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EQUIVALENT SYSTEM VERIFICATION AND EVALUATION OF AUGMENTATION EFFECTS ON FIGHTER APPROACH AND LANDING FLYING QUALITIES

VOLUME 1 - SUMMARY

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This executive summary reports an analysis of an approach and landing evaluation program using the AFWAL/Calspan NT-33 variable stability aircraft to test the suitability of representing aircraft with complex flight control systems by an equivalent simplified system.

An evaluation of the equivalent systems includes effects of time delay, correlations with Pilot Ratings and comparison of frequency response characteristics for both high-order and low-order configurations. Analytical

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) and fast Fourier transform Bode diagrams of the configurations have been plotted with the corresponding step time histories. The effects of gain parameters on the matching of equivalent systems are presented. The resulting response characteristics also serve as a check on the predicted responses as defined by the analytical descriptions programmed in the NT-33.

The equivalent systems data have been evaluated with the Neal and Smith closed-loop analysis technique. For the longitudinal evaluations, the validity of the equivalent system approach for evaluation of the flying qualities of complex aircraft was generally verified. The data for the lateral equivalent system evaluations were inconclusive.

FOREWORD

This report was prepared for the United States Navy and Air Force by McDonnell Aircraft Company, St. Louis, Missouri with McDonnell-Douglas Independent Research and Development funding. The Air Force Wright Aeronautical Laboratories (AFWAL) task number 24030519 "Military Flying Qualities Research" was under Project Number 2403, "Stability and Control of Aerospace Vehicles."

The report describes the results of analyses of an inflight evaluation program designed to verify the equivalent system flying qualities concept for a variety of control system dynamics.

The in-flight evaluation program reported by Calspan Corporation, Buffalo, NY was performed by the Flight Research Branch of Calspan under sponsorship of the Naval Air Test Center, NAS Patuxent River, Maryland and the Flight Dynamics Laboratory, Wright-Patterson AFB, OH, working through a Calspan contract with FDL. This work was part of Project 6241-F, NT-33 Task 3. Mr. Jack Barry was the Program Manager for FDL; his assistance deserves special acknowledgement.

Completion of the in-flight program was dependent on the contributions of individuals from the McDonnell-Douglas Corporation, Navy, Air Force and Calspan. LCdr John Padgett of NATC served as Test Director; without his enthusiastic support in this capacity and his truly professional contributions as an evaluation pilot, this program would not have been possible. The engineering assistance of Mr. Bill McNamara and Mr. Tom Galloway of NATC and Mr. Tom Black of FDL is also acknowledged. In addition, the interest and support of Mr. Ralph A'Harrah of NAVAIR during the program was appreciated.

This report represents the combined efforts of several individuals from the aforementioned organizations. The authors wish to acknowledge the contributions of Mr. K. A. Johnston of MCAIR.

The authors also wish to express their thanks to Mr. David Bischoff, NADC for his review of the report. Mr. D. J. Moorhouse and Mr. R. J. Woodcock, AFWAL made many constructive changes during their very thorough review.

The time period covered by the analysis of the in-flight data extends from August 1978 through May 1981. The report, submitted by the authors in July 1981, is in two volumes. Volume I presents a summary of the program and results. Volume II is a more detailed documentation of the in-flight evaluation program.

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INTRODUCTION AND PURPOSE

The demand for increased fighter capability and the demonstrated reliability of modern electronic systems have led to increased flight control system complexity. For example, the F-18, YF-17 and F-16 utilize responses as high as fiftieth order or more. The order of these responses has to be reduced to apply classical aircraft response parameters, such as those presented in MIL-F-8785C, Military Specification Flying Qualities of Piloted Airplanes.

Reduced-order "equivalent systems," studied intensively by McDonnell Aircraft Company (MCAIR), were examined in this exploratory simulation.

Objectives were:

- To compare pilot ratings and comments for complex flight control systems with ratings and comments for their equivalent systems. The equivalents were simplified models of classic order plus a transport time delay, with frequency responses matched to the high order systems.

- To study the effects of transport time delay on longitudinal approach and landing flying qualities.

- To obtain lateral approach and landing flying qualities data for aircraft with significant additional control system dynamics in the form of transport time delays and lag filters.

SUMMARY AND CONCLUSIONS

The USAF/Calspan NT-33 was used, in a joint Calspan/MCAIR simulation, to explore landing flying qualities of augmented fighter aircraft. Conclusions were:

1. Longitudinal low-order equivalent systems, as required in MIL-F-8785C, generally had flying qualities similar to their high-order counterparts.

2. Mismatches between the low-order and high-order systems, and the corresponding pilot rating *differences*, were consistent with frequency response envelopes of tolerable amplitude and phase mismatch proposed for the flying qualities MIL Standard.

3. Special networks to cancel local phase lags did not improve systems with broadband phase lags due to delays.

4. Time delays degraded longitudinal flying qualities, ultimately causing control loss in pilot-induced oscillations.

5. The longitudinal short period requirements of MIL-F-8785C are reasonably consistent with the data.

6. Though the lateral landing task (without gusts or crosswinds) was less demanding than other tasks, it showed flying qualities degradation due to time delays and lag filters.

7. Though a demanding offset spot landing task gave generally consistent pilot ratings, pilots occasionally were able to mask poor handling qualities by use of special piloting techniques. Valid evaluations require strict adherence to a demanding task and the use of representative piloting techniques.

DEFINITION OF EQUIVALENT SYSTEMS

Longitudinal

The short-term, or short-period, pitch rate response was selected as the appropriate dominant response for the approach and landing task. The essentially constant long-term response and the flight path response were considered satisfactory and ignored.

The low-order system was:

$$\frac{\dot{\theta}}{F_{ES}} = K_{\dot{\theta}} \frac{(T_{\theta_e} s + 1)e^{-\tau s}}{\left(\frac{s^2}{\omega_e^2} + \frac{2\zeta_e}{\omega_e} s + 1\right)}$$

where T_{θ_e} is an equivalent T_{θ_2} ($\cong 1/L_\alpha$).

