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A STUDY OF RELATIONSHIPS BETWEEN AIRCRAFT SYSTEM PERFORMANCE AND PILOT RATINGS

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16. Abstract

This study examines the relationship between man-machine system performance and pilot evaluation data. Pilot ratings and pilot evaluation comments have been the only consistent means for evaluating the physical characteristics of the pilot-aircraft system. On the other hand, efforts have been made to develop analytical predictors of man-machine performance, such as the pilot transfer functions or quadratic performance indices. Analytical predictors of performance must be validated by experiments and the results reconciled with the evaluation pilot's comments. The intent of this experiment is to add to the library of knowledge concerning the possible relationships that may exist between analytical performance predictors and pilot evaluation data for a complete pilot task.

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SYMBOLS USED IN THIS REPORT

α	Angle of attack
$\dot{\alpha}$	Rate of change of angle of attack
α_T	Trim angle of attack
α_g	Gust angle of attack
β	Sideslip angle
$\dot{\beta}$	Rate of change of sideslip
β_g	Sideslip gust
δ_a	Aileron displacement
δ_e	Elevator displacement
δ_{es}	Elevator stick displacement
δ_R	Rudder displacement
δ_X	Throttle displacement
δ_Z	Flap displacement
Z_α	$= -\frac{\bar{q} S}{m V_T} C_{L_\alpha}$
Z_{δ_e}	$= -\frac{\bar{q} S}{m V_T} C_{L_{\alpha_e}}$
Z_{δ_Z}	$= -\frac{\bar{q} S}{m V_T} C_{L_{\alpha_Z}}$
Z_θ	$= -\frac{g \theta_T}{V_T}$
Z_V	$= -\frac{1}{m} e S C_{L_t}$
ζ_{sp}	Short period damping ratio
ζ_p	Phugoid damping ratio
n_y	Lateral acceleration
n_z	Normal acceleration

SYMBOLS USED IN THIS REPORT (Cont.)

θ	Pitch angle
$\dot{\theta}$	Pitch rate
$\ddot{\theta}$	Pitch acceleration
θ_T	Trim pitch angle
σ_V	RMS intensity of side gust
σ_W	RMS intensity of vertical gust
ϕ	Roll angle
$\dot{\phi}$	Roll rate
$\ddot{\phi}$	Roll acceleration
ϕ_{α_g}	α Gust spectrum
ϕ_{β_g}	β Gust spectrum
ψ	Yaw angle
$\dot{\psi}$	Yaw rate
ω_p	Phugoid natural frequency
ω_{sp}	Short period natural frequency
ω	Frequency radians/second
D_α	$= \frac{1}{m}\left(q\, S C_{D_\alpha} - \alpha_T T_T - W\right)$
D_{δ_x}	$= -\frac{1}{m} \frac{\partial T}{\partial \delta_x}$
D_{δ_z}	$= \frac{\bar{q} S}{m} C_{D_{\delta_z}}$
D_V	$= \frac{1}{m}\left(\rho V_T S C_{D_T} - \frac{\partial T}{\partial V}\right)$
F_{es}	Elevator stick force
g	Gravity
h	Altitude

SYMBOLS USED IN THIS REPORT (Cont.)

$\dot{h}$	Altitude rate
I_{xx}	Moment of inertia about x axis
I_{yy}	Moment of inertia about y axis
I_{zz}	Moment of inertia about z axis
I_{xz}	Product of inertia
L_{α}	$= \dfrac{\bar{q} S}{m V_T} C_{L_{\alpha}}$
L_{β}	$= \dfrac{\bar{q} S b}{I_{xx}} C_{L_{\beta}}$
L_{δ_a}	$= \dfrac{\bar{q} S b}{I_{xx}} C_{L_{\delta_a}}$
L_{δ_r}	$= \dfrac{\bar{q} S b}{I_{xx}} C_{L_{\delta_r}}$
L_p	$= \dfrac{\bar{q} S b}{I_{xx}} \dfrac{b}{2 V_T} C_{L_p}$
L_r	$= \dfrac{\bar{q} S b}{I_{zz}} \dfrac{b}{2 V_T} C_{L_r}$
L_v	Scale factor
L_w	Scale factor
M_{α}	$= \dfrac{\bar{q} S c}{I_{yy}} C_{n_{\alpha}}$
$M_{\dot{\alpha}}$	$= \dfrac{\bar{q} S c}{I_{yy}} \dfrac{c}{2 V_T} C_{m_{\dot{\alpha}}}$
M_{δ_e}	$= \dfrac{\bar{q} S c}{I_{yy}} C_{m_{\delta_e}}$
M_{δ_x}	$= \dfrac{z_T}{I_{yy}} \dfrac{\partial T}{\partial \delta_x}$
M_{δ_z}	$= \dfrac{\bar{q} S c}{I_{yy}} C_{m_{\delta_z}}$
M_V	$= \dfrac{\bar{q} S c}{I_{yy}} \left(\dfrac{2}{V_T} C_{m_T} + \dfrac{\partial C_m}{\partial V} \right) + \dfrac{z_T}{I_{yy}} \dfrac{\partial_T}{\partial_V}$
$M_{\dot{V}}$	$= \dfrac{1}{I_{yy}} \dfrac{\partial M}{\partial \dot{V}}$

$M_q = \frac{\bar{q}Sc}{I_{yy}} \frac{c}{2V_T} C_{m_q}$

$N_\beta = \frac{\bar{q}Sb}{I_{zz}} C_{n_\beta}$

$N_{\delta_a} = \frac{\bar{q}Sb}{I_{zz}} C_{n_{\delta_a}}$

$N_{\delta_r} = \frac{\bar{q}Sb}{I_{zz}} C_{n_{\delta_r}}$

$N_p = \frac{\bar{q}Sb}{I_{zz}} \frac{b}{2V_T} C_{n_p}$

$N_r = \frac{\bar{q}Sb}{I_{zz}} \frac{b}{2V_T} C_{n_r}$

r Yaw rate

$\dot{r}$ Yaw acceleration

T Thrust

t Subscript trim

V Velocity

$\dot{V}$ Rate of change of velocity

$Y_\beta = \frac{\bar{q}S}{mV_T} C_{Y_\beta}$

$Y_{\delta_a} = \frac{\bar{q}S}{mV_T} C_{Y_{\delta_a}}$

$Y_{\delta_r} = \frac{\bar{q}S}{mV_T} C_{Y_{\delta_r}}$

$Y_p = \frac{\bar{q}S}{mV_T} \frac{b}{2V_T} C_{Y_p}$

$Y_r = \frac{\bar{q}S}{mV_T} \frac{b}{2V_T} C_{Y_r}$

I. INTRODUCTION

This study examines the relationship between man-machine system performance and pilot evaluation data. Pilot ratings and pilot evaluation comments have been the only consistent means for practical evaluation of the physical characteristics of open- and closed-loop aircraft and pilot-aircraft systems. Analytically determined predictors of performance must be validated by experiment, and in some way must be reconciled with the evaluation pilot's comments obtained in the experiment. The complete nature of a pilot's task, including mental work load and decision making, has never been described explicitly in any form of analytically determined pilot transfer function or performance index. However, it is usually assumed that there exists an analytical relationship between pilot comment, or rating data, and airplane performance. The intent of the experiment described herein is to add to the library of knowledge concerning quantitative analytical measures of pilot-airplane performance for a complete task.

Previous to this study, Cornell Aeronautical Laboratory, Inc. (CAL), conducted a research study involving synthesis methods for manual control systems, under Contract NAS1-7141. In the course of that study, described in Reference 1, two simulation experiments were performed. Performance measures were used to obtain objective measures of overall system performance, for different parameter settings in the closed-loop aircraft dynamics. Subjective pilot evaluation data were also taken for each parameter setting. A non-parametric Spearman rank correlation coefficient was computed between measured man-machine performance values and pilot evaluation data. The subjective and objective performance measures appeared to be highly correlated. It was found, for example, that for a measure of pitch error, or pitch error and stick motion, very high correlation values were obtained. Thus, in the experiments performed, there appeared to be a strong correspondence between man-machine system performance and pilot rating. The above experiments were only preliminary since the scope of effort allotted to that specific task did not allow a thorough examination of the relationship between man-machine performance and pilot evaluation.

The investigation herein reported is an expansion of the earlier study, conducted to look in depth into objective and subjective pilot performance measures. A fixed-base ground simulator was used. Care was taken to obtain a realistic simulation by using real cockpit displays, experienced evaluation pilots and comprehensive equations of motion.

The first task undertaken was to examine the nonparametric Spearman rank test to determine its efficiency as a tool for providing a basis from which a firm judgment can be made. Hypothetical data, chosen to be typical of pilot rating data, was used to study the Spearman rank test and the results indicated that extremely high correlation coefficients (≈ 0.95) should be obtained for modest sample sizes (10 to 15). The test was then used on real pilot rating data in which two pilots had rated the same configurations. For a sample size of 15, the computed correlation coefficient was 0.942 which is extremely significant and well above the values generally accepted as statistically meaningful. Therefore, the correlation coefficient required for physical significance is greater than that required for statistical significance. That is, if a hypothesized performance measure is to be at least as reliable as pilot rating, then this performance measure must correlate with pilot rating to the same extent, or more strongly, than ratings among pilots will correlate, or it will obviously not be giving as consistent data as pilots themselves do give. It is also true that a high correlation between pilot ratings and a hypothetical performance index does not constitute proof that the performance index explains the data. This kind of proof can come only from an examination of the physical meaning of the performance index.*

The above considerations were made in the determination of the experiment design used in the research described herein. The gist of the approach is to obtain sufficient pilot rating data that the statistics of that data can be well examined. Then hypothetical performance indices are chosen and precisely the same statistics are examined. If the performance index has the same statistics as the pilot rating data then the two sets of data can be considered to be statistically sensitive to the same degree. It then becomes necessary to physically determine why the performance index works.

*Refer to Appendix A for an illustrative example that demonstrates the use of the Spearman Rank Test on actual pilot ratings.

II. APPROACH USED IN THE EXPERIMENT

To seek a relationship between subjective pilot ratings and system performance that can be applied to real-world situations, it is clearly necessary that experienced handling qualities evaluation pilots be used as subjects in the experiment. For such an experiment a full-task situation must be presented to the pilot or he will feel that he is involved in a game that, no matter how interesting, is not related to flying an airplane. Therefore, he cannot be expected to perform as a pilot would in a real situation.

The task chosen was to fly an ILS approach from outer marker to middle marker. To properly load the pilot, both longitudinal and lateral-directional dynamics were used as well as a full instrument presentation which included throttle, stick, elevator trim, aileron, and rudder as the operable controls. Side gusts were provided in the lateral-directional modes through sideslip in the equations of motion. Moreover, the lateral-directional dynamics were purposely chosen to be poor. Thus, the attention required for the lateral task, plus the coupling from the lateral mode into the longitudinal mode through the pilot presented a complex overall flying task. Although gusts were not injected into the longitudinal equations, the activity and concentration required of the pilot to maintain heading caused him to introduce noise into the longitudinal motions, mainly by his having to realistically divide his attention among the many flying sub-tasks. Thus, the approach taken was based on a real and complete task, which should make it more meaningful to relate the results to real flying tasks. Moreover, the usual difficulty in relating simpler laboratory experiments involving single-axis tasks to aircraft system is greatly reduced.

In rating each configuration the pilots rated the longitudinal mode only, the lateral-directional mode only, the total overall airplane, and whether or not the airplane could be landed. They were very successful in accomplishing the multi-rating of each configuration.

Five pilots performed the experiment. Four pilots performed each set of configurations three times and the fifth pilot performed each set twice. The configurations were performed in a random order; no pilot had the same random order twice, and no pilot had a random order that had been assigned another pilot. Each pilot was given a training period of one to two hours before data was taken. Then, for every data run with a specific configuration there were two preliminary practice runs in which the pilot was free to make maneuvers, including getting off glide slope, and/or making large corrections, to help him determine the characteristics of the configuration.

The only task that was rated was the ability to maintain the glideslope and localizer acceptably well for the ILS task. For example, although the airplane could be oscillating extremely in pitch, the main task of holding glideslope and localizer could be accomplished. The ratings are to be understood in this context. There was no sensation of "g" and no "g" meter was used in the simulator.

1. Simulation of Aircraft Configurations

A fixed-base aircraft simulator was used in the study. (See Figure 1.) The cockpit instrumentation included: airspeed, altitude, pitch angle, bank angle, heading, glide slope and localizer, outer marker, flap position, turn rate, sideslip ball, rate of climb (VSI), and % RPM. (See Figure 2.) Aircraft dynamics were introduced through a set of six degree-of-freedom equations. An analog computer was used to simulate the aircraft equations of motion and to drive the aircraft instruments.

Six degree-of-freedom equations of motion were selected for the study. Small perturbations were permitted, so that airspeed, altitude, bank angle, and heading could be changed.

The equations used are the following:

$$\left(\frac{g}{57.3}\right)\theta + \dot{V} + D_V V + \frac{D_\alpha}{57.3}\alpha = \frac{-D_{\delta_x}}{57.3}\delta_x + \frac{-D_{\delta_z}}{57.3}\delta_z$$

$$-\dot{\theta} - Z_\theta \theta + \left(\frac{57.3\alpha_t}{V_t}\right)\dot{V} - 57.3 Z_V V + \dot{\alpha} - Z_\alpha \alpha = Z_{\delta_e}\delta_e + Z_{\delta_z}\delta_z$$

$$\ddot{\theta} - M_q\dot{\theta} - 57.3\left(M_V V + M_{\dot{V}}\dot{V}\right) - M_{\dot{\alpha}}\dot{\alpha} - M_\alpha \alpha = M_{\delta_e}\delta_e + M_{\delta_x}\delta_x + M_{\delta_z}\delta_z$$

$$-(\alpha_t + Y_p)\dot{\phi} - \left(\frac{g}{V_t}\right)\phi + (1 + \alpha_t\theta_t + \theta_t Y_p - Y_p)r + \dot{\beta} - Y_\beta\beta = Y_{\delta_a}\delta_a + Y_{\delta_r}\delta_r$$

$$\ddot{\phi} - L_p\dot{\phi} - \left(\frac{I_{xz}}{I_{xx}} + \theta_t\right)\dot{r} + (\theta_t L_p - L_r)r - L_\beta\beta = L_{\delta_a}\delta_a + L_{\delta_r}\delta_r$$

$$-\left(\frac{I_{xz}}{I_{zz}}\right)\ddot{\phi} - N_p\dot{\phi} + \left(1 + \theta_t\frac{I_{xz}}{I_{zz}}\right)\dot{r} + (\theta_t N_p - N_r)r - N_\beta\beta = N_{\delta_a}\delta_a + N_{\delta_r}\delta_r$$

These equations provide control through elevator, aileron, rudder and throttle (δ_x) and changes in flap setting (δ_z). Elevator trim was also provided.

The emphasis in the program was on the longitudinal short-period undamped natural frequency and damping ratio combinations. Because of this emphasis, and because the phugoid can affect the instrument landing approach, it was desirable to attempt to keep the phugoid reasonably constant. The phugoid is controlled by the terms M_V, $M_{\dot{V}}$, and D_V, and was established at a damping ratio of 0.05 and a period of 35 seconds.

Lateral-directional characteristics were selected to be representative of a typical large airplane. Again, the emphasis on the longitudinal short-period characteristics made it necessary to attempt to keep the lateral-directional characteristics relatively constant. Coefficients were determined to simulate the approach to landing task for ILS conditions. They are shown in Table 1.

