

EFFECTS OF CONTROL SYSTEM DYNAMICS ON
FIGHTER APPROACH AND LANDING LONGITUDINAL
FLYING QUALITIES

by

Rogers E. Smith
Calspan Advanced Technology Center
Buffalo, New York 14225

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ABSTRACT

The effects of significant control system dynamics on fighter approach and landing longitudinal flying qualities were investigated in flight using the USAF/Calspan variable stability NT-33 aircraft. Two pilots evaluated 49 different combinations of control system and short period dynamics while performing representative approach and landing tasks. The landing task for the majority of the evaluations included an actual touchdown. Pilot rating and comment data, supported by task performance records, indicate that the landing task, in particular the last 50 ft of the task, is clearly the critical task for aircraft with significant control system lags. For these aircraft, a sharp degradation in flying qualities takes place during this critical phase of the landing task; for example, severe pilot induced oscillations occurred during the landing task but were not in evidence during the approach task. The results provide a data base for the development of suitable flying qualities requirements which are applicable to aircraft with significant control system dynamics; the results show that the present landing approach requirements in MIL-F-8785B(ASG) are not adequate; in particular, they are not applicable to aircraft with complex flight control systems.

Section 1 INTRODUCTION AND PURPOSE

In recent years, the demand for increased fighter capability, in combination with the demonstrated reliability of modern electronic systems, has led to more complex flight control systems. For example, the latest fighter aircraft designs include sophisticated digital flight control concepts and revolutionary fly-by-wire flight control systems. The additional complexity of these highly augmented aircraft designs is not a problem in itself; however, significant additional control system dynamics are typically introduced which can potentially alter the flying qualities of the aircraft dramatically. Flying qualities requirements, or control system design criteria, must account for the effects of these additional control system dynamics to be of any value. Unfortunately, response criteria based on classical aircraft characteristics, such as those presented in MIL-F-8785B (Reference 1) are not adequate to evaluate the flying qualities of modern highly augmented fighter aircraft.

A necessary first step in the development of suitable flying qualities evaluation criteria for aircraft with significant control system dynamics was the collection of applicable flying qualities data. In response to this need, a series of research programs was conducted using the USAF/Calspan NT-33A variable stability aircraft (References 2, 3, 4 and 5). These programs concentrated on the longitudinal flying qualities of highly augmented fighter aircraft for maneuvering and tracking tasks (Flight Phase Category A). In particular, pitch maneuver response criteria which consider the total aircraft dynamic system were developed by Neal and Smith (Reference 4) for fighter aircraft performing tracking tasks. The closed-loop pitch attitude tracking criterion of Reference 4 has, in fact, been used with good success as a flying qualities evaluation tool for today's complex fighter aircraft.

In the absence of suitable flying qualities data for the landing approach task (Flight Phase Category C), the concepts developed in Reference 4 were modified somewhat and extrapolated to cover this flight phase (References 6 and 7). Unfortunately, this attempt to provide a suitable

flying qualities criterion for this important flight phase which is applicable to fighter aircraft with significant control system dynamics failed its first real test.

Briefly the story of the test is as follows. Prior to their first flights, both the YF-16 and YF-17 prototypes were simulated in the NT-33A in-flight simulator (Reference 8); these aircraft are both highly augmented and exhibit higher order responses to pilot inputs due to the presence of significant control system dynamics. Of particular interest at this point is the experience in the NT-33A with the landing approach simulation of the YF-17.

- First, the original longitudinal flight control system as simulated in-flight, resulted in very poor flying qualities in the landing approach task, particularly in the final stages of the approach close to the runway.
- Second, this landing problem was not predicted by existing pitch maneuver response criteria, including the extrapolation of the closed-loop Neal/Smith criterion.
- Third, the very poor longitudinal flying qualities in the landing approach were not observed during ground simulation studies on a very sophisticated simulator; however, the deficiencies were dramatically exposed during the initial in-flight simulation sorties.

Control system modifications were then proposed, implemented, and evaluated in the NT-33A until satisfactory longitudinal flying qualities were observed.

The lessons presented by the YF-17 landing approach simulation experience, in combination with the previous research programs documenting the significant effects of control system dynamics on longitudinal flying qualities, clearly indicated the need for landing approach flying qualities data applicable to highly augmented aircraft. Further, the evidence showed that the tasks must include actual touchdowns. The research program described in this paper was conceived in response to these observations.

The purpose of the research program described in this paper may be summarized as follows:

- To gather pertinent background data on the longitudinal flying qualities of highly augmented fighter aircraft for the landing approach flight phase - including the flare and touchdown (Flight Phase Category C, Class IV.)
- To show whether the flare and touchdown tasks are indeed more demanding than the approach task alone and therefore are the critical landing approach task.
- To lay the groundwork for the development of longitudinal response criteria for the landing approach tasks which are applicable to aircraft with complex control systems, as well as those whose dynamics can be described by classical parameters.
- To gather data on pilot induced oscillations (PIO's) in the landing task with which existing PIO criteria can be evaluated.

The results of the research program using the NT-33A in-flight simulator to study the effects of control system dynamics on landing approach longitudinal flying qualities are summarized in the remainder of this paper. A more detailed account of this research program is presented in the final report, Reference 14.

Section 2 EXPERIMENT DESIGN

2.1 OBJECTIVES

The objective of the in-flight simulation program was to produce an approach and landing longitudinal flying qualities data base from which a suitable response criterion, applicable to highly augmented fighter aircraft, can eventually be developed. Accordingly, the primary evaluation characteristics were selected using the rationale that a broad range of representative aircraft and control system dynamics should be explored rather than specific control system augmentation schemes. In addition, a small portion of the flight program was devoted to the evaluation of configurations with special features; the details of these configurations are discussed in Subsection 2.5. The following subsection is directed at the primary evaluation configurations.