ω_e is an equivalent short-period natural frequency

ζ_e is an equivalent short-period *damping ratio*

Lateral

The roll rate response was selected as the appropriate dominant lateral response for the approach and landing task. The spiral mode was approximately neutral and the Dutch roll poles approximately cancelled the roll rate transfer function zeros. The low order system was:

$$\frac{\dot{\phi}}{F_{AS}} = K_{\dot{\phi}} \frac{e^{-\tau s}}{(\tau_{Re} s + 1)}$$

where τ_{Re} is an equivalent roll mode time constant.

Figure 1 illustrates example frequency and time responses of equivalent systems.

We avoided excessive trial and error calibration by simulating low-order systems which were not necessarily precisely the optimum match (i.e., the true equivalent) of the high-order systems. This factor did not invalidate the results.

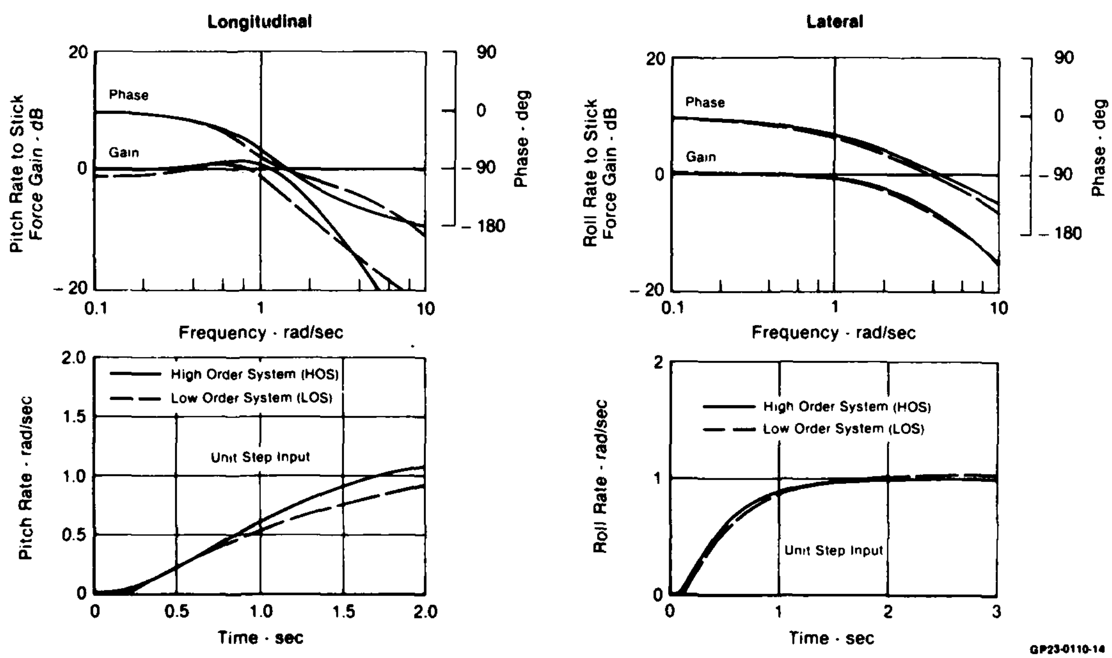


Figure 1. Examples of Longitudinal and Lateral Equivalent System Responses

MISMATCH

The low-order equivalent system frequency responses are matched to the high-order responses by minimizing a cost, or mismatch function. The cost sums the squared errors in gain and phase between the low and high order transfer functions at a number of frequency values.

$$\text{"Cost"} = \Sigma\{[\Delta\text{Gain (dB)}]^2 + .017\ [\Delta(\text{Phase (deg)})]^2\}$$

The weighting factor of .017 assigns the same significance to one dB of gain mismatch as to approximately eight degrees of phase mismatch. A match frequency range between .1 and 10 rad/sec was used.

EQUIVALENT TIME DELAY

In both longitudinal and lateral axes, a *pure time delay*, $e^{-\tau s}$ in Laplace notation, approximates the high frequency phase lags introduced by actuation, sensors, and compensation. A time delay of τ seconds has *no* effect on response amplitude versus frequency. However, time delay contributes to phase lag and for any frequency does equate to phase angle by $\tau\ (57.3\ \omega)$.

QUESTIONS RAISED BY EQUIVALENT SYSTEMS

For specification use the question arises, what constitutes a "reasonably close" match between the high-order and low-order equivalent response?

Freeing the short-period pitch numerator in the matching process is one way to reduce the mismatch. The resulting equivalent system is valid only for the pitch degree of freedom, so this approach may be questionable.

Because path control and normal-acceleration cues are neglected, at high frequencies, high-order dynamics often produce large lags which cannot be approximated by simple low-order equivalent modal parameters. Pilots describe these responses as delayed. The question arises as to whether an equivalent delay simulates the high-order response with sufficient accuracy to yield the same pilot rating.

To answer these questions, we simulated systems of appropriate order. By relating differences in pilot comments and ratings to analytical differences between the high and low order responses, allowable levels of mismatch were to be defined. Further, cases were chosen so that mismatches fell in different frequency ranges.

USAF/CALSPAN VARIABLE STABILITY NT-33 AIRCRAFT

In the NT-33, (Figure 2), the evaluation pilot occupies the front cockpit, while the system operator acts as safety pilot in the rear cockpit. A "configuration" for evaluation is established by the safety pilot setting the fly-by-wire system gain controls. Several configurations were evaluated per flight.

Figure 2. USAF/CALSPAN Variable Stability NT-33

LONGITUDINAL EXPERIMENT PLAN

Longitudinal Mechanization

The longitudinal mechanization block diagram is shown in Figure 3. This applies to all configurations except for two advanced fighter aircraft configurations.

Evaluation Configurations

The table in Figure 3 separates the configurations into data sets of equivalent system or time delay variations.

Longitudinal Command Gains

The constant-speed, steady-state pitch rate per pound of stick force, q_{ss}, was usually constant within a particular set of configurations. Target values of q_{ss} were taken from previous investigations. Some variations of q_{ss} were also made.