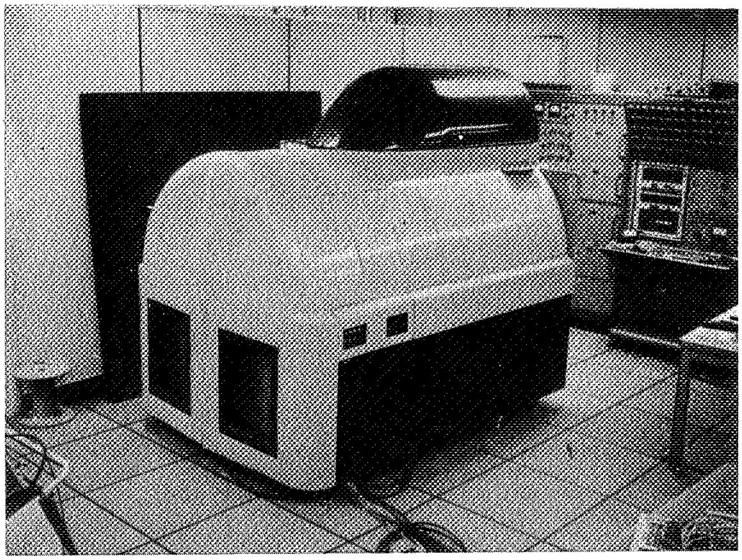


Figure 1 - Landing Simulator

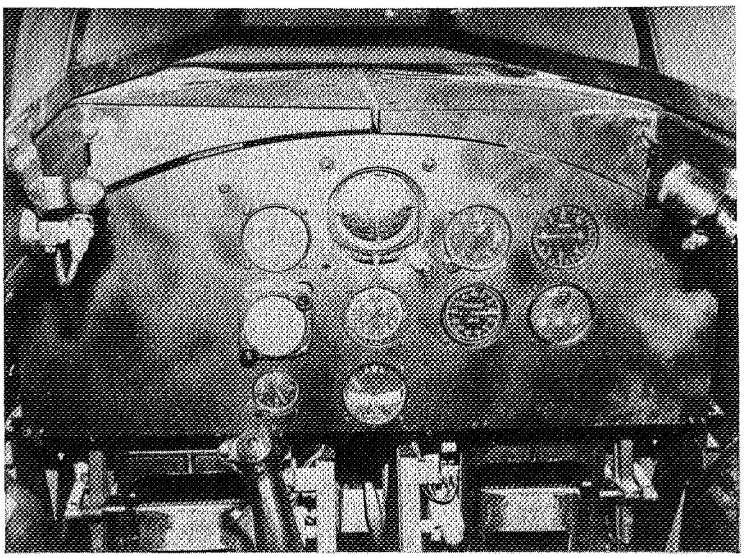


Figure 2 - Landing Simulator Instruments

Table 1 STABILITY DERIVATIVES

CASE	M_V	$M_{\dot{V}}$	M_α	$M_{\dot{\alpha}}$	M_q	Z_{δ_e}	ζ_{sp}	$\omega_{n_{sp}}$	ζ_p	ω_p
NOM.	-.00019	0.00000	- 1.029	- .1882	-.599	-.0306	.618	1.211	.0477	.149
0.,.5	.0002	.00105	- 0.100	0.912	-.215	-.0306	.0096	.505	.0506	.178
0.,1.	.00060	.00100	- .5708	1.283	-.599	-.0306	.0108	.996	.0521	.185
0.,3.	-.00019	0.00000	- 8.436	1.283	-.599	-.0306	.0037	2.98	.0513	.183
0.,6.	-.0010	0.00000	-34.91	1.283	-.599	0.0000	.00164	5.94	.0571	.186
.3,3.	-.00019	0.00000	- 8.436	- .493	-.599	-.0306	.302	2.98	.0524	.183
.3,6.	-.0010	0.00000	-34.91	-2.272	-.599	0.0000	.301	5.94	.0574	.186
.6,.5	.00020	.00098	- 0.100	0.312	-.215	-.0306	.601	.506	.0527	.178
.6,1.	.00060	.00100	- .5708	.0976	-.599	-.0306	.604	.997	.0572	.185
.6,3.	-.00019	0.00000	- 8.436	-2.272	-.599	-.0306	.601	2.98	.0536	.183
.6,6.	-.0010	0.00000	-34.91	-5.814	-.599	0.0000	.599	5.94	.0577	.186
1.,.5	.00020	.00092	- 0.100	-0.088	-.215	-.0306	.996	.506	.0558	.178
1.,1.	.00065	.00100	- .5708	- .6923	-.599	-.0306	1.000	1.000	.0546	.188
1.,3.	-.00019	0.00000	- 8.436	-4.615	-.599	-.0306	.994	2.98	.0552	.183
1.,6.	-.0010	0.00000	-34.91	-10.56	-.599	0.0000	.998	5.94	.0581	.186
$(\zeta_{sp}\ \omega_{sp})$										

For all cases:

$D_V = 0.0223$ $D_\alpha = -24.507$ $D_{\delta_x} = 6.478$ $D_{\delta_z} = 0.0$

$Z_V = -0.0011$ $Z_\alpha = -0.6971$ $Z_\theta = -0.0071$ $Z_{\delta_e} = -0.0302$

$Z_{\delta_z} = 0.0$ $M_q = -0.5991$ $M_{\delta_e} = -0.8382$ $M_{\delta_z} = 0.0$

$M_{\delta_x} = 0.0601$

A constant stick force per "g" was used for each configuration and then, for a smaller set of configurations, it was varied. To vary F_{es}/nz the procedure was to keep M_{δ_e} constant and let F_{es}/nz be proportional to $\omega^2 n_{sp}$ ($\approx M_\alpha$). A simple steady- state expression for exemplifying control over F_{es}/nz is

$$\frac{F_{es}}{\delta_{es}} \times \frac{\delta_{es}}{\delta_e} \times \frac{\delta_e}{\alpha} \times \frac{\alpha}{n_z} = \frac{F_{es}}{n_z}$$

$$\frac{\alpha}{n_z} = \frac{g}{VL_\alpha}; \qquad \frac{\delta_e}{\alpha} = \frac{\omega^2_{n_{sp}}}{M_{\delta_e}}$$

or

$$\frac{F_{es}}{n_z} = \frac{F_{es}}{\delta_{es}} \times \frac{\delta_{es}}{\delta_e} \times \frac{\omega^2_{n_{sp}}}{M_{\delta_e}} \times \frac{g}{VL_\alpha}$$

$$= K \frac{\omega^2_{n_{sp}}}{M_{\delta_e}}$$

The stick spring rate (F_{es}/δ_{es}) and the stick gearing (δ_{es}/δ_e) were constants. The fourteen conditions (✓ or ✗) were done with the same F_{es}/nz chosen to be typical for the $\omega_{n_{sp}} = 1.0$, $\zeta_{sp} = 0.60$ case. The two conditions marked (✗) were run holding M_{δ_e} constant and allowing F_{es}/n_z to vary with M_α. Again, the base condition was for $\omega_{n_{sp}} = 1.0$ and $\zeta_{sp} = 0.60$.

2. The Pilot Task

The task was an ILS approach to landing in light to moderate turbulence. The pilot was given the airplane at the glide slope intercept altitude of approximately 1500 feet, approximately one mile out from the outer marker. The airplane was trimmed and on the localizer. The task was to fly into the outer-marker (glide slope intercept) at 1500 feet and then to follow the localizer and glide slope down to 200 feet altitude. A flare was not made. All pilots were currently active test pilots, who were experienced in handling qualities evaluations.

Simple turbulence models were introduced as a sideslip perturbation. Details of the turbulence model are found in Appendix B.

ζ_{sp} \ $\omega_{n_{sp}}$	0.5 rad/sec	1.0	3.0	6.0
0	✓	✓	✓	✓
.3			✓	✓
.6	✓	✗	✓	✗
1.0	✓	✓	✓	✓

The pilot was told to fly a minimum-deviation ILS approach as he would do in a large airplane. He was told to take the airplane down to fifty feet, although data was used down to only 200 feet. This assured that the pilot was paying maximum attention to the task through the end of each data run. The minimum deviation aspect of the approach was also stressed, because not all pilots actually fly a minimum deviation approach. Some pilots fly a path more like the one a flight director would compute. However, by giving the minimum deviation criteria each pilot would be flying by the same rule.

The elevator, aileron, rudder and throttle were active controllers, and the pilots were permitted to use all of them. Provision for flaps was also made.

3. Pilot Comment Card and Rating Scale

The pilots' understanding of the specific task to be done and the purposes of the comment card are crucial to obtaining consistent and interpretable pilot evaluation data. The importance of the pilot comment card dictates that it be devised with care, and therefore it is discussed in detail here.

Some preliminary remarks are in order to put in proper perspective the need for and use of the card. The objective of the study was to devise an aircraft performance index that is as sensitive a measure as is pilot rating, and one that reflects the reason for the rating given. This was clearly a task of making the math fit the problem rather than making the problem fit the math. For this reason it was necessary to obtain as much guidance as possible from the pilot to understand why the pilot does what he does and how he reacts to what he is doing. This knowledge is necessary in choosing the important variables and relative weighting of them in devising a performance index. It is considered very probable that the relative weighting of the important variables changes with distance inbound from the outer marker. Perhaps some new variable enters as altitude becomes low. The only person who describe these occurrences is the pilot, and therefore it was necessary for him to make comments. However, since comments can be given in many different ways, consistency in them is required for comparative and analysis purposes. Therefore, a card that educes sufficient consistency in the comments without overconstraining the pilot was desirable. If the comment card is too constraining, then data will be lost. Yet the ILS task is a maximum attention task and the pilot cannot recall, after the task, all of the subtilities he noticed during performance of it. It was therefore necessary for the pilot to memorize the comment card. To record their comments, the pilots were given a hot mike while they performed the task, yet the concentration on the task was so high that none of them commented while performing the task. In fact, they found that to do so affected task performance. Therefore, pilot comments were obtained immediately at the conclusion of each approach.

The variables the pilot perceives may not be exactly the physical parameters of the experiment, but they are manifestations of the physical parameters. The comment card must therefore be general enough to cover the perceived variables as well as the physical ones. The comment card used, and which we believe to be successful in achieving these objectives, is shown in Figure 3.

Task - Large Transport, Minimum Error ILS Pilot Comments		
Pilot	Run No.	Date
Comment On: Forces Pitch Response Control of Pitch Attitude Control of Pitch Rate Altitude Control Altitude Rate Control Control of Glide Slope - Glide Slope Rate Throttle Technique Lat.-Dir. Comments: Rate: 1. Longitudinal Only 2. Lat.-Dir. Only 3. Overall Airplane 4. Is Airplane Landable?		

Figure 3 PILOT COMMENT CARD

The rating scale used was the Cooper-Harper, ten point scale shown in Fig. 4.

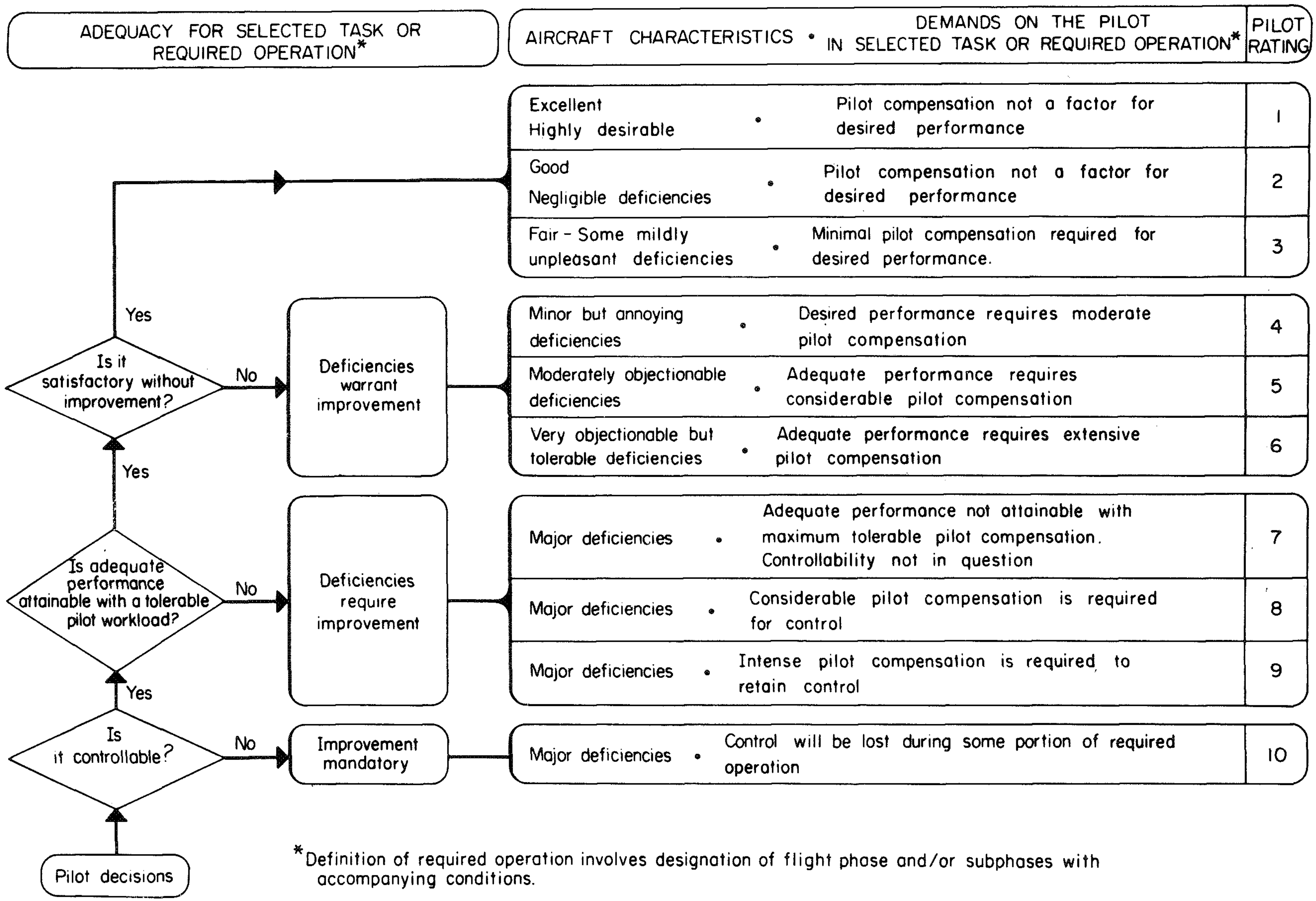


Figure 4 HANDLING QUALITIES RATING SCALE

III. EXPERIMENTAL DATA OBTAINED

Data were taken for all five pilots for each of the fourteen configurations used. These data exist in three forms: analog records on two ten-channel recorders; digital tape recordings were made on 22 channels; pilot comments were recorded after each run. Thus, a vast amount of data was recorded, in several forms, during the experiment. These data are described below.

1. Analog Records

One of the ten-channel recorders was used to record eight channels of data from the longitudinal mode. These included elevator inputs, throttle inputs, pitch rate, pitch attitude, airspeed, rate of change of altitude, altitude, and glide slope. Time markers were recorded, as were the outer and inner marker signals. A second recorder was used to record eight channels of data from the lateral-directional mode. These included rudder and aileron inputs, sideslip, bank angle, heading and heading rate, vertical acceleration, and the localizer.

Samples of these data are shown in Figures 5 through 11. Figure 5 shows a complete set of longitudinal and lateral-directional data as recorded on analog records. The figure is included to illustrate the nature and scope of the recordings and behavior of the variables.

Figures 6 through 11 show longitudinal data only, for pilot 1, and the third set of runs. Figure 6 shows results for zero damping and natural frequencies of 0.5 and 1.0 radians. The pilot ratings are also given in the figure.

Figure 7 indicates results obtained for an airplane having a natural frequency of three radians and damping ratios of zero and 0.3. It is pointed out here that practice may have a marked effect on the data. This effect is dramatically illustrated in Figures 7a and 8, all three of which show results for the same pilot and the same configuration. Figure 8 shows data for the two practice runs and Figure 7a shows the results for the third run which was the data run. (The fact that Figure 7a represents the third run for this pilot and this configuration should not be confused with the fact that all three are in the third set of all configurations for this pilot.)

Figure 9 shows longitudinal data for the one radian airplane, for two damping ratios. Figures 10 and 11 show data for the six radian airplane for four different damping ratios.

Note that for all cases except the 0.5 and 1.0 radian airplane at zero damping (Figure 6), the glide slope errors do not vary significantly. Note also that for these eight configurations pilot rating is not readily apparent from records of glide slope error. It is pointed out here that glide slope error is computed over the interval from the outer marker to the middle marker,