2.2 EXPERIMENT VARIABLES

The block diagram of Figure 2-1 represents how the pilot would view the total longitudinal pitch dynamic "package" which he flies.

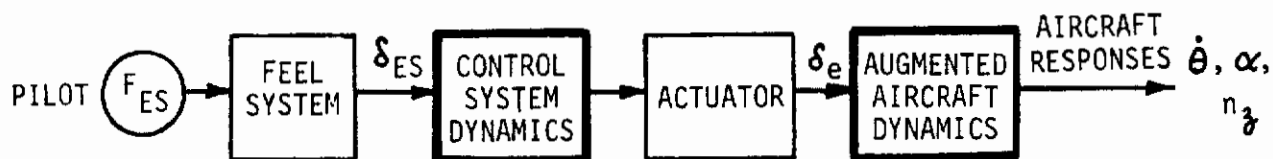


Figure 2-1. LONGITUDINAL RESPONSE BLOCK DIAGRAM

The primary variables in the experiment are the dynamic elements in the heavy blocks: the control system dynamics and the aircraft dynamics. One assumes that we are dealing with aircraft in which the desired augmented aircraft dynamics are achieved, but additional dynamics are introduced in the form of prefilters, compensation networks, or digital computational

delays - to produce a higher-order system. The term "higher-order system" is used to describe a system with additional significant dynamic modes in addition to the classical short period and phugoid longitudinal response modes. An alternate viewpoint would be that the aircraft dynamics, representing the bare airframe, are combined with prefilter dynamics to produce a higher-order system. The controlled experiment variables may be summarized as follows:

- Aircraft short period dynamics
- Control system dynamics
- Task
 - Full task, including flare and touchdown, or
 - Approach-only task with no touchdown

The details of the aircraft dynamics and control system dynamics selected to form the primary evaluation configurations are discussed in the following subsections.

2.3 AIRCRAFT SHORT PERIOD DYNAMICS

In the absence of significant control system dynamics the constant speed transfer function relating pitch attitude to pilot stick displacement is:

$$\frac{\theta}{\delta_{ES}} = K_{\theta} \frac{(\tau_{\theta_2} s + 1)}{s \left(\frac{s^2}{\omega_{SP}^2} + \frac{2\zeta_{SP}}{\omega_{SP}} s + 1 \right)}$$

Five combinations of ω_{SP} and ζ_{SP} were selected to span fairly wide ranges, relative to the requirements of MIL-F-8785B (Category C). These configurations represent the experiment base configurations; each set of evaluation configurations consists of a base configuration in combination with a variety of control system dynamics. The five base configurations (1-1 through 5-1) are compared with the Category C MIL-F-8785B requirements in Figure 2-2 for the nominal landing flight condition, which is:

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- V_{ind} = 120 knots
- V_T = 205 ft/sec
- n_z/α = 4.5 g/rad
- τ_{θ_2} = 1.4 sec
- $1/\tau_{\theta_2}$ \approx 0.7 rad/sec

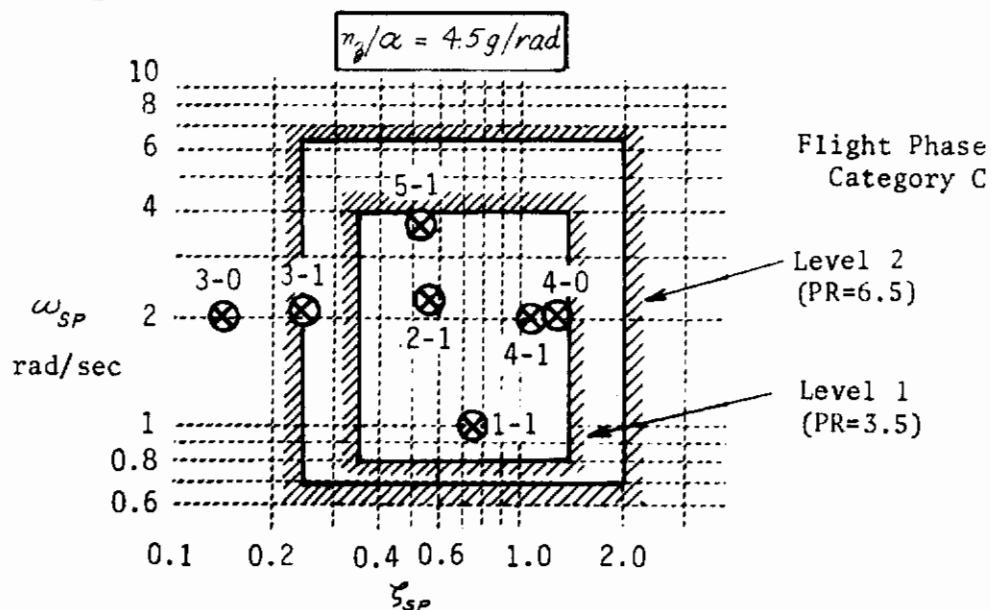


Figure 2-2. COMPARISON OF PRIMARY SHORT PERIOD CONFIGURATIONS WITH MIL-F-8785B

Configurations 3-0 and 4-0, shown in Figure 2-2, represent alternate base configurations which were never evaluated in combination with additional control system dynamics. The very lightly damped configuration (3-0) was specifically selected because it was predicted to be PIO-prone. Along with those configurations in which the addition of control system dynamics produce PIO's, this configuration was intended as an appropriate test of the PIO criterion of Reference 9. Configuration 4-0 was selected as a representative heavily damped configuration but was rejected as a base configuration in the initial phases of the evaluation flying because it was rated unsatisfactory by the pilot.