Special Lead-Lag Networks

First order lead-lag networks were sometimes necessary to modify the pitch rate transfer function by open-loop cancellation and substitution:

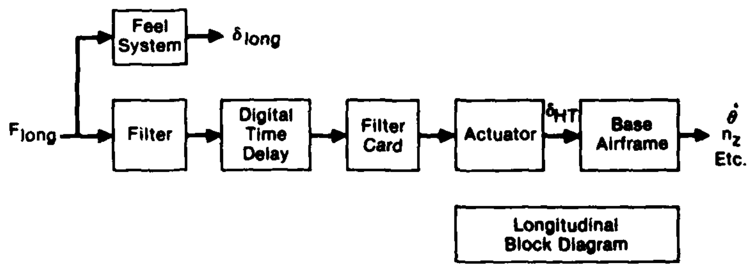
- o Some configurations required pitch numerator root values different from the NT-33 values (for example, Configuration P2).
- o For Configuration P3, P6 and P9 the requisite ω_e was beyond the capability of the NT-33 simulator in the landing approach condition.

Long Term Pitch Characteristics

Phugoid parameters were approximately $\omega_{ph} \approx .15$, $\zeta_{ph} \approx .15$, $\tau_{\theta 1} \approx 12$ sec. All the evaluations were on the "front side" of the power required versus airspeed curve.

Lateral-Directional Characteristics

A "good" set of lateral-directional characteristics was used, configuration L-5.



Note: $L_\alpha \geq \frac{1}{T_{\theta_2}}$, for pitch response only, match process

Longitudinal Evaluation Configurations

Configuration	Remarks
P1	Advanced Fighter HOS (45° Flap)
P2	ES for P1, L_α Fixed
P2A	P2 with Gain Changed
P3	ES for P1, L_α Free
P3A	P3 with Gain Changed
P4	Advanced Fighter HOS (30° Flap)
P4A	P4 with Gain Changed
P5	ES for P4, L_α Fixed
P5A	Modified ES for P4
P5B	P5 with Gain Changed
P5C	Modified ES for P4
P6	ES for P4, L_α Free
P7	LAHOS 4-3, Force Commands
P8	ES for P7, L_α Fixed
P9	ES for P7, L_α Free
P10	LAHOS 2-1, Force Commands
P10A	P10 Plus Feel System Delay
P10B	P10 Plus Time Delay
P10C	P10 Plus Time Delay
P10D	P10 Plus Time Delay
P11	LAHOS 2-11, Force Commands
P11A	HOS P11 Plus Feel System Delay
P12	ES for P11, L_α Fixed
P12A	P12 with S + 2/S + 6 Filter Added
P12B	P12 with S + 10/S + 20 Filter Added
P12C	P12B with Gain Changed
P12D	P12A with Gain Changed
P13	LAHOS 4-7, Force Commands
P13A	P13 Plus Feel System Delay
P14	ES for P13, L_α Fixed
P15	LAHOS 1-4, Force Commands
P16	ES for P15, L_α Fixed
P16A	Modified ES for P15
P17	ES for P15, L_α Free

Figure 3. Longitudinal Block Diagram and Longitudinal Evaluation Configurations

LATERAL EXPERIMENT PLAN

Lateral Mechanization

The lateral mechanization block diagram is shown in Figure 4. This applies to all configurations except two advanced fighter aircraft configurations.

Evaluation Configurations

The evaluation configurations are presented in the table in Figure 4. Both first-order lags and pure time delays were evaluated.

Lateral Command Gains

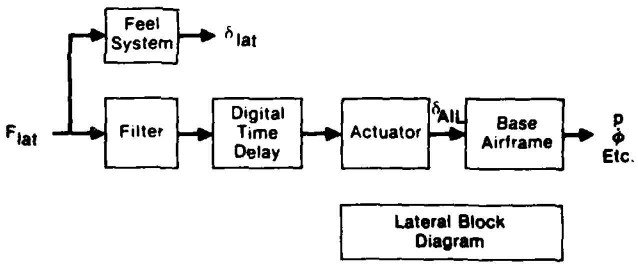
The steady-state roll rate per pound of stick force was representative of modern fighters and was usually constant within a set of configurations.

Other Lateral-Directional Characteristics

The spiral and Dutch roll effects on the roll rate transfer function were neglected, though insufficient time was available to remove them totally from the responses.

Longitudinal Characteristics

A "good" set of longitudinal characteristics was used, configuration P-10.



Note. Short time constant, $\tau_R = 0.4$ sec
Long time constant, $\tau_R = 0.9$ sec

Lateral Evaluation Configurations

Configuration	Remarks
L1	Advanced Fighter HOS (45° Flap)
L2	ES for L1
L3	Advanced Fighter HOS (30° Flap)
L4	ES for L3
L4A	L4 with Gain Changed
L5	Short Time Constant - Lag
L5A	L5 without Lag
L6	Short Time Constant - Lag
L7	Short Time Constant - Lag
L7A	L7 with Time Delay
L8	Short Time Constant - Lag
L8A	Short Time Constant - Lag
L8B	Short Time Constant - Lag
L9	Short Time Constant - Time Delay
L10	Short Time Constant - Time Delay
L10A	L10 without Filter
L11	Short Time Constant - Time Delay
L11A	L11 with Gain Change
L11B	L11 with Gain Change
L11C	Short Time Constant - Time Delay
L11D	Short Time Constant - Lag Plus Time Delay
L12	Long Time Constant - Lag
L12A	L12 without Lag
L13	Long Time Constant - Lag
L14	Long Time Constant - Lag
L14A	Long Time Constant - Lag
L14B	Long Time Constant - Lag
L15	Long Time Constant - Time Delay
L16	Long Time Constant - Time Delay
L16A	Long Time Constant - Time Delay

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Figure 4. Lateral Block Diagram and Lateral Evaluation Configurations

EVALUATION PILOTS

Four evaluation pilots flew the NT-33 in the two-week program:

Pilot A: LCDR J. Padgett, Navy Test Pilot and Test Director (Primary Evaluator)

B: LCDR S. Abbot, Navy Test Pilot

C: LCDR R. Richards, Navy Test Pilot

D: Mr. R. Scott, Test Pilot, Northrop Aircraft Company

In 18 sorties, the pilots evaluated 91 configurations in about 250 landings.

