION	ELEVATOR RATE WITH (deg/sec)	POR	PILOT COMMENT SUMMARY
			WITH NO DISTURBANCE
1	20 (also with no rate limit)	7	Adequate performance is not attainable consistently with tolerable workload. Gets away some percentage of time. If try to make fast correction to arrest excessive sink rate, develops divergent oscillations (unforgiving). Need better control of attitude in order to adjust sink rate.
4	None	5	Performance barely adequate, lacks consistency. Attitude is sluggish, has some (undesirable) overshoot. Do not have precision control over rate. Considerable compensation required if get behind. Very unforgiving.
	26	5	Could not see any difference from above.
	26 (later in session)	5	Pitch response very slow, with overshoot. Cannot make large rapid attitude changes required near touchdown. Appears a little better than previous runs of same configuration.
5	26	5	Sluggish attitude with overshoot so cannot adjust sink rate precisely near touchdown. Very unforgiving.
6	26	5	Familiar configuration characterized by sluggish attitude response with considerable overshoot, making it difficult to set the attitude quickly and precisely.
7	26	5	Sluggish attitude response, inability to set attitude precisely, results in inability to set sink rate precisely. Very unforgiving; if try to tighten up, get fairly severe oscillations.
			WITH RANDOM SHEAR
5	26	8	Problems magnified by random shear. PIO 20-30 percent of time. Considerable pilot compensation required to keep from being out of control.
6	26	7	Being aggressive with loose attitude system like this causes oscillation. Lacks consistency. Quite objectionable. Deficiencies require improvement; would not want to fly it as is.
7	26	6	Had difficulty setting sink rate on two of ten runs due to sluggish attitude response and overshoot.

- Attitude response sluggish with overshoot.
- Inability to set sink rate precisely with attitude.
- Lacks consistency.
- Very unforgiving.

To summarize the data just presented in Fig. B-9 and Table B-3, the Orbiter OFT was found to have a sluggish attitude response which together with its slow settling, overshoot characteristic made it difficult to control sink rate precisely. As a result, attempts by the pilot to "close the loop" tightly tended to induce oscillations. This behavior made it "unforgiving" of any pilot "errors"; and desired performance could not consistently be achieved.

The pilot rating for the OFT configuration settled out at a consistent 5, "deficiencies warrant improvement," "moderately objectionable deficiencies," "adequate performance, requires considerable pilot compensation." Repeated exposure did not improve this system rating.

Comparison of Orbiter OFT with YF-12 and 747. The question arises: how much better would a "good" system be? To answer this question, two aircraft known to have good handling qualities (the YF-12 and the 747) were "flown." In addition, to examine the effects of pilot location on handling qualities, two additional "configurations" were flown:

- The OFT with pilot location moved forward to make the altitude/attitude dynamics similar to the YF-12.
- The YF-12 with pilot location moved rearward to make the altitude/attitude dynamics similar to the OFT.

The results for these configurations are summarized in Fig. B-10 and Table B-4.

The pilot ratings in Fig. B-10 are plotted versus (three-degree-of-freedom) unstable frequency, ω_u, the frequency at which the phase angle of the closed-loop dynamics, $q/\delta_s]'$ (see Table B-2), cross 180 deg. This parameter provides a relative measure of the bandwidth available to the pilot. All subsequent plots of ratings are versus ω_u.

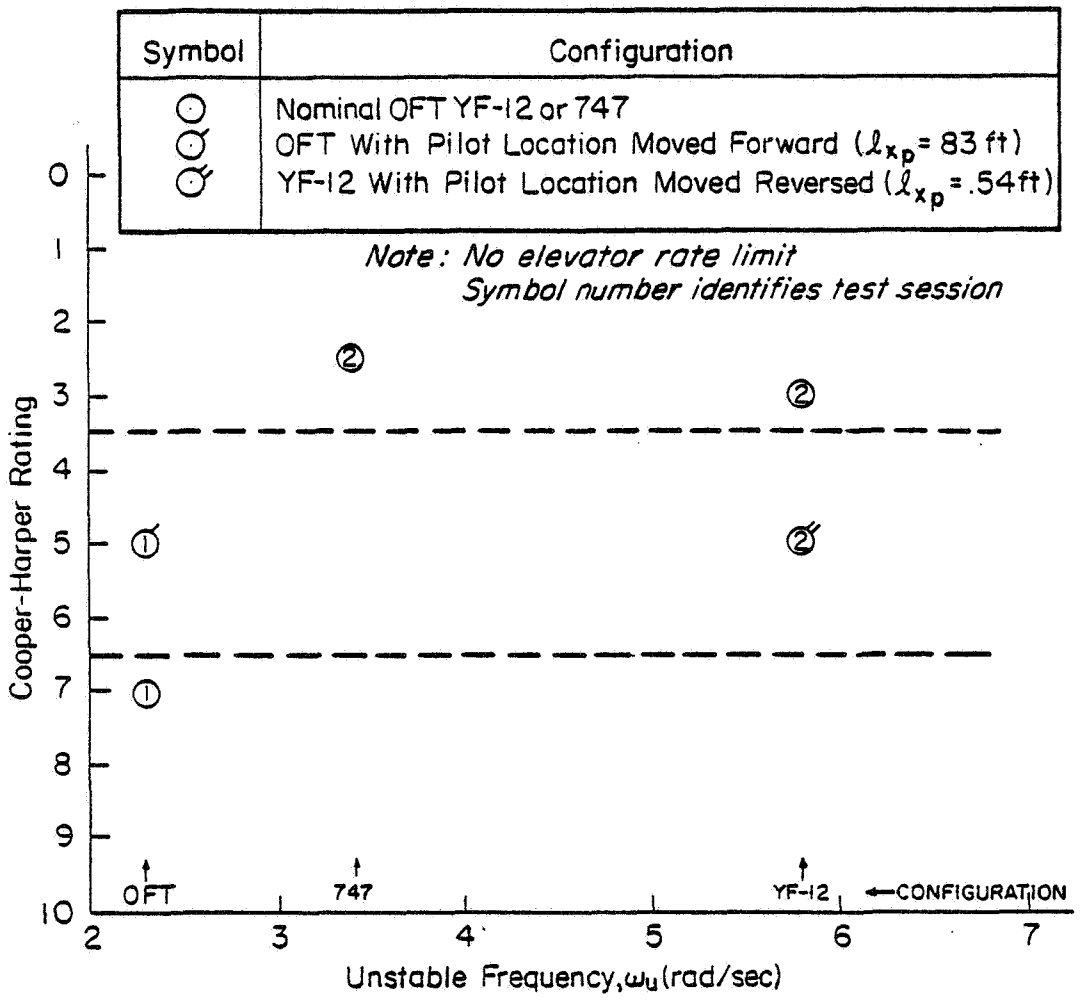


Figure B-10. Comparison of Pilot Ratings for OFT, YF-12 and 747

TABLE B-4

SUMMARY OF PILOT COMMENTS ON OFT, YF-12, AND 747

CONFIGURATION[a]	PILOT OPINION RATING	PILOT COMMENT SUMMARY
OFT	7 (Session 1)	Adequate performance is not attainable consistently with tolerable workload. Gets away some percentage of time. If try to make fast correction to arrest excessive sink rate, develops divergent oscillations (unforgiving). Need better control over attitude in order to adjust sink rate.
OFT with pilot location moved forward (ℓ_{x_p} = 83 ft)	5 (Session 1)	Never got away. Adequate performance with tolerable workload. Required pulsing to establish desired sink rate.
YF-12 with pilot location moved rearward (ℓ_{x_p} = .54 ft)	5 (Session 2)	Higher stick sensitivity than OFT. Attitude response excellent, but noticeable reversal in sink rate response to attitude; effective lag, so impossible to do precision tracking.
YF-12	3	Attitude response satisfactory, but not as snappy as Config. 3. No reversal in sink rate response to attitude. Reasonably consistent performance; forgiving.
747	2.5	Attitude response quite sluggish, extremely well damped, but high correlation with sink rate made it extremely easy to land. Never any concern about getting behind; very forgiving. Task seemed to happen in slow motion.

[a]No elevator rate limit for any of the configurations.

Figure B-10 shows:

- Both "good" aircraft are "satisfactory without improvement" —— a rating far better than the OFT's, which was found to have "deficiencies requiring improvement" in its initial test.

- Moving the OFT pilot location forward substantially improves the pilot's ability to perform the task.

The YF-12 has both a favorable pilot location and a "good" (fast) attitude response. The pilot commentary summary in Table B-4 elaborates further on these qualities. Moving the YF-12 pilot location rearward causes "a noticeable reversal in sink rate response," making it "impossible to do precision tracking." The attitude response of the YF-12 was found satisfactory. It appears from Fig. B-10 that both these qualities contribute roughly equally to the YF-12's advantage over the Orbiter OFT in handling qualities.

The 747 does not have a good attitude response. Its response was found to be "quite sluggish and extremely well damped." Interestingly, though, it was rated slightly better than the YF-12, because of the "high correlation between attitude and sink rate." Apparently, its heave dynamics in combination with the pilot location made it possible to control flight path directly without the use of attitude. Clearly, ω_u or $q/\delta_s]'$ bandwidth is not the sole determinant of handling qualities adequacy.

Time traces for typical (formal) runs of the YF-12 and 747 are shown in Figs. B-11 and B-12, respectively. The performance shown in these figures reflects the handling qualities superiority of those aircraft over the Orbiter OFT configurations. Most notably, the sink rate traces show considerably less oscillation than those for the OFT, previously shown in Fig. B-8. The Fig. B-11 and B-12 traces also seem to support the pilot's preference for the 747 over the YF-12 in this task. The 747 altitude and sink rate traces are extremely consistent and well behaved.

Note, incidentally, that, despite the differences in dynamics and performance, the pilot control technique remains the same for all three configurations. He uses pulsatile, rather than continuous, stick inputs to adjust sink rate.

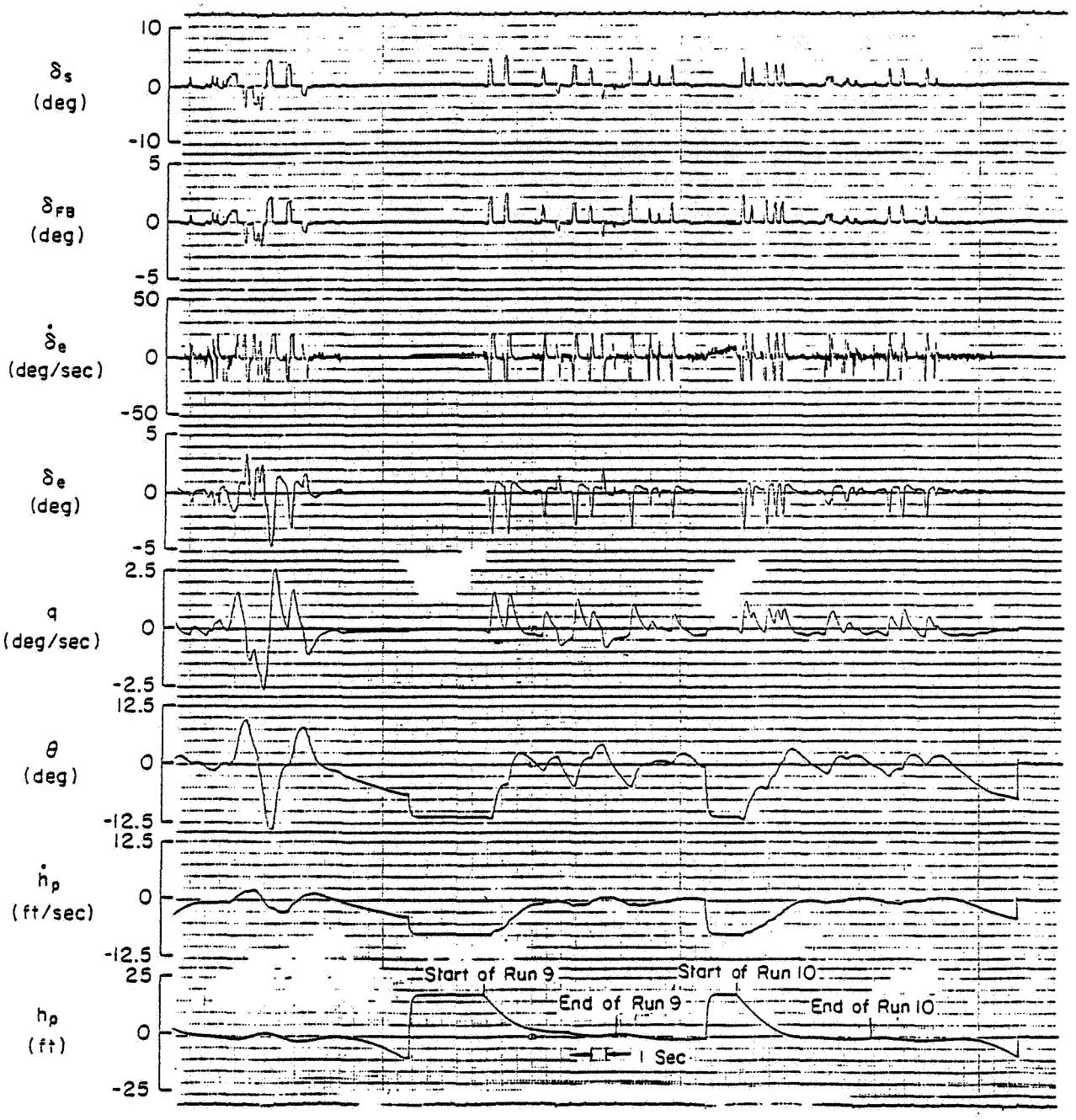


Figure B-11. Typical YF-12 Runs

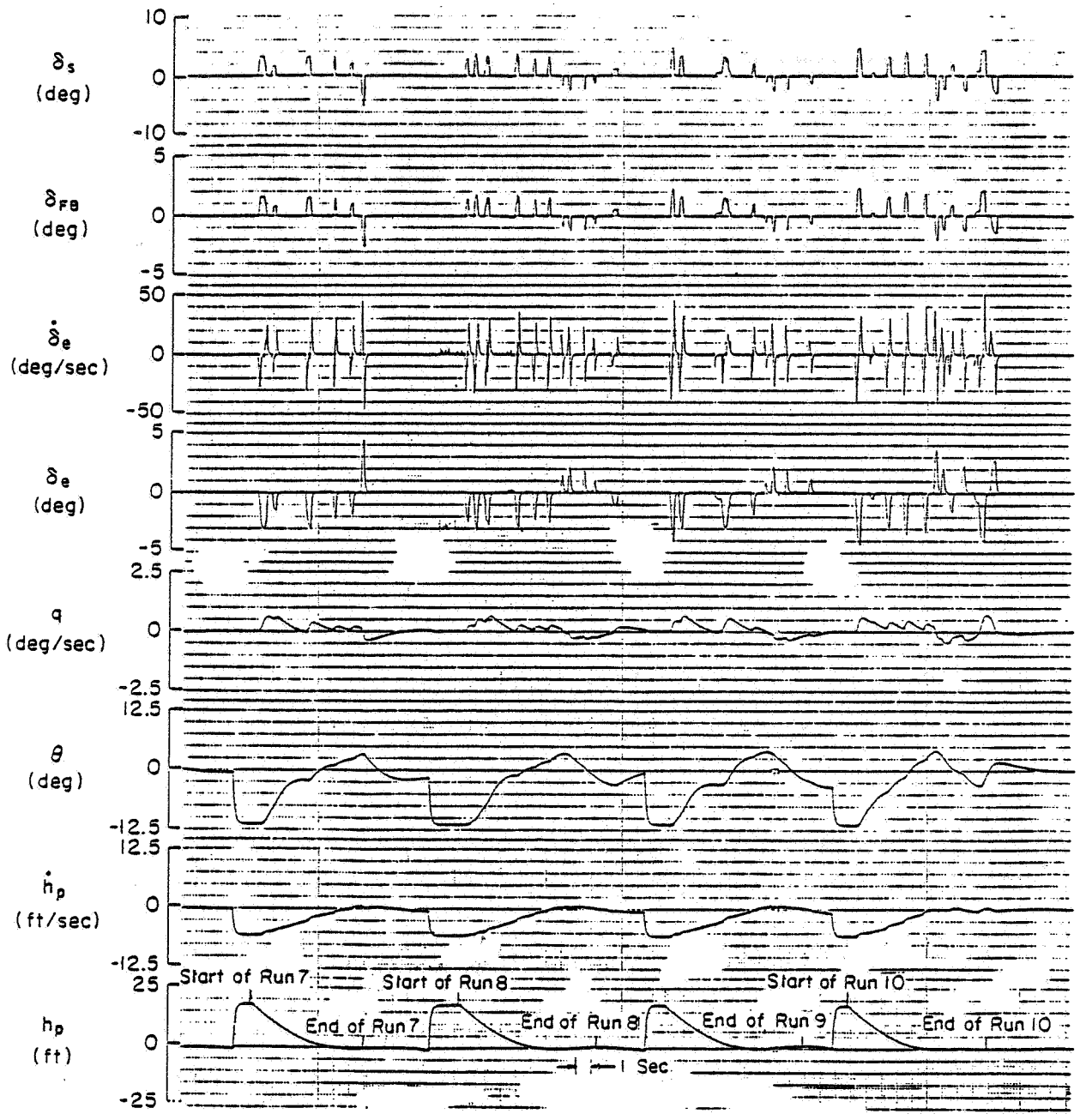


Figure B-12. Typical 747 Runs

In summary, comparison of the OFT configuration with the YF-12 and 747 indicates that the latter two aircraft provide considerably better handling qualities and performance. While this is due to some extent to favorable pilot location, the YF-12 data suggest that improving the OFT attitude response may substantially improve the handling qualities.