2.4 CONTROL SYSTEM DYNAMICS

Each base short period configuration was evaluated in combination with a variety of representative control system dynamics. The various forms of the control system dynamics selected which are representative of typical modern flight control system elements are summarized as follows:

- First order lag, $\frac{1}{\tau_2 s + 1}$, or
- First order lead/lag, $\frac{\tau_1 s + 1}{\tau_2 s + 1}$, or
- Second order lag prefilter $\frac{1}{\frac{s^2}{\omega_3^2} + \frac{2\zeta_3}{\omega_3} s + 1}$, or
- Fourth order lag prefilter $\frac{1}{\left(\frac{s^2}{\omega_3^2} + \frac{2\zeta_3}{\omega_3} s + 1\right) \left(\frac{s^2}{\omega_4^2} + \frac{2\zeta_4}{\omega_4} s + 1\right)}$

2.5 ADDITIONAL EVALUATION CONFIGURATIONS

Since the approach and landing results of the YF-17 simulation program conducted in the NT-33 (Reference 8) represent such a significant example of the effects of control system dynamics on longitudinal flying qualities, the previously simulated original and modified YF-17 configurations were selected for evaluation in this program. The original YF-17 landing case also represents an excellent data point for testing the PIO criterion suggested in Reference 9. In addition, inclusion of this case affords the opportunity to evaluate thoroughly a significant anomaly in the world of simulation: the extreme PIO problem was not observed during ground simulation studies but was clearly evident in the in-flight simulation. The configurations are identified as:

- 6-1: YF-17 original control system
- 6-2: YF-17 modified control system

In support of suggested revisions to MIL-F-8785B in the area of longitudinal static instability, three statically unstable configurations were evaluated. Essentially these configurations are Configuration 2-1 with the center of gravity moved aft of the neutral point ($M_{\alpha} > 0$). These configurations are representative of failure states which could possibly occur in highly augmented aircraft like the F-16 which operate at negative static margins. If the angle of attack feedback should fail in this condition the pilot could be faced with landing a statically unstable aircraft. These configurations are identified as:

- 7-1, 7-2, 7-3

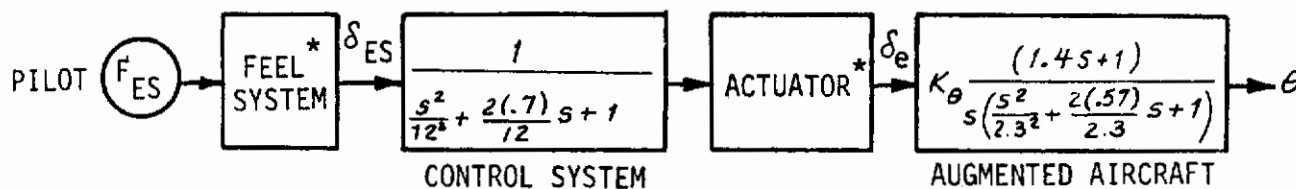
2.6 CONFIGURATION SUMMARY

A total of 49 configurations were evaluated: 44 basic control system/short period configurations and 5 additional configurations, as summarized in Figures 2-3 and 2-4.

The existing Neal/Smith longitudinal flying qualities evaluation criterion (Reference 4) and the results of a study of the YF-16, YF-17 simulation program (Reference 10) were used to guide the initial configuration selection; the digital computer version of the criterion developed by Mayhew (Reference 11) was used in this process.

Before attempting to interpret the configuration summaries in Figures 2-3 and 2-4, a brief review is in order. A typical evaluation configuration consists of the dynamic elements of the feel system, control system, aircraft and actuator in series. For example, the constant speed transfer function of pitch attitude response to pilot stick force for Configuration 2-7 is:

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* Feel system and actuator dynamics were fixed; details are in Subsection 2.7.

The value of K_{θ} is a function of the elevator gearing selected by the evaluation pilot as discussed in Subsection 2.8.

The CONTROL SYSTEM and AIRCRAFT DYNAMICS for the primary evaluation configurations are summarized in Figure 2-3; the important characteristics of the additional configurations are summarized in Figure 2-4. Remember that the total configuration dynamic model for each configuration includes the fixed dynamic contribution of the feel system and the actuator.

For the majority of the configurations (1 through 6), the phugoid, or long term, response characteristics are those of the NT-33 as modified somewhat by the longitudinal feedback gains used to achieve the short period dynamics. Details are given in Reference 14. From the flight path control viewpoint, all the evaluations were on the "front side" of the power required versus drag curve.