APPROACH AND LANDING TASKS AND GROUNDRULES

- 3 touch-and-go flared landings (actual touchdowns) for each evaluation.
- First landing from a straight-in approach.
- Second landing out of a mild sidestep maneuver (75 ft lateral offset, 50 ft high, initiated at 1/4 mile).
- Third landing out of an aggressive sidestep maneuver (150 ft lateral offset, 100 ft high, initiated at 1/2 mile).
- 500 ft touchdown zone (importance of not abandoning task stressed).
- Touchdown ± 10 ft of runway centerline.
- Approach airspeed ± 5 KIAS; nominal approach angle of attack was 10 units (approximately 6 degrees). At nominal gross weight NT-33 approach speed was 135 KIAS.

The procedure was to assign a pilot Cooper-Harper Rating immediately after the task was completed, make the comments using the pilot comment card, and finally revise the rating if desired. During the flare and landing phase of the task the airspeed decreased approximately 15 knots below the approach value.

PILOT COMMENT CARD
(used with the rating scale of Figure 5)

1. Feel characteristics: Forces, displacements satisfactory?
   - Any complaints about sensitivity?
2. Pitch attitude response to inputs <u>required to perform tasks</u>:
   - Initial response, predictability of final response.
   - Any special pilot inputs?
   - Any tendency towards a Pilot-Induced Oscillation (PIO)?
3. Velocity control: satisfactory?
4. Bank angle control:
   - Satisfactory?
   - Any tendency to PIO? Overcontrol?
5. Turn coordination: a problem?
6. Performance:
   - Approach.
   - Landing, most difficult?
7. Effects of wind/turbulence.
8. Summary comments (brief), any change in rating?

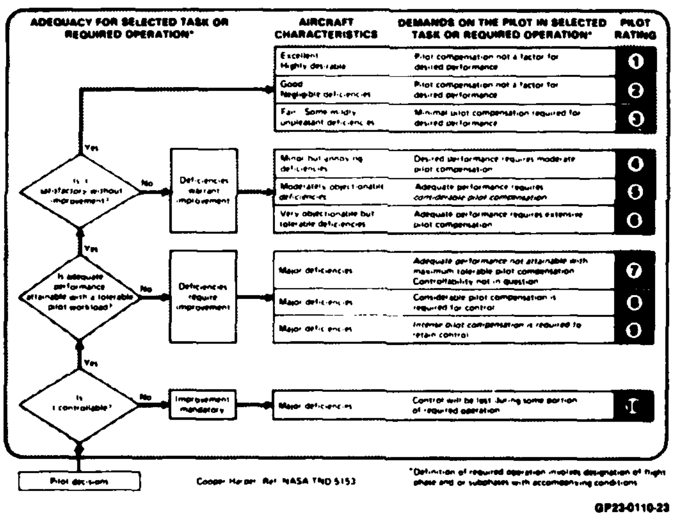

Figure 5. Cooper-Harper Handling Qualities Rating Scale

RESULTS OF DIFFERING PILOTING TECHNIQUES

For the flare and touchdown, the last 50 feet of altitude were critical. Provided that the pilots strived for a precise touchdown point, the handling qualities evaluations were consistent.

Occasionally a pilot used a predictive piloting technique to land a poor configuration with little drama. (e.g., landing 2 in Figure 6). However, the specialized technique was difficult to maintain and the poor characteristics usually emerged eventually (e.g., the dramatic pilot-induced oscillation of Landing 1 in Figure 6). In these cases the pilot sometimes viewed the poor landing as momentary pilot error (e.g., a rating of 5 was at first awarded to the configuration in the Figure, though a 9 or 10 was warranted).

The main evaluation pilot in this study did not adopt specialized piloting techniques and his ratings were reliable.

We conclude, however, that acceptance of a configuration by one pilot, even in multiple landings, is no guarantee of its general acceptability. Seasoned test pilots, usually involved in development testing, have the largest repertoire of specialized techniques. Flying qualities problems have emerged relatively late in the design of some modern aircraft (e.g., F-18, YF-17, F-16, Space Shuttle, Tornado). We speculate that test piloting techniques may have been a factor.