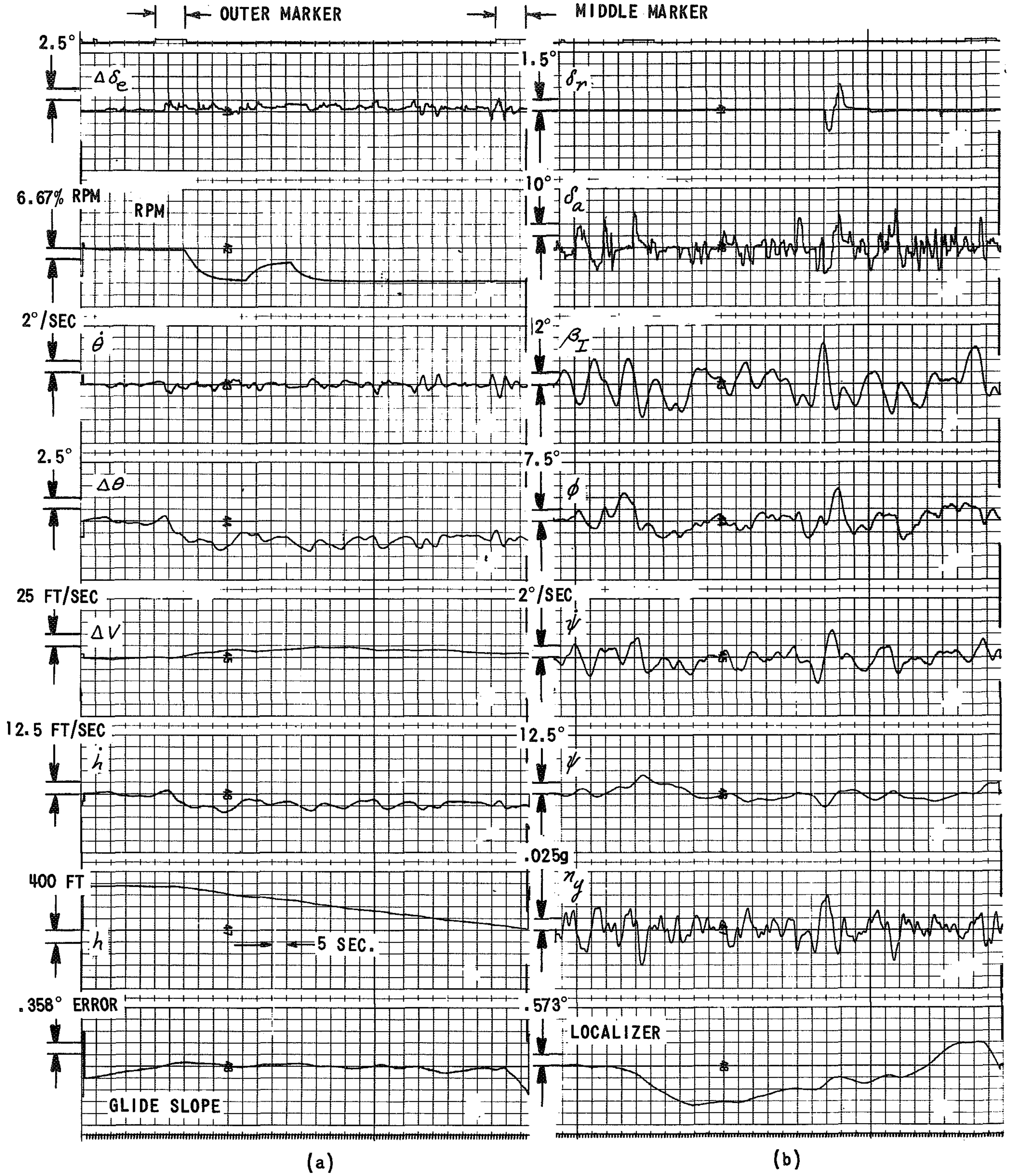
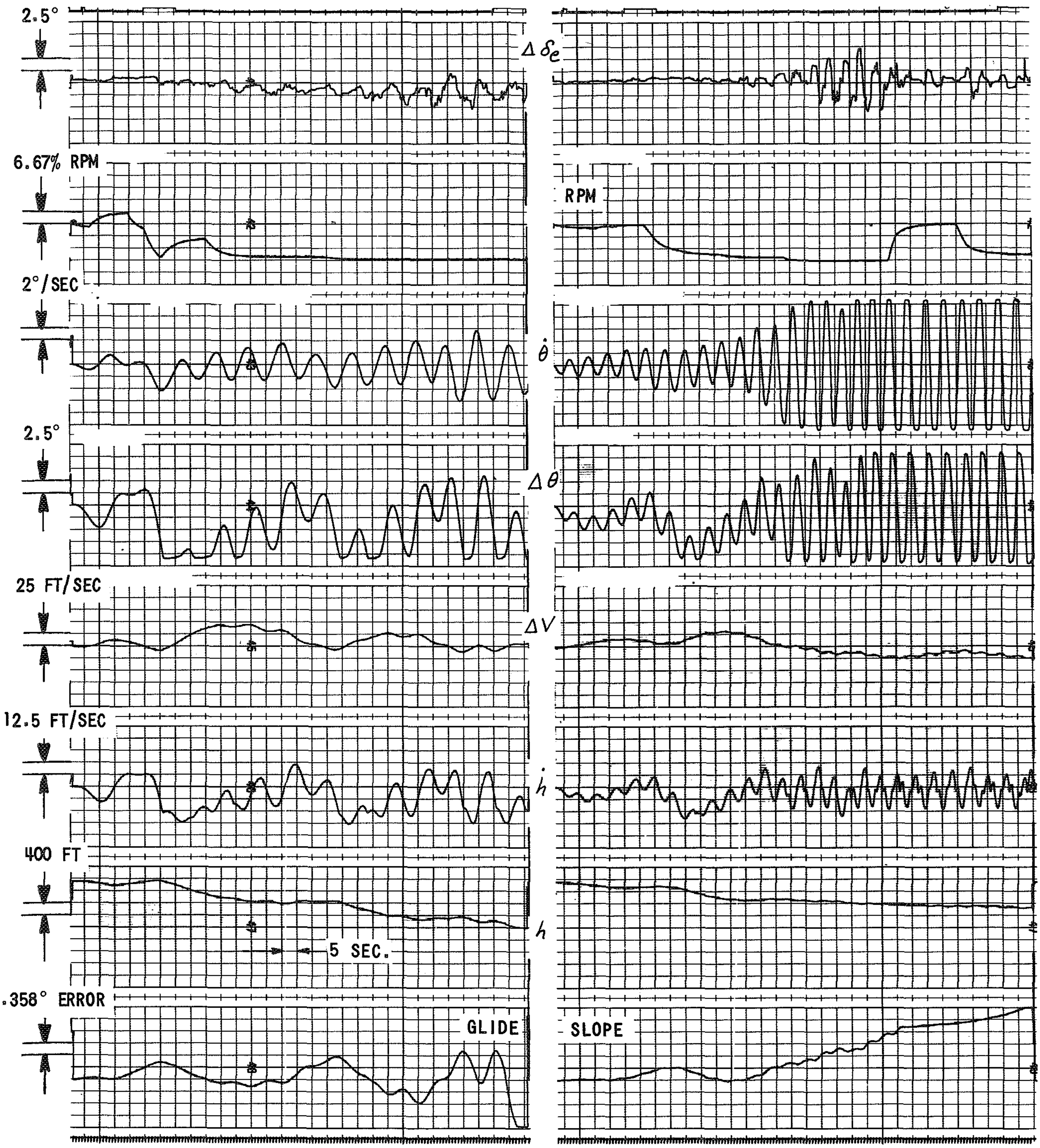


Figure 5a LONGITUDINAL MODE DATA - NOMINAL AIRPLANE $\zeta_{sp} = 0.6$

Figure 5b LATERAL-DIRECTIONAL MODE DATA - NOMINAL AIRPLANE $\omega_{sp} = 1.2$

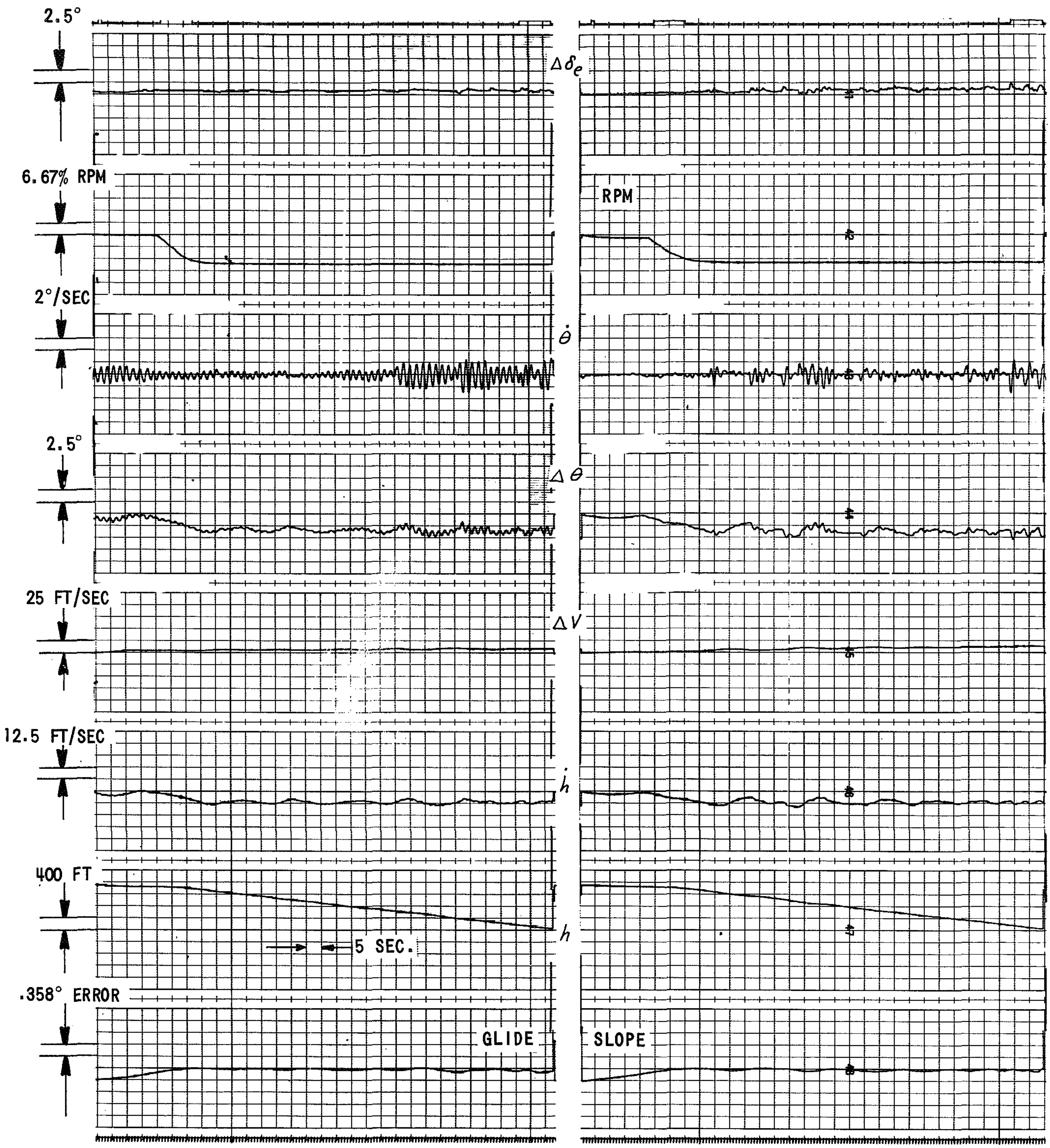


(a)
PILOT RATING 9-1/2

(b)
PILOT RATING 10

Figure 6a LONGITUDINAL DATA - $\zeta_{sp} = 0$; $\omega_{sp} = 0.5$

Figure 6b LONGITUDINAL DATA - $\zeta_{sp} = 0$; $\omega_{sp} = 1.0$

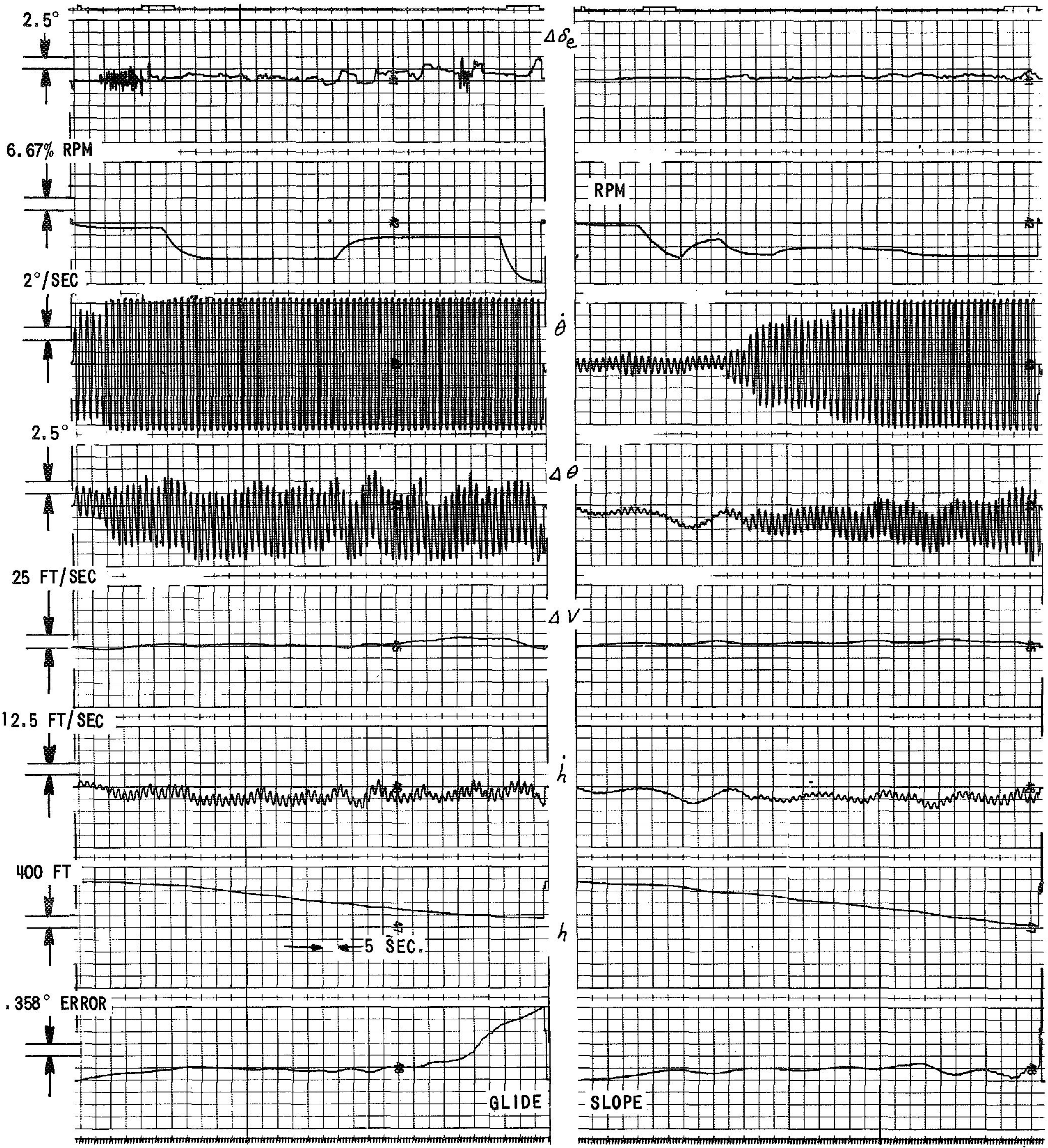


(a)
PILOT RATING 9

(b)
PILOT RATING 2-1/2

Figure 7a LONGITUDINAL DATA - $\zeta_{sp} = 0$; $\omega_{sp} = 3.0$

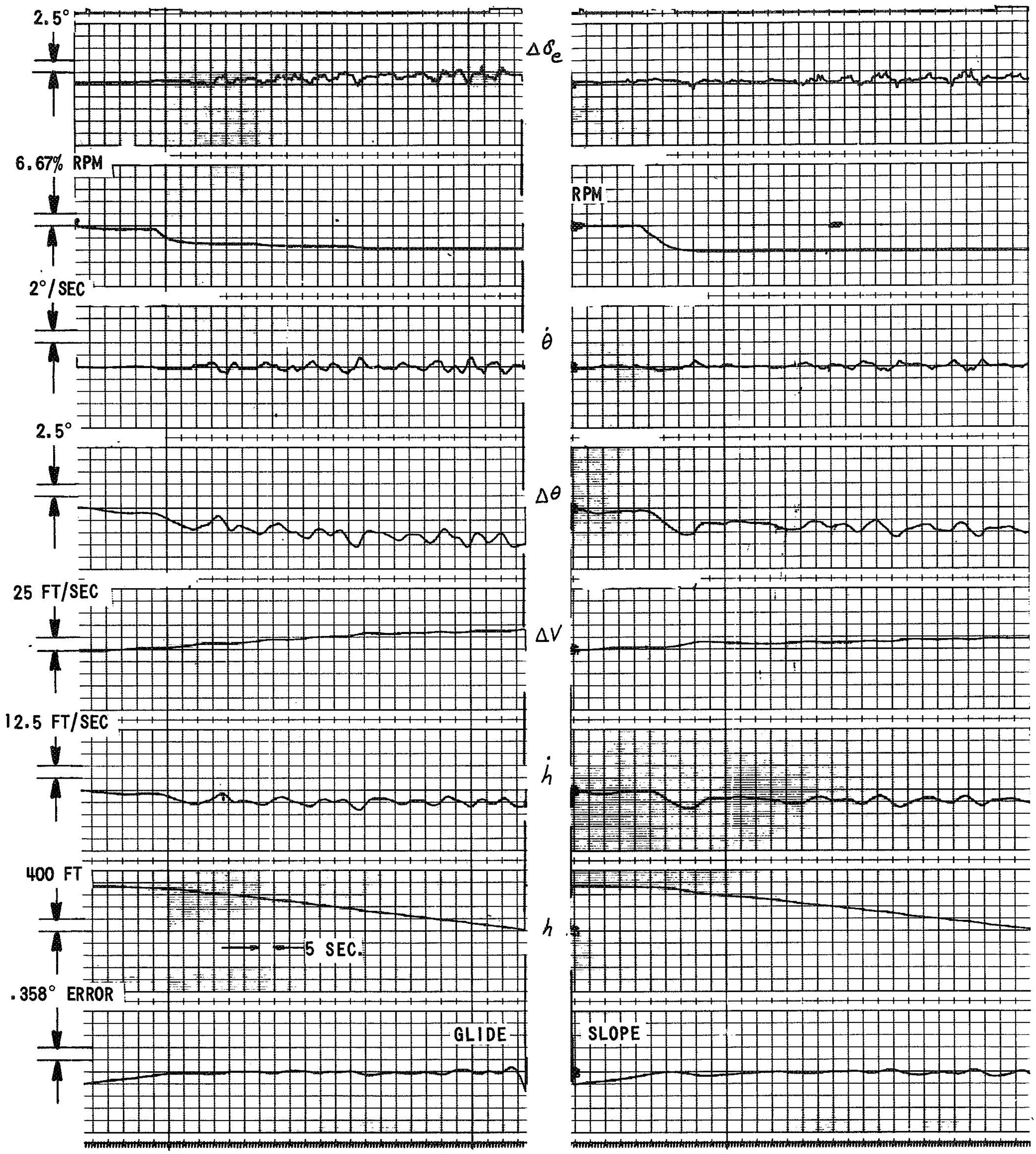
Figure 7b LONGITUDINAL DATA - $\zeta_{sp} = 0.3$; $\omega_{sp} = 3.0$



(a) (b)

Figure 8a LONGITUDINAL DATA - $\zeta_{sp} = 0$, $\omega_{sp} = 3.0$ - FIRST PRACTICE RUN

Figure 8b LONGITUDINAL DATA - $\zeta_{sp} = 0$, $\omega_{sp} = 3.0$ - SECOND PRACTICE RUN