Effects of Orbiter Control System Modification. Figure B-13 and Table B-5 summarize the pilot ratings and comments for the various Orbiter configurations tested. Note that the data:

- Are all for no-disturbance conditions.
- Come from both earlier (Sessions 1 and 2) and later (Sessions 3, 4, 5) tests, as indicated by the number within the symbols.
- Include configurations run with no elevator rate limit and with 20-30 deg/sec elevator rate limits.

Because of the previously discussed learning effects and the effects of the elevator rate limits, the rating data taken as a whole show considerable scatter. However,if one partitions the data along these lines, i.e., earlier vs. later data, and no elevator rate limit vs. either 20 deg/sec (earlier data) or 26 deg/sec (later data) elevator rate limit, some fairly consistent trends emerge. These trends have been characterized by the solid and dashed lines in Fig. B-13. These trend lines are based on the few data points in the plot appropriately averaged in some cases, with the pilot comments providing more subtle interpretation.

While the trend lines are, of course, approximate, they do serve to illustrate those features shown by both the ratings and comments:

- With no elevator rate limit, handling qualities improve monotonically with increasing ω_u (or increasing system bandwidth or faster attitude response). Furthermore, exclusive of learning effects (i.e., for the experienced pilot), a relatively small increase in ω_u provides a substantial portion of the available improvement.

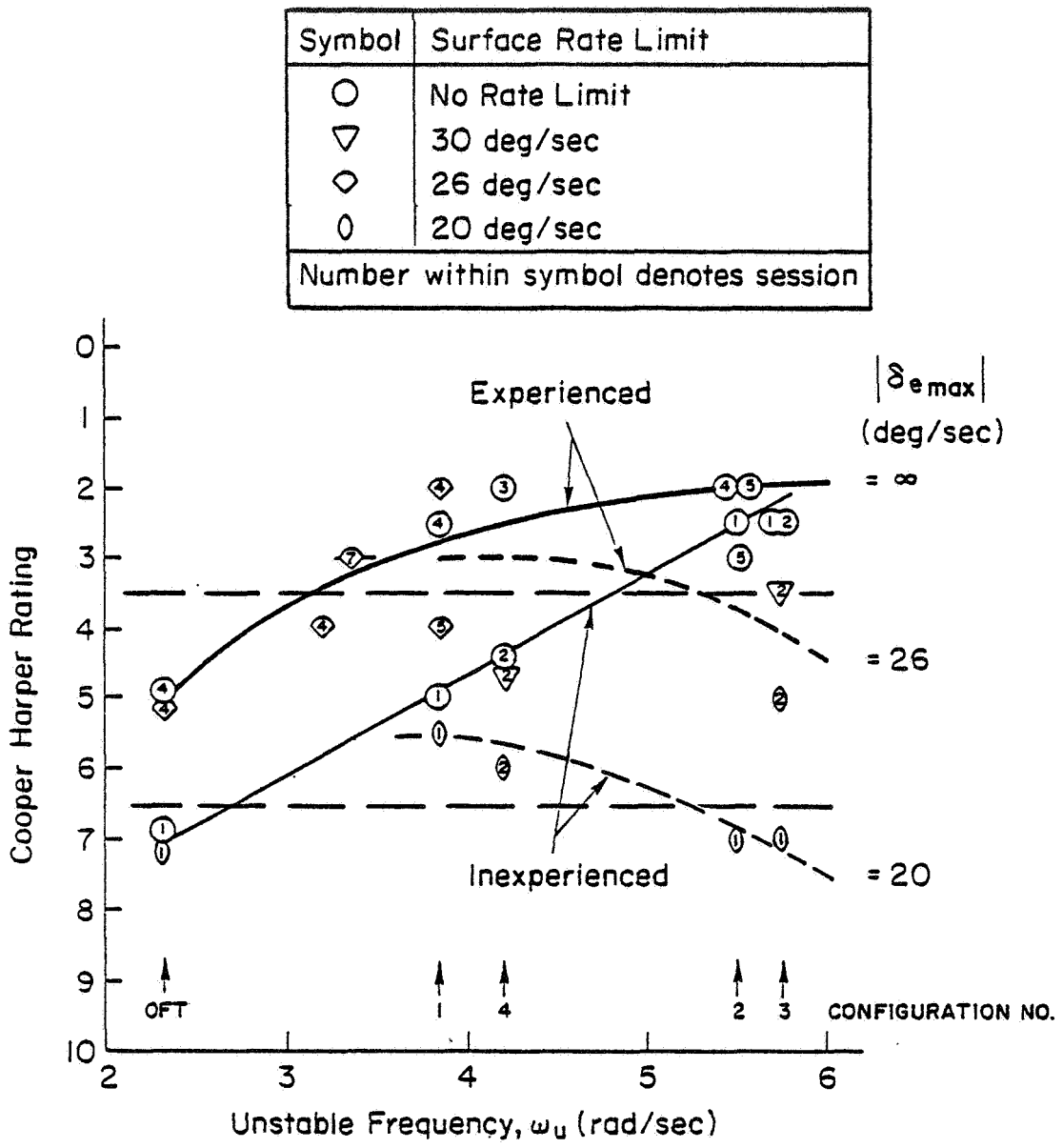


Figure B-13. Effects of Orbiter Control System Modifications on Pilot Ratings

TABLE B-5. SUMMARY OF PILOT COMMENTS ON VARIOUS ORBITER CONTROL SYSTEM CONFIGURATIONS

CONFIGURATION	SESSION	NO ELEVATOR RATE LIMIT		WITH ELEVATOR RATE LIMIT		
		POR	PILOT COMMENTS SUMMARY	RATE LIMIT (deg/sec)	POR	PILOT COMMENTS SUMMARY
OFT	4	5	Performance barely adequate, lacks consistency. Attitude is sluggish, has some undesirable overshoot. Do not have precision control over sink rate. Considerable compensation required if get behind. Very unforgiving.	26	5	Could not see any difference from no rate limit
				26	5	Pitch response very slow, with overshoot. Cannot make large rapid attitude changes required near touchdown. Appears a little better than previous runs of same configuration.
1	4	2.5	Very good pitch attitude response; rapid, no overshoot.	26	2	Pitch attitude control excellent; crisp, no overshoot — after slight initial delay
	5			26	4	Fairly good attitude response; good time-to-peak, no overshoot. Initial delay is minor deficiency. Required moderate compensation to adjust sink rate rapidly, which calls for precise attitude changes.
4	3	2	Excellent attitude dynamics, no overshoot. Lacks attitude/sink rate consonance. Consistent, well behaved even when abused.			
2	1	2.5	Very good pitch attitude control, good sink rate control. Good attitude/sink rate consonance. Could make large pitch correction near touchdown. A little compensation required; have to adjust sink rate with attitude, but easy to do.			
	4 5	2 3+2	Excellent Attitude response excellent; very rapid, easy to make large, accurate attitude changes; very minor overshoot.			
3	2	2.5	Much improved attitude response and control over sink rate, compared to Config. 4. Very much on control all the time, can make aggressive inputs. Very forgiving. Task (sink rate control) still requires some compensation.	30, 40	3.5	Attitude response not as crisp as with no rate limit;thus sink rate a little less positive, only notice deficiency when get behind in flare.
				20	5	Attitude response more sluggish than with 30 or 40 deg/sec rate limit, significantly more so than with no rate limit. Got some oscillations when got behind in flare and tried to to tighten up.

- The imposition of an elevator rate limit causes a reversal in the above trend, i.e., above some value of ω_u, handling qualities degrade with increasing ω_u.

Based on these data, it appears that Configurations 1 or 4 would offer a good compromise between the high system bandwidth needed for good attitude response and the bandwidth limitation imposed by a 26 deg/sec elevator rate limit. It is not clear which of these would be preferred. Configuration 3 is just Configuration 1 with the bending mode filter moved to the feedback path. This reduces forward path lag, quickening attitude response, but it also increases elevator rates. In any case, for the actual Shuttle there are a number of other factors which should be considered in selecting a configuration. Some of these will be examined or discussed in the remainder of this section.

Random Shear. The effects of including a "random shear" in the simulation task are summarized in Fig. B-14 and Table B-6. Data for three Orbiter configurations whose ω_u's span the range tested and for wind shears of 0.5 kt/sec, 1 kt/sec, and 2 kt/sec are included.

It should be recalled that the random shear was actually present on only four of ten formal runs, and then only during the last 5 sec of these 9 sec runs. For the 0.5 kt/sec shear, the pilot noted in his comments on more than one occasion that it was "difficult to perceive any (wind) shear." This is not surprising. Even when the wind shear was present, its effects would not be seen until near the end of the run, particularly for the lower magnitudes of shear. By this time the disturbance could be difficult to distinguish from the normal response to pilot input. The main effect of the lower magnitude shear then was to force the pilot to maintain a tight loop closure. With tight control, system deficiencies are more likely to be amplified. Extrapolating the data shown in Fig. B-14 to take into account learning effects, the result for the 0.5 kt/sec random shear is estimated to be a decrease of about 1 rating point for the poorer configurations (e.g., OFT) to about one-half or less rating points for the best configurations (Nos. 2

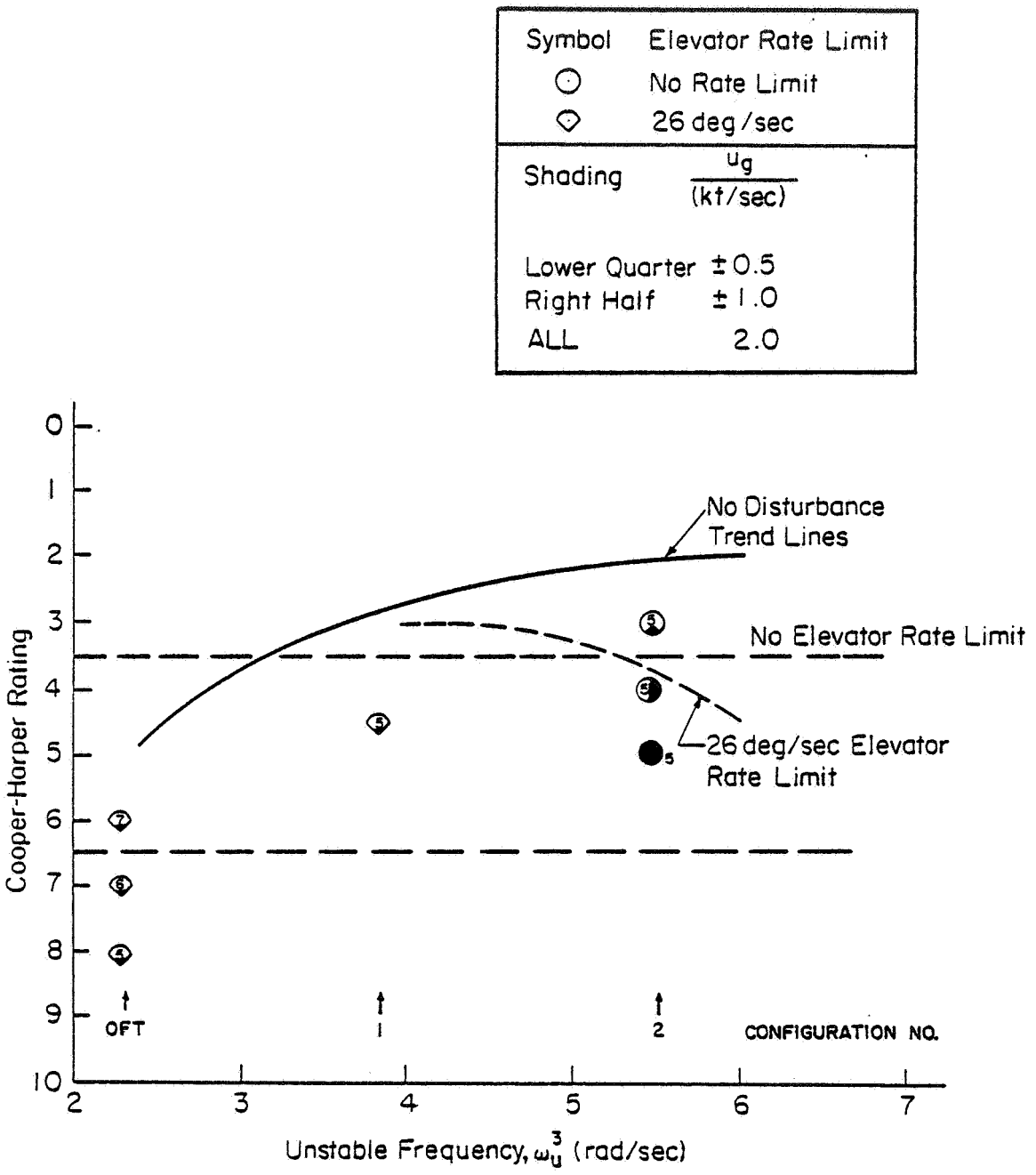


Figure B-14. Effects of Random Shear on Pilot Rating

TABLE B-6

SUMMARY OF PILOT COMMENTS ON VARIOUS ORBITER CONFIGURATIONS IN RANDOM SHEAR

CONFIG-RATION	SESSION	$\lvert u_g \rvert$ (kt/sec)	POR	PILOT COMMENT SUMMARY
OFT, 26 deg/sec elevator rate limit	5	0.5	8	Problems magnified by random shear. PIO 20-30 percent of time. Consider-pilot compensation required to keep from being out of control.
	6		7	Being aggressive with loose attitude system like this causes oscillation. Lacks consistency. Quite objection-able. Deficiencies require improve-ment; would not want to fly it as is.
	7		6	Had difficulty setting sink rate on 2 of 10 runs due to sluggish attitude response and overshoot.
1 26 deg/sec elevator rate limit	5		4.5	Difficult to perceive shear. Delay in pitch attitude response seemed empha-sized near end of a few runs, but got away. Consistency not bad.
2 no eleva-tor rate limit	5		3	Very difficult to perceive any wind shear. Some very slight bobbling, most runs well within desired performance without a lot of compensation.
		1.		Good control over sink rate. A little bobbling near the end; seemed to be ex-cited by wind shear. Moderate compen-sation required.
		2.		Lack of consistency. Extreme varia-tions in performance. Some large oscil-lations in sink rate when wind shear in unfavorable direction.

or 3). This would make Configuration 1_{RL}* (about 3.5 — just barely satisfactory without improvement.

With the higher shear magnitudes, the effects of the shear become more apparent. For Configuration 2,‡ the pilot notes:

- (at 1 kt/sec shear) "seemed to be excited by wind shear."
- (at 2 kt/sec shear) "large oscillations in sink rate when wind shear in unfavorable direction."

Even for this good configuration, pilot ratings drop substantially with increasing wind shear magnitude.

The effects of increased wind shear on the poorer configurations and of pilot familiarity (learning) with these disturbances, are not easily estimated from the available data. The importance of the wind shear magnitude depends on the actual landing environment. For the purposes of this simulation, nominal level (about 0.5 kt/sec) appears to serve the purpose of insuring that the pilot does not rely on precognitive inputs and a relaxed control mode to perform the task.

Typical time traces for Configurations OFT_{RL}, 1_{RL}, and 2 are shown in Figs. B-15, B-16, and B-17, respectively. Comparison of these figures shows:

- The differences in achievable path control are not that great.
- Handling qualities differences show up in the run-to-run consistency in the sink rate and attitude variations needed to control path. The larger variations in these variables reflect the increasing pilot compensation required with decreasing system bandwidth.