CONTROL SYSTEM DYNAMICS				SHORT PERIOD DYNAMICS (Nominal)				
				$V_{ind} = 120 \text{ Kt}$				
				$n_z/\alpha = 4.5 \text{ g/rad}; \tau_{\theta_2} = 1.4 \text{ sec}$				
				ω_{SP}/ζ_{SP}				
τ_1	τ_2	ω_3/ζ_3	ω_4/ζ_4	1.0/.74	2.3/.57	2.2/.25	2.0/1.06	3.9/.54
0.4	0.1	-	-	1-A	2-A			
0.3	0.1	-	-	1-B				
0.2	0.1	-	-	1-C	2-C	3-C	4-C	
↓	0	-	-	1-1	2-1	3-1(3-0)*	4-1(4-0)*	5-1
	0.1	-	-	1-2	2-2	3-2		
	0.25	-	-	1-3	2-3	3-3	4-5	5-3
	0.5	-	-	1-4	2-4		4-4	5-4
	1.0	-	-					5-5
	0	16/.7	-	1-6	2-6	3-6	4-6	5-6
	↓	12/.7	-		2-7	3-7	4-7	5-7
	↓	9/.7	-	1-8				
	↓	6/.7	-		2-9			
	↓	4/.7	-		2-10		4-10	
	0	0	16/.93	16/.38	1-11	2-11		4-11

* ω_{SP}/ζ_{SP} for Configuration 3-0 is 2.1/.14; for Configuration 4-0, 2.1/1.23

- NOTES:
- First number indicates base aircraft configuration simulated; second number or letter identifies control system dynamics; letters for control system lead; numbers for lag.
 - Total configuration dynamic model includes feel system and actuator dynamics (see Subsection 2.7).

Figure 2-3. SUMMARY OF PRIMARY EVALUATION CONFIGURATIONS

CONFIGURATION	CONTROL SYSTEM DYNAMICS	ω_{SP} / ζ_{SP}
6-1 (YF-17 Original)	$\frac{(.5s+1)(.43s+1)}{(.2s+1)(1.1s+1)\left(\frac{s^2}{4^2} + \frac{2(.7)}{4}s+1\right)}$	1.9 / .65
6-2 (YF-17 Modified)	$\frac{(.5s+1)(.43s+1)(.065+1)}{(.2s+1)(.1s+1)(1.1s+1)}$	1.9 / .65
	Time to Double Amplitude, T_d (Sec)	
7-1		≈ 6
7-2		≈ 4
7-3		≈ 2

NOTES: • Total configuration dynamic model includes feel system and actuator dynamics (see Subsection 2.7).

Figure 2-4. SUMMARY OF ADDITIONAL EVALUATION CONFIGURATIONS

2.7 PITCH FEEL SYSTEM AND ACTUATOR CHARACTERISTICS

The feel system characteristics were held fixed for all the configurations evaluated in the program; a representative spring gradient of 8 lb/in was chosen and essentially zero breakout or friction forces were present. The feel system transfer function is:

$$\frac{\delta_{ES}}{F_{ES}} = \frac{.125}{\left(\frac{s^2}{26^2} + \frac{2(.6)s}{26} + 1\right)} \quad (\text{in./lb})$$

The NT-33 pitch actuator characteristics were essentially constant for all configurations with the following values:

$$\omega_a = 75 \text{ rad/sec}$$

$$\zeta_a = 0.7$$

2.8 PITCH CONTROL SENSITIVITY

The gearing ratio between the elevator and the stick position was selected by the pilot for each flight evaluation of a configuration, as discussed in more detail in Section 3. Ideally each dynamic configuration should have been evaluated with several values of gearing ratio, but this procedure was beyond the scope of this flight program.

Section 3 CONDUCT OF THE EXPERIMENT

The control system and aircraft dynamics discussed in Section 2 were mechanized in the USAF variable stability NT-33, operated by Calspan (see Figure 3-1) and described in Reference 12.



Figure 3-1. USAF/CALSPAN VARIABLE STABILITY NT-33 AIRCRAFT

3.1 SIMULATION SITUATION

For this program, the simulated aircraft was defined as an all-weather, single seat, fighter aircraft (Class IV). The pilot was therefore required to extrapolate to this environment which would include additional duties such as navigation and communication.

Since inclusion of wind and turbulence as controlled variables was beyond the limited scale of this program, flights were, of necessity, conducted in a wide range of wind and turbulence; conditions encountered are considered normal for typical fighter operations. The pilots were asked to evaluate the aircraft in the conditions of the day, but to comment, if desired, on the projected effects of different wind and turbulence conditions.

3.2 EVALUATION TASK SUMMARY

Since the exact definition of the task is important to any flying qualities investigation, the details of the tasks performed during each evaluation are summarized below. These tasks, in combination, provide the pilot with a solid basis for assessing the landing approach flying qualities of an evaluation configuration.

- ILS approach under simulated instrument conditions, down to 200 ft above runway, followed by a visual landing, plus
- Two visual close patterns and landings, with an intentional offset maneuver on close final in each case.

For those evaluations which intentionally did not include a touch-down, the same tasks were performed but a go-around was initiated at 50-100 ft above the runway.

Great care was taken to ensure that the evaluation pilots performed these tasks in a realistic fashion. For example, they were instructed to consider each approach and landing as a final "must land" situation; the 500 ft touchdown zone on the 9100 ft runway was clearly marked on the runway, beginning approximately 1500 ft from the threshold for flight safety reasons. The pilots were not allowed by the safety pilot to back out of the task and let the touchdown point drift down the runway in an unrealistic fashion. These instructions were not interpreted by the pilots to mean that the task was treated as an unrealistic "game" demanding unrealistic precision on the part of the pilots. Touchdown with normal sink rates could be made in the NT-33.

3.3 EXPERIMENT DATA

The data from the experiment take three forms: pilot ratings, pilot comments, and records of task performance, including the discrete error tracking tasks. Examples of the performance records are presented in Appendix II. The pilot ratings and comments are clearly tied together and should not be viewed as separate data. At the completion of the evaluation tasks, the pilot was asked to assign an overall pilot rating using the Cooper-Harper Rating Scale (Reference 13). In addition, for the evaluations which included the complete landing task, the pilot was asked to give a separate rating for the approach task alone (down to approximately 50 feet above the runway). Only during the last half of the program did the pilots feel confident enough to give both ratings. The pilots were asked to assign the ratings before making detailed comments since their task performance was then fresh in their minds.