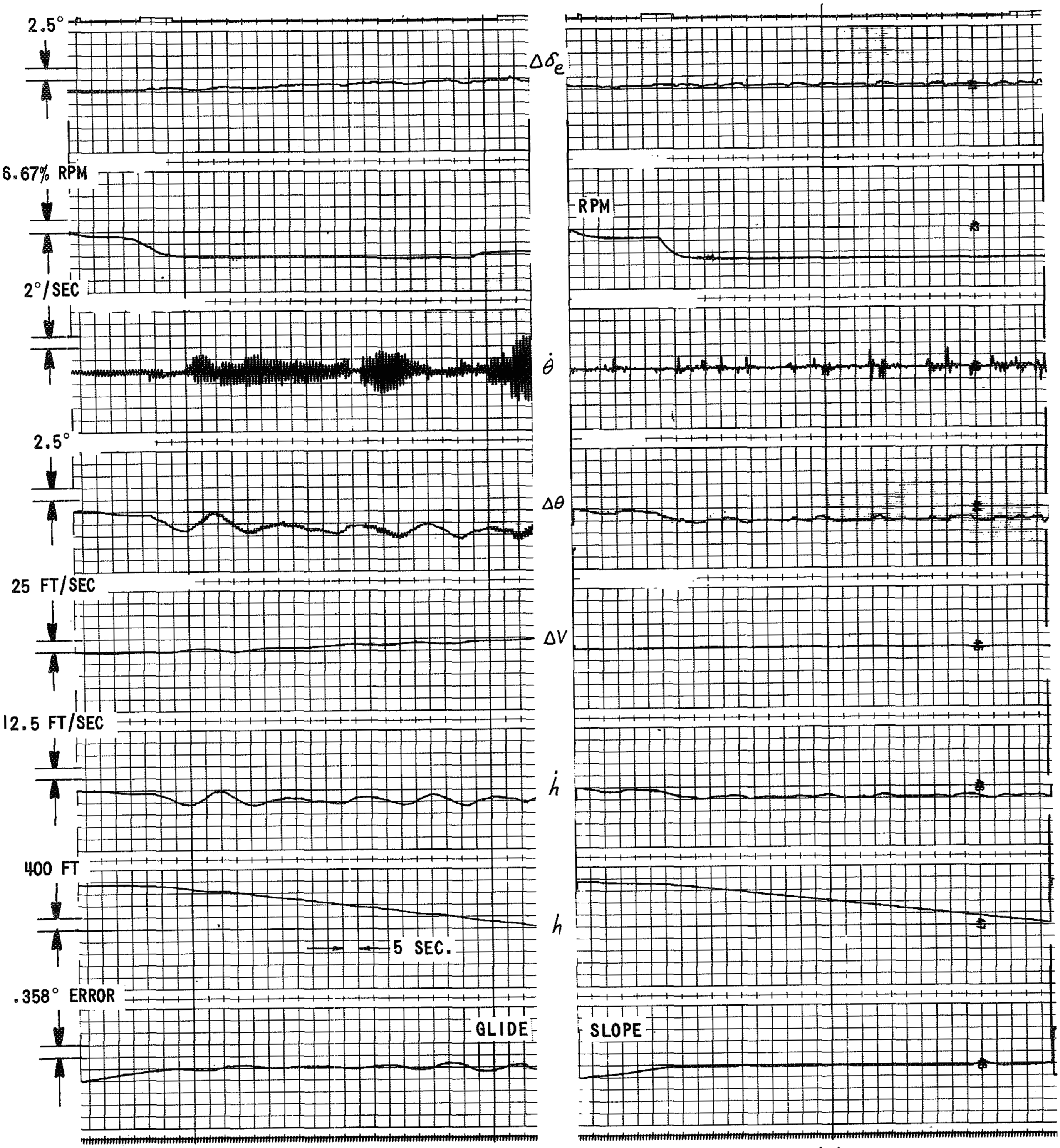


(a)
PILOT RATING 5

(b)
PILOT RATING 4-1/2

Figure 9a LONGITUDINAL DATA - $\zeta_{sp} = 0.6$, $\omega_{sp} = 1.0$

Figure 9b LONGITUDINAL DATA - $\zeta_{sp} = 1.0$, $\omega_{sp} = 1.0$

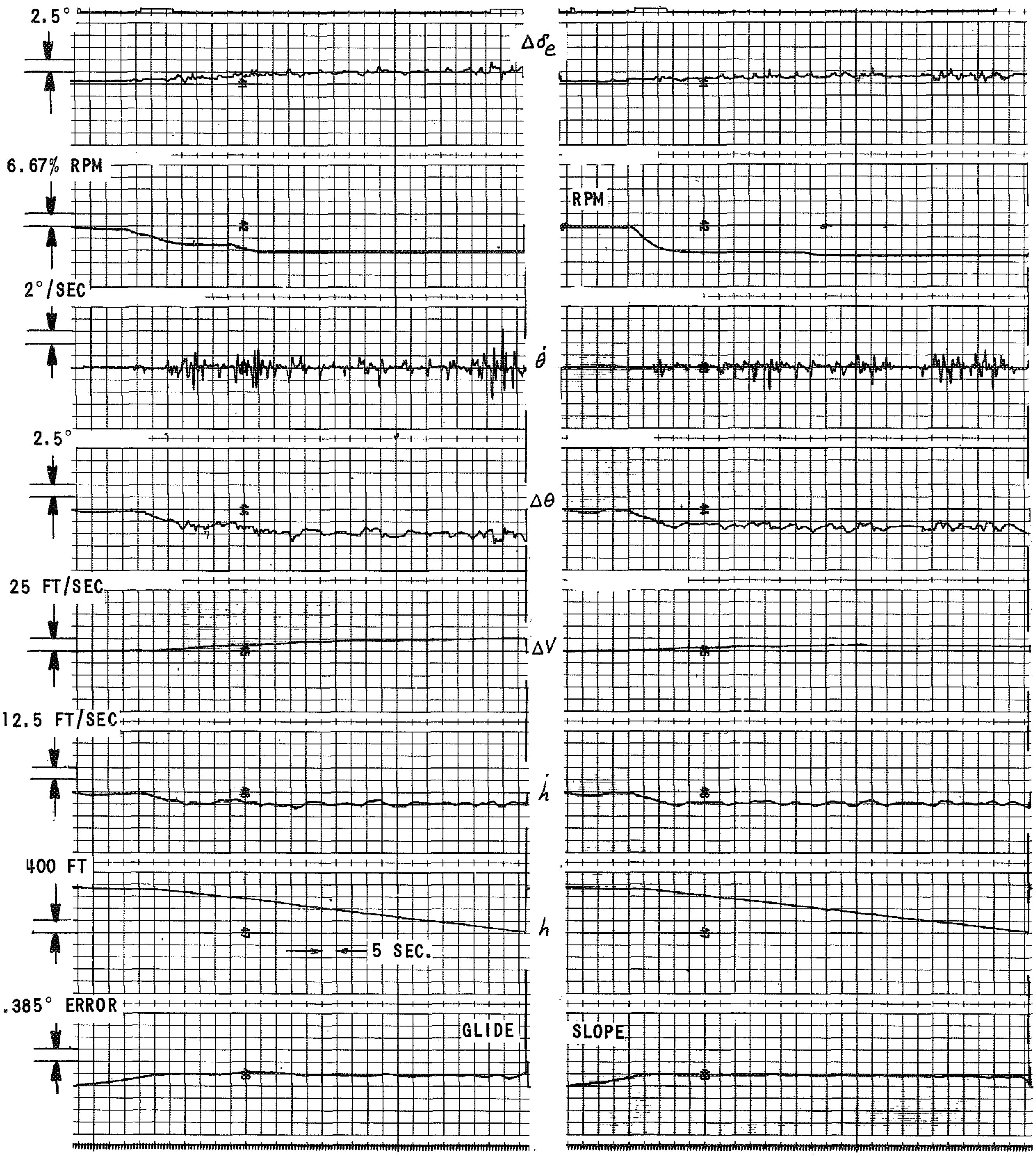


(a)
PILOT RATING 8-1/2

(b)
PILOT RATING 2-1/2

Figure 10a LONGITUDINAL DATA – $\zeta_{sp} = 0$, $\omega_{sp} = 6.0$

Figure 10b LONGITUDINAL DATA – $\zeta_{sp} = 0.3$, $\omega_{sp} = 6.0$



(a)
PILOT RATING 3

(b)
PILOT RATING 5

Figure 11a LONGITUDINAL DATA - $\zeta_{sp} = 0.6$, $\omega_{sp} = 6.0$

Figure 11b LONGITUDINAL DATA - $\zeta_{sp} = 1.0$, $\omega_{sp} = 6.0$

indicated by the pulses on the top channel of the analog reading. Although the case with the largest glide slope error (Figure 10a) was rated 8 1/2 by the pilot, a case with a much smaller glide slope error (Figure 7a) was rated 9. Two configurations with glide slope errors very nearly the same as that rated 9 were rated 2 1/2 and 3 (Figures 10b and 11a). These examples suggest that glide slope error and pilot ratings are not correlated.

2. Digital Tape Records

Real-time digital recordings were also made for all runs of the experiment. An off-line analog-to-digital converter multiplex digital recording system was used to record twenty-two channels of data. These included all those shown on the analog records plus elevator trim, angle-of-attack, and gust disturbance input. Thus, a significant amount of data were recorded directly on digital tape, for analysis in this study. Such a store of data will also be of great potential use for future analyses which are beyond the scope of this particular study.

3. Pilot Comment Tape Records

As mentioned earlier in this report, pilot evaluation comments contain what previous experience has shown to be the most reliable means for practical evaluation of physically significant aircraft flying qualities. Thus, in this experiment pilot comments were recorded after each run. An excerpt from one of these runs is included below, for the 0.3 damping three radian airplane.

> "I did not find time to make any comments (during the run). I wasn't too happy with my performance in the practice run. Did much better with the configuration. I think it is just another example with what was run (before). I never let things get very far (off) initially. A lot of it got out of hand briefly, and it kind of upsets things. You can be content with making gross maneuvers. You just don't seem to get back down to small errors so you can use small precise control inputs to do the job. I kind of worry when I see these (things) happen when I know people are measuring some sort of performance index. I once again do not like the control forces. (In) pitch response there was a slight tendency to overshoot with any kind of abrupt input, so the general control technique was to fly this (airplane) smoothly and carefully, but not really drive it with any kind of high pilot gains. If you did put in rapid inputs, you would run into a small oscillation. Control of pitch attitude in normal flying - no difficulty. There did seem to be a tendency to overshoot on occasion. Altitude control and altitude rate control - no problems, no complaints. (The) control (of) the glidepath I thought would be good. Throttle techniques - once again I set the throttle to initial rate of descent, and I tried to make small

changes about the glidepath with pitch attitude. Lateral-directional - once again I am not very happy - it's a continual roll oscillation excited by the lateral gust. I think (the) lateral-directional was the source of problem in doing the job properly, and initially there was a little inattention in the lateral. This was allowed to build up with subsequent large errors in the localizer, so that from then on the performance was poor as I tried to get back on the localizer and glidepath. I do not like the lateral characteristics - I cannot turn quickly enough in heading. I cannot be precise enough in heading. I have to use 10 degrees in bank in order to get some sort of heading change, and the tendency is to let that build up to larger bank angles and start scurrying back and forth across the localizer. Longitudinal comments and longitudinal control - certainly controllable and adequate for the mission. Don't really think it is satisfactory. Small tendency to overshoot. I think it makes it unsatisfactory. I consider that deficiency minor and coupled with the control forces (is) annoying. It gets a 4. Lateral-directional - do not like it - controllable, but it requires too much attention to control, so I am going to say it required improvement and is a major deficiency. It is going to get a 7. Overall airplane is a 7 and I do think you can land this airplane."

General comments on the entire experiment were also given by two of the pilots. Some excerpts of these are given below.

"I find that as far as explaining, maybe, some of the performance differences or similarities between different configurations you use different techniques in flying - both flying techniques and scan pattern (of) instruments you monitor. (For the very highly oscillatory ones, and the very, very sluggish ones, you don't try and manhandle the stick too much; you use trim or you use throttle, you use very smooth, gentle inputs. In one case you do it for the oscillatory one, so as not to excite the short period, (you have it oscillating on you). In the latter it doesn't do you any good; it's just so inert it doesn't do you any good to push much on the stick. (In) a lot of these runs, even though the longitudinal short period does vary, the pilot has to excite it before it will affect his rating. Now, this last one, I would guess the damping ratio was .3, (that area) moderate frequency - while most of the time I flew it, I was able to put my inputs smooth enough so I don't really think I excited the longitudinal short period. If I don't really excite it, then possibly my rating or my performance might be very similar to that (which) I gave for the same frequency with a higher damping ratio. It wasn't until the very end when things got away from me that the oscillatory nature of this airplane became evident to me, and it was only the last few seconds of the last run that the relatively low damping of the longitudinal for the short period would affect my rating, and it did, and I downrated it for that. So, sometime on performance, even though the longitudinal short period has changed the way the pilot flies it, he very often doesn't excite the short period, or he does his best not to. On the other hand, there are some other variables in this thing that I think I can sense, so on this when you are trying not to excite the short period you are not flying it actively through the short period, you are not flying pitch attitude. When you take the approach that you are not going to fly pitch attitude to close that loop that tightly, then what you do, is you probably close on rate of descent, and you do that through throttle; yes - also through elevators of course. It seems that those characteristics change, that sometimes trim seems very effective; sometimes the stick force per knot seems greater than other times; sometimes power seems to really affect the trim. With the ones where I don't want to excite the short period, I intentionally do not put in high frequency responses; I try to put in these gentle responses, and in this case I am monitoring maybe primarily the rate of climb indicator, and not sweating pitch attitude too much. So in that case you might not see high frequency elevator motion, rather lower frequency and possible fairly low amplitude. Now, this is what I try and do, but very often by the middle marker everything starts to become unglued and as much as you want to try and fly it smoothly, you have to get in there and really start moving the elevator around. So, I would guess that maybe the kind of technique and performance you see around the middle marker might be more representative of a pilot really getting in there and flying aggressively. In other words, I think (that when) he has less opportunity, he flies more like a simple sort of a mechanism. I think when you are out at the outer marker you apply all sorts of tricks and subtilities to suppress or circumvent the deficiencies that you know to exist in the airplane, whereas by the middle marker sometimes when everything starts to (come apart) on you, you have to revert back to the closing (of) very simple loops, and close them in a very simple way, just probably with very high gain, and I don't know how much lead or lag. I think there you probably act more like the kind of pilot models we can think about. At the outer marker the pilot can just do an awful lot of things, (and) there really are a lot of tricks he can do that gives him good performance and maybe even small elevator inputs. And yet, because he <u>knows</u> that he is having to adopt these very particular techniques (and) that he has to work very hard not to excite the short period. He <u>knows</u> that it's a bad airplane; he <u>knows</u> that when he's in turbulence he will have a real bag of tender worms on his hands. He will downgrade it, so I think in some of those things it might be pretty hard to correlate performance, depending of course what performance measure you use. (For) some of the more obvious one, I would think it would be kind of hard to correlate some of the performance parameters with the pilot rating."

"These are further comments on the definition of the task the rating scale given not while I'm flying down the ILS, which is distracting, but separately. I'm defining the task as a genuine ILS approach in real weather, over real ground in a real, large airplane, and the task is not just to play games with the simulator. The task includes more than just keeping the needle centered. The task includes keeping the needle centered as close as you can, plus having the airplane approach the bottom of the ILS that is the minimum (which is in this case 200 feet) in a stabilized flight condition, so that you have the pitch angle, the roll, and the roll rate and all that, such that the airplane is reasonably steady and it would be sensible and feasible for the pilot to take over at that point and land visually. I am not rating the airplane for the landing. Some of these airplanes couldn't possibly be landed, but I am willing to admit that's a separate problem and not what I'm rating the airplane on. I'm rating it on whether I can bring the airplane down the ILS and present it to the pilot in a condition that would give him confidence that he could land. I am also taking into account that this is not a one time proposition. I'm not interested that maybe I can do it on this approach, or gee, I happen to hit that approach very nicely, so I can do it on this approach. Instead, I am interested in whether it is good enough so that I can do this thousands and thousands of times without risk of busting the airplane, and another way I look at it is whether I am willing ro ride in the back while the minimum competence pilot on the whole airline flies it. If the answer is no I don't want to do that, then I say you cannot fly this airplane to within the tolerances you need. So that's the task. The rating scale I am interpreting in this way. The task requires that I control the airplane to within the limits that I just described. In other words, the airplane must be brought out at the bottom end of the ILS with the airplane flying steadily and with the pitch and the localizer and glide path error small enough to be tolerable. I'm more willing to tolerate a small error in the displacement of the cross pointers than I am willing to tolerate wobbliness in the attitude of the airplane. In other words, if I were off a quarter of an inch or so on the cross-pointer meters, but everything was steady I would consider that an acceptable approach, But if the cross pointer meter bars are centered exactly, but the airplane is wobbling then that is a completely unacceptable approach. So the task then becomes the one of flying within these rather stringent limits, and if I can't do it, trying as hard as I can - if I cannot keep the airplane steady, then I say I cannot control the airplane well enough to do the task, so therefore it's 10 by definition. That's uncontrollable. Now, I do not mean that a 10 means I'm falling out of the sky. Except for a few very bad longitudinal characteristics that I have seen, there has been no question of falling out of the sky. I am defining my task as bringing the airplane down to 200 feet, which is mighty low, or even 100 feet, steadily, aimed right, and in the right position in space, and do it every time. That's my task, and that is the task to which I have to control."

4. Frequency Response Data

The phase shift of the open-loop aircraft at 3 rad/sec, for the fourteen configurations studies, is listed below. Several typical frequency response curves, from which this data was excerpted, are given in Figures 12 through 14 (zero damping and a natural frequency of 1/2 given in rad/sec).