We therefore recommend, for development test flying,

1. Strict adherence to a demanding task

2. Variation of piloting techniques

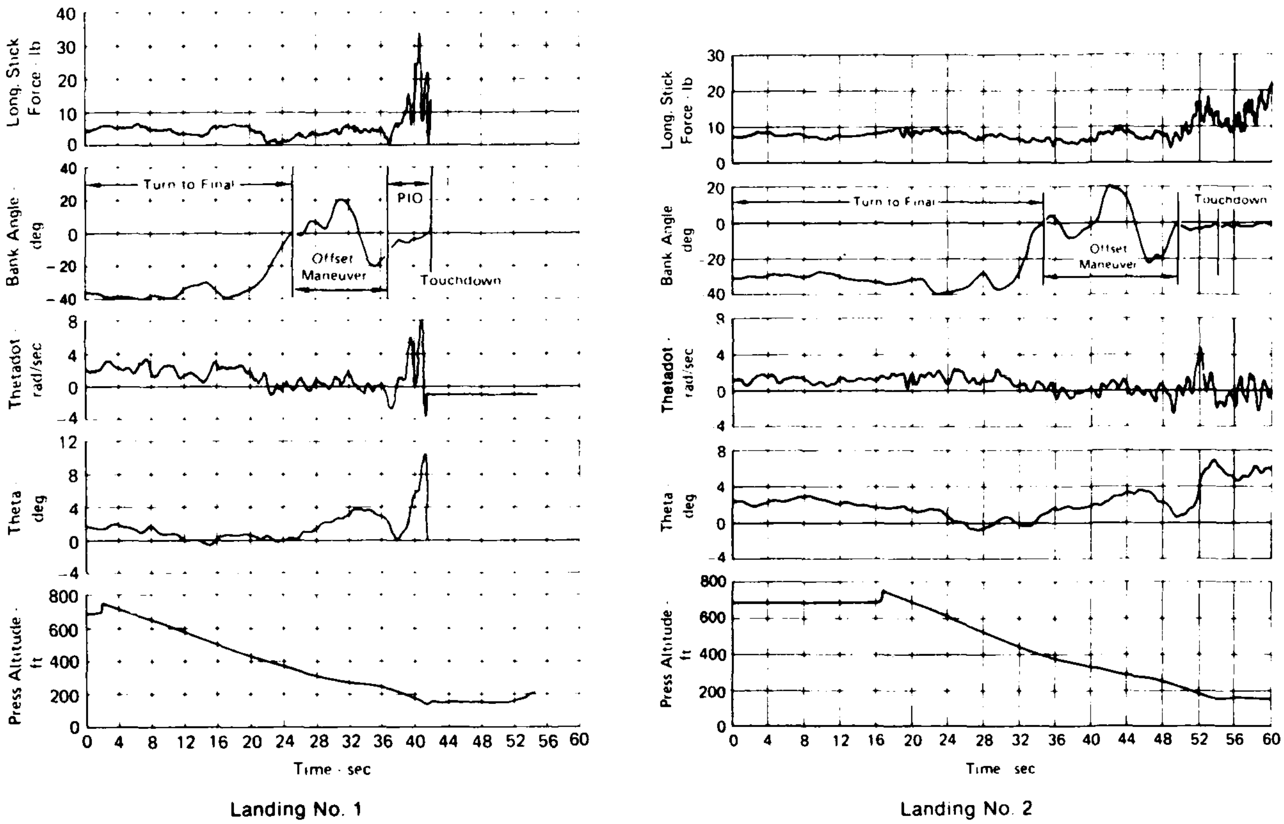

Figure 6. Pilot-Induced Oscillation at Touchdown, Configuration P12

Medium Offset Approach (75 Ft Lateral, 50 Ft Vertical)

LONGITUDINAL EXPERIMENT RESULTS

Figure 7 tabulates the pilot rating results for the ; irs of high order and equivalent systems.

Where appropriate, the values of the MCAIR equivalent system "cost function" are included. The safety pilot rating (SPR) is included as a measure of task performance.

Config		LOS Parameters				Flight Data Match		Optimized Match*		Pilot Ratings		
HOS	LOS	ω	ζ	$1/T_{\theta_2}$	τ	Gain	Cost	Gain	Cost	A	B	SPR
P1	(P1)	(1.55)	(0.937)	(0.55)	(0.136)	0.8	—	(0.93)	(36.0)	2	2	3
	P2	1.5	1.1	0.5	0.165	0.6	136	0.96	43.0	2	—	3
	P3	3.5	0.6	6.3	0.115	0.6	348	1.19	29.0	3	—	3
	P3A	3.5	0.6	6.3	0.115	0.9	34	1.19	29.0	—	3	3
P4	(P4)	(1.96)	(1.35)	(0.55)	(0.128)	1.3	—	(0.95)	(20.0)	3	3	3
	P5-1	1.9	1.4	0.55	0.165	1.1	59	0.99	23.0	6	—	6
	P5-2	1.9	1.4	0.55	0.165	1.1	116	0.99	23.0	—	6	5
	P6	5.3	0.7	12.5	0.105	1.1	197	1.17	35.0	4	4	4
P7	(P7)	(1.61)	(0.827)	(0.8)	(0.116)	0.8	—	(0.96)	(14.0)	3	4	3
	P8	1.6	0.8	0.8	0.145	0.8	18	0.96	15.0	5	—	[illegible]
	P9	4.0	0.75	∞	0.020	0.9	45	1.19	40.0	3	—	4
P11	(P11)	(2.6)	(0.60)	(0.8)	(0.19)	0.4	—	(1.0)	(0.25)	6	4	5
	P12	2.6	0.6	0.8	0.215	0.4	0.3	1.0	0.27	8	6	7.5
P13	(P13)	(2.22)	(1.05)	(0.8)	(0.14)	0.5	—	(0.99)	(2.1)	3	—	3
	P14	2.1	1.0	0.8	0.135	0.5	12	1.0	12.0	5	—	4
P15	(P15)	(0.79)	(0.47)	(0.8)	(0.178)	1.5	—	(0.86)	(156.0)	8	9	9
	P16	0.8	0.6	0.8	0.205	1.4	179	0.87	176.0	8	—	9
	P17	1.9	0.8	∞	0.020	1.2	121	1.0	49.0	9	—	10

HOS is High Order System
LOS is *Low* Order System
( ) Optimized equivalent system matched to HOS
*Gains are matched to normalized HOS gains = 1.0
Cost is the sum-of-squares frequency response difference between LOS and HOS, *for example* P2-P1 difference is 136 for no optimization performed
Time delay includes actuator, 0.02 sec

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Figure 7. Equivalent System Program Matches

RESULTS ON EQUIVALENCE OF LONGITUDINAL SYSTEMS

Pilot Rating Repeatability

Before comparing ratings for low-order and high-order systems, we examined Cooper-Harper rating repeatability (Figure 8).

The intra-pilot scatter is $\Delta PR = 2$. This is consistent with rating scatter in other experiments.

Pilot Ratings for High and Low Order Systems

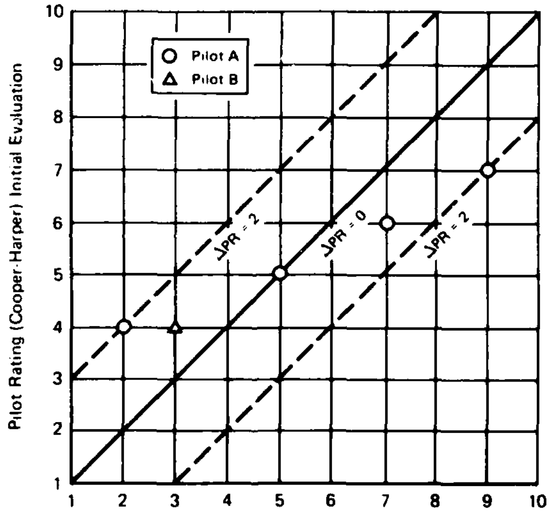
Ratings are compared in Figure 8. We conclude that:

(a) The rating of each low order system generally was equivalent to that of the high-order system.