After the initial ratings, the pilot was asked to make recorded comments on specific items listed in the Pilot Comment Card.

3.4 EVALUATION SUMMARY

The two pilots performed a total of 83 flight evaluations of the 49 different configurations during the program requiring 24 flights of approximately 1½ hours each. The distribution of evaluations and flights between the pilots is as follows:

	<u>PILOT A</u>	<u>PILOT B</u>
Flights:	17	7
Evaluations with Landings:	51	21
Evaluation with Low-Approach Only:	8	3

Section 4 EXPERIMENT RESULTS

The results of the experiment described in the preceding sections are in the form of pilot ratings, comments and records of task performance. Since a complete analysis of the data and the development of appropriate design criteria or flying qualities requirements is clearly beyond the scope of this program, the discussion of the results in this section is centered on the pilot rating and comment data; a limited discussion of the applicability of the Neal/Smith closed-loop pitch attitude tracking criterion is, however, included.

A summary of the pilot ratings for each configuration is presented in Table 4-1.

4.1 CORRELATION WITH MIL-8785B

The overall pilot ratings for the base configurations from each set of configurations - those with no significant additional control system dynamics - are compared in Figure 4-1 with the ω_{sp} , ζ_{sp} Category C boundaries from MIL-F-8785B (Reference 1). For these comparisons, the nominal 120 KIAS data are used.

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TABLE 4-1: PILOT RATING DATA SUMMARY

Config. No.	Aircraft ⁽¹⁾ ω_{so} / ζ_{so}	Control System ⁽²⁾			PILOT RATINGS			
					OVERALL ⁽⁴⁾		APPROACH ⁽³⁾	
		ζ_1	ζ_2	ω_3	PILOT A	PILOT B	PILOT A	PILOT B
1-A	1.0/.74	0.4	0.1	-	6(4TD)			
B		0.3	0.1	-	5			
C		0.2	0.1	-	4	4		
1-1		-	-	-	4	4		2
-2		-	0.1	-	5			
-3		-	0.25	-	9	10	6*	6*
-4		-	0.5	-	10			
-6		-	-	16	5		5*,2	
-8		-	-	9		8		5
-11		-	-	16(4th)		9		5
2-A		2.3/.57	0.4	0.1	-	4	6	2
-C	0.2		0.1	-	1½,4,3,1½		3	
2-1	-		-	-	2	2	3*	
-2	-		0.1	-	4½	4		
-3	-		0.25	-	6			
-4	-		0.5	-	9		5*	3*
-6	-		-	16	5		1½	
-7	-		-	12	7	6	4	3
-9	-		-	6		10		5
-10	-		-	4	10			
-11	-		-	16(4th)		8		4
3-C	2.2/.25	0.2	0.1	-	2	5(4TD)		5
3-0	2.1/.14	-	-	-	5,4			
3-1	2.2/.25	-	-	-	5(4TD)4	7(5TD)	5	7
-2	-	-	0.1	-	7		6*	
-3	-	-	0.25	-	10		7*	
-6	-	-	16	7	6	5	5	
-7	-	-	12	8		5		

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TABLE 4-1: PILOT RATING DATA SUMMARY (CONT.)

Config. No.	Aircraft ⁽¹⁾ ω_{sp} / ζ_{sp}	Control System ⁽²⁾			PILOT RATING			
					OVERALL ⁽⁴⁾		APPROACH ⁽³⁾	
		τ_1	τ_2	ω_3	PILOT A	PILOT B	PILOT A	PILOT B
4-C	2.0 / 1.06	0.2	0.1	-	3	3	1½	2
4-0	2.1 / 1.23	-	-	-	6			
4-1	2.0 / 1.06	-	-	-	2			
-3		-	0.25	-	5,7	8	2	5
-4		-	0.5	-	7	6	5*,4	3
-6		-	-	16	4		1½	
-7		-	-	12	3		3	
-10		-	-	4	9		6	
-11		-	-	16(4th)	8		3	
5-1	3.9 / .54	-	-	-	7	5		4
-3		-	0.25	-	4½,8	6	4*,3	3*,2
-4		-	0.5	-	6		2	
-5		-	1.0	-	7		2	
-6		-	-	16		6		3
-7		-	-	12	6		2	
-11		-	-	16(4th)	7		3	
6-1	1.9 / .65	Unmodified YF-17			10			
-2		Modified YF-17			2			
	T_d (Sec)							
7-1	≈ 6	-	-	-	4			
-2	≈ 4	-	-	-	3			
-3	≈ 2	-	-	-	4	6(3TD)	2	6

NOTES: (1) Aircraft dynamics are for 120 KIAS nominal case:

$$V_T = 205 \text{ ft/sec}; \quad n_z/\alpha = 4.5 \text{ g/rad}; \quad \tau_{\theta_2} = 1.4 \text{ secs.}$$

- (2) Complete control system includes feel system and actuator dynamics (see Subsection 2.7); 16 rad/sec fourth order prefilter designated: 16(4th)
- (3) Asterisk (*) indicates evaluations for low-approach only task
- (4) TD stands for "touchdown"; pilot rating better for landing than for approach in these cases.