	Phaseshift At 3 rad/sec		
Configuration Damping/Freq.	h/δ_e	θ/δ_e	α/δ_e
0.0/0.5	-540°	- 13°	-355°
0.0/1.0	-540°	- 10°	-355°
0.0/3.0	-510°	-345°	-330°
0.0/6.0	-360°	-190°	-180°
0.3/3.0	-460°	-280°	-265°
0.3/6.0	-380°	-215°	-200°
0.6/0.5	-527°	-360°	-343°
0.6/1.0	-527°	-350°	-328°
0.6/3.0	-470°	-280°	-265°
0.6/6.0	-400°	-232°	-220°
1.0/0.5	-515°	-355°	-335°
1.0/1.0	-510°	-337°	-346°
1.0/3.0	-480°	-280°	-265°
1.0/6.0	-412°	-245°	-233°

5. Pilot Ratings

Pilot Ratings are given in Table 2 and Table 3. Table 2 shows all data for all runs, including ratings for the longitudinal mode, the lateral-directional mode, the overall airplane and whether or not the airplane could be landed.

Table 3 shows ratings for longitudinal data only.

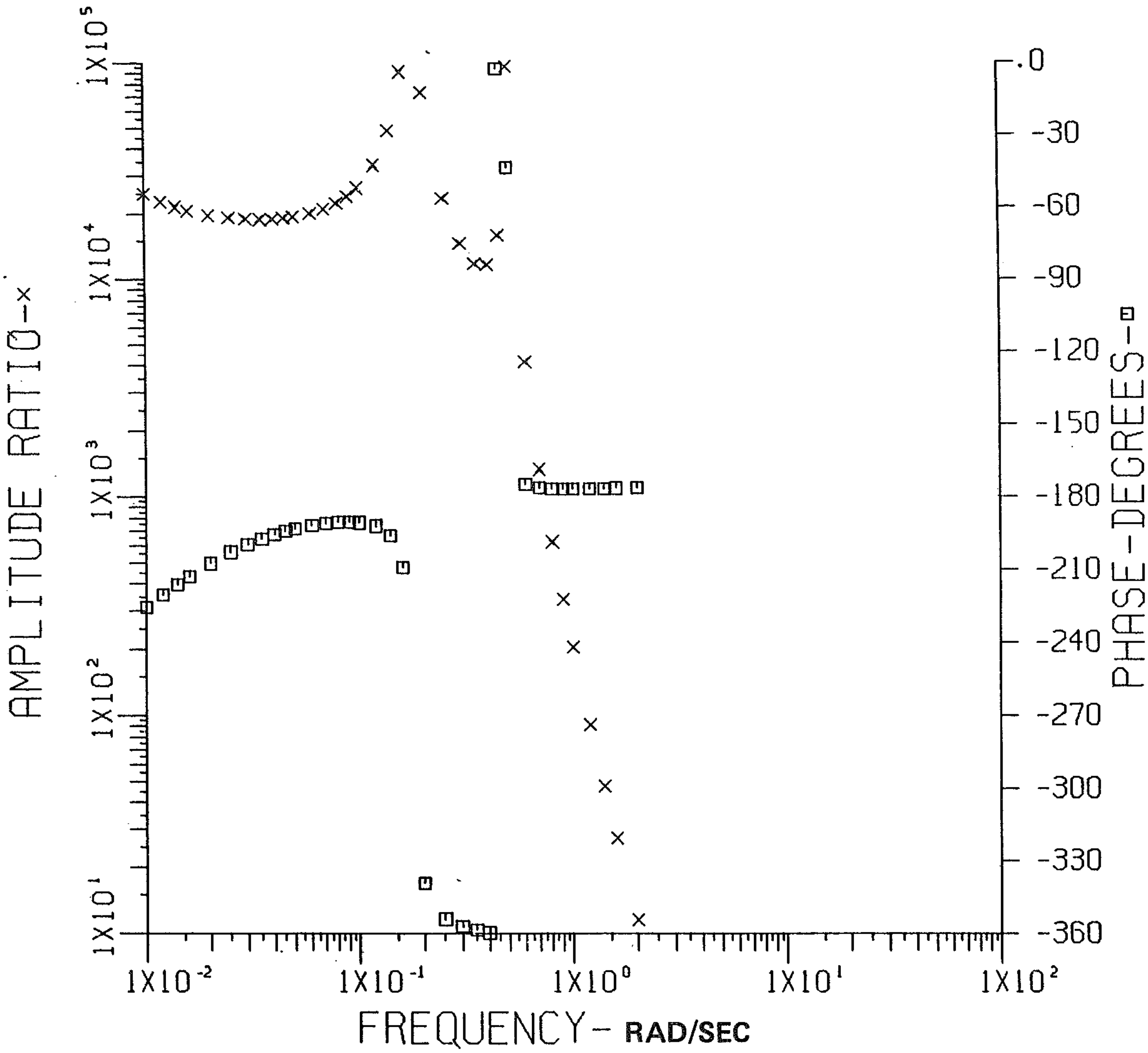


Figure 12 h/Se BODE PLOT

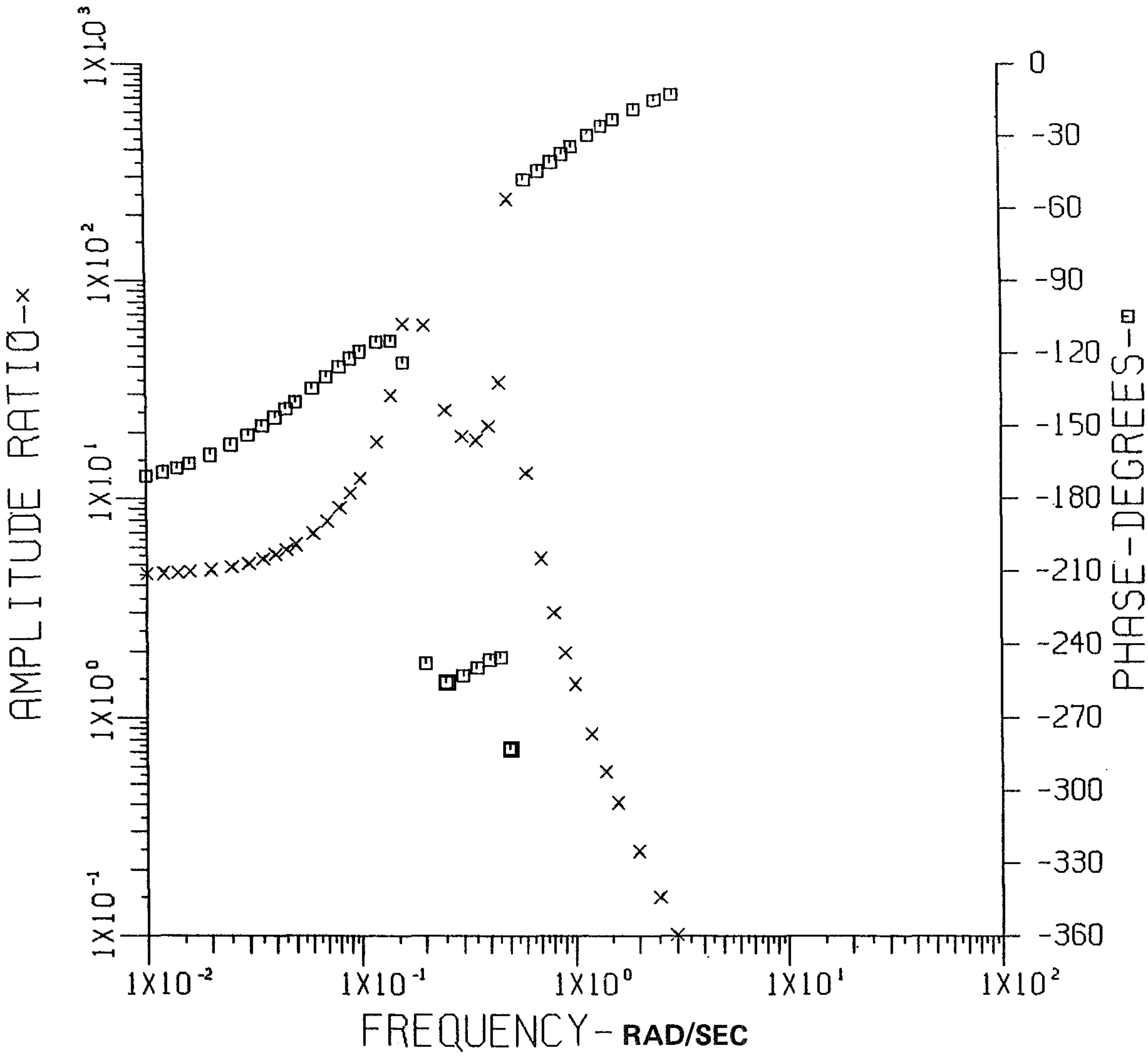


Figure 13 θ/Se BODE PLOT

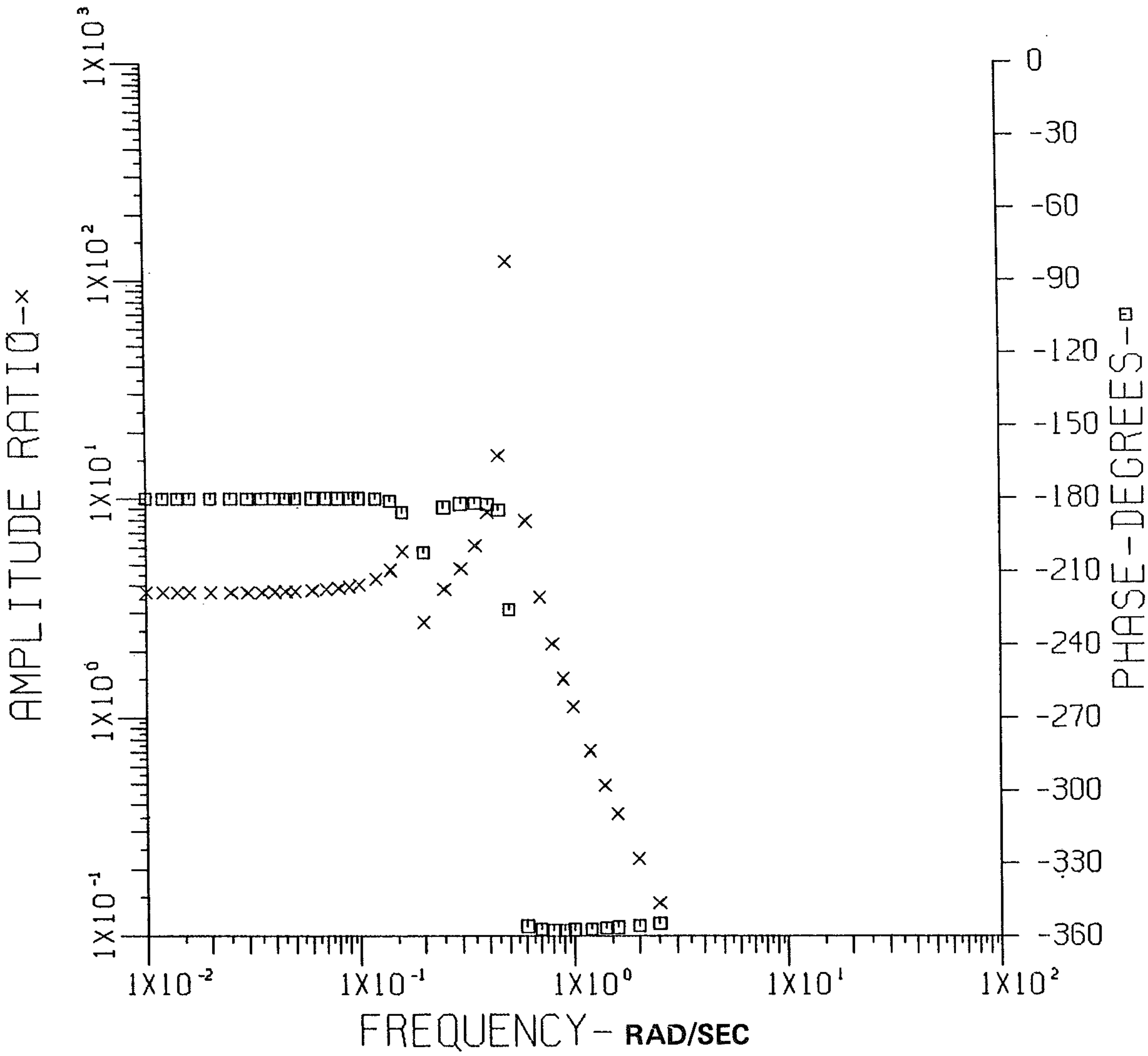


Figure 14 α/Se BODE PLOT

TABLE 2
ALL DATA

			PILOT 1												PILOT 2											
			SET 1				SET 2				SET 3				SET 1				SET 2				SET 3			
DAMPING	CONFIGURATION	FREQUENCY	LONG.	LAT. DIR.	OVERALL	LANDABLE?	LONG.	LAT. DIR.	OVERALL	LANDABLE?	LONG.	LAT. DIR.	OVERALL	LANDABLE?	LONG.	LAT. DIR.	OVERALL	LANDABLE?	LONG.	LAT. DIR.	OVERALL	LANDABLE?	LONG.	LAT. DIR.	OVERALL	LANDABLE?
0	2	0.5	10.0	6.0	10.0	NO	9.0	7.0	9.0	NO	9.5	6.0	9.5	NO	10.0	7.0	10.0	NO	10.0	6.0	10.0	NO	10.0	7.0	10.0	NO
	3	1.0	10.0	7.0	*	NO	10.0	7.0	10.0	NO	10.0	7.0	10.0	NO	8.0	7.0	9.0	NO	10.0	7.0	10.0	NO	10.0	7.0	10.0	NO
	4	3.0	10.0	7.0	10.0	NO	9.0	6.0	9.0	NO	9.0	5.0	9.0	NO	7.0	8.0	8.0	NO	6.0	6.0	6.0	NO	6.0	6.0	6.0	NO
	5	6.0	8.0	6.0	*	NO	9.0	7.0	9.0	NO	8.5	6.0	8.5	NO	7.0	8.0	8.0	NO	6.0	6.0	6.0	NO	6.0	6.0	6.0	NO
0.3	6	3.0	4.0	7.0	7.0	YES	2.5	5.0	5.0	YES	2.5	6.0	6.0	YES	4.5	6.0	5.0	YES	5.0	6.0	6.0	YES	5.0	6.0	4.0	YES
	7	6.0	4.0	7.0	7.0	YES	3.0	5.0	5.0	YES	2.5	5.0	5.0	YES	7.0	7.0	7.0	NO	3.0	6.0	5.0	YES	3.0	5.0	4.0	YES
	17	1.0	7.0	6.0	*	NO	4.0	5.0	5.0	YES	5.0	6.5	6.5	YES	5.0	6.0	6.0	YES	7.0	7.0	9.0	NO	7.0	6.0	5.0	YES
0.6	10	3.0	3.0	6.0	6.0	YES	2.0	5.0	5.0	YES	2.5	5.0	5.0	YES	3.0	7.0	6.0	YES	2.0	6.0	4.0	YES	2.0	6.0	5.0	YES
	18	6.0	3.0	5.5	5.5	YES	3.0	5.0	5.0	YES	3.0	5.5	5.5	YES	2.0	6.0	5.0	YES	4.0	6.0	6.0	YES	4.0	6.0	4.0	YES
	9	1.0	7.5	6.0	7.5	NO	7.0	7.0	7.0	YES	9.0	7.0	9.0	NO	7.0	7.0	8.0	NO	8.0	7.0	9.0	NO	8.0	6.0	8.0	NO
	11	6.0	5.5	6.0	*	YES	7.5	6.0	7.5	NO	6.0	6.0	6.0	NO	7.0	7.0	10.0	NO	9.0	7.0	9.0	NO	9.0	6.0	5.0	YES
1.0	13	1.0	7.0	5.5	7.0	YES	7.0	5.0	7.0	YES	4.5	6.0	6.0	YES	5.0	7.0	6.0	YES	8.0	7.0	8.0	NO	8.0	6.0	5.0	YES
	14	3.0	4.0	6.5	*	YES	3.0	5.5	5.5	YES	2.0	5.0	5.0	YES	4.0	7.0	6.0	YES	4.0	6.0	5.0	YES	4.0	6.0	5.0	YES
	15	6.0	3.0	6.0	6.0	YES	3.0	5.0	5.0	YES	4.0	5.5	5.5	YES	3.0	7.0	7.0	YES	2.0	6.0	5.0	YES	2.0	6.0	4.0	YES