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*From this point on, the subscript "RL" is used to indicate use of 26 deg/sec elevator rate limit.

‡Configuration 2 (with no elevator rate limit) was run to provide an estimate of the upper bound of handling qualities and performance, given Orbiter dynamics and pilot locations.

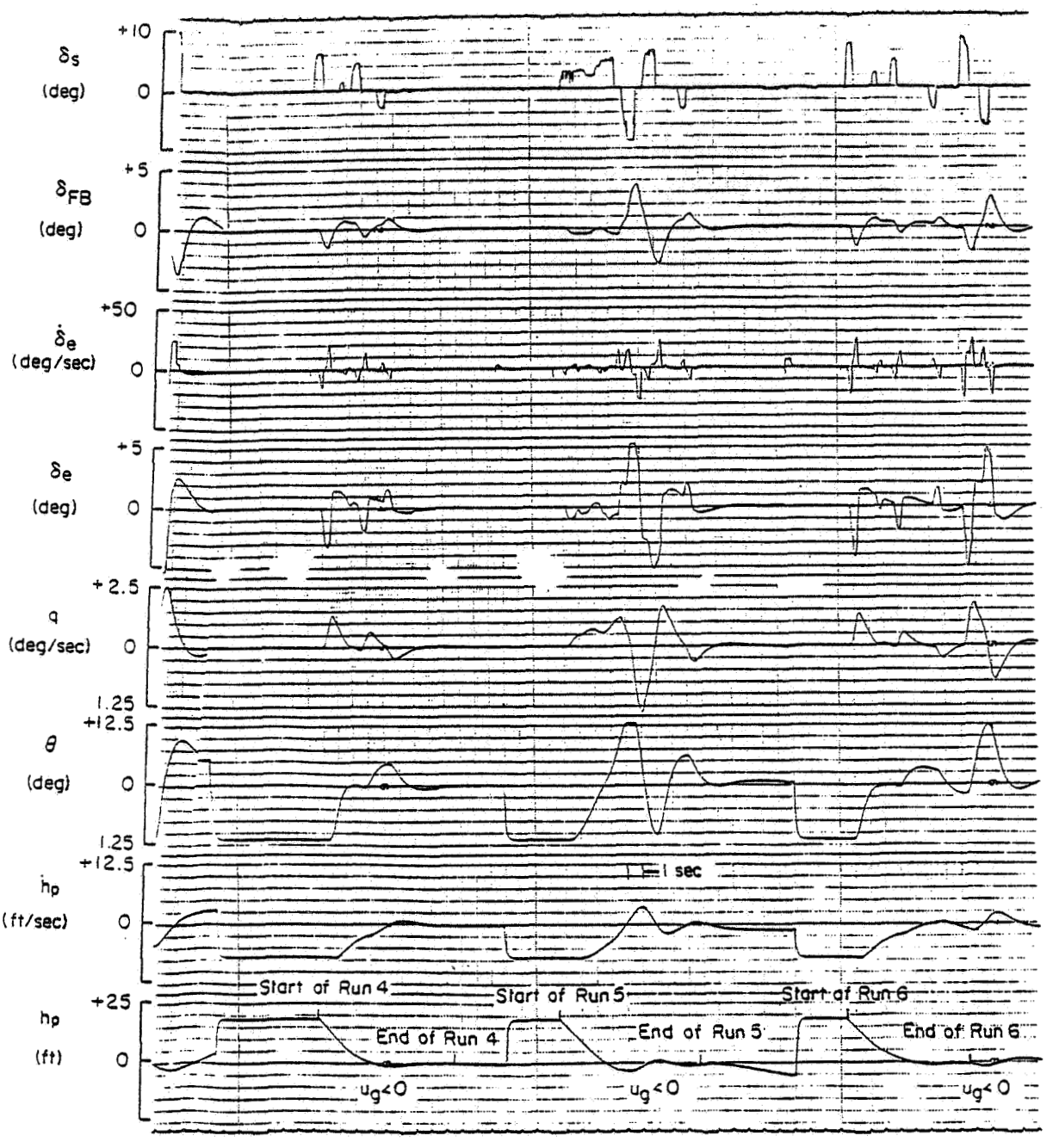

Figure B-15. Typical OFT_{RL} Runs with Random Shear of 0.5 kt/sec (Session No. 5)

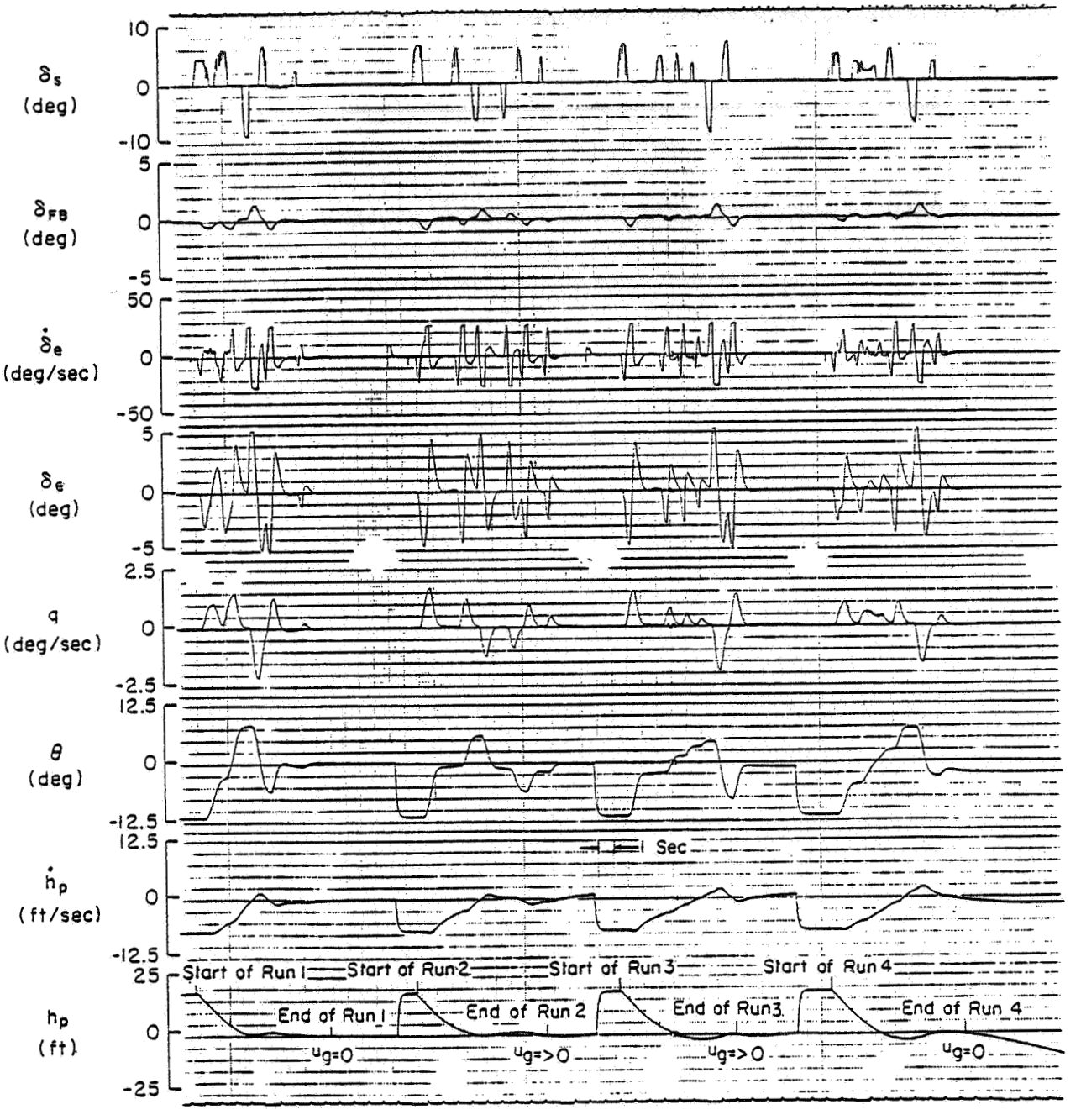

Figure B-16. Typical Configuration 1_{RL} Runs with Random Shear of 0.5 kt/sec (Session No. 5)

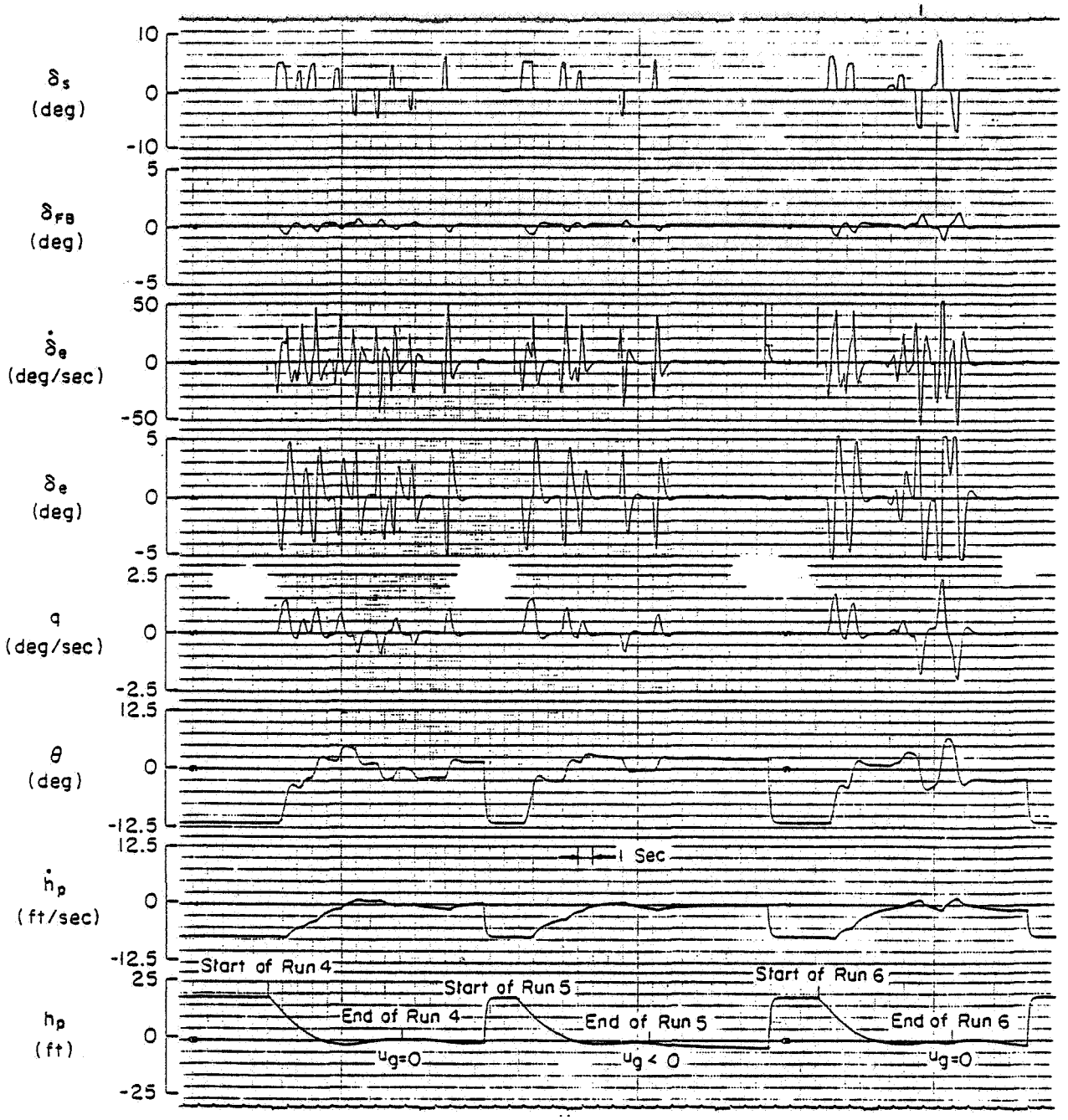

Figure B-17. Typical Configuration 2 Runs with Random Shear of 0.5 kt/sec (Session No. 5)

- Increased elevator activity for the higher bandwidth systems. With Configuration OFT_{RL}, elevator rate rarely reaches the 26 deg/sec limit; whereas with Configuration 2, rates as high as 50 deg/sec are not uncommon. The increased control surface activity reflects the pilot's use of the greater bandwidth available.

Run-to-run variability makes it difficult to fully appreciate differences in system performance. Perhaps Fig. B-18 provides a better perspective. Figure B-18 compares worst runs (of the ten formal runs) for each of three configurations. The attitude, sink rate, and altitude trces for Configuration 1_{RL} are very similar to those for Configuration 2. The corresponding traces for the OFT configuration show markedly poorer performance. Whereas it appears in the formal runs that the pilot is in control at end of run, the OFT run "ends" with an incipient PIO, marked by rate-limited elevator excursions uncharacteristic of the "typical" runs.

Interestingly, the 0.5 kt/sec wind shear was not actually present on any of the three runs shown in Fig. B-18.

Task Parameter Variations. The objective of the task parameter variations was to look at the effects of task severity on handling qualities. First, the initial trim pitch angle was halved to reduce sink rate. The initial altitude was kept the same. This is analogous to flying a reduced glide slope or flaring from the same glide slope at a higher altitude. The net effect is to give the pilot a less rapid adjustment to make in sink rate.

It was found that 9 sec was not long enough for the pilot to make a smooth flare with these initial conditions. Task times were therefore increased. A task time of 15 sec was proved adequate for a smooth flare. Longer task time did not change the flare part of the maneuver; it merely increased the duration of the subsequent zero altitude hold request.

Formal runs were made first with the standard random shear of 0.5 kt/sec for the last 5 sec. Wind shear magnitude was then increased to 1 kt/sec. Finally, the wind shear duration was lengthened to 10 sec with

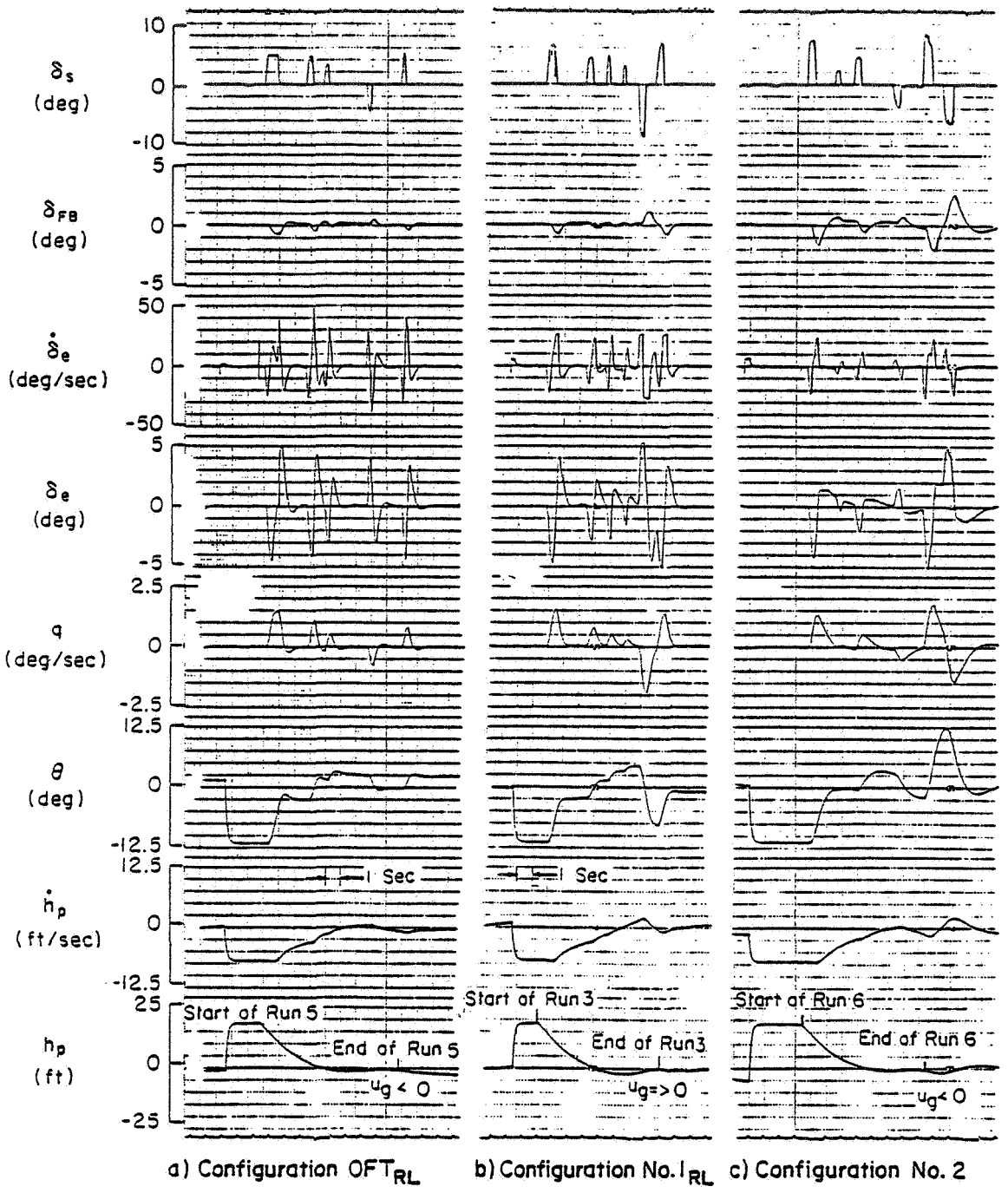

Figure B-18. Comparison of Worst Runs for Configurations OFT_{RL}, 1_{RL}, and 2

the 1 kt/sec shear to give the pilot more time to respond to the disturbance.