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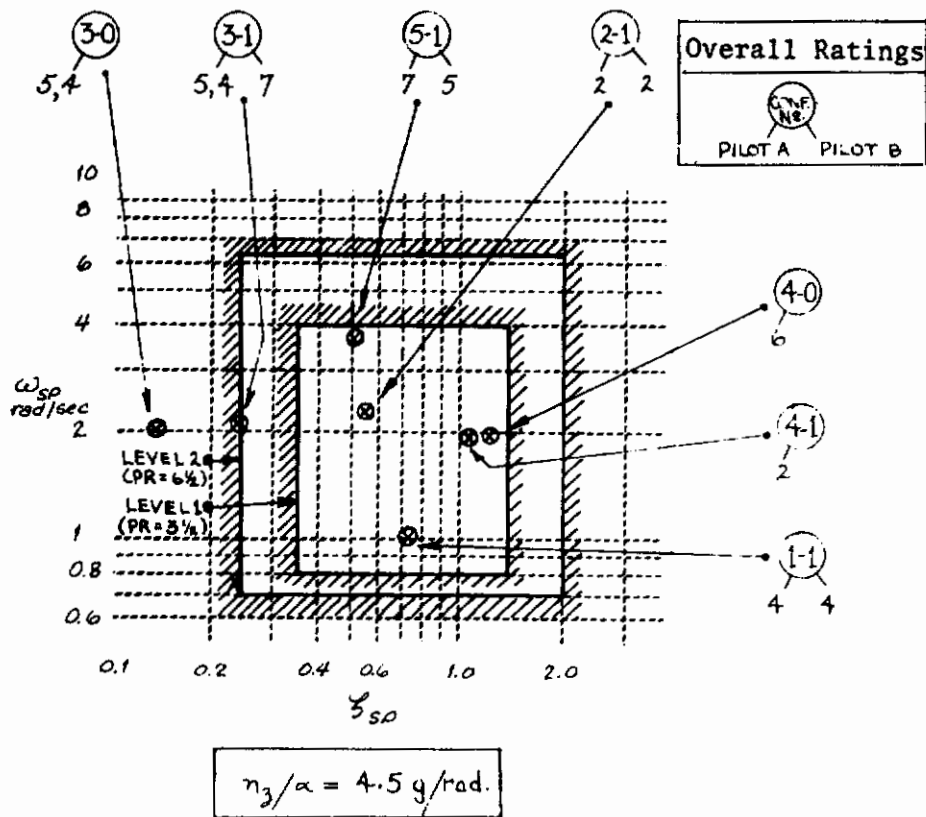


Figure 4-1. CORRELATION OF BASE CONFIGURATIONS WITH MIL-F-8785 (CATEGORY C)

Although the quantity of data is hardly enough to allow definitive comments, the following comments can be made. The pilot ratings for Configurations 2-1 and 4-1 agree reasonably well with the -8785B Level 1 boundaries, while the ratings for Configuration 1-1 indicate that the lower frequency Level 1 boundary is too lenient. For Configuration 3-1, and the alternate base Configuration 3-0, the ratings are somewhat less severe than the -8785B boundaries would predict. Since all of these ratings were obtained in relatively smooth air and turbulence effects would certainly degrade these configurations, the correlation is considered reasonable. The results for Configuration 5-1 indicate that the Level 1 upper boundary on ω_{sp} is too lenient. Although the configuration is likely only of academic interest since aircraft are typically low frequency in the landing approach, the boundary in -8785B does appear to be suspect. Evaluation of this configuration in moderate turbulence would further emphasize the lack of correlation.

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The rating for the alternate base Configuration 4-0 should be viewed with some caution. Although the pilot substantiated his rating on a subsequent flight, the sharp change in rating between Configurations 4-1 and 4-0 is somewhat hard to understand.

These comparisons with -8785B Category C flying qualities boundaries serve two purposes: first, the reasonable correlation of several of the configurations (2-1, 3-1 and 4-1) with the existing boundaries lends credibility to the overall experiment; second, the lack of correlation with the high frequency Level 1 boundary and the questions raised about the high damping ratio boundary indicate the need for more landing approach data in these areas. The fact that the majority of the original background data for -8785B in the landing approach flight phase did not include actual landings should not be forgotten. Since the landing task is clearly a "higher pilot gain task" than the approach task, Category A boundaries may very well be more appropriate for the approach and landing task requirements.

The general credibility of the pilot rating data for the base configurations provides a solid base from which to view the remainder of the pilot rating data for these same configurations evaluated with significant additional control system dynamics.

MIL-F-8785B presently contains a requirement which is intended to place limits on control system dynamics by restricting the phase lag, at the short period frequency, between the stick force input and the control surface response. Although the Category A substantiation data (from Reference 3) used for the requirement were not really applicable to the landing approach task (Flight Phase Category C), the requirement applies to this flight phase. In light of the observations from this experiment, this previously unfounded extrapolation has some merit since the two tasks are not apparently that different. The original data suggested a limit of 30 deg of phase lag for Level 1 flying qualities; as shown in Reference 4, this requirement, in its present form, does not apply to aircraft with significant control system

dynamic elements whose characteristics frequencies are close to the aircraft's short period frequency. The results from this experiment corroborate this finding; for example, consider Configurations 1-2 and 2-11. In each case the phase lag of the control system at the short period frequency is on the order of 30 deg, yet the pilot ratings are Level 3.

As observed in the previous control system dynamics experiment in the NT-33 (Reference 4), the pilot evaluates the total response of the aircraft to his inputs and is not concerned with, or even aware of, the characteristics of the individual dynamic elements which combine to produce that response. The step response time histories for the evaluation configurations are presented in Appendix III and illustrate the effects of the various types of control system dynamics evaluated. The high frequency elements, such as the "-6" cases, effectively preserve the shape of the short period response but introduce a transport time delay; while the low frequency elements, such as the "-4" cases, significantly alter the shape of the response to pilot inputs.