			PILOT 3												PILOT 4												PILOT 5											
			SET 1				SET 2				SET 3				SET 1				SET 2				SET 3				SET 1				SET 2				SET 3			
DAMPING	CONFIGURATION	FREQUENCY	LONG.	LAT. DIR.	OVERALL	LANDABLE?	LONG.	LAT. DIR.	OVERALL	LANDABLE?	LONG.	LAT. DIR.	OVERALL	LANDABLE?	LONG.	LAT. DIR.	OVERALL	LANDABLE?	LONG.	LAT. DIR.	OVERALL	LANDABLE?	LONG.	LAT. DIR.	OVERALL	LANDABLE?	LONG.	LAT. DIR.	OVERALL	LANDABLE?	LONG.	LAT. DIR.	OVERALL	LANDABLE?	LONG.	LAT. DIR.	OVERALL	LANDABLE?
0	2	0.5	10.0	7.0	10.0	NO	10.0	8.0	10.0	NO	9.0	7.5	10.0	NO	10.0	7.0	10.0	NO	10.0	10.0	10.0	NO	10.0	-	10.0	NO	10.0	10.0	10.0	NO	10.0	10.0	10.0	NO	10.0	10.0	10.0	NO
	3	1.0	9.0	7.0	9.0	NO	8.0	7.0	8.0	NO	8.0	7.0	8.0	NO	8.0	8.0	9.0	*	10.0	10.0	10.0	NO	10.0	7.5	10.0	NO	10.0	10.0	10.0	NO	10.0	10.0	10.0	NO	10.0	10.0	10.0	NO
	4	3.0	7.0	7.0	8.5	NO	8.0	8.0	9.0	NO	7.5	7.0	8.0	NO	7.0	7.0	7.0	YES	7.0	7.0	7.0	YES	7.0	5.0	7.0	YES	10.0	10.0	10.0	NO	10.0	10.0	10.0	NO	10.0	10.0	10.0	NO
	5	6.0	9.0	8.0	9.0	NO	7.5	7.5	8.0	NO	8.0	6.0	8.0	NO	8.0	8.0	9.0	NO	7.0	6.0	7.0	YES	7.0	6.0	8.0	-	10.0	10.0	10.0	NO	10.0	10.0	10.0	NO	10.0	10.0	10.0	NO
0.3	6	3.0	4.5	6.5	6.5	YES	5.0	7.0	6.5	YES	5.5	6.0	7.0	YES	4.0	7.0	7.0	YES	4.0	6.0	6.0	YES	3.5	5.0	5.0	YES	3.5	10.0	10.0	NO	3.0	10.0	10.0	NO	4.0	10.0	10.0	NO
	7	6.0	6.0	5.0	6.0	YES	6.0	6.0	6.0	YES	5.0	6.0	7.0	YES	6.0	8.0	8.0	YES	2.0	5.0	5.0	YES	3.0	5.0	5.0	YES	5.5	10.0	10.0	NO	6.0	10.0	10.0	NO	5.0	10.0	10.0	NO
	17	1.0	5.0	6.0	6.0	YES	3.0	5.0	5.0	YES	7.0	6.0	7.0	YES	5.0	7.0	7.0	YES	8.0	7.0	9.0	NO	4.0	6.0	6.0	YES	7.0	10.0	10.0	NO	9.0	10.0	10.0	NO	5.0	10.0	10.0	NO
0.6	10	3.0	6.0	7.0	6.0	YES	5.0	6.0	6.0	YES	3.0	5.5	5.5	YES	6.0	7.0	7.0	YES	5.0	6.0	6.0	YES	3.0	5.0	5.0	YES	5.0	10.0	10.0	NO	5.0	10.0	10.0	NO	5.0	10.0	10.0	NO
	18	6.0	4.5	5.5	6.0	YES	4.0	5.0	6.0	YES	4.5	6.0	5.5	YES	4.0	7.0	7.0	YES	3.0	6.0	6.0	YES	2.0	5.0	5.0	YES	5.5	10.0	10.0	NO	4.0	10.0	10.0	NO	7.0	10.0	10.0	NO
	9	1.0	6.0	5.0	6.5	NO	8.0	7.0	8.0	NO	7.5	6.5	7.0	NO	10.0	8.0	10.0	NO	10.0	10.0	10.0	NO	10.0	6.0	10.0	NO	10.0	10.0	10.0	NO	10.0	10.0	10.0	NO	10.0	10.0	10.0	NO
	11	6.0	6.0	5.0	6.0	NO	4.5	6.5	6.0	NO	7.0	5.5	7.5	NO	5.0	7.0	7.0	YES	5.0	6.0	6.0	YES	6.0	6.0	7.0	YES	9.5	10.0	10.0	NO	9.0	10.0	10.0	NO	10.0	10.0	10.0	NO
1.0	13	1.0	6.0	6.0	6.5	YES	6.0	6.0	6.0	NO	7.0	6.0	7.0	NO	6.0	6.0	6.0	YES	5.0	6.0	6.0	YES	6.0	6.0	6.0	YES	9.5	10.0	10.0	NO	9.0	10.0	10.0	NO	10.0	10.0	10.0	NO
	14	3.0	4.0	6.0	5.0	YES	4.5	5.5	5.5	YES	4.0	5.0	6.0	YES	5.0	7.0	8.0	NO	4.0	6.0	6.0	YES	5.0	6.0	5.0	YES	6.5	10.0	10.0	NO	9.0	10.0	10.0	NO	4.0	10.0	10.0	NO
	15	6.0	3.5	6.0	5.0	YES	7.0	7.5	7.0	YES	4.0	6.0	5.0	YES	8.0	8.0	9.0	NO	4.0	6.0	6.0	YES	3.0	5.0	5.0	YES	5.0	10.0	10.0	NO	6.0	10.0	10.0	NO	4.0	10.0	10.0	NO

TABLE 3

ALL DATA

LONGITUDINAL ONLY

Pilot	Set	0				.3		.6					1.0			ζ_{sp}
		0.5	1	3	6	3	6	1	3	6	*1	*6	1	3	6	ω_{sp}
	1	10	10	10	8	4	4	7	3	3	7.5	5.5	7	4	3	
1	2	9	10	9	9	2.5	3	4	2	3	7	7.5	7	3	3	
	3	9.5	10	9	8.5	2.5	2.5	5	2.5	3	9	6	4.5	2	4	
	1	10	8	7	7	4.5	7	5	3	2	7	7	5	4	3	
2	2	10	10	6	6	5	3	7	2	4	8	9	8	4	2	
	3	10	10	6	5	3	2	5	4	3	7	4	4	4	4	
	1	10	9	7	9	4.5	6	5	6	4.5	6	6	6	6	6	
3	2	10	8	8	7.5	5	6	3	5	4	8	4.5	6	4.5	7	
	3	9	8	7.5	8	5.5	5	7	3	4.5	7.5	7	7	4	4	
	1	10	8	7	8	4	6	5	6	4	10	7	6	5	8	
4	2	10	10	7	7	4	2	8	5	3	10	5	5	4	4	
	3	10	10	7	7	3.5	3	4	3	2	10	6	6	5	3	
	1	10	10	10	10	3.5	5.5	7	5	5.5	10	9.5	9.5	6.5	5	
5	2	10	10	10	10	3	6	9	5	4	10	9	9	9	6	
	3	10	10	10	10	4	5	5	5	7	10	10	10	4	4	

*Heavy Stick Forces

IV. ANALYSIS OF DATA AND RESULTS

1. Analysis of Variance

The data format of this experiment is directly amenable to use of the analysis of variance. This analysis technique is used to determine the statistics of the pilot rating data. The entire format of data is not orthogonal as it stands, because not each of the frequencies was examined for every damping ratio that was used. Therefore, two different sub-sets of the data which gives orthogonal comparisons are used in the analysis of variance.

The first sub-set of pilot rating to be analyzed is for undamped natural frequencies for the short period of 1, 3 and 6 radians/second, each at damping ratios of 0, 0.6 and 1.0. Because each pilot did each set of runs three times, a test for learning may be made. The main factors in the analysis are, therefore, learning, frequency and damping ratio. The input data are shown in Tables 4 and 5.

The second sub-set of pilot rating data to be analyzed was for undamped natural frequencies for the short period of 3 and 6 radians/second each at a damping ratio of 0, 0.3, 0.6 and 1.0. These input data are shown in Tables 6 and 7.

Results of the analysis of variance calculations for pilot ratings are shown in Tables 8 through 11.

In Case I, the analysis shows that set (or learning) is not significant, and that both frequency and damping ratio are significant at the 5% level. This sub-set of the data was analyzed in both the raw and normalized form, and the results are the same for both analyses.

For Case II, both in the normalized and raw forms, the results are that both set (learning) and damping ratio are significant at the 5% level and frequency is not significant.

In each of the analyses of variance none of the interactions between or among set, frequency, or damping ratio are significant. The model for these analyses include the pilots in the error term, and therefore, there is no measure of significant differences among the pilots.

The analysis of variance using rms glide slope error shows results which agree with the similar analysis of the pilot rating data for the main effects of frequency and damping. However, it also adds the interaction between frequency and damping ratio as significant at the 5% level, for Case I, the sub-set of data with short period frequencies 1, 3 and 6 radians/second each at a damping ratio of 0, 0.6 and 1.0.

TABLE 4

INPUT DATA FOR ANALYSIS OF VARIANCE

CASE I 3x5x3x3

Pilot	Set	0			0.6			1.0			ζ_{SP}
		1	3	6	1	3	6	1	3	6	ω_{SP}
1	1	10	10	8	7	3	3	7	4	3	
	2	10	9	9	4	2	3	7	3	3	
	3	10	9	8.5	5	2.5	3	4.5	2	4	
2	1	8	7	7	5	3	2	5	4	3	
	2	10	6	6	7	2	4	8	4	2	
	3	10	6	5	5	4	3	4	4	4	
3	1	9	7	9	5	6	4.5	6	6	6	
	2	8	8	7.5	3	5	4	6	4.5	7	
	3	8	7.5	8	7	3	4.5	7	4	4	
4	1	8	7	8	5	6	4	6	5	8	
	2	10	7	7	8	5	3	5	4	4	
	3	10	7	7	4	3	2	6	5	3	
5	1	10	10	10	7	5	5.5	9.5	6.5	5	
	2	10	10	10	9	5	4	9	9	6	
	3	10	10	10	5	5	7	10	4	4	

TABLE 5

CASE I (NORMALIZED DATA)*

(FOR EACH PILOT: MEAN = 0, STD. DEV. = 1)

Pilot	Set	0			0.6			1.0			ζ_{SP}
		1	3	6	1	3	6	1	3	6	ω_{SP}
1	1	1.68	1.68	.98	.63	- .77	- .77	.63	- .42	- .77	
	2	1.68	1.33	1.33	- .42	-1.12	- .77	.63	- .77	- .77	
	3	1.68	1.33	1.12	- .07	- .95	- .77	-.25	-1.12	- .42	
2	1	1.43	.97	.97	.05	-1.14	-1.34	.05	- .41	-1.14	
	2	2.35	.51	.51	.97	-1.34	- .41	1.43	- .41	-1.34	
	3	2.35	.51	.05	.05	- .41	-1.14	-.41	- .41	- .41	
3	1	1.83	.61	1.83	- .61	0.00	- .91	0.00	0.00	0.00	
	2	1.22	1.22	.91	-1.83	- .61	-1.22	0.00	- .91	.61	
	3	1.22	.91	1.22	.61	-1.83	- .91	.61	-1.22	-1.22	
4	1	1.21	.75	1.21	- .19	.28	- .65	.28	- .19	1.21	
	2	2.15	.75	.75	1.21	- .19	-1.12	-.19	- .65	- .65	
	3	2.15	.75	.75	- .65	-1.12	-1.59	.28	- .19	-1.12	
5	1	1.19	1.19	1.19	0.00	- .79	- .79	.99	- .20	- .79	
	2	1.19	1.19	1.19	.79	- .79	-1.19	.79	.79	- .40	
	3	1.19	1.19	1.19	- .79	- .79	0.00	1.19	-1.19	-1.19	

*Normalized data is computed by taking the mean pilot rating, subtracting the particular pilot rating to be normalized, and then dividing this difference by the standard deviation of the pilot ratings.

TABLE 6

INPUT DATA FOR ANALYSIS OF VARIANCE

CASE II 3x5x2x4 DESIGN

Pilot	Set	0		.3		.6		1.0		ζ_{SP}
		3	6	3	6	3	6	3	6	ω_{SP}
1	1	10	8	4	4	3	3	4	3	
	2	9	9	2.5	3	2	3	3	3	
	3	9	8.5	2.5	2.5	2.5	3	2	4	
2	1	7	7	4.5	7	3	2	4	3	
	2	6	6	5	3	2	4	4	2	
	3	6	5	3	2	4	3	4	4	
3	1	7	9	4.5	6	6	4.5	6	6	
	2	8	7.5	5	6	5	4	4.5	7	
	3	7.5	8	5.5	5	3	4.5	4	4	
4	1	7	8	4	6	6	3	5	8	
	2	7	7	4	2	5	3	4	4	
	3	7	7	3.5	3	3	2	5	3	
5	1	10	10	3.5	5.5	5	5.5	6.5	5	
	2	10	10	3	6	5	4	9	6	
	3	10	10	4	5	5	7	4	4	

TABLE 7

CASE II (NORMALIZED DATA)

Pilot	Set	0		0.3		0.6		1.0		ζ_{SP}
		3	6	3	6	3	6	3	6	ω_{SP}
1	1	1.68	.98	-.42	-.42	-.77	-.77	-.42	-.77	
	2	1.33	1.33	-.95	-.77	-1.12	-.77	-.77	-.77	
	3	1.33	1.12	-.95	-.95	-.95	-.77	-1.12	-.42	
2	1	.97	.97	-.18	.97	-1.14	-1.34	-.41	-1.14	
	2	.51	.51	.05	-1.14	-1.34	-.41	-.41	-1.34	
	3	.51	.05	-1.14	-1.34	-.41	-1.14	-.41	-.41	
3	1	.61	1.83	-.91	0.00	0.00	-.91	0.00	0.00	
	2	1.22	.91	0 .61	0.00	-.61	-1.22	-.91	.61	
	3	.91	1.22	-.32	-.61	-1.83	-.91	-1.22	-1.22	
4	1	.75	1.21	-.65	.28	.28	-.65	-.19	1.21	
	2	.75	.75	-.65	-1.59	-.19	-1.12	-.65	-.65	
	3	.75	.75	-.89	-1.12	-1.12	-1.59	-.19	-1.12	
5	1	1.19	1.19	-1.39	-.60	-.79	-.79	-.20	-.79	
	2	1.19	1.19	-1.59	-.40	-.79	-1.19	.79	-.40	
	3	1.19	1.19	-1.19	-.79	-.79	0.00	-1.19	-1.19	

TABLE 8

ANALYSIS OF VARIANCE FOR PILOT RATING ... CASE 1, NORMALIZED

Levels of Factors

A 3 Set
B 5 Pilot
C 3 Frequency
D 3 Damping Ratio

Grand Mean 0.14474

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F
A	1.40985	2	0.70493	3.05
B	0.66065	4	0.16516	
AB	1.87874	8	0.23422	
C	18.94722	2	9.47361**	27.10
AC	0.92741	4	0.23185	
BC	2.86780	8	0.35848	
ABC	6.60028	16	0.41252	
D	79.85873	2	39.92937**	210.00
AD	0.54489	4	0.13622	
BD	1.50145	8	0.18768	
ABD	8.76978	16	0.23561	
CD	0.53472	4	0.13368	
ACD	0.63825	8	0.07978	
BCD	5.13030	16	0.32064	
ABCD	10.98097	32	0.34316	
TOTAL	136.24602	134		

TABLE 9

ANALYSIS OF VARIANCE FOR PILOT RATING ... CASE 2, NORMALIZED

Levels of Factors

A 3 Set
B 5 Pilot
C 2 Frequency
D 4 Damping Ratio

Grand Mean -0.25858

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F
A	3.53584	2	1.76792**	6.55
B	0.58577	4	0.14644	
AB	2.15884	8	0.26986	
C	0.00217	1	0.00217	
AC	0.22306	2	0.11153	
BC	0.85694	4	0.21424	
ABC	1.45463	8	0.18183	
D	65.15251	3	21.71750**	67.8
AD	0.78591	6	0.13098	
BD	3.90481	12	0.32540	
ABD	6.84927	24	0.28539	
CD	0.54124	3	0.18041	
ACD	1.34937	6	0.22490	
BCD	2.74368	12	0.22864	
ABCD	5.83815	24	0.24326	
TOTAL	95.98212	119	0.24326	

TABLE 10

ANALYSIS OF VARIANCE FOR PILOT RATING ..... CASE 1

Levels of Factors

A 3 Set
B 5 Pilot
C 3 Frequency
D 3 Damping Ratio

Grand Mean 6.06296

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F
A	7.24815	2	3.62407	3.87
B	94.71481	4	23.67870	
AB	7.47407	8	0.93426	
C	98.27036	2	49.13518**	25.80
AC	4.36296	4	1.09074	
BC	15.22963	8	1.90370	
ABC	28.74814	16	1.79676	
D	405.71460	2	202.85730**	60.3
AD	3.08519	4	0.77130	
BD	26.95184	8	3.36898	
ABD	17.02592	16	1.06412	
CD	3.26296	4	0.81574	
ACD	3.77037	8	0.47130	
BCD	29.07036	16	1.81690	
ABCD	48.28517	32	1.50891	
TOTAL	793.21387	134	1.50891	

TABLE 11

ANALYSIS OF VARIANCE FOR PILOT RATING .....CASE 2

Levels of Factors

A 3 Set
B 5 Pilot
C 2 Frequency
D 4 Damping Ratio

Grand Mean 5.13333

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F
A	16.05415	2	8.02708**	7.5
B	78.61665	4	19.65416	
AB	8.69583	8	1.08698	
C	0.00833	1	0.00833	
AC	0.80417	2	0.40208	
BC	2.99167	4	0.74792	
ABC	7.94583	8	0.99323	
D	338.58325	3	112.86108**	29.7
AD	4.12917	6	0.68819	
BD	47.83333	12	3.98611	
ABD	30.70416	24	1.27934	
CD	2.47500	3	0.82500	
ACD	6.21250	6	1.03542	
BCD	14.69167	12	1.22431	
ABCD	22.62082	24	0.94253	
TOTAL	582.36572	119		

For Case II, the sub-set of 3 and 6 radians, for four damping ratios, the results are very much different. In this case there were no significant main effects or interactions. The results for these cases are shown in Tables 12 and 13.