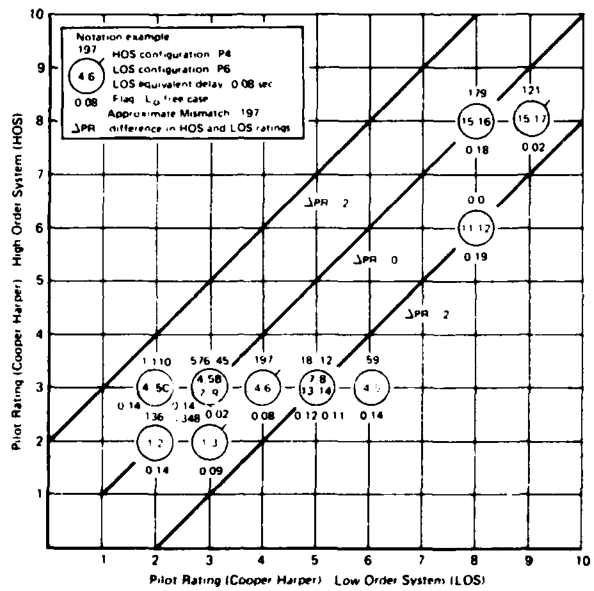
(b) Though differences are generally within pilot repeatability, the low-order systems were rated somewhat worse than were the high-order systems.

(c) Differences in rating were not correlated with differences in the analytical mismatch, or cost, function.

(d) Differences in rating sometimes were correlated with frequency response differences at frequencies above 10 rad/sec.



Repeatability



Pilot Rating Comparison for High Order vs Low Order Equivalent Systems

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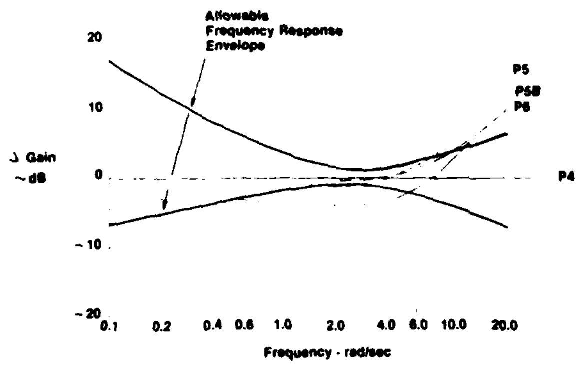
Figure 8. Pilot Rating Repeatability, and Rating Comparison for High Order and Low Order Equivalent Systems

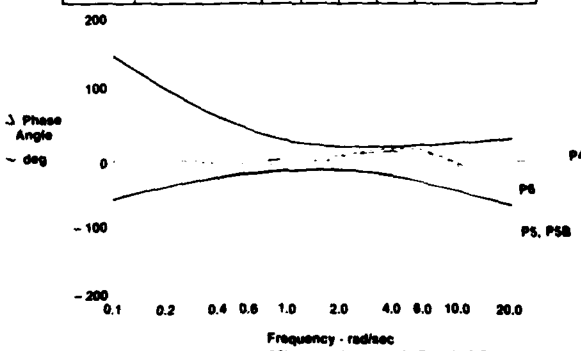
COMPARISON OF MISMATCHES WITH FREQUENCY RESPONSE ENVELOPES

Large mismatches proved insignificant to the pilot. Therefore we examined frequency response envelopes of allowable mismatch which were constructed in a separate MCAIR study. These envelopes utilized those high-order dynamics in the Neal-Smith and LAHOS experiments which caused a degradation in rating when added to low order dynamics.

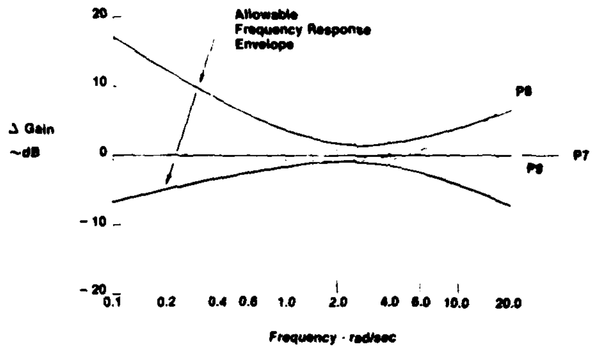
For example, Figure 9 compares mismatches with the envelopes. With a minor expansion of the envelopes, particularly in the high frequency gain, the envelopes function well. Mismatches within the envelopes have rating differences within the allowable rating repeatability.



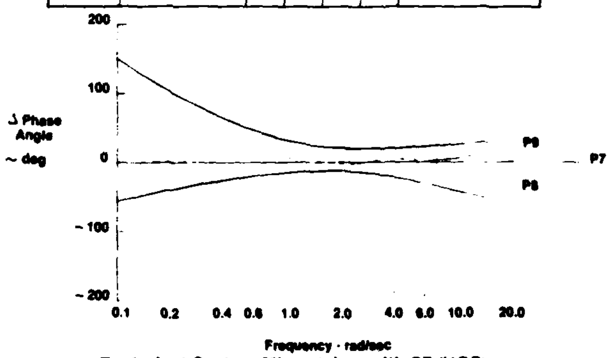
Pilot Rating	Configuration		ω	ζ	L_α	τ	Remarks
3		P4		-		-	HOS-2
6	....	P5	1.9	1.4	0.55	0.12	ES for P4, L_α Fixed
3	— — —	P5B	1.9	1.4	0.55	0.12	P5 with Gain Changed
4	— — — —	P6	5.3	0.7	12.5	0.06	ES for P4, L_α Free



Equivalent System Mismatches with P4 (HOS)
Faired Fourier Transform Data



Pilot Rating	Configuration		ω	ζ	L_α	τ	Remarks
4		P7	-	-	-		(HOS LAHOS Config 4-3)
5	— — — —	P8	1.6	0.8	0.8	0.10	ES for P7, L_α Fixed
3	— — —	P9	2.6	0.6	∞	-	ES for P7, L_α Free



Equivalent System Mismatches with P7 (HOS)
Faired Fourier Transform Data

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Figure 9. Example Comparison of Frequency Response Mismatches with Frequency Response Envelopes

RESULTS OF LEAD-LAG NETWORKS

A low-frequency lead/lag network was added to cancel control system lag at the short-period natural frequency.

Such filters have been considered a "fix" for configurations which do not meet the MIL-F-8785B or C requirement 3.5.3, which limits phase lag at the short-period frequency. The pilot ratings in Figure 10 show that this filter was not effective. Nor was another network which cancelled higher frequency phase lags. Modifying the gain did not alter this conclusion. Broadband phase lag due to a delay consistently degraded the rating.