Requirements are obviously needed for the landing flight phase which are based on the characteristics of the total response and are not dependent on identifying the response with certain modes of motion, such as the short period response.

4.2 THE CRITICAL TASK: FLARE AND TOUCHDOWN

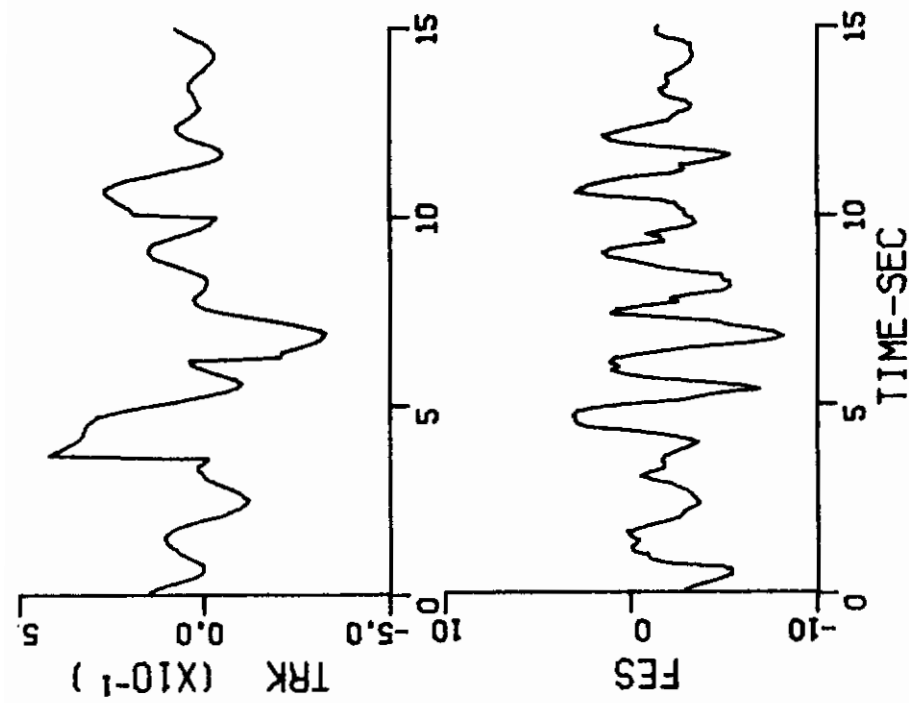
One of the objectives of the experiment was to determine whether the final stage of the approach and landing task - the flare and touchdown - is the critical piloting task. Evidence from the simulation of the YF-17 prototype with the original control system (Reference 12) suggested that the major pitch flying qualities problems occurred close to touchdown.

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The pilot rating data for the majority of the configurations clearly indicate that the landing task, which means the last 50 ft to touchdown, is the critical task. For the approach task, that is down to 50 ft above the runway, the pilot ratings are typically better than for the overall task which includes the landing task; the difference is dramatic when significant additional control system dynamics are present. Aircraft with good longitudinal flying qualities, such as Configurations 2-C, 2-1, and 4-C, show little difference in the pilot ratings for approach alone versus the overall task with a landing. On the other hand, aircraft with significant additional lag dynamics in the control system, such as Configurations 2-4 and 4-10, show significant differences between the approach alone and overall pilot ratings. The more stringent flare and touchdown task exposes the "flying qualities cliffs" hidden in these aircraft.

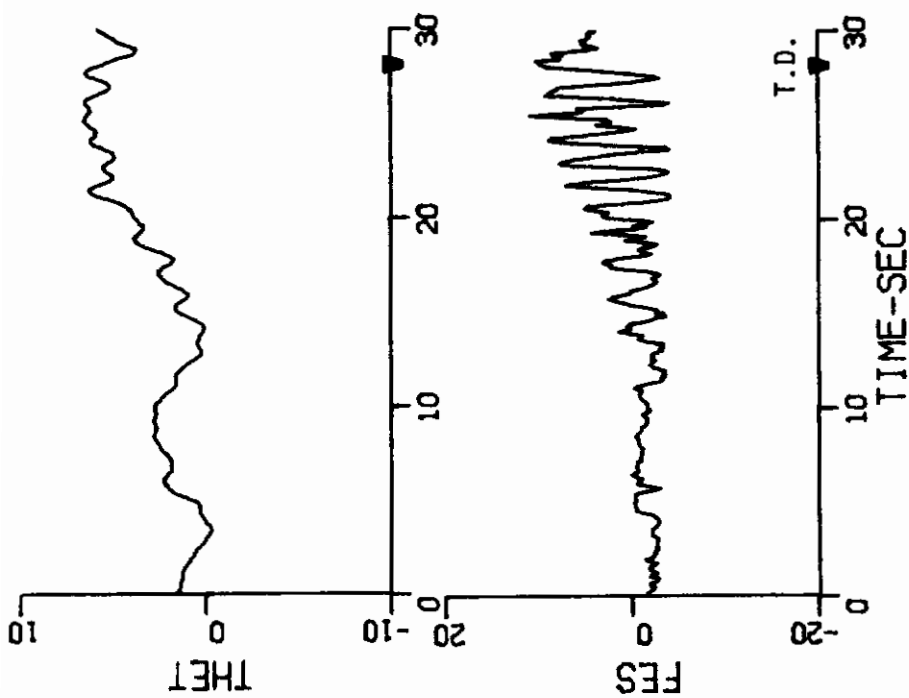
For those approach pilot ratings marked with an asterisk, a go-around was initiated 50 to 100 ft above the runway. The other approach ratings represent the pilot's assessment of the approach portion of the overall task while performing the complete touchdown task. The approach-only ratings confirm the same differences between the approach task and the landing task observed previously, except that the approach pilot ratings for a configuration tend to be worse when only the approach was performed. In general, this difference is not significant except for the approach-only rating given to Configuration 1-6 (PR=5). The configuration received a PR=2 when evaluated in the total task later on the same flight; this variation in rating on the same flight tends to reduce the significance of this rating anomaly.