Once again the range of ω_u was spanned with Configurations OFT_{RL}, 1_{RL}, and 2.

Pilot ratings and comments are summarized in Fig. B-19 and Table B-7. Figure B-19 shows:

- With no disturbance, pilot ratings remain about the same as those projected for the standard task, except for the OFT configuration.
- The differential effect of the random shear is the same as that for the standard task, with the expected variability in pilot ratings.
- Lengthening the gust duration did not appear to substantially affect pilot ratings, although pilot comments indicate that the pilot noticed the difference and felt this as a "more realistic" input.

The improvement in the rating of the OFT configuration with the less severe task over that with the standard task bears further discussion. As indicated in the Session 6 pilot comment transcript in Appendix C, the pilot originally rated this combination a 5. This was based on a run on which he intentionally "abused" the configuration by using an excessive input and trying to correct at the last instant. After further consideration of the task definition, it was decided that the task did not <u>require</u> the kind of control he had forced on the run mentioned. He made several more runs with this in mind and amended his rating to the 4 shown in Fig. B-19. However, he still described the system as "very unforgiving" and noted that it was "difficult to set attitude precisely." These are basically the same comments he used to describe the OFT configuration for the stndard task. Moreover, in the formal runs, with the threat of a random shear making the pilot more aggressive, the rating dropped to a 5. As previously noted, tightening the loop closing tends to emphasize system deficiencies. Thus, the improvement in pilot rating with a decrease in task severity is not really meaningful for the actual Orbiter landing task. In the more complex real-world situation where the pilot is much more likely to have to tighten up his control,

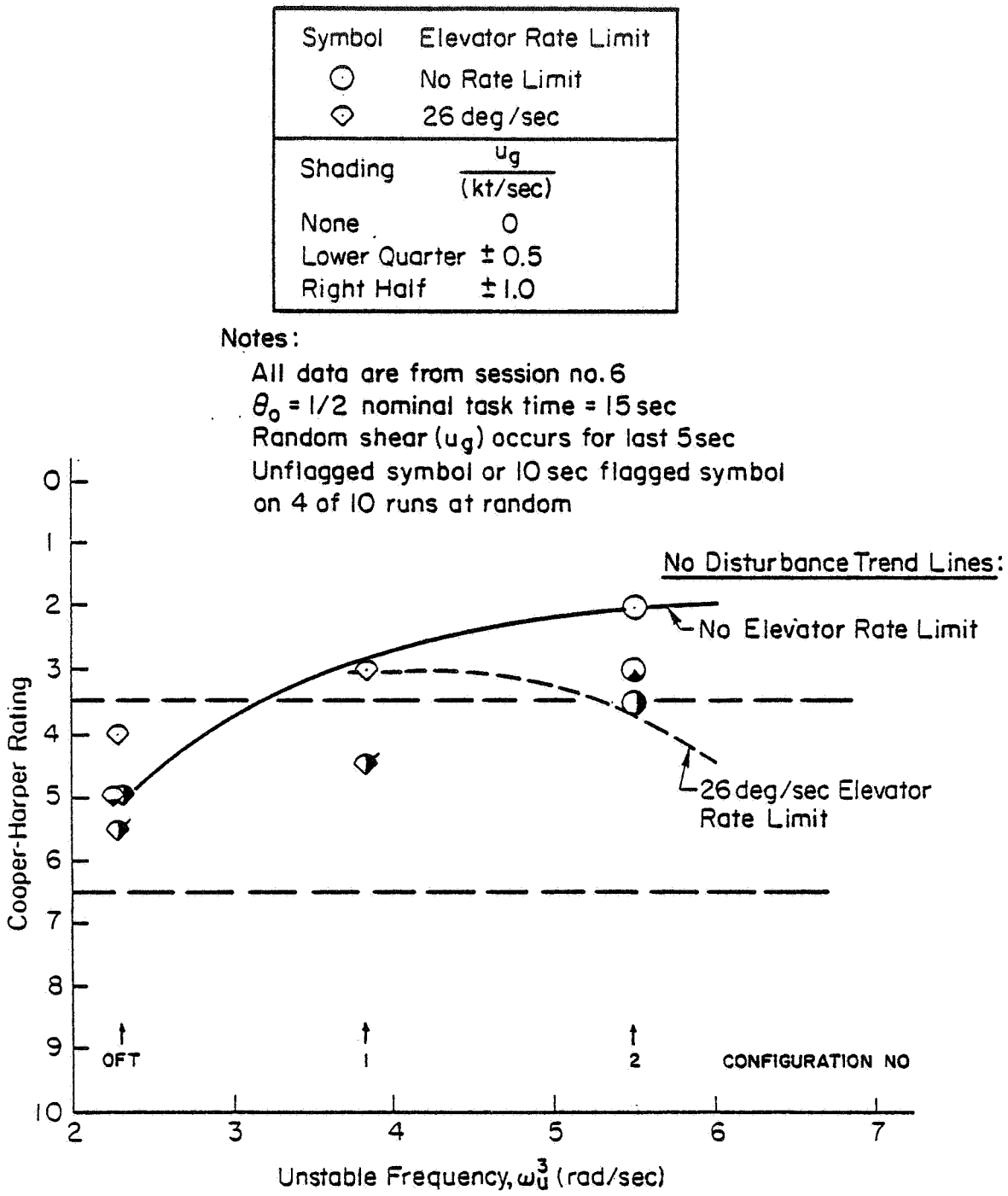

Figure B-19. Effects of Task Parameter Variations on Pilot Rating

TABLE B-7. SUMMARY OF PILOT COMMENTS ON VARIATIONS IN TASK PARAMETERS

CONFIGURATION	RANDOM SHEAR		
	NONE	0.5 KT/SEC FOR LAST 5 SEC	1.0 KT/SEC FOR LAST T [ ] SEC
OFT 26 deg/sec elevator rate limit	(4) Desired performance requires moderate compensation. Difficult to set attitude precisely. Very unforgiving.	(5) Same as with no random shear, except on 1 or 2 runs fot into fairly severe pitch bobble. Attitude response sluggish, with overshoot; moderately objectionable deficiencies. Cannot separate own inputs from disturbance.	(5) [T = 5 sec] Difficult to spot increased disturbance magnitude. Same basic (OFT) deficiencies. Oscillations on 1 or 2 runs. (5-1/2) [T = 10 sec] Disturbance comes in earlier at critical time; got far behind it at times. This earlier input more realistic.
#1 26 deg/sec elevator rate limit	(3) Easy to set attitude, reasonably nice response. A little pitch bobble close in.	Not run.	(4-1/2) [T = 10 sec] Disturbance definitely noticeable,, sometimes got oscillations but could get back in control; minor but annoying bobble.
#1 No rate limit	(2) Easy to make quick and accurate changes in attitude, very crisp response, gives good control over sink rate. Very forgiving. No tendency to oscillate near touchdown.	(3) Could not see disturbance. Some minimal pilot compensation required to get performance. Satisfactory without improvement.	(3-1/2) No comments.

the deficiencies in the OFT configuration are not likely to be overcome by diminishing the severity of the landing maneuvers.

In summary, the severity of the task maneuver does not substantially change effective handling qualities.

Evaluation of Configuration 5. Configuration 5 was designed by DFRC. It has an unstable frequency slightly higher than halfway between those of the OFT configuration and Configuration 1. It is, however, notably different from those systems because it uses a vertical accelerometer feedback in addition to the pitch rate feedback which they use. As a result the pitch rate response to a step stick input for Configuration 5 has substantially more overshoot than that for either of the other two sysems.

Pilot ratings for Configuration 5 (with no disturbance) are shown in Fig. B-20, against the background of the trend line previously developed for Orbiter control system variants. These ratings appear to be consistent with the trend lines, within the scatter of the data.

The following is a summary of the pilot's comments on Configuration 5 with 26 deg/sec rate limit:

> Pitch attitude response somewhat sluggish...some overshoot. Some chasing and bobbling. Very much like the OFT configuration.

As indicated in Fig. B-20, this condition was run in Session 4, while the no-rate-limit and 20 deg/sec rate limit condition were run in Session 3. Pilot comments for the earlier run conditions were considerably more optimistic. The traces (not shown) indicate that the pilot was considerably more aggressive in the later run condition. This might account for the difference in the ratings.

Overall, Configuration 5 behaved as one might expect based on consideration of it closed-loop characteristics.

Evaluation of DFRC PIO Suppression Filter. The DFRC PIO suppression filter defined earlier in this section was tried in combination with Configurations OFT_{RL}, 1_{RL}, and 5_{RL}. Pilot ratings and comments are summarized in Fig. B-21 and Table B-8.

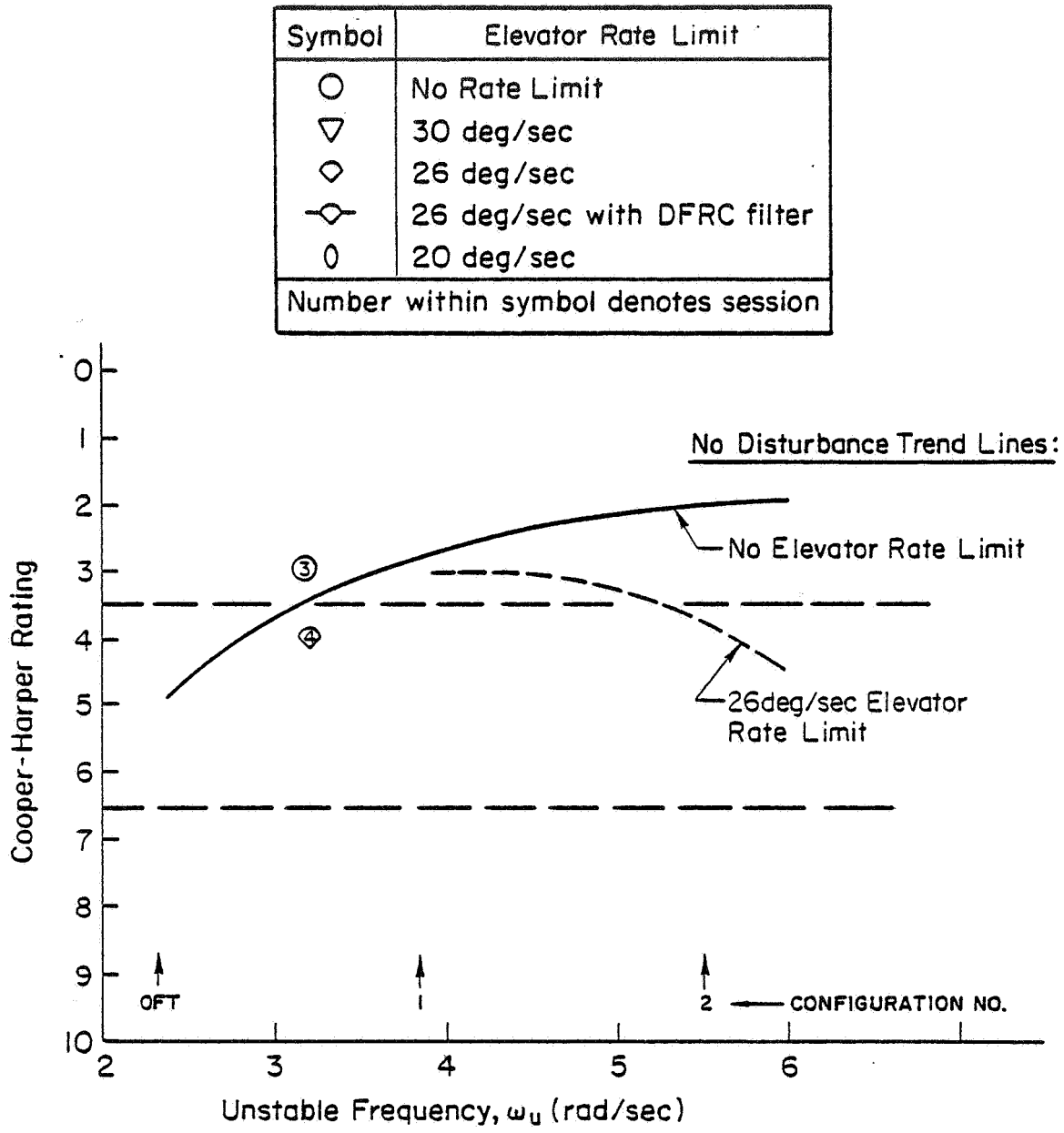

Figure B-20. Pilot Ratings for Configuration 5 (with No Disturbance)