It is interesting that the Case I glide slope rms data shows significant trends, especially since the glide slope rms does not correlate with pilot rating as is shown in Figure 15. An investigation of the data shows a strong interaction for the zero damping ratio, one radian/second point and it is this single point that gives rise to the significance shown. The significance can therefore be considered spurious.

2. RMS Glide Slope Error and Its Relationship to the Frequency Responses of the Aircraft

It was hypothesized that the Bode plots which characterize the aircraft's responses could be related to an increase or decrease in the RMS glide slope error. Specifically, it was felt that an increase in the phase lag of the h/δ_e, θ/δ_e and α/δ_e transfer functions at 3 radians/second might exhibit a high correlation with an increase in the RMS glide slope error.

To test this hypothesis, the frequency responses for these transfer functions (i.e., h/δ_e, θ/δ_e and α/δ_e) were plotted and the phase shift at 3 radians/second recorded for the 14 configurations tested. Representative Bode plots are given in Figures 12, 13 and 14 of Section III.

Plots of the phase lag versus glide slope error are given in Figures 16, 17 and 18 of this section. Since many of the configurations had essentially the same phase shift at 3 radians/second, it became necessary to code the data. For example, in the θ/δ_e data, several configurations had the same phase shift of 264° - hence the necessity of coding the $\zeta_{sp} = .6$, $\omega_{n_{sp}} = 3$ radians/second data with X's and so on.

The results of the test are rather clear, since an inspection of these "scatter" diagrams does not reveal any sort of obvious correlation (linear or nonlinear) between the phase lag and the RMS glide slope error.

3. Linear Combinations of RMS Errors

Since in this experiment such a large body of data of rms errors was available, e.g., five pilots doing fourteen configurations and each repeating these runs, a set consisting of a rather large number of mean square errors is available. This suggests that comparisons of these error scores might reveal some additional insight into relationships of pilot ratings and analytical performance measures.

TABLE 12

ANALYSIS OF VARIANCE FOR GLIDE SLOPE ERROR ....CASE 1

Levels of Factors

A 3 Set
B 5 Pilot
C 3 Frequency
D 3 Damping Ratio

Grand Mean 0.10661

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F
A	0.06242	2	0.01621	3.01
B	0.09250	4	0.02313	
AB	0.04277	8	0.00535	
C	0.16559	2	0.08280**	5.18
AC	0.09759	4	0.02440	2.08
BC	0.12863	8	0.01608	
ABC	0.18708	16	0.01169	
D	0.27059	2	0.13530**	6.75
AD	0.03120	4	0.00780	1.20
BD	0.20221	8	0.02528	
ABD	0.10422	16	0.00651	
CD	0.34114	4	0.08528**	5.07
ACD	0.04290	8	0.00536	0.85
BCD	0.26927	16	0.01683	
ABCD	0.20851	32	0.00636	
TOTAL	2.21161	134		

TABLE 13

ANALYSIS OF VARIANCE FOR GLIDE SLOPE ERROR ....CASE 2

Levels of Factors

A 3 Set
B 5 Pilot
C 2 Frequency
D 4 Damping Ratio

Grand Mean 0.07636

Source of Variation	Sums of Squares	Degrees of Freedom	Mean Squares	F
A	0.06586	2	0.03293	4.0100
B	0.03790	4	0.00947	
AB	0.06571	8	0.00821	
C	0.00481	1	0.00481	0.2938
AC	0.01599	2	0.00799	0.9467
BC	0.06547	4	0.01637	
ABC	0.06750	8	0.00844	
D	0.02679	3	0.00893	1.4450
AD	0.03432	6	0.00572	1.3120
BD	0.07410	12	0.00618	
ABD	0.10464	24	0.00436	
CD	0.02135	3	0.00712	1.3210
ACD	0.03953	6	0.00659	1.6730
BCD	0.06466	12	0.00539	
ABCD	0.09453	24	0.00394	
TOTAL	0.78316	119		

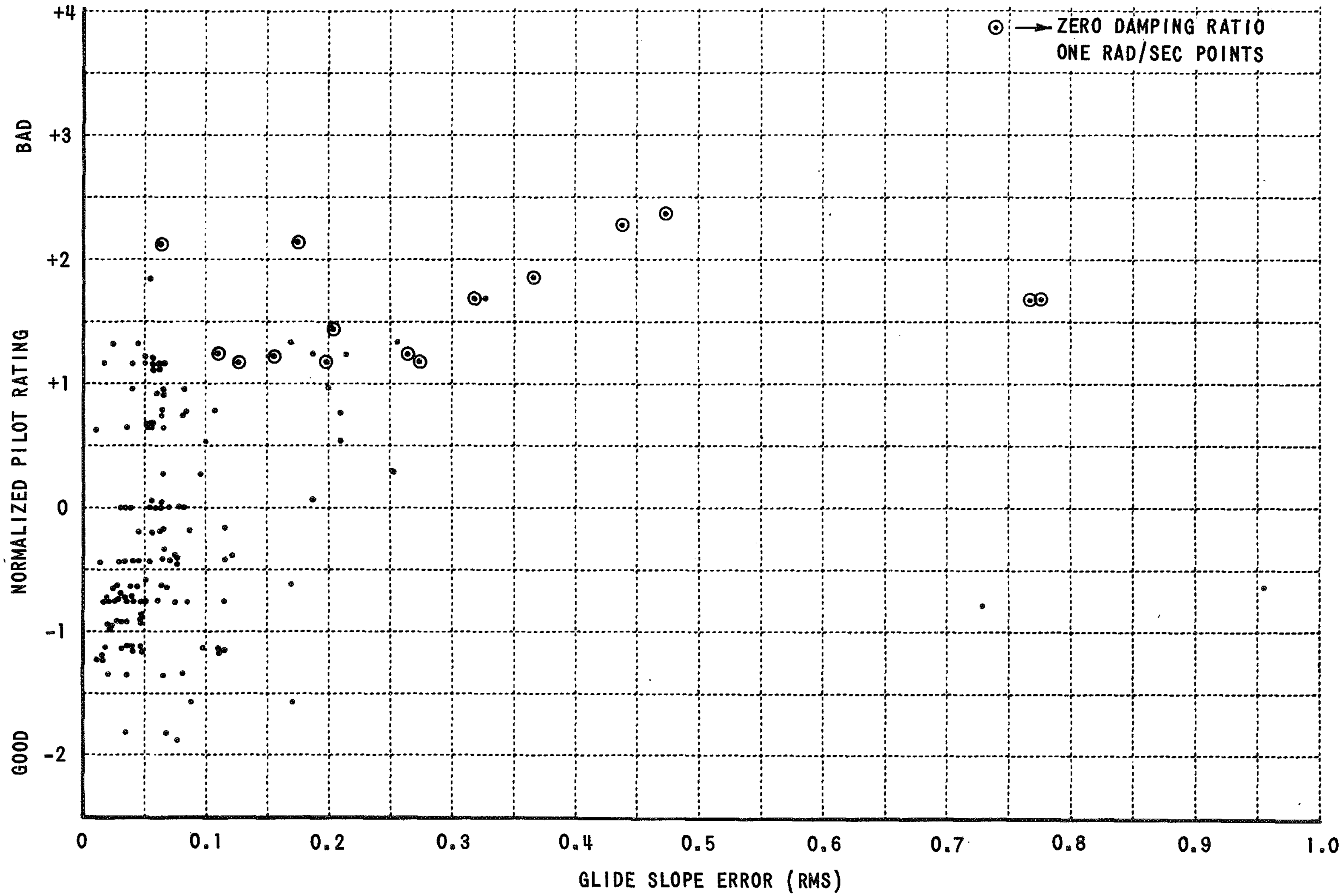


Figure 15 PILOT RATING VS. GLIDE SLOPE ERROR

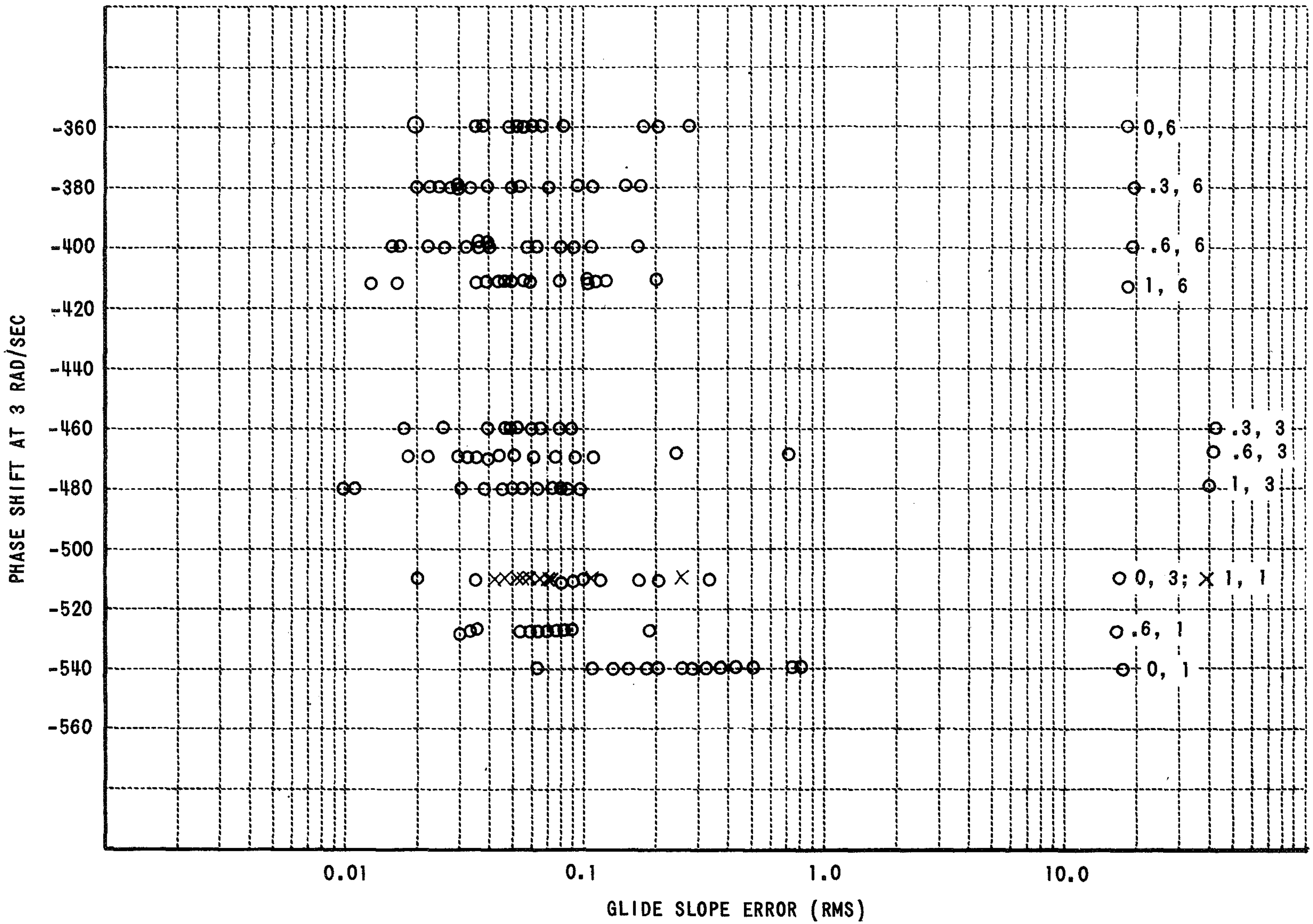


Figure 16 PHASE SHIFT AT 3 RAD/SEC VS. GLIDE SLOPE ERROR FOR h/δ_e

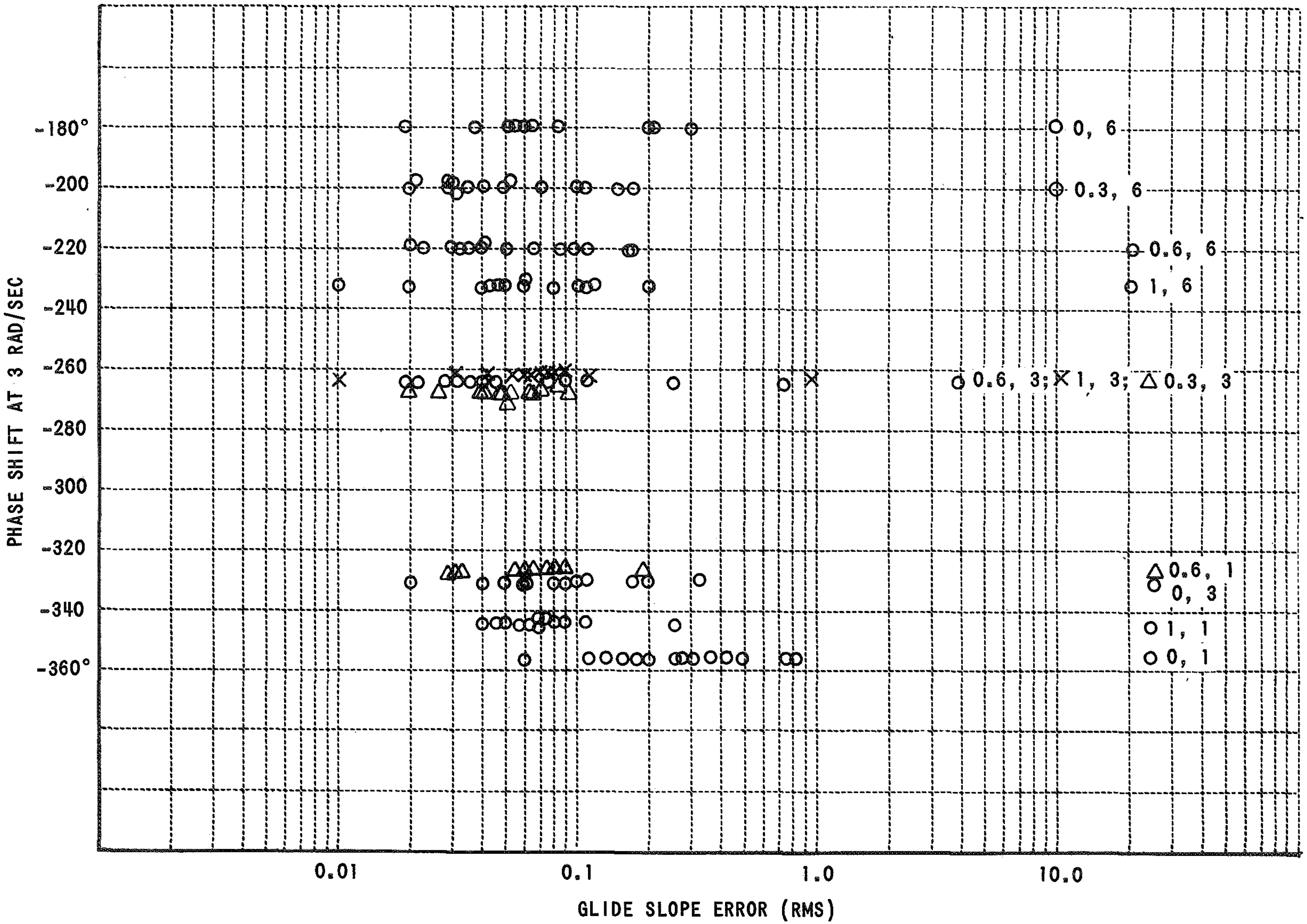


Figure 17 PHASE SHIFT AT 3 RAD-SEC VS. GLIDE SLOPE ERROR; α/δ_e

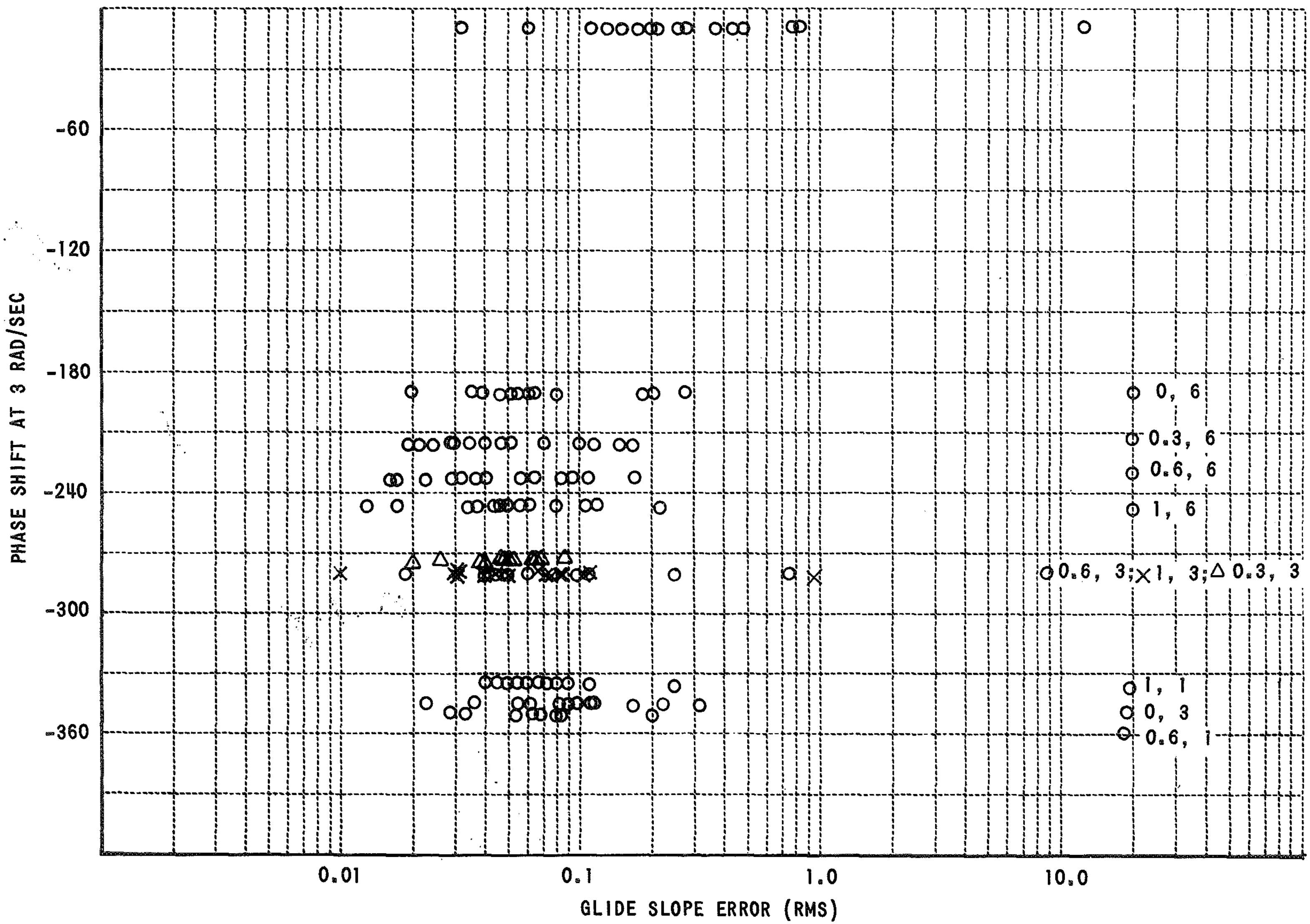


Figure 18 PHASE SHIFT AT 3 RAD/SEC VS. GLIDE SLOPE ERROR FOR θ/δ_e

An initial attempt was made to determine whether any such relationship exists for these data. The approach used was to write the matrix equation

$$AK = R,$$

where A is a 7 x 7 matrix of known constants (rms errors),

K is a 7 x 1 column vector of unknown constants, and

R is a 7 x 1 column vector of known pilot ratings.

and solve for the unknown K vector

$$K = A^{-1}R$$

where A^{-1} is the inverse of A.