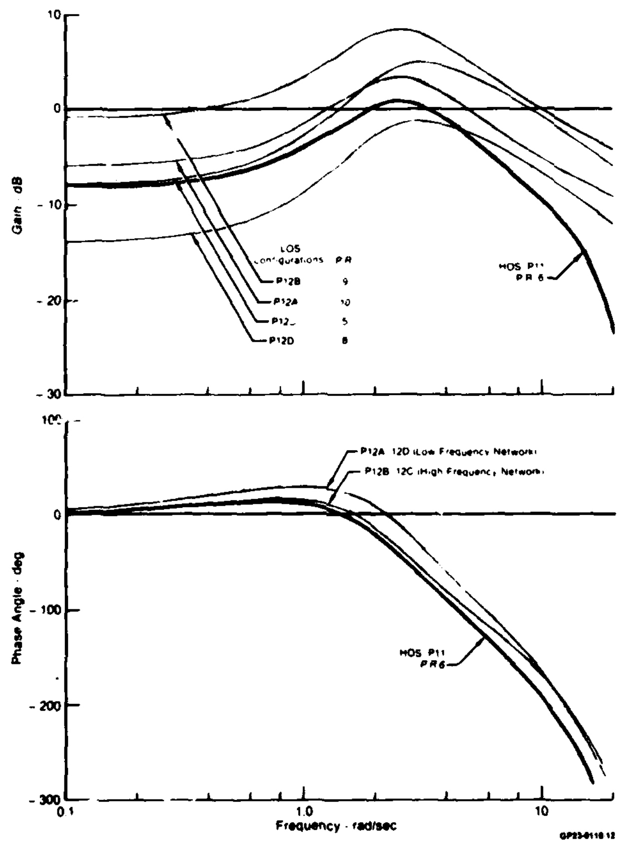

Figure 10. Frequency Response for Pitch Rate to Stick Force and Pilot Ratings for Configuration with Delay and for Configurations Cancelling Phase Lag at Low and High Frequencies

TIME DELAY EFFECTS

Figure 11 shows a threshold of about 145 millisecs (125 ms time delay plus 20 ms for the actuator) before time delay degrades the pitch flying qualities of a basic Level 1 aircraft.

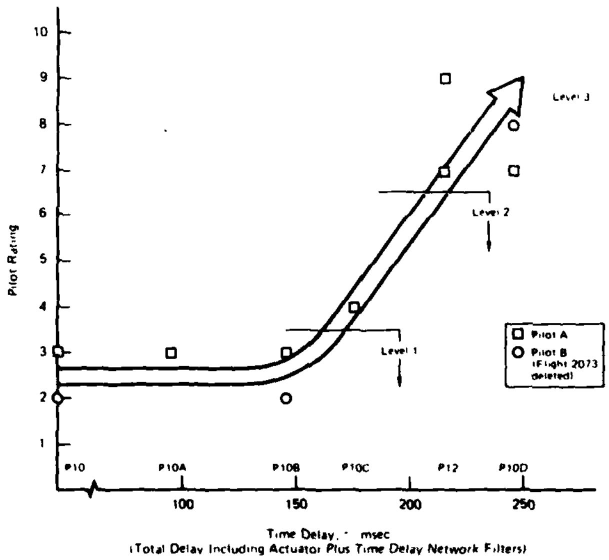

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Figure 11. Effect of Time Delay (Pitch)

COMPARISON OF LONGITUDINAL DATA WITH MIL-F-8785C

The low-order equivalent system parameters were used to evaluate the longitudinal maneuvering and dynamic characteristics of MIL-F-8785C. The short-period specification requirements show good agreement with the levels actually reported by the pilots for the equivalent system values reported in Figure 12.

Configuration	Levels of Flying Qualities per MIL-F-8785C					Levels Based on Pilot Ratings from ESP Data
	Maneuvering Characteristics			Dynamic Characteristics		
	$\omega_{n_{sp}}$ and n_z/α	ζ_{sp}	F_S/n	Allowable Phase Lag	Allowable Time Delay	
	Paragraph 3.2.2.1.1	Paragraph 3.2.2.1.2	Paragraph 3.2.2.3.1	3.5.3 (Table XVIII)	3.5.3 (Table XIV)	
P2	1	1	1	2	2	1
P2A	1	1	1	2	2	2
P3	1	1	1	1	1	1
P3A	1	1	1	1	1	1
P5-1	1	2	1	2	2	2
P5-2	1	2	1	2	2	2
P5A	2 and 3	2	1	1	2	3
P5B	1	2	1	2	2	1
P5C	1	2	1	2	2	1
P6	1	1	1	2	1	2
P7	1	1	1	1	1	1
P8	1	1	1	1	2	2
P9	—	1	1	1	1	1
P10	1	1	1	1	1	1
P10A	1	1	1	1	1	1
P10B	1	1	1	1	2	1
P10C	1	1	1	2	2	2
P10D	1	1	1	2	3	3
P11	1	1	1	2	2	2
P12	1	1	1	2	3	3
P12A	1	1	1	2	3	3
P12B	1	1	1	2	3	3
P12C	1	1	1	2	3	2
P12D	1	1	3	2	3	3
P13	1	1	1	2	2	1
P14	1	1	1	1	2	2
P15	2 and 3	1	1	2	2	3
P16	2 and 3	1	1	2	3	3
P16A	2 and 3	1	1	2	2	3
P17	2 and 3	1	1	1	1	3

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Figure 12. Comparison of Data with Longitudinal Short-Term Dynamic Requirements of MIL-F-8785C

LATERAL EXPERIMENT RESULTS

Suitability of the Task

A subsequent NT-33 experiment (LATHOS) has shed new light on flying qualities evaluation tasks for lateral dynamics. It now appears that our offset landing task, without gusts, was not sufficiently demanding in the lateral axis for the pilots to discriminate lateral control system effects for fighter aircraft.

Lateral Equivalence

Results were inconclusive, probably because of the task.