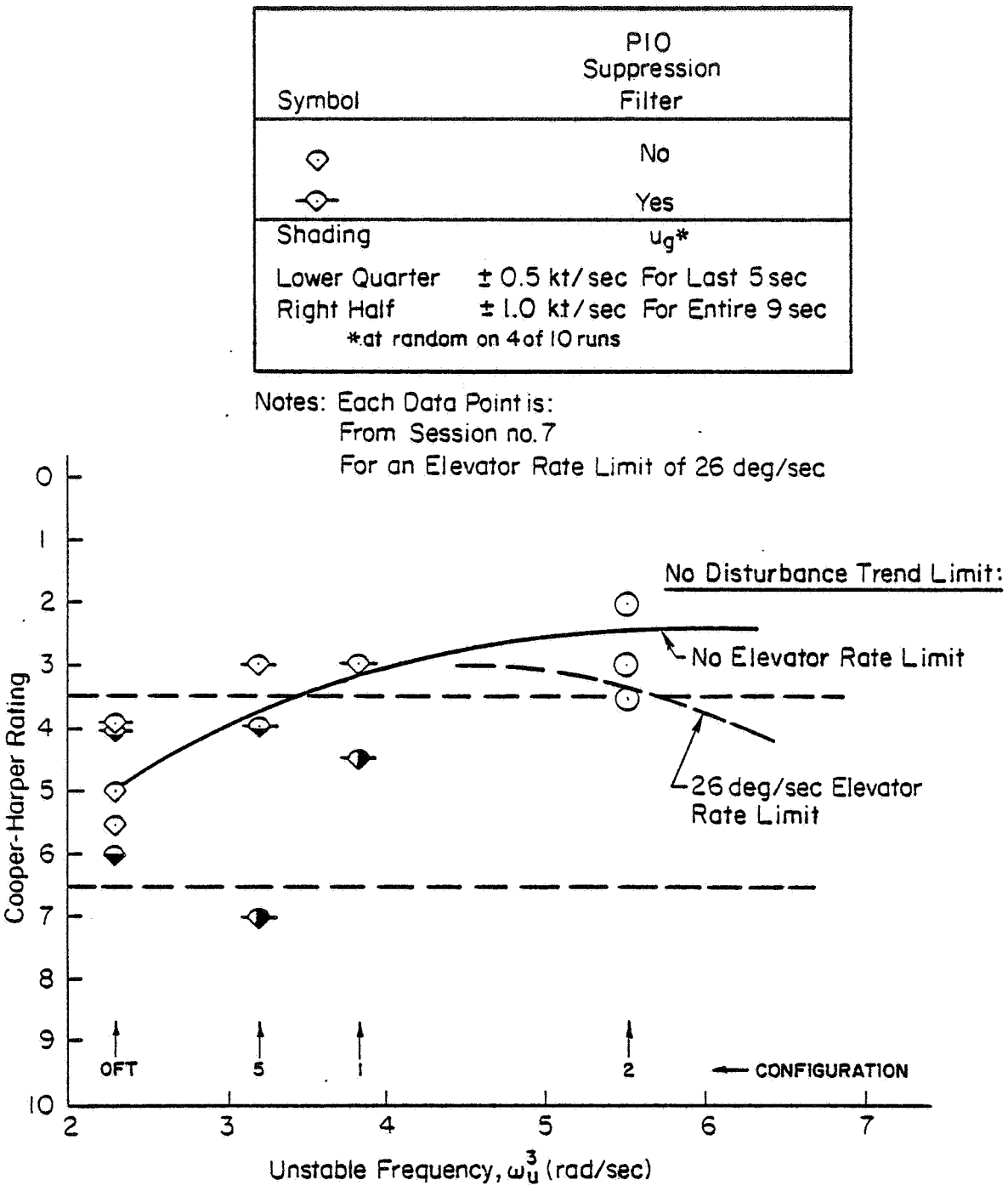

Figure B-21. Effect of DFRC PIO-Suppression Filter on Pilot Ratings

TABLE B-8. SUMMARY OF PILOT COMMENTS ON DFRC PIO SUPPRESSION FILTER

CONFIGURATION*	RANDOM SHEAR**		
	NONE (WARMUP RUNS)	0.5 KT/SEC FOR LAST 5 SEC	1.0 KT/SEC, FOR ENTIRE 9 SEC RUN
WITHOUT DFRC PIO SUPPRESSION FILTER			
OFT	(5) Sluggish attitude response, inability to set attitude precisely results in inability to set sink rate precisely. Very unforgiving; if try to tighten up get fairly severe oscillations.	(6) Had difficulty setting sink rate on 2 of 10 runs due to sluggish attitude reponse and overshoot.	Not run.
WITH DFRC PIO SUPPRESSION FILTER			
OFT	(4) Same sluggish, overshooting response as without filter, lower effective attitude-to-stick gain. Like having no control right near touchdown, but do not get into attitude oscillations either because no response to rapid stick inputs.	(4) Could not detect wind shear. Never got into attitude oscillations. Feel only partly in control; large gusts throughout run might cause trouble.	Not run.
#5	(3) Considerably better than OFT, attitude less sluggish. Still has annoying overshoot, requiring compensation. Easy to make precise attitude changes and still not get oscillation if tighten up.	(4) Had problems with precise control of sink rate with attitude. Overshoot seems to be more of factor (than wind shear), requires moderate pilot compensation to tighten up. However, definitely preferred over OFT because more responsive to stick inputs.	(7) Unsuccessful in making required very large precise attitude changes required to correct for disturbance. Deficiencies require improvement. Adequate performance not attainable with any amount of pilot compensation. Noticed secondary modes on attitude response; lack of high-frequency consonance between attitude and stick.
#1	(3) Attitude a touch sluggish, no overshoot (a lot snappier without rate limit). Lacks high-frequency response to stick.	Not run.	(4-1/2) Ability to regulate against these very large disturbances quite impressive, with only unpleasant to annoying deficiencies. Because of large inputs, adequate performance requires considerable pilot compensation.

Notes:
All data from Session No. 7.
*All configurations have 26 deg/sec elevator rate limit.
**Pilot opinion rating in parentheses.

Figure B-21 shows that the PIO suppression filter improved the pilot ratings of each of the three systems. However, this amount of improvement appears to be inversely related to system bandwidth. With no disturbance, for Configuration 1_{RL} the pilot rating with the filter is just above the trend line and is equal to the actual (average) rating without the filter.

The pilot comments explain the improvement; for the OFT configuration "you don't get into attitude oscillations." The filter apparently does what it is supposed to do, eliminating response to rapid stick inputs. Since it does nothing to make system response better, this effect can only improve a system up to a point. On the other hand, by reducing "high-frequency response to stick" inputs, the filter leaves the pilot feeling that he has "no control right near touchdown."

Once concern about such a system is that the pilot could find himself unable to regulate against disturbances occurring close to touchdown. A random shear of 0.5 kt/sec for the last 5 sec did not appear to degrade pilot rating substantially. When this shear was increased to 1 kt/sec for the last 9 sec the pilot found that for Configuration 5_{RL} "adequate performance was not attainable with any amount of compensation." He also noticed "secondary modes on attitude response," and he apparently was disturbed by the "lack of high-frequency consonance between attitude and stick." Even though Configuration 1_{RL} did not fare nearly as poorly, this still leaves some reservations as to the advisability of incorporating the PIO suppression filter into the Orbiter system.

C 2

APPENDIX C

SIMULATION RESULTS

This appendix catalogs the raw results for the simulation described in Section II and Appendix B. These results consist of pilot opinion ratings and associated comments for each simulated condition.

Figure C-1 is a reproduction of the Cooper-Harper scale on which conditions were rated. A complete chronological summary of all conditions simulated with the resultant pilot ratings is given in Table C-1. Transcripts of tape-recorded pilot comments for each of the simulated conditions follow. In the discussion of each configuration, elevator rate limit, if any, follows the configuration designation. The transcripts have been minimally edited for clarity.

SESSION NO. 1 (1 MAR 79)

Configuration OFT, 20 deg/sec Elevator Rate Limit

Adequate performance didn't really seem to be attainable at tolerable pilot workload so that puts it in the 7-9 range. The reason is that if I made a precognitive pitch input that was proper and causes sink rate to decrease exponentially things worked out very well. But if it wasn't the proper open-loop input and I had to use closed-loop control to try to regulate the thing to touchdown, it was very easy to get way behind the airplane and develop diverging oscillations. Because of those cases where that happened, I think that adequate performance is just not attainable in a consistent way. I think that consistency is the key point here, because a lot of the runs were OK, but there were a few that were not. I think that lack of consistency indicates the fact that when you need to tighten up and regulate is when you get in trouble with this configuration. So, the pilot rating on this one is a 7.

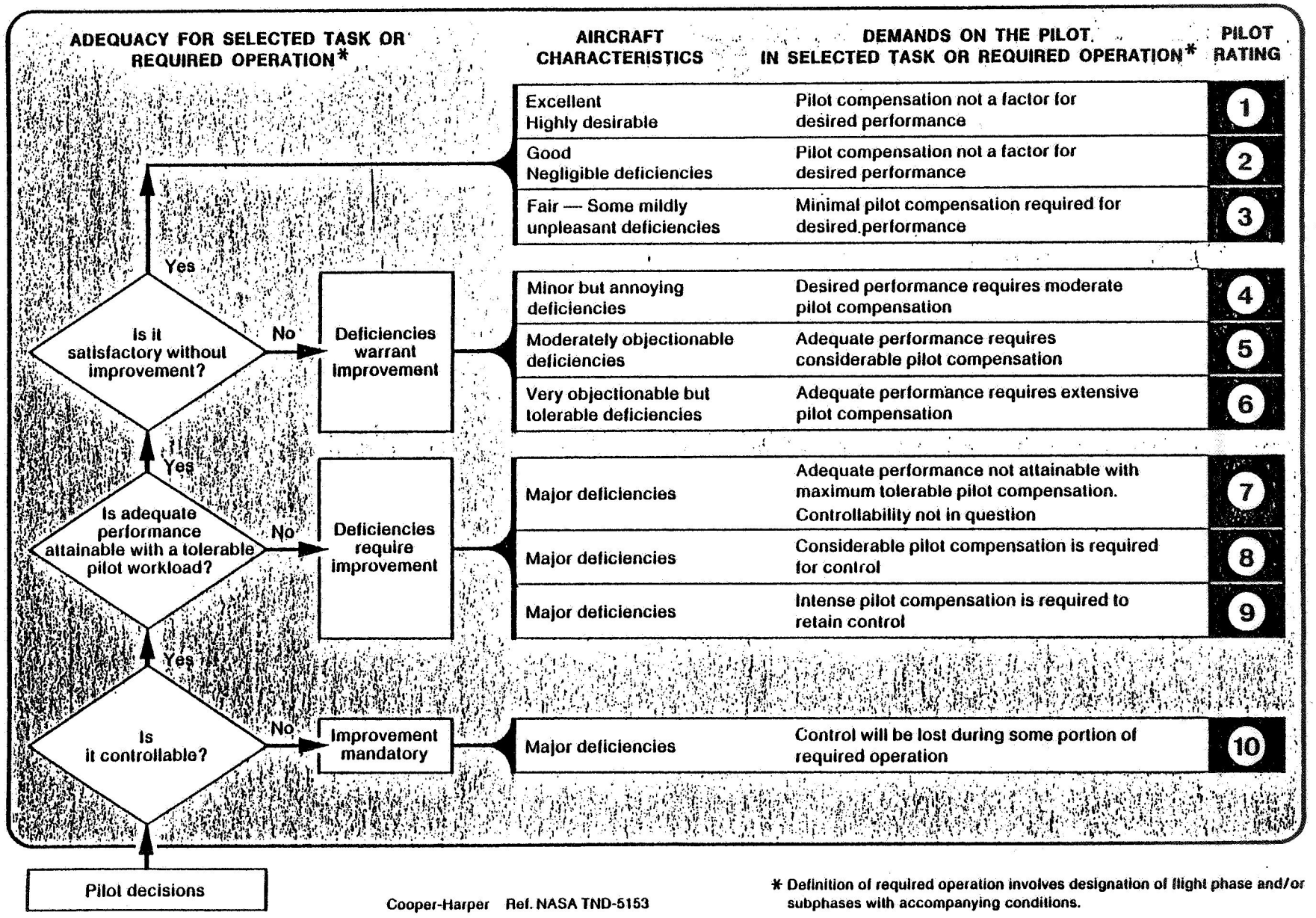

Figure C-1. Cooper-Harper Pilot Opinion Rating Scale

TABLE C-1

SIMULATION SUMMARY RUN LOG

SESSION/ PURPOSE	CONFIGURATION		TASK VARIABLES				PILOT RATINGS[a]	
	AIRFRAME PLUS CONTROL SYSTEM	ELEVATOR RATE LIMIT deg/sec	T sec	θ_o deg	$\lvert u_g \rvert$ kt/sec	ΔT_g sec	NO DISTURBANCE	RANDOM SHEAR
1 1 Mar 79 Survey Effects of Variations in Controlled System Dynamics	OFT	20	9	-1.16	No disturbance		7	Not run
	OFT	None					7	
	OFT[b]	None					5	
	#1	None					5	
	#1	20					5.5	
	#2	None					2.5	
	#2	20					7	
	#3	None					2.5	
	#3	20					7	
2 9 Mar 79 Survey Effects of Variations in Controlled-System Dynamics	#4	None	9	-1.16	No disturbance		4.5	
		40					5	
		30					4.5	
		20					6	
	#3	None					2.5	
		40					3.5	
		30					3.5	
		20					5	
	YF-12[c]	None					5	
	YF-12	None					3	
		20					3	
		10					6	
		15					3	
	747	None					2.5	
3 13 Apr 79 Evaluate DFRC a_z' Feedback Control System	#5	None	9	-1.16	No disturbance		3	
	#5	20					3	
	#6	None					2	
		20					5	
		30					4	
		26					3	
	#4	None					2	
4 19 Apr 79 Examine Effects of Random Disturbance	#1	None	9	-1.16	0	5	—	[2.5][d]
					2			[6][d]
					1			[5][d]
	#2				0			[2][d]
	#2				1			[3][d]
	OFT	None	9	-1.16	0	5	5	—
					1		—	5
					2		—	7
		26			2		(5)	6
							(5)	6
	OFT[e]						(4)	6
	#1						(2)	6
	#5						(4)	6

a,b,c,d,e See notes on following page.

SESSION/ PURPOSE	CONFIGURATION		TASK VARIABLES				PILOT RATINGS[a]	
	AIRFRAME PLUS CONTROL SYSTEM	ELEVATOR RATE LIMIT deg/sec	T sec	θ_o deg	$\lvert u_g \rvert$ kt/sec	ΔT_g sec	NO DISTURBANCE	RANDOM SHEAR
5	#2	None	9	-1.16	2	5	(3)	5
23 Apr 79	↓	↓	↓	↓	1	↓	(2)	4
					0.5		—	3
Examine Effects	OFT	26			↓		(5)	8
of Random Disbance	#1	26	↓	↓	↓	↓	(4)	4.5
6	OFT	26	9	-1.16	0.5	5	(5)	7
26 Apr 79	↓	↓	25	-0.58	↓	↓	(2)/(4)	5
			9				(4)	5
Examine Effects			15				(4)	5
of Task	↓	↓	20		↓		(4)	—
Severity	#2	None	15				(2)	3
	#2	None	↓		1	↓	—	3.5
	OFT	26			↓		—	5
	OFT	↓				10	—	5.5
	#1	↓	↓	↓	↓		(3)	4.5
7	OFT	26	9	-1.16	0.5	5	(5)	6
1 May 79	OFT[f]	↓	↓	↓	↓	↓	(4)	6
	#5[f]				↓	↓	(3)	4
Examine DFRC	#5[f]				1	9	—	7
PIO Suppression	#1[f]	↓	↓	↓	1	9	(3)	4.5
Filter								

Notes:

[a]With the exceptions noted below, pilot ratings are based on 10 or more runs with a given configuration, preceded by a pilot-determined number of warmup runs whenever the configuration was changed. For the random shear ratings, 2 runs each with a positive and a negative wind shear (4 total) of the magnitude and duration defined in the table were randomly interspersed in the 10 formal (rated) runs; the "no disturbance" ratings shown in the same row (in parentheses) are based on the warmup period, in which no disturbance was applied. "Random shear" ratings (in brackets) made as part of the determination of a suitable level of wind shear are based on 10 or fewer runs, on most of which a positive or negative wind shear was applied.

[b]OFT configuration with the pilot location moved forward to 83.02 ft ahead of the center of gravity.

[c]YF-12 configuration with the pilot location moved rearward to 0.54 ft ahead of the center of gravity.

[d]Gust magnitude determination study. See note a.

[e]OFT with digital stick shaping (additional 20 ms delay).

[f]Configuration run with DFRC PIO suppression filter on the pilot stick input.

Configuration OFT

I really could not tell a lot of difference on this one. I'm aware of the fact that the rate limits were removed; however, the basic deficiencies of the airplane still exist. It's still a pilot rating of 7, mainly because it gets away from me some percent of the time. When that happens and I try to tighten up, things only get worse. Any attempt to use large rapid control inputs to stop a sink rate which seems excessive near touchdown always results in a large divergent oscillation, which results in either a ballooning or a hard touchdown. So, what I really need is better control over attitude so that I can adjust the sink rate, and I don't seem to have that here, or I'm not even close to it. So the pilot rating is still a 7.

Configuration OFT, $\ell_{x_p} = 83$ ft

Control over sink rate was much better than for the previous configurations and there never seemed to be anything that ever got away from me. In this case adequate performance was attainable with a tolerable pilot workload, so that puts it in the 4-6 range. I would say the deficiencies, though, were still moderately objectionable in that the pitch attitude was still sluggish and it required a pulsing of the controls in order to get the sink rate where I wanted it. So, on that basis I'd give it a pilot rating of 5. I might make a comment about the task here, and that is that what I am doing is placing a lot of emphasis on making sure that the short line which converges to a dot is on the horizon at the same time it converges to a dot. So, if it's not on the horizon as it's shrinking towards zero, then I increase my effort to try to make it be there. If there's any tendency to have problems with the closed-loop control it would be toward the end of the task, and that's very similar to a landing task where, when near touchdown, the pilot tightens up in an attempt to make a smooth touchdown. The primary constraint in that problem is the same as here and this is that delaying will use up a lot of runway; here delaying lets it converge to a dot at an unfavorable location. If I get the short line to the horizon before

it converges to a dot, then I make my task one of keeping it on the horizon.

Configuration No. 1

That one was a little surprising, because on the warmup runs it was obvious that I had a much better attitude system and it was better from two standpoints than the previous configurations. That it, it was less sluggish, it seemed a lot snappier, and the second thing is that it had no overshoot. So the responses, open-loop and quantitatively, seemed very good. The problem seemed to be more one of unpredictability of the ground, and that is, I seem to have the sink rate under control and then it would apparently start to diverge and I was unable to stop it as quickly as I thought I should be able to. As a result, I got some runs that resulted in hard touchdowns because I didn't pitch up enough, and it just flew right into the ground. There were others where I over-rotated, and there seemed to be abrupt changes in the sink rate that I was unable to stop or counter, even though I had a pretty good attitude SAS. So, it was unpredictable; some runs were very good and others seemed like I was on the verge of losing control of it. I want to emphasize that I never felt out of control, but I always felt like a hard touchdown was a distinct possibility, and it was not consistent. I think that lack of consistency due to the inability to predict the change in sink rate with an attitude change is the reason for the rating of 5.