An attempt was then made to relate the K thus obtained with other sets of rms errors, A, to estimate the actual R vector for that set of runs. In this way an attempt to estimate pilot ratings as a linear combination of mean square errors of the variables which appear in the equation of motion was made.

A comparison of K vectors obtained for five configurations and associated A and R matrices is shown below. No trend or consistency can be observed in these data, shown below.

K_1	K_2	K_3	K_4	K_5	K_6	K_7
21.49	5.23	-11.06	2.23	- 3.47	-26.76	- 4.58
66.84	6.95	-26.82	-1.85	-11.795	7.82	8.63
- 0.23	- 2.89	13.73	4.88	4.09	-21.85	- 2.06
92.78	- 1.44	- .137	6.98	- 7.17	10.74	-10.88
170.29	-10.62	18.39	1.79	5.27	63.65	1.62

One of these K vectors, the first one, was multiplied by A matrices for three different runs (sets of configurations). The results are shown below (R is the actual pilot rating while $\hat{R}$ is the estimated rating).

	R_1	R_2	R_3	R_4	R_5	R_6	R_7
R	10	10	10	5	5	8	4
$\hat{R}$	30	- 0.2	9.3	-2.6	8.6	18.8	2
R	10	9	6	6	6	5	4.5
$\hat{R}$	11	4.9	-17.9	7.6	6.7	8	-0.14
R	9.5	10	9	6	4.5	5	2.5
$\hat{R}$	5	-15	31	-5	5.9	-9.5	0.7

Here, as before, it is evident that no relationship exists among the linear combination of rms errors and pilot ratings.

V. CONCLUSIONS

From this experiment it is concluded that:

1. Glide slope rms error score does not correlate with pilot rating for the ILS task.

2. There is no apparent linear combination of rms error scores that correlates with pilot rating for the ILS task.

3. There is no correlation between glide slope rms error and phase shift at 3 radians/second for h/δ_e, θ/δ_e and α/δ_e.

4. The analyses of variance of glide slope rms error do not indicate that this measure is as sensitive as pilot rating.

5. Pilots frequently give a lower rating because of relatively poorer performance as they approach the middle marker.

6. Pilot rating is not readily apparent from records of glide slope error. The pilots fly a poorer configuration more tightly then a good one because they are afraid of "losing it." With a relatively well behaved configuration, they will tolerate more error since recovery is easier.

VI. RECOMMENDATIONS

It is expected that the lack of correlation between the pilot rating data and the numerical data reflects the inability of the numerical data to account for pilot technique and for the pilot's mental processes. It is recommended that a more thorough examination of the data, with a broader scope of performance indices, be carried out.

In addition, it is recommended that the data generated on the present project be used to compute pilot transfer functions for the multi-controller, multi-loop ILS task. The existence of this data presents a unique opportunity, since vector representations of the pilot transfer functions have never before been attempted.

Appendix A

APPLICATION OF THE SPEARMAN RANK TEST TO PILOT DATA

The Spearman rank test referred to in the introduction involves the judging of a set of objects by two judges. After the judges have performed their duties and some items are judged differently by them, one wishes to know if these differences are real or if they represent a reasonable chance effect with high probability of occurrence. For the problem depicted there is no knowledge of the underlying distribution functions and a nonparametric test is desirable. The Spearman test is such a test and is used in the following way.

Suppose there are eight items to be judged and let them be A through H. The sample size, N, is eight. Let each judge give a rating on a numerical scale of his own choice. Further, allow them to rate with plus and minus suffixes to differentiate, say, a 2+ from a 2 from a 2-. Suppose the results are as follows:

Item	Judge 1	Judge 2
A	1	2
B	6	18
C	3	8
D	2	3
E	7+	20
F	7	22
G	5	14
H	8	23

It appears the two judges used very different rating schemes, but so be it. The question is, do they give the same information? Proceed by assigning ranks to each judge's ratings. The data then becomes:

Item	Ranks for Judge 1	Ranks for Judge 2	Difference
A	1	1	0
B	5	5	0
C	3	3	0
D	2	2	0
E	6	6	0
F	7	7	0
G	4	4	0
H	8	8	0

It is obvious that the rank correlation is perfect, but to make this example complete it is also computed. The formula is

$$\rho = 1 - \frac{6 \sum_i d_i^2}{N(N^2 - 1)}$$

where ρ is the correlation coefficient.

d_i is the difference between ranks in the i^{th} row.

N is the sample size.

and for the example $\rho = 1 - \frac{6(0)}{8(64-1)} = 1$

which means that the two judges gave us the same information.

An example wherein the rankings are different is given next.

Item	Ranks for Judge 1	Ranks for Judge 2	d_i	d_i^2
A	1	3	2	4
B	8	6	-2	4
C	7	5	-2	4
D	3	1	-2	4
E	5	7	2	4
F	4	2	-2	4
G	2	4	2	4
H	6	8	2	4

$\sum d_i^2 = 32$

There are two forms of tables in use from which the extent of correlation can be judged. One form of table is based upon Σd_i^2 and sample size and the other is based on the value of ρ and sample size. The null hypothesis that is tested is that the two judges' ratings are not correlated.

For the purpose of the first type of table mentioned $\Sigma d_i^2 = 32$ and the sample size is 8. From such a table it is found that this indicates there may barely be a significant correlation at the 5% level. That is, there is not strong evidence that the judges rated the same way.

For the purpose of the correlation coefficient table

$$\rho = 1 - \frac{6(32)}{8(63)} = 0.619$$

and this is not significant at the 5% level according to the table.

It is of interest, from a knowledge of pilot rating data, to estimate what values of the correlation coefficient should be expected if pilots are considered to be the judges.

It is usual that two pilots will rate the same airplane configuration within plus or minus one rating unit of each other. If we hypothesize that the rankings reflect this difference of plus or minus one rating unit as plus or minus one ranking, then we will have a maximum Σd^2 of $N d_i^2 = N$ and the formula for the minimum ρ becomes

$$\rho \geq 1 - \frac{6N}{N(N^2-1)} = 1 - \frac{6}{N^2-1}$$

This indicates that we need to obtain values of ρ versus sample size as indicated in the following table.

N	ρ
8	0.9046
10	0.9394
15	0.9732
20	0.9850
25	0.9904

The indicated value of ρ must be obtained for comparisons between a pilot and any other form of judging (such as performance indices) if the other judgment form is to be as sensitive as a pilot can be.

Having dealt with these preliminaries, it becomes instructive to investigate real data. The ratings given are for two different pilots who rated fifteen configurations. Each of the configurations is different from any other one. The ratings are on a one to ten scale.

Configuration	Rating by Pilot One	Rating by Pilot Two	Ranks for Pilot One	Ranks for Pilot Two
A	4	4	5	6
B	7	7.5	13.5	13
C	6	5	10.5	8
D	3	2	3	2
E	2	2	2	2
F	5	6	8.5	9.5
G	7	7	13.5	12
H	1.5	2	1	2
I	6	7	10.5	12
J	7	8	13.5	14
K	5	4.5	8.5	7
L	4	3	5	4.5
M	4.5	6	6	9.5
N	7	7	13.5	12
P	4	3	5	4.5

From the ranking data the computed $\rho = 0.9421$, which is extremely significant (even at the 0.0005 level) and signifies that the null hypothesis (i.e., the pilots rated independently) must be rejected. The Pearson product moment correlation coefficient has also been computed and its value is 0.896 which is also extremely significant. These coefficients, obtained from real data, indicate the values of the coefficients that should be attained for a comparison between a pilot and any other rating scheme if this other rating scheme is to be as sensitive as the pilot. Mere statistical significance is not a sufficient indicator.

It may be noticed from the actual pilot data that there are repeated ratings by each pilot. To determine ranks for these repeated ratings one applies to each like rating the average of the rank positions that these ratings would take. For instance Pilot One rates configurations F and K the same and these would take ranking positions 8 and 9. Therefore, the rank applied to these two configurations is 8.5.

The other characteristic to be noticed from the table of pilot data is that the maximum difference in pilot ratings (between pilots) is 1.5 rating units for configuration M. There are seven differences of one rating unit, three differences of one-half a rating unit, and four ratings that are alike. However, in terms of ranks there is one difference of three and a half, one difference of two and a half, four differences of one-half and one pair of rankings that are alike. Therefore, there is greater dispersion among the ranks than there is among the pilot ratings and this contributes to the reason why the predicted ρ for N = 15 is 0.973 whereas the ρ computed for the data is 0.942.

Because values of ρ on the order of 0.94 to 0.97 are indicated as necessary to obtain (but on the other hand are statistically very improbable) then the implication is that a statistically sensitive and sufficient program design must be used. A large enough program should be used to be able to define with strong significance the pilot variability so that reasonable conclusions about comparisons of pilot rating scales and other rating procedures can be made.

Appendix B

TURBULENCE MODEL

The gust model is the Dryden spectral form. A distinction is made in the model for turbulence characteristics above 1000 feet above ground level and below 1000 feet above ground level. Turbulence above 1000 feet is assumed to be isotropic, while below 1000 feet turbulence is assumed to be anisotropic. A slight problem occurs here, since the current study involved altitude variations from 2500 feet to ground level, and the 1000 foot assumption lies midway in the resultant altitude profile. For this present study the model valid below 1000 feet was used for the entire altitude range.

The model accounts for the anisotropic character of the turbulence by providing an rms intensity factor, σ_w, and a scale factor, L_w for the vertical gust components in the horizontal direction. Although the intensity factors and scale factors are a function of altitude, these factors will be determined for an average altitude and used over the entire range of altitude in the simulation.

The philosophy used in the development of the model is to seek the transfer functions of a filter, such that, with a white noise signal input, the filtered output has the same spectral characteristics as the turbulence. Thus, an appropriately filtered white noise signal can be used to simulate random gust inputs.

Gust models for gust signals which affect β were used in our simulation. Other gust signals will be neglected; (i.e., u, v, w, p, q, r, $\dot{\alpha}$ gust signals). Although only the β gust input was used, both α and β gust signals are included in this discussion.

The Dryden spectra formulas for α and β gust signals are:

$$\phi_{\alpha_g}(\omega) = \frac{1}{V^2}\,\sigma_w^2\,\frac{L_w}{\pi V}\;\frac{1 + 3\left(\frac{L_w}{V}\omega\right)^2}{\left[1 + \left(\frac{L_w}{V}\omega\right)^2\right]^2} \tag{1}$$

and

$$\phi_{\beta_g}(\omega) = \frac{1}{V^2}\,\sigma_v^2\,\frac{L_v}{\pi V}\;\frac{1 + 3\left(\frac{L_v}{V}\omega\right)^2}{\left[1 + \left(\frac{L_v}{V}\omega\right)^2\right]^2} \tag{2}$$

These can be simplified to

$$\phi_{\alpha_g}(\omega) \cong \sigma_w^2 \frac{L_w}{\pi V^3} \frac{1}{1+\left(\frac{L_w}{V}\omega\right)^2} \tag{3}$$

and

$$\phi_{\beta_g}(\omega) \cong \sigma_v^2 \frac{L_v}{\pi V^3} \frac{1}{1+\left(\frac{L_v}{V}\omega\right)^2} \tag{4}$$

V is true airspeed, in feet/second
L is in feet
σ is in feet/second

Scales and intensities are related by

$$\frac{\sigma_v^2}{L_v} = \frac{\sigma_w^2}{L_w} \tag{5}$$

and

$$L_w = h \tag{6}$$

and

$$L_v = 100 \sqrt[3]{h} \tag{7}$$

An estimate of the rms intensity of the vertical gust, σ_w, is obtained statistically, and is given in the form of a Rayleigh Distribution. A value of σ_w = 2.7 feet/second will be assumed for this study.

If the average altitude is used, h_{av} = 1250 feet, then

$$L_w = 1250$$

and

$$L_v = 1077$$

and

$$\sigma_v = 3.13$$

Thus

$$\phi_{\alpha_g}(\omega) = \frac{6750}{\pi} \quad \frac{1}{1 + \left(\frac{1250}{V}\,\omega\right)^2} \tag{8}$$

and

$$\phi_{\beta_g}(\omega) = \frac{6742}{V^3} \quad \frac{1}{1 + \left(\frac{1077}{V}\,\omega\right)^2} \tag{9}$$

It is assumed that these two gust signals are statistically independent.

The transfer function for the white noise filters to be used to obtain the gust signals are

$$T_{\alpha_g}(s) = \sigma_{w_g}\sqrt{\frac{2 L w_g}{\pi V^3}} \quad \frac{1}{1 + \frac{L w_g}{V} s} \tag{10}$$

and

$$T_{\beta_g}(s) = \sigma_{v_g}\sqrt{\frac{2 L v_g}{\pi V^3}} \quad \frac{1}{1 + \frac{L v_g}{V} s} \tag{11}$$

The gust signals enter the equation of motion in the aerodynamic terms; (i.e., not in the inertial or gravity terms). Thus, the equations of motion are appropriately modified as follows:

Longitudinal

$$\left(\frac{g}{57.3}\right)\theta + \dot{V} + D_V V + \frac{D_\alpha}{57.3}\alpha = \frac{-D_{\delta_x}}{57.3}\delta_x \quad \frac{-D_{\delta_z}}{57.3}\delta_z$$

$$-\dot{\theta} - Z_\theta\theta + \left(\frac{57.3\alpha_t}{V_t}\right)\dot{V} - 57.3 Z_V V + \dot{\alpha} - Z_\alpha(\alpha + \alpha_g) = Z_{\delta_e}\delta_e + Z_{\delta_z}\delta_z$$

$$\ddot{\theta} - M_q\dot{\theta} - 57.3(M_V V + M_{\dot{V}}\dot{V}) - M_{\dot{\alpha}}\dot{\alpha} - M_\alpha(\alpha + \alpha_g) = M_{\delta_e}\delta_e + M_{\delta_x}\delta_x + M_{\delta_z}\delta_z$$

Lateral-Directional

$$-(\alpha_t + Y_p)\dot{\phi} - \left(\frac{g}{V_t}\right)\phi + (1 + \alpha_t\theta_t + \theta_t Y_p - Y_r)r + \dot{\beta} - Y_\beta(\beta + \beta_g) = Y_{\delta_a}\delta_a + Y_{\delta_r}\delta_r$$

$$\ddot{\phi} - L_p\dot{\phi} - \left(\frac{I_{xz}}{I_{xx}} + \theta_t\right)\dot{r} + (\theta_t L_p - L_r)r - L_\beta(\beta + \beta_g) = L_{\delta_a}\delta_a + L_{\delta_r}\delta_r$$

$$-\left(\frac{I_{xz}}{I_{zz}}\right)\ddot{\phi} - N_p\dot{\phi} + \left(1 + \theta_t\frac{I_{xz}}{I_{zz}}\right)\dot{r} + (\theta_t N_p - N_r)r - N_\beta(\beta + \beta_g) = N_{\delta_a}\delta_a + N_{\delta_r}\delta_r$$

α_g and β_g are the outputs of the filters, $T_{\alpha_g}(s)$ and $T_{\beta_g}(s)$, each of which has a white noise source input.

Reference

1. W.W. Wierwille and J.R. Knight, "Synthesis Methods for Manual Aerospace Control Systems with Applications to SST Design," CAL Report No. IM-2429-B-1, Project WEIWOHO, Contract No. NAS1-7141, March 1968.

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