Lag Effects

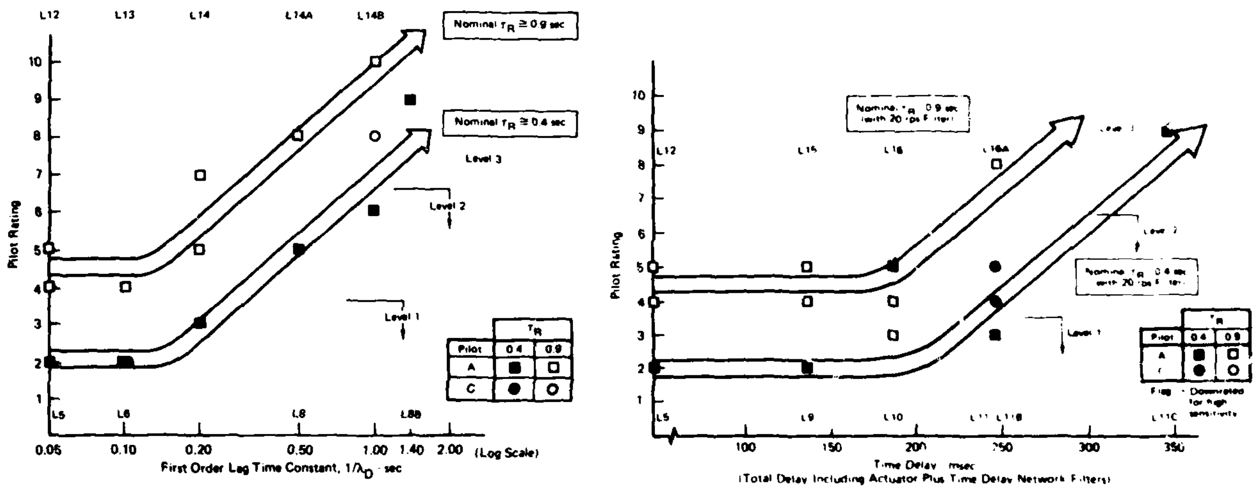
The pilot ratings for Pilots A and C in Figure 13 are plotted against the time constant ($1/\lambda_D$) of the first-order control system lag.

Both the Level 1 (L5) and the Level 2 (L12) baseline configurations (τ_R of 0.4 and 0.9 sec respectively) are unaffected by control system lag until the time constant reaches about .15 secs. The degradation rate with further increases in time constant is similar for both values of τ_R.

Time Delay Effects

The pilot ratings of Pilots A and C are plotted against the control system time delay in Figure 13. For an otherwise satisfactory aircraft the control system time delay should be less than approximately 200 millisec, or the time delay degrades the flying qualities of a basic Level 1 aircraft.

Because of the task, caution should be exercised if these data are used as design guides.



Effect of Lag (Roll)

Effect of Time Delay (Roll)

Figure 13. Effects on Pilot Rating of First Order Lag and Time Delay

LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

dB	Decibels (20 $\log_{10}$ (Amplitude ratio))
F_{AS}, F_{LAT}	Roll control stick force, positive right (lb)
F_{ES}, F_{LONG}	Pitch control stick force, positive aft (lb)
$F_{s/n}$	Gradient of steady-state pitch control force versus normal acceleration (pounds per g)
HOS	High order system
$K_{\dot\theta}$	Steady-state gain of constant speed $\dot\theta/F_{ES}$ transfer function
$K_{\dot\phi}$	Steady-state gain of $\dot\phi/F_{AS}$ transfer function
L	$= 1/\tau_{\theta 2}$
n_z	Incremental normal acceleration at c.g., positive for pull up (g's or ft/sec^2)
n_z/α	Steady-state normal acceleration per angle of attack (g's/rad or ft/sec^2/rad)
p	Body axis roll rate (deg/sec or rad/sec)
p_{ss}	Steady-state roll rate per lb of lateral stick force (deg/sec per lb)
q	Body axis pitch rate (deg/sec or rad/sec)
q_{ss}	Steady-state pitch rate per lb of pitch stick force (deg/sec per lb)
s	Laplace operator (1/sec)
$T_{\theta e}$, $T_{\theta 2}$	Numerator term in pitch transfer function (sec)
α	Angle of attack (deg or rad)
δ_{AIL}	Aileron deflection (deg or rad)
δ_{AS}, δ_{LAT}	Roll control stick motion, positive right (inches)
δ_{ES}, δ_{LONG}	Pitch control stick motion, positive aft (inches)

LIST OF SYMBOLS AND ABBREVIATIONS (Continued)

Symbols

δ_{HT}	Horizontal tail deflection
Δ	Denotes a difference in gain or phase
ζ_{SP}	Short period damping ratio
ζ_{ph}	Phugoid damping ratio
ζ_e	Equivalent damping ratio
θ	Pitch attitude (deg or rad)
ϕ	Roll attitude (deg or rad)
$\lambda_{N,D}$	Filter breakpoint frequencies (rad/sec)
τ	Time delay constant (sec)
τ_R	Roll Mode time constant (sec)
τ_{Re}	Equivalent roll mode time constant (sec)
$\tau_{\theta 1}$	Low frequency pitch numerator term (sec)
$\tau_{\theta 2}$	Airframe lead time constant speed θ/F_{ES} transfer function (sec)
ω	Frequency of excitation (rad/sec)
ω_e	Equivalent natural frequency (rad/sec)
ω_{SP}	Undamped natural frequency of short period mode (rad/sec)
ω_{ph}	Undamped natural frequency of phugoid mode (rad/sec)
$(\dot{\ })$	Rate of Change of ( ) with time (1/sec)

LIST OF SYMBOLS AND ABBREVIATIONS (Continued)

Abbreviations

AFWAL	Air Force Wright Aeronautical Laboratories
CAS	Control Augmentation System
deg	Degree
ESP	Equivalent Systems Program
ES	Equivalent System
FDL	Flight Dynamics Laboratory
HOS	High Order System
in	Inch
KIAS	Knots, Indicated Airspeed
lb	Pound
LOS	Low Order System
MCAIR	McDonnell Aircraft Company
ms	Milliseconds
NADC	Naval Air Development Center
NATC	Naval Air Test Center
PIO	Pilot Induced Oscillation
PR	Pilot Rating
rad	Radian
SPR(SP)	Safety Pilot Rating
LAHOS	Landing Approach Higher Order System (AFWAL Report TR-78-122)
LATHOS	Lateral High Order System (AFWAL Report TR-81-3171, Calspan Report 6645-F-8)
ft	Feet

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