Configuration No. 1, 20 deg/sec

All the comments I made for the previous configuration apply to this one. In fact, it was pretty obvious that it was the same configuration. There was one run where the sink rate got a little further away from zero than I liked, considering how small the line was getting, and I went after it with a fairly large input, and that made things diverge. That made the rate limit kind of apparent, and then I was briefed on the fact that this had a rate limit in it. I think because of that, you

could get in trouble with it, so based on that one run I'll move it from a 5 up to a 5.5. So, the final pilot rating is 5.5.

Configuration, No. 2

This one is a considerable improvement over all the ones I've flown so far. I had what I felt like was very good pitch attitude control and also good control over the sink rate. There seemed to be good consonance between the sink rate and the pitch attitude. That's just my perception of it; I just felt that I could adjust the pitch attitude in a very fine way so as to adjust the sink rate. As a result I felt that my performance was quite good, and if I made a mistake and stopped the sink rate too soon, I could control it down to the ground with a nice slow sink rate. Or if I didn't pitch enough and I felt my sink rate was too high, just as I was approaching the ground I could make a large pitch correction and stop it without over-rotating or having any significant bobbling of pitch attitude. It seemed to be fairly forgiving of errors, and in that respect was also very consistent and that's very desirable. So, it's definitely in the 1-3 region. I would say the pilot rating of that is 2.5. There's a little pilot compensation required because you need to adjust pitch to control sink rate, so that requires a continuous scan and division of attention, and the mental workload consists of looking at the sink rate and making the appropriate pitch attitude adjustment. The feature of this configuration that made it desirable is that the pitch attitude adjustment was easy to make; once I decided what to do, I could do it very easily.

Configuration No. 2, 20 deg/sec

The major deficiency on that configuration was the extreme lack of consistency. I felt that if I got behind the airplane or if I made an error in my pitch attitude adjustment that it became very unforgiving. I had one or two runs with excellent performance, and I believe those runs were more an accident than any skill, in that I just happened to

pick the right pitch attitude, which allowed the thing to do an exponential flare and land. In fact, any time I got the sink rates somewhere near an acceptable range near touchdown, my technique was to leave it alone because I know that any attempt to make adjustments near touchdown frequently made things worse, especially if it required a large stick input. Though, I would have to say, looking at the Cooper-Harper scale, now, that the thing is not adequate. You don't get adequate performance with tolerable pilot workload, and controllability is not really a question, so I would say it's a pilot rating of 7. I should point out again that consistency is the main thing here, and this in some cases the performance was excellent. But in some cases it was bad; it was just not adequate.

Configuration No. 3

It looked a lot like Configuration No. 2 (no rate limit) in that I seemed to have very good control over the sink rate, and the attitude control was good. My open-loop attitude responses during the warmup showed a slight amount of overshoot, but I think from a piloting standpoint that it totally negligible and I would never have noticed it if I hand't been told it was there. I did notice in one case where I was just tracking the dot (ground plane) after the task was over that there seemed to be some lag in the sink rate response to attitude. I don't know if that's something that has any effect on the task or not. But, in terms of the task, I had good control over sink rate with pitch attitude. It felt in control all the time, so it's a pilot rating of 2.5.

Configuration No. 3, 20 deg/sec

This configuration, I felt, was basically very bad in that it was very unforgiving of any errors. As a result I would have to classify it "deficiencies warrant improvement." Most of my runs had what I consider to be quite good performance, and it was just on a few occasions where I made an erroneous control input and tried to recover that the deficiencies of the configuration became very apparent. This especially

occurred on Run 9, the next to the last run, where I overflared and then tried to work it back down to touchdown before the line converged to a dot, and got a fairly severe overshoot and a very hard "touchdown." So, I'd have to say that's a very objectionable deficiency; in fact, I'd classify it as a major deficiency, because it could easily result in a crash. Any time tight closed-loop control is required, you get in trouble with this vehicle, so therefore I'd give it a 7. I might add that several of my runs had excellent performance because I lucked out and just put in the right pulse input initially and got exactly the right attitude, which resulted in an exponential flare. Those I classify as luck. They were probably motivated by the fact that I realized that any tight closed-loop control was disastrous, and so my attempt then was to put in some open-loop inputs that would obviate the need for later closed-loop control. A couple of times I lucked out, but on Run 9 I attempted that and overflared, a little too much open-loop flare, and that resulted in some severe pitching and bobbling, which I think is indicative of the devious nature of this configuration. So, it's a 7.

SESSION NO. 2 (9 MAR 79)

Configuration No. 4

My major problem on that configuration seems to be an inability to make the sink rate exactly what I wanted it to be. I felt somewhat confused about that because the attitude control, in its own right, seemed to be adequate, but when I tried to use attitude to adjust sink rate, there appeared to be a large lag. I would say that it is not satisfactory without improvement and that it was somewhere between minor deficiencies and moderately objectionable deficiencies, so that would put a pilot rating at 4.5. I am not sure if it was because I'm just starting out here and not up on the learning curve or if it is something to do with the configuration, but it seemed difficult to figure out exactly what the deficiency was that was causing my problem with that one. My qualitative feeling about performance is that it wasn't unacceptable but that I just didn't have tight control when I got behind the airplane,

and so I would have to judge that as being somewhat unforgiving, but not dangerous.

Configuration No. 4, 40 deg/sec

It was difficult to tell whether the rate limit had any influence. It seemed to fly very much like the basic configuration (4, with no rate limit). What did become apparent was that there was considerable compensation required to do the task; it required a lot of concentration and I'm not sure if that had to do anything with the rate limit or just continued experience with this configuration. My pilot rating is 5. I might add that on the last two runs I found I could make the task come out perfectly by just putting the pitch attitude (horizon line) on a certain point on the display. I don't think those runs are really representative of the dynamics of the situation and really more or less represent being able to trick the task, and so I'm really not rating those runs. In a physical context, I think it's more important to rate the ability to do the task when you get a little bit behind the airplane and things are not working out just right. So, the rating of 5 really reflects very much the inability for me to be consistent and have good performance when I get a little bit behind the task.

Configuration No. 4, 30 deg/sec

Pilot rating on that is 4.5. Most of the runs were no problem performance wise. I just noticed if I got behind it that closed-loop control in trying to get the touchdown sink rate down became a problem, and so that put it between minor-but-annoying deficiencies and moderately-objectionable-deficiencies. The fact that it is a half a pilot rating better than the last condition is, I think, in the noise level, but I don't really feel justified in giving this one a 5 just because I know it's a 30 deg/sec rate limit. It really didn't seem to be bad enough to warrant a 5. Again, the primary problem is one of consistency, and that is, most runs have pretty good performance but one or two I got behind the airplane, and in one case I had a very high touchdown sink rate and

there was some bobbling and just a general sluggish attitude response which shouldn't allow me good, precise control over the touchdown sink rate and altitude.

Configuration No. 4, 20 deg/sec

This configuration required a very light touch on the controls. There was a lot of motivation to get the right precognitive pitch input in, because I found that if I got behind the airplane during the flare and tried to aggressively close the loop and adjust the sink rate I could get into a divergent PIO. On one of the practice runs I completely lost it. On one of the runs during the formal run series the oscillations got fairly large. So there seems to be some potential for getting into a lot of trouble. The pilot rating is 6 and the very objectionable but tolerable deficiency that goes along with that 6 rating is based on the inconsistency. On most runs it's not too bad, but if you get behind it and try to aggressively close the loop, it can diverge very rapidly. The thing that makes it tolerable is the fact that once you know that you can only make small inputs, it's unlikely that you would ever aggressively midhandle the airplane. The thing you need to accept in that case is that if you get behind it you are going to get a very hard "touchdown. You really are not in a position to be able to fix up an off-nominal sink rate near the ground.

Configuration No. 3

It was much better than the Configuration No. 4 series (with various rate limits). The pilot rating is 2.5. The thing that was most obvious to me in going from Configuration No. 4 to Configuration No. 3, was the much improved attitude response which in turn gave me a much improved response over sink rate. I felt very much in control all the time. It's a very forgiving configuration in that you can make a mistake or get behind it and still recover without any problem. The thing I like best about this configuration is the fact that I can make aggressive inputs and not get in trouble. The reason the pilot rating isn't better than 2.5 is just because the task itself requires some compensation.

Configuration No. 3, 40 deg/sec

The attitude response of that configuration seemed just a little bit sluggish; it wasn't as crisp as the previous one. As a result, control over sink rate felt a little less positive. However, on the whole I think it was an acceptable configuration and therefore gave a pilot rating of 3.5. Again, as with the other configurations, the only time I could notice any deficiency was when I got behind it in a flare. There is some temptation here to find in this task the right pitch attitude to do a perfect flare and just kind of leave it alone. I am trying to avoid that temptation and do some closed-loop control in order to make the ground line come to the center of the display (fixed aircraft wings symbol) as rapidly as possible, and therefore induce some closed-loop control. If I get behind it, this attempt to do closed-loop control tends to aggravate the less desirable configurations.

Configuration No. 3, 30 deg/sec

I could not detect any difference between this one and the last condition (i.e., same configuration with 40 deg/sec elevator rate limit), so the pilot rating is still 3.5 and all the comments also apply.

Configuration No. 3, 20 deg/sec

You could get into trouble with this one. Most of the runs I made were not bad, but once in a while I got behind it, and in an attempt to go after it and close a tight loop to get the sink rate under control I found myself getting into some oscillations that I couldn't seem to damp out quickly enough before touchdown. There was a definite feeling of being behind the airplane and there was a definite lack of consistency. The attitude response to the stick seemed qualitatively more sluggish than Configuration No. 3 with 40 deg/sec and 30 deg/sec elevator rate limits, and significantly more sluggish than Configuration No. 3 with no rate limit. This sluggish attitude manifests itself as a feeling of being somewhat less in control of the task. The pilot rating is a 5,

and, as in most of these configurations, that 5 is primarily oriented toward those runs where I got a little behind the airplane during the flare and had to tighten up.

Configuration YF-12, ℓ_{x_p} = 0.54 ft

The very first impression on this configuration is of a much higher stick sensitivity, that is, the attitude (change-to-stick-deflection) seems a lot higher. However, it was not that difficult to adapt to, so I wouldn't say it was necessarily objectionable; it just took several runs to get adapted to the much higher sensitivity. I'm not sure if it's because of the very high attitude sensitivity or because I just happened to notice it, but on this configuration there is very definitely a reversal in sink rate and attitude. That is, the initial sink rate to an attitude input is in a wrong direction and then in the right direction, so there is an effective lag between sink rate and attitude. During these practice runs that lag is pretty apparent and is somewhat of a problem. The annoying feature is that the attitude response seems excellent, but that a sink rate response is not consistent with that excellent attitude response. The high-frequency reversal in sink rate to an attitude input continued to be a problem throughout the formal runs. It's most noticeable during tight closed-loop tracking just right near the ground. After I've contacted the ground and am trying to hold the line (ground plane) on the center of the display until it converges to a dot, and am making small high-frequency inputs, the reversal in sink rate attitude makes it impossible to do precision tracking. The pilot rating is 5.

Configuration YF-12

The pilot rating is 3. The high-frequency reversal in path to attitude changes is gone for this configuration, which makes it considerably better. The attitude response is still slightly sluggish, but not to the point where it is unsatisfactory. It's possible to get behind this configuration and recover. It is a forgiving configuration, and my

performance felt reasonably consistent. Therefore, it is a pilot rating of 3. In terms of comparison, I think Configuration No. 3 was a little snappier in attitude, and therefore somewhat more desirable than this one.

Configuration YF-12, 20 deg/sec

I really couldn't tell any difference between this one and the previous one (without an elevator rate limit). It's a pilot rating of 3 and all the comments that apply to the previous one also apply to this one. I did not know that this had a rate limit on it, and perhaps the reason it never showed up is that I never really got behind the airplane on any of the runs and so perhaps the rate limit never really showed up. But, based on those 10 runs and my practice runs, the pilot rating is still 3.

Configuration YF-12, 10 deg/sec

My first couple of runs were almost uncontrollable. However, once I got used to the configuration I could settle down and get reasonably acceptable performance. One thing is clear and this is that if you get behind this configuration, there is no way you are going to tighten up and get good tight closed-loop control of attitude and sink rate. So, it is a very unforgiving configuration. That showed up on a few of my runs during the 10 run (formal) series. However, I think the performance on the traces is going to look a lot better than it felt to fly; I felt a bit behind and knew that if I made a mistake it would be very difficult to recover. I think that's a very objectionable deficiency and therefore I give it a 6.

Configuration YF-12, 15 deg/sec

That configuration was a pretty good one, and in fact it seemed very much like the YF-12 with no rate limit and the YF-12 with the 20 deg/sec rate limit, so the comments I made on those apply to this one as well.

It's a pilot rating of 3. I should note on that last series of runs that there was a slight tendency for the pitch to drift, I believe nose down, and so whenever I needed to get a slight nose-down correction I just put the stick to neutral, and that's why the stick probably looks very one sided for that last series of runs. [Editor's note: a slight bias had developed in the control stick position sensing circuitry. It was nulled out after this condition was run.]

Configuration 747

The attitude response to a stick input felt quite sluggish and extremely well damped. It was my distinct perception that the sink rate response to an attitude change was extremely well behaved and that there was a high degree of correlation between changes in pitch attitude and changes in the sink rate which made this configuration extremely easy to land. Even though the pitch response was not a high bandwidth response, there was never any concern about getting behind the airplane. It was a very forgiving configuration. The best way I can describe doing this task (in this configuration, as compared to other configurations) was that it all seemed to happen in slow motion here. The pilot rating is 2.5.

SESSION NO. 3 (13 APR 79)

Configuration No 5

It seemed like a reasonably good configuration. The sink rate and attitude consonance seemed very good. The only complaint I might have about it is that the attitude seemed slightly sluggish. I think that was kind of a minor effect, and so the pilot rating for that is 3. Given a choice, however, I would like to have a little tighter pitch attitude dynamics. One good thing about that configuration is that if I got off a little bit and got near the ground with a high sink rate or ballooned near touchdown, if I tightened up on it, it seemed to be very well behaved. That is, tightening up always improved my performance.

Configuration No. 5, 20 deg/sec

I didn't know it had a rate limit when I ran it; it seemed to go almost identically the same. I did pick up a little more insight into the attitude dynamics this time. There seemed to be some overshoot during the practice runs, and I don't know if the rate limit does that or if it's just there inherently. I thought it was going to be a problem, but during the actual run it wasn't. The pilot rating on that is a 3, and it's a good 3. It might almost go to a 2.5. I might add that since I didn't know it had a rate limit I didn't make any special efforts to tighten up near touchdown or see if tightening up in a critical situation would cause the effective gain to be lower, and so most of my runs were pretty low-gain runs where no tightening was required.

Configuration No. 6

That one was extremely easy to fly. In fact, I found myself not having to concentrate on the task very much at all, and getting pretty good performance. I'd have to call that a 2. My performance seemed to be quite repeatable, and if I got in trouble due to an overflare or too high a sink rate near touchdown, tightening up always seemed to be very effective. I did notice during the practice runs that it had a lot of overshoot, and I'm not sure if the overshoot is changing on these runs or if I'm getting more aware of it. The only time I notice the overshoot, however, is on the practice runs when I'm playing with it. During the actual run the overshoot does not seem to be a problem. So, I should qualify these results by saying that for this task the overshoot is not a problem and the pilot ratings are quite good — for this particular task, I want to emphasize that.

Configuration No. 6, 20 deg/sec

I did not know it had a rate limit until finishing the runs. This one was a little confusing because there was a lack of consistency. When everything was well behaved, my performance was quite good, and in

those cases there was minimal pilot compensation. Given only those cases I would have rated it a 3, and it seemed like all the other ones. In cases where I got a little behind the task and tried to tighten up, I notice that the performance got very loose. In one or two cases I actually got way behind it, particularly a case early in the run series (about the third or fourth run). It probably would have been a very hard touchdown; it might have even been classified a PIO. I was definitely behind it, and controllability was possibly a question. That particular run I would have rated a 6 or 7. So, there is a definite lack of consistency which seems to appear mostly when I have to tighten up, and therefore the overall pilot rating is a 5.

Configuration No. 6, 30 deg/sec

During the trial runs that one seemed very good and I was really prepared to give it a 2. But during the actual task I found that I had some problems right near touchdown, some bobbling, and I just didn't seem to have the precision attitude control I needed to adjust the sink rate for touchdown. Things seemed a little bit loose right down where I wanted to tighten up, and so it's a pilot rating of 4. That rating is based primarily on the moderate pilot compensation required if you have to close the loop right near touchdown and tighten up. That's kind of an annoying deficiency.

Configuration No. 6, 26 deg/sec

During the training runs I was not very happy. I kind of got behind it and had some bobbling and, in general, when I got in and horsed around with it, it seemed to come back a bit, but in an unfavorable way. In doing the task I never really had to tighten up and it seemed fairly well behaved. I wasn't aware it hd the 26 deg/sec rate limit, so I didn't really try to exercise that. But I did not find any problems, so I would have to give it a pilot rating of 3 for that task. Everything seemed to go very well during the runs.

Configuration No. 4

This one seemed extremely well behaved. The overshoot is gone and the attitude dynamics seem excellent. My performance was really quite good, so the pilot rating is a 2. My only reservation about the configuration is that the attitude dynamics seemed so good that I expected really better sink rate in the performance. That is, attitude-sink rate consonance, and it seemed like if I abused it my performance was not all that hot. However, I never got behind it and it seemed consistent. It's at least as good as Configuration No. 6, and actually better. The fact that Configurations 6 and 4 are both rated 2 is probably misleading, because I believe 4 is a better configuration. The attitude dynamics are significantly better than they were on 6. Given the two airplanes, I'd much rather have 4. During the warmup, where I do a lot of abuses and mishandling of the configuration, 4 was very well behaved, whereas when I did that with Configuration No. 6 I recall it tended to be a little bit squirrelly when I put in large abuses. Configuration No. 4 seems extremely well behaved and consistent. Of them all so far (in this session), I like it best.

SESSION NO. 4 (19 APR 79)

WIND SHEAR MAGNITUDE SENSITIVITY STUDY

Configuration No. 1

We are just looking at different levels of disturbance. Configuration No. 1 is a very good configuration with very good pitch attitude response to stick, no overshoot, and a nice rapid reponse. With no disturbance of that it is like a 2 to 2.5. With a disturbance level of 2 (u_g = 2 kt/sec for last 5 sec), the rating goes all the way down to 6, and that is because at just about touchdown the ground line either goes right through the horizon at a very rapid rate, requiring a large pitch to try to stop it, or it stops short of the horizon and then in an attempt to catch it I get a lot of large ocillations, and because in an

attempt to track the horizon I am getting pitch attitudes of 20 to 25 percent full scale, without any apparent improvement in my tracking. So I am getting a large pitch attitude excursion and poor tracking, which is a pilot rating of 6, maybe even a 7, because the performance is really not adequate.

Configuration No. 1

We are still really sizing the disturbance here rather than making formal runs, and this is a rating of about 5 (u_g = 1 kt/sec). The reason for that is that performance requires considerable compensation. The thing that is most noticeable is that the rate of disturbance is pretty high, so it requires a very large aggressive pitch attitude change to stop it, and even with a large aggressive pitch attitude change the error becomes considerably large because you can't really correct the error until it develops. Once it develops it is difficult to stop before it gets to a considerably large magnitude. So the basic problem with this one is that the adequate performance is very difficult to obtain.

Configuration No. 2

This is really an excellent configuration. Without any random shear disturbance the rating is 2. With the shear (u_g = 1 kt/sec), the rating drops to a 3; but to be honest, there were times when I wasn't even sure whether I had the disturbance or not, so I would'nt place a lot of weight on that 2 to a 3. In fact, I'm very surprised that with this level of attitude augmentation that I am so able to regulate against the same disturbance as I had so much trouble with it on Configuratin 1, where I had to give it a 5. So, improving the pitch attitude augmentation from Configuration No. 1 to No. 2 really made a big difference in regulating against this disturbance.

FORMAL RUNS

The scenario for the formal runs will be as follows. During the practice runs there will be no disturbance, and when I feel up on the learning curve during the practice runs I will give a rating for the no disturbance case. Then we'll run the 10 formal runs with random shears, and that rating will be for random shear. [Editor's Note: "Random shear" means u_g of ± indicated magnitude occurs during run.]

Configuration OFT

I've just finished the practice runs and I really don't like this one very much at all. It is quite sluggish — the reponse of attitude to a stick input is sluggish — it has some overshoot, and this is undesirable. It really interferes with my ability to do the task. I don't have very good precision control over sink rate because I can't set my pitch attitude, and so I find that my run-to-run variability seems to be poor. Performance is probably adequate but barely so considering the lack of consistency. The compensation is considerable, especially if I get a little bit behind it. It's very unforgiving. If I have to make a large attitude change to recover from an error, then things go bad very rapidly, because I can't make a large attitude change with any precision. So I call that one a 5. That's without a disturbance.

With random shear of 1 kt/sec, the pilot rating is still a 5. There was one run where I really got behind it, and if I was rating that one run I would probably call it a 7. But, all the rest of the runs were a 5 and there doesn't seem to be enough evidence to rate it down as a lack of consistency, at least not below 5. Interestingly enough, I wasn't able to perceive the disturbance that well, and it was difficult to tell whether the excursions of the ground plane were due to incorrect pitch attitude or a random shear, and I just adjusted pitch attitude without knowing whether I was regulating against an input or my own erroneous pitch attitude.

Configuration OFT, 26 deg/sec

Without turbulence, I couldn't see any difference, so it is still a 5. With a random shear of 2 kt/sec I had a couple of runs that kind of got away from me; at least I think those runs were ones which included wind shear. My consistency was not all that good. I had some very good runs and a couple very bad ones, so I would have to rate it a 6 based on those.

[Editor's note: For the remainder of this session the random shear magnitude is 2 kt/sec (for the last 5 sec).]

Configuration OFT, 26 deg/sec

This is after lunch, a repeat run. I really don't see much difference between this and the one without rate limit, but I can't really perceive that I am getting on the rate limits. So, without random shear, it's about a 5, because of the very slow pitch response and the overshoot.

With the random shear, because of the problems right near touchdown, it is a 6. Specifically, those problems relate to the large accurate pitch attitude changes that are required that I can't achieve with this attitude system, and, I should add, those attitude changes are not only large but also rapid, very rapid, to handle large altitude changes that are required. This configuration appeared to be a little better than the others just on the basis of the practice runs and those that were without turbulence.

Configuration OFT (With Digital Stick Shaping), 26 deg/sec

The attitude response is still pretty sluggish, and there is still an overshoot, but subjectively it appears to be just a little bit better. I'm not sure if that has to do with the learning effect or if I am really seeing an improvement. So without random shear we'll give that one a pilot rating of 4.

With random shear the big problem was lack of consistency and the same sort of comments apply that I've been making all along about inability to make large rapid precision pitch changes that are required in order to maintain control over sink rate; so the pilot rating is a 6. The 6 is based primarily on the fact that in order to get performance it requires extensive pilot compensation, basically the limit of the workload, It's even questionable whether it should be a 7, because on the runs with the large shears —— there are some cases with large shears I don't feel that performance was even acceptable. Call it a basic 6, but leaning towards 7.

[Editor's note: The following two configurations were run toward the end of the day. Consequently, in order to get them both in, less time was spent on them than on previous configurations.]

Configuration No. 1, 26 deg/sec

With no disturbance, this is a 2. The pitch attitude control is excellent. There might be a slight delay in pitch in response to stick input, but that doesn't seem to affect my ability to do this task. There is no overshoot and the response is very crisp; the only thing I can notice at all to complain about is perhaps a little delay in the beginning of the response after I put a stick input in.

With random shear that configuration is very sensitive. It appears like I'm unable to keep up with the wind shears. I get a lot of large pitching and sloshing around the ground plane, and it appears like that little lag I was noticing earlier keeps me from really being able to close the loop tightly and aggressively track the sink rate. So, when I get excursions in sink rate and try to track attitude aggressively, it feels like I am not getting the response as quickly as I need it. Even though I do get it, it is very crisp. So my qualitative feeling is that there is a large time delay between the pitch response and my stick inputs, and this causes a problem for tracking with a disturbance. Several times I felt like I was in an oscillation —— perhaps a PIO because of a very large lack of consistency run to run. On some runs I

got way behind it and had real problems; other runs were nothing. Based on that lack of consistency I would have to say the deficiency is very objectionable; therefore, this will be a pilot rating of 6.

Configuration No. 5, 26 deg/sec

With no disturbance it is not a real good configuration. The pitch attitude response is somewhat sluggish and there is some overshoot. It looks very much like some of the earlier configurations we were flying that I was rating a 5 — I believe Configuration OFT looks a lot like that. Sometimes you luck out and get the right attitude and can get the right attitude and can make reasonably good landings, but for the most part there is some chasing and bobbling going on. I would like to have a much tighter pitch response, so let's give that a pilot rating of 5 (with no disturbance).

All right, we just ran the formal run series and the ones in which there was no disturbance. With random shear I believe it was a 5.5 to a 6. Let's call it a 6, because there were cases where it really got away from me. So I am primarily rating those cases where it seemed there was no way I was going to get it back toward the end of the run, and I attribute most of that to the sluggish attitude response.

SESSION NO. 5 (23 APR 79)

Configuration No. 2

With no disturbance, the attitude response seemed excellent. There is a very minor overshoot, but the response seemed very rapid and it was easy to make fairly large, accurate pitch attitude changes. I had some minor problems controlling sink rate, and I suspect that's because I just started this session and am not really up on the learning curve. However, those problems were not associated with large excursions and touchdown but rather the smoothness with which I approached touchdown. Because of these problems the pilot rating is 3, and I suspect with practice it would move up to 2.

With random shear in the ten formal runs, this configuration is somewhat difficult to rate, because of the extreme variations in performance I ran into. In some cases I could see a disturbance, but everything was very much under control and so it made it quite easy to regulate against the disturbance. In other cases I was a little behind the airplane, that is, my touchdown sink rate wasn't exactly what I wanted it to be, and in the process of correcting for that, the addition of the turbulence sometimes was in an unfavorable direction, making my original correction inappropriate. In those cases I got quite far behind the airplane; I think you can see on the strip chart that I had about two or three runs during that series where there were some large oscillations in sink rate near touchdown. Based on those runs, the pilot rating is a 5. I should emphasize that the ratings for landings are a very strong function of consistency —— that is, run-to-run consistency. And in cases like this last series of ten runs, seven out of the ten were excellent and three were kind of bad, and so there is some indication of a lack of consistency that makes the overall configuration a 5.

Configuration No. 2

[Editor's Note: This repeat of the previous configuration was done without the pilot's knowledge to verify the assessment for this configuration. Comments were made only after the warmup was completed.]

It turns out this was a repeat of Configuration No. 2, and the pilot rating I gave was a 2, which was up one rating point from the first time I rated it. As I mentioned earlier, with some practice I felt it should come up to a 2, which it did.

The following comments are for the formal runs wih random shear of 1 kt/sec, not 2 kt/sec as for the previous set of formal runs with Configuration No. 2. For the most part, my control over sink rate was quite good. There tended to be a little bobbling near the end when I could not put it exactly where I wanted it in terms of attitude and sink rate, and this seemed to be somewhat excited by the wind shear. On those runs I think my compensation was classified as moderate, and the pilot rating would accordingly be a 4.

With a random shear of 0.5 kt/sec, it was very difficult to sort out when there was and when there was not a wind shear. Although there was some very slight bobbling, most of my runs were well within the desired performance without a lot of compensation. The pilot rating is a 3. Incidentally, part of my getting up on the learning curve has been to use some semi-precognitive attitude inputs; the way I have been flying in the most recent runs is to pitch to the horizon initially, which slows the sink rate, and then to make minor adjustments in pitch attitude to achieve a final decrease in the sink rate to touchdown. I classify this final portion of the run as very much closed-loop tracking in that I adjust my pitch rate according to the sink rate I perceive on the ground plane all the way to the end of that run. Also, as the altitude becomes less —— that is, as the distance between the ground plane and the zero reference approaches zero —— I work quite a bit harder to get the sink rate where I want it.

Configuration OFT, 26 deg/sec

Incidentally, I have no information on the configurations before the start of the run. The rating on that is 5, with no disturbance, and the deficiencies are a sluggish attitude response with an overshoot. Interestingly, I can do very well on many of the runs. If I get ahead of the airplane and set the pich attitude very carefully, the sink rae goes to zero very nicely and monotonically. However, if I miss on the initial pitch attitude and get into a closed-loop situation near touchdown, the sluggish attitude reponse does not allow me to adjust sink rate precisely. This is really the root of the reason it is a 5 and makes the configuration very unforgiving, that is, if you get behind it, it is difficult to catch up, because pitch attitude is hard to set and therefore sink rate is hard to set.

With random shear of 0.5 kt/sec, all the problems I discussed above for this configuration really were magnified. On a few of the runs where the wind shear caused me to have to make some reasonably large and precise pitch attitude changes, I got far enough behind the airplane that it probably would be considered a crash. It's a very large

attitude/sink rate oscillation that would definitely be classified as an oscillation or perhaps pilot-induced oscillation. Those runs occurred maybe 20 to 30 percent of the time. Again, consistency is a major factor, and so those runs have a very heavy weighting. I'd say that will be an 8, because of those runs. There is considerable pilot compensation required for control, and that is exactly what is going on; it was basically having to try to keep from being out of control. [Editor's note: There followed a discussion between the simulation conductor and pilot in which the former pointed out that on some of the runs on which the pilot had trouble there was wind shear.] I think the reason for this is that on warmup runs, with no disturbance, I know with 100 percent confidence that all the responses are due to my inputs and, when the sink rate is not what I think it should be, I know for sure it's because of erroneous input; so I make a small input in the other direction. On the other hand, when wind shear is a possibility, then I tend to be more aggressive with my inputs. This is a direct result of the possibility that the sink rate may get away from me because of the large wind shear. If I see it starting to diverge, I'll tend to put a larger, more aggressive input in to stop the divergence. When the configuration is unforgiving, then my attempt to make those large corrections leads to some oscillations. I think that is what happened in the last case where I gave it an 8. Even with these considerations in mind, I still feel that this configuration (with random wind shear) is an 8, because of its fairly extreme unforgivingness.

Configuration No. 1, 26 deg/sec

That configuration had a fairly good attitude response in terms of its time-to-peak, and there was no overshoot. However, there seemed to be an initial delay which was annoying and made it difficult to get the attitude response when I wanted it. It was easy to set the attitude at some value, given that I had enough time, but if I got down near touchdown and needed some rapid adjustments in sink rate, which called for some precise attitude changes, I got into a little bit of trouble. And so I think those deficiencies are perhaps somewhat minor but they are

annoying and require moderate compensation to try to overcome that initial delay. So the pilot rating is a 4.

Random shear of 0.5 kt/sec did not seem to play that big a factor in this particular configuration. It was difficult for me to perceive when the wind shear was in and when it wasn't. There were a few runs when that delay I mentioned earlier seemed to be emphasized near the end of the run. However, in no case did it ever get away from me or did the consistency seem all that bad, so I'd make that rating a 4.5.

SESSION NO. 6 (26 APR 79)

Configuration OFT, 26 deg/sec

This is a familiar configuration; we have talked about it in previous sessions. It is characterized primarily by a sluggish attitude response with a considerable overshoot, making it difficult to set the attitude quickly and precisely. As a result, the problem rating is a 5 (with no disturbance).

With random shear of 0.5 kt/sec, it was difficult to perceive when the turbulence was actually on. I think the major effect of random shear is, as I mentioned last session, to make me a little bit more aggressive, knowing there is some wind shear possible. Being aggressive with a loose attitude system like this one sometimes gets me into an oscillation. I experienced some of those during this formal run series. And, because of one or two of those on which it kind of got out of hand, the configuration is kind of objectionable. I think it puts it in a "deficiencies that require improvement" range. I wouldn't want to fly this without it's being improved, so it would be a 7. I should have pointed out, as I have in the past, that consistency is a major factor and that even though some of the runs probably look very good, some of the other runs look very bad, and that lack of consistency is the thing that makes it such that the deficiencies require improvement and that they are really in the major category.

[Editor's Note: The preceding run of the "nominal" OFT configuration (OFT with 26 deg/sec elevator rate limit), flown in the "standard" task (task time, T, of 9 sec; initial pitch angle, θ_o, of -1.16 deg; and random shear, $|u_g|$ of 0.5 kt/sec for a duration, ΔT_g, of 5 sec) was run as a tie-in to previous and subsequent sessions. The remainder of this session's runs were flown with a θ_o of -0.58 deg, and with T, $|u_g|$ and ΔT_g as indicated in brackets.]

Configuration OFT, 26 deg/sec [T = 25 sec; $|u_g|$ = 0.5 kt/sec; ΔT_g = 5 sec]

This task requires a much smaller initial pitch to stop the sink rate, and it's a far more benign task on account of that. The poor attitude dynamics are somewhat masked by the task until right near touchdown when I make a small attitude change and stop the very low sink rate. As we near touchdown, there tends to be some bobbling. That bobbling is somewhat annoying, and it is somewhat aggravated by random shear. It becomes apparent at that point that I'm behind the airplane, which results in several oscillations before I finally settle down. Because of that it is a 5 (with random shear). Some of the runs, where there was no turbulence, I got way ahead of it and literally selected the proper pitch attitude to do an almost open-loop flare. For those particular runs (with no disturbance), the pilot rating would be a 2, because it required virtually no compensation. [Editor's note: see later comment, suggesting pilot rating of 4, on same configuration with T = 20 sec.] However, any disturbance into this system requires a precise attitude change and excites the poor dynamics and that immediately puts it down into the 5 range.

Configuration OFT, 26 deg/sec
[T = 9 sec; $|u_g|$ = 0.5 kt/sec; ΔT_g = 5 sec]

As with the previous condition, the initial sink rate is low, and this eliminates the need for the large attitude change at the beginning of the run that we've had in all the previous sessions, and that large attitude change, to stop the initial high sink rate, tends to excite the

system, and so this alleviates the task somewhat. The drawback to this setup (with T so short) is that if you rotate too much, too soon, you run out of time, and so you have to be careful to let the aircraft come down close to the ground and then rotate. My rating on that (with no disturbance) is a 4, because of that problem. It may even move up to a 3, if I got used to doing the task that way. Really, the reduced critical sink rate eliminates the initial pitch, and then the rest of the task remains the same. Eliminating that initial pitch, however, as I indicated earlier, is somewhat of a benefit, because you don't excite the poor dynamics, and therefore the pilot rating is a 4.

On the formal runs I couldn't detect any disturbance. However, in a few cases I over-rotated and had a hard time getting the aircraft down toward the ground before the line went to a dot, and so I had to pitch down and increase the sink rate and then decrease it again, and because of the poor attitude dynamics got behind the thing. However, in no case was it ever really a disaster, and so the pilot rating would be a 5. The initial slow sink rate, I think, is responsible for the rating being as good as it is. There is never a need to make a large attitude change and, as a result, you never excite thoe poor dynamics.

Configuration OFT, 26 deg/sec
[T - 15 sec; $|u_g|$ = 0.5 kt/sec; ΔT_g = 5 deg]

With no disturbance, if you get way ahead of it, it is easy to get good performance. However, if it is slightly abused, then the poor attitude dynamics become a factor and that, primarily, drives the rating. In this case, the rating is a 5, and that's based primarily on my last run during these warmups where I purposely got off and got quite far behind trying to get back on. If I were to rate only the runs where I did not get off, where I kind of played pinball with it and put very small inputs in to watch the response, and I knew there was no disturbance — if I were to rate those runs — it would be a 3. But, I think if you account for the possibility of abusing it a little bit and then having to try to catch up with it, it would have to be a 5. It's very unforgiving once you get behind it. [Editor's note: the pilot and test

conductor discussed the rating just given with relation to the task being rated. Following this discussion, the pilot changed the rating as described below.]

For this particular task, which does not include abusing it, perhaps the ratings should be a little better. The abusive treatment I gave it on the one run, which resulted in my giving it a 5, is really not the assigned task. So the rating for this task is a 4. I made some more runs with this latter concept in mind, and the 4 is based on the fact that the desired performance requires moderate pilot compensation, and that's primarily right near touchdown. My technique with this lower sink rate is to let it sink pretty much without any control input until near touchdown, then slow the rate and finally to arrest the sink rate just at touchdown. It is this final attitude, precise attitude, requirement that results in a pilot rating of 4, because it's so difficult to set this particular configuration accurately — to set the attitude accurately. So, we're going to revise the rating to a 4 for the no-turbulance case. However, I think the comments I made earlier, which gave it a 5, still apply in terms of abuse cases.

With random shear, for the most part the runs were essentially the same as the ones with no disturbance, except that on one or two I got into a fairly severe pitch bobble or pitch sink rate oscillation near touchdown, and, in those cases, it really was apparent the attitude response was sluggish and the overshoot is kind of undesirable. I would say those would have to be classified as moderately objectionable deficiencies, so therefore the pilot rating is 5. It is difficult for me to say whether the decrease in rating from 4 to 5 is due to the fact that a disturbance excited the motions, or whether I just was flying more aggressively and making the pitch attitude deficiencies more apparent. I really can't tell whether or not there is a disturbance or separate out my inputs from the turbulence.

Configuration OFT 26 deg/sec
[T = 20 sec; $|u_g|$ = 0.5 kt/sec; ΔT_g = 5 deg

My real problems areaat the end of the run when I get into this oscillation between pitch attitude and sink rate and try to get the two settled down, so making the test longer doesn't really help because in the other cases (with shorter task time) I already have enough time to bring it in slow. The real problem is right near touchdown when I'm trying to make that last attitude correction — to zero sink rate. It tends to either squirt through zero or stop short and go the other way, and then there's some bobbling and I think that sort of sloshy dynamics warrants at least a 4 (with no turbulence). Earlier when we had this same configuration with a 25 sec task time, I gave it a 2. I think that was an anomalous point, because I had several runs in a row where I happened to do very well. I believe that configuration is really more of a 4 than a 2, because of the inability to make precise and quick attitude changes near touchdown. [Editor's note: no formal runs were done with random shear, based on preceding comments.]

Configuration No. 2 [T = 15 sec; $|u_g|$ = 0.5 kt/sec; ΔT_g = 5 sec] This is a major improvement over the last configuration. The attitude response is very crisp, and it's easy to make quick and accurate changes in pitch attitude, which in turn allows me good control over sink rate. It's very forgiving. If I get behind it, it's easy to make an abrupt attitude change and catch up; there's no tendency to oscillate near touchdown like there was in the last one. So, I would give that a pilot rating of 2.

With random shear I couldn't really see the effects of the disturbance at all. There were some cases, however, where I had to tighten up somewhat in order to achieve control over sink rate, and so I'd have to say that there was at least some minimal pilot compensation required to get the performance. However, I do think it's satisfactory without improvement, and therefore a 3. [Editor's note: a second set of 10 formal runs with $|u_g|$ = 1 kt/sec followed. The pilot rating was 3.5. There were no additional comments.]

Configuration OFT, 26 deg/sec
[$T = 15$ sec; $|u_g| = 1$ kt/sec; $\Delta T_g = 5$ sec]

It was difficult for me to spot the increased wind shear. The configuration still has the basic deficiencies we've noted all along. As I've noted earlier, the possibility of a disturbance makes my fly all the runs more aggressively, and I occasionally get behind it and start oscillating, which is what happened on one or two of the runs and makes a pilot rating of 5. Then all the attitude deficiencies I've quoted earlier still apply. One thing I might add is that the disturbance doesn't seem to have come in until the very end of the run, so there's very little you can do to respond to it. By the time the thing starts ramping off due to the wind shear, the run is virtually over — at least that's my perception of what's going on.

[Editor's note: Based on the pilot's observations, another set of runs was made with the gust duration increased to the final 10 sec of the task ($\Delta T_g = 10$ sec). On these, the disturbance inputs came in a little earlier and caused me additional problems, because now I had a disturbance that came in at a very critical time. Because of the imprecise attitude characteristics of this configuration, there were times when I got quite far behind it. The pilot rating for that one is 5.5, and I do feel that this type of input is more realistic a wind shear during the flare than the other ones, which occurred, I think, considerably too late in the run. Here I had a chance to actually do some closed-loop control to regulate against the disturbance.

Configuration No. 1, 26 deg/sec
[$T = 15$ sec; $|u_g| = 1$ kt/sec; $\Delta T_g = 10$ sec]

This configuration appears to have a reasonably nice attitude response. It's easy to set the attitude. I did, for some reason, have a little pitch bobble down in close, and I'm not quite sure if that was real or what was going on there, but the pilot rating on that is a 3 with no disturbance.

With random shear the disturbance was definitely noticeable. In some cases I got kind of behind it in terms of getting a few oscillations, but I felt comfortable that I could get back in control because of the reasonably good pitch dynamics. I would say that those times that I did kind of get some bobbling going on would be described as minor, but annoying, and so I'd give that a pilot rating of 4. In fact, I think we'd better make that 4.5, because there were some cases where I got pretty far behind the airplane trying to make this sink rate converge to zero the same time as the altitude went to zero.

SESSION NO. 7 (1 MAY 1979)

[Editor's note: for this session the task reverted to the nominal , with T = 9 sec and $|u_g|$ = 0.5 kt and ΔT_g = 5 sec, except as noted.

Configuration OFT, 26 deg/sec

The pilot rating without turbulence is a 5, primarily because of the sluggish attitude response and the inability to set attitude precisely and the resulting inability to control sink rate precisely. This configuration is very unforgiving of any errors. If you get behind it during the flare and attempt to tighten up, the sluggish attitude control results in fairly severe oscillations.

With random shear the rating is a 6, and the 6 is predicated mainly on 2 of the 10 runs, where I believe there was wind shear and the sluggish attitude response plus the overshoot made it very difficult to set the sink rate with attitude.

Configuration OFT, 26 deg/sec
and DFRC PIO Suppression Filter

My initial impression just from flying it for 5 or 10 minutes is that there is very little difference between the dynamics with and without the suppression filter. It has the same sluggish response and the same overshoot characteristics. I have noticed that it seems to take a

lot more stick to get a given pitch rate, and so the gain seems to be a lot lower, and if I get at all behind the task it requires large stick inputs, which is a little bit undesirable. It is now [after a few runs] becoming apparent that the high-frequency attitude response to stick inputs is severely attenuated, and this results in two things. One is that I have no control, or very little control, right near touchdown, and if I have to make an immediate attitude change that's not possible. The other thing is that there is less of a tendency to get into an oscillation because the attitude won't response to rapid stick inputs. Previously, on this configuration, without the suppression filter, when I tried to tighten up after getting behind on the task I would get into an attitude/sink rate oscillation, while here that rarely happens. Instead, what happens is that when I make an immediate or rapid input, attitude does not respond at all, and therefore I am unable to change the high sink rate which motivated me to put in the rapid input in the first place. So, for example, if I have a high sink rate near touchdown and I want to pitch up rapidly to stop that, I don't get the rapid attitude response, and I just touch down hard. It is like having no control right near touchdown. I don't think that is any more desirable than getting into an oscillation, and the pilot rating stays about the same. It is a 5. The primary problems then with this configuration are sluggish attitude response, overshoot, and, in this case, a lack of response for high-frequency stick inputs, and apparent decreased attitude-to-stick gain, resulting in large stick inputs which are somewhat undesirable.

With random shear I really could not detect wind shear on any of the runs. One thing I did notice, though, is that I never got into the attitude oscillations that I got into without the suppression filter, and that with more experience I could do quite well with it. And so I think my initial impression (no disturbance warmup runs) where I gave it a 5 was probably too severe, and I would like to change that to a 4. Since I couldn't detect any difference with random shear for the formal runs I would like to leave that a 4. So that is a 4 with no disturbance, and a 4 with random shear for these formal runs. The reason it is not a 3 or a 2 is because the attitude responwe is still quite

sluggish, and I have a feeling of only being partly in control because of the lack of high-frequency attitude response to high-frequency stick inputs and the general sluggishness and overshoot of the pitch attitude to low-frequency inputs. I have the intuitive feeling, which may or may not be correct, that if this configuration was disturbed with some large gust inputs throughout the run that I would be unable to control attitude because of the lack of response to high-frequency stick inputs and the general sluggishness of pitch attitude. So, with high-frequency large inputs which occur during the middle of the run or early in the run, I would guess that the pilot ratings would be very poor, but there is no way of knowing without actually running that. Some additional points are pertinent. When we ran the formal series with the random occurring wind shear I tended to fly more aggressively, and that resulted in a considerable downgrading of the basic configuration, without the suppression filter. In the present case, with the suppression filter in, I also tend to fly more aggressively, but the suppression filter won't let me get into the oscillations, which resulted in the severe downgrading of the basic configuration. And so in that respect you would have to say that the suppression filter is working. My only question is, if you have some real gusts —— large shears which occur earlier in the run —— which would require precise pitch attitude changes, would that cause me a lot of trouble because of the lack of response at high frequency.

Configuration No. 5, 26 seg/sec
and DFRC PIO Suppression Filter

This is considerably better than the previous configuration, because the attitude response is somewhat less sluggish. It still has the overshoot, but the combination of the suppression filter plus the higher or less sluggish attitude response makes it somewhat nicer to fly. I think it has improved my performance considerably. The pilot rating on that is a 3, and the reason it is not better than a 3 is because the overshoot is still there...and so compensation is required to account for that overshoot. However, it is quite easy to make precise attitude changes and control sink rate, and I can tighten up on it if I get

behind the task and still not get into an oscillation, which is a desirable feature. So, it looks like a real good configuration with the exception of the attitude overshoot, which is a little bit annoying. It is a 3.

With random shear it is particularly difficult to rate, because I did have some problems with precise control over sink rate with pitch attitude on a few of the runs — and, as we have said in the past, consistency is very important. I am not sure if those problems were due to wind shear or due to my being aggressive and making erroneous inputs and then having the problem of having to tighten up. The overshoot characteristic is still there, and it is somewhat undesirable. It seems to be more of a factor when I have to tighten up and be aggressive with pitch attitude. So, I really cannot call that a 3; it drops to a 4 where the deficiencies are annoying and require moderate pilot compensation. I would leave that a 4. However, it is a more desirable configuration than Configuration OFT was with the suppression filter and, for that reason, I feel uncomfortable with the fact that they are both rated a 4. I want to state that there is a definite preference for Configuration No. 5, because of the apparently more responsive attitude changes to stick inputs. The pilot ratings in this case don't really reflect this preference. It is more than a minor effect.

[Editor's note: a second set of formal runs followed with random shear increased in magnitude and duration ($|u_g|$ = 1 kt/sec; ΔT_g = 9 sec)] What I saw was a much larger input much earlier in the run, which required very large, precise attitude changes to correct. I was relatively unsuccessful with this configuration in making those large attitude changes. For this task with this input, I believe that the deficiencies require improvement; you need a much tighter, much more precise attitude system to regulate againt this type of disturbance. Certainly, adequate performance is not attainable with the gust inputs with any amount of pilot compensation, and on that basis the pilot rating is a 7. I noticed that there seemed to be secondary modes in the attitude response when I was trying to regulate against the large gusts, and in making large attitude changes I got into some fairly aggressive attitude maneuvering. It seemed like the attitude for stick input would change

and appear to be settling down and then take off, and I am not sure if that was the overshoot from a previous input or if it was something to do with this suppression filter, but there seemed to be a lack of consonance between the attitude and stick when I got into aggressive high-frequency attitude maneuvering. There were times when I was surprised with what the pitch attitude was doing.

Configuration No. 1, 26 deg/sec
and DFRC PIO Suppression Filter

Pilot rating for that is a 3. It no longer has any overshoot, which is nice. The attitude is just a touch on the sluggish side. Without the rate limit, the attitude was a lot snappier, and looked like it was going to be a 2; but with the rate limit I think it is like a 3. The thing that keeps it from becoming a 2 is the lack of high-frequency response to a stick input.

With random shear there's somewhat of a quandary here on the pilot rating scale. The configuration itself is quite good, and the ability to regulate against these very large disturbances is quite impressive. So, in terms of aircraft characteristics, I want to say that it has minor but annoying deficiencies or, perhaps, it's even fair with unpleasant deficiencies — somewhere between a 3 and a 4. But in terms of demand on the pilot in selected task, those two columns are not consistent. I would like to pick a rating for aircraft characteristics of 3.5, and for demands on the pilot, of 5. If I had to given an overall rating, it would be 4.5, because of the task. [Editor's note; "columns" refers to the descriptor pilot rating lists for "Aircraft Characteristics" and "Demands on the Pilot in Selected Task or Required Operation" on the Cooper-Harper scale.]

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15. Supplementary Notes

16. Abstract

This report summarizes a study of the Shuttle Orbiter approach and landing conditions. Causes of observed PIO-like flight deficiencies are identified and potential cures are examined. Closed-loop pilot/vehicle analyses are described and path/attitude stability boundaries defined. The latter novel technique proved of great value in delineating and illustrating the basic causes of this multiloop pilot control problem. The analytical results are shown to be consistent with flight test and fixed-base simulation. Conclusions are drawn relating to possible improvements of the Shuttle Orbiter/Digital Flight Control System.

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