The critical nature of the last 50 ft of the task environment is dramatically illustrated in the task performance time histories for Configurations 2-4 and 6-1 in Figures 4-2 and 4-5, where a PIO suddenly develops at this point in the task. For contrast, the task performance time histories for Configurations 2-1 and 6-2, without the additional control system dynamics are presented in Figures 4-3 and 4-4. On the figures, THET is pitch attitude in degrees and FES is longitudinal stick force in pounds; TRK is the pitch



CONFIG. 2-4, $\left(\frac{1}{.5 S+1}\right)$, PILOT A/1888,

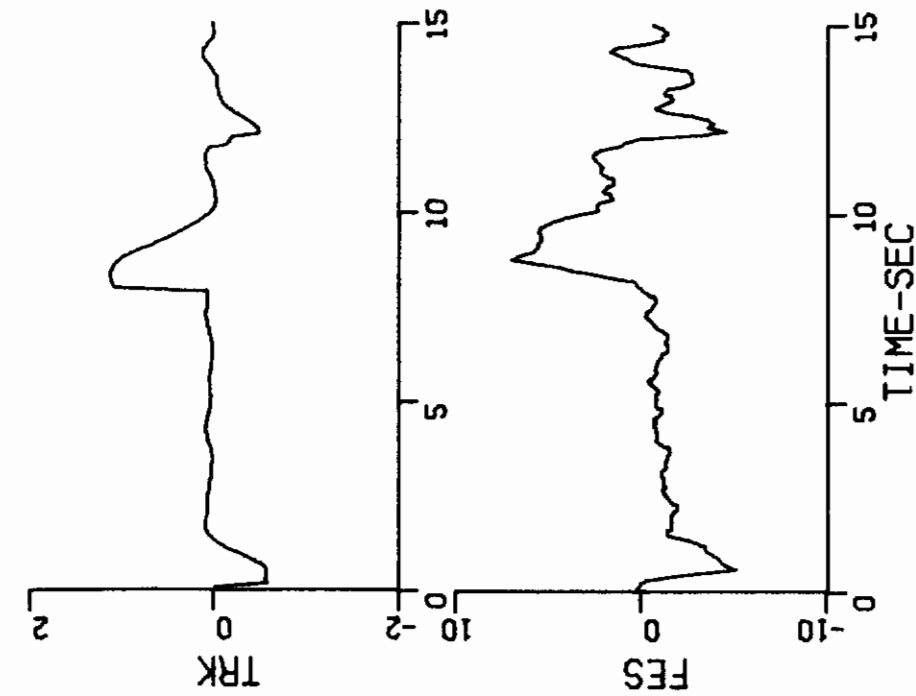
PITCH TRACKING TASK



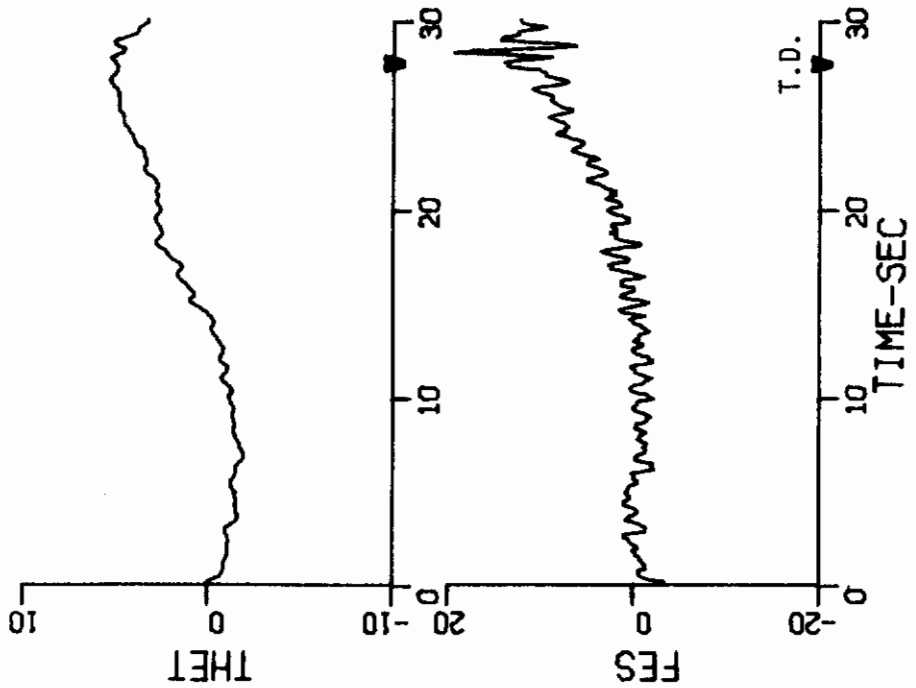
CONFIG. 2-4, $\left(\frac{1}{.5 S+1}\right)$, PILOT A/1888,

VISUAL LANDING TASK (PR = 9)

FIGURE 4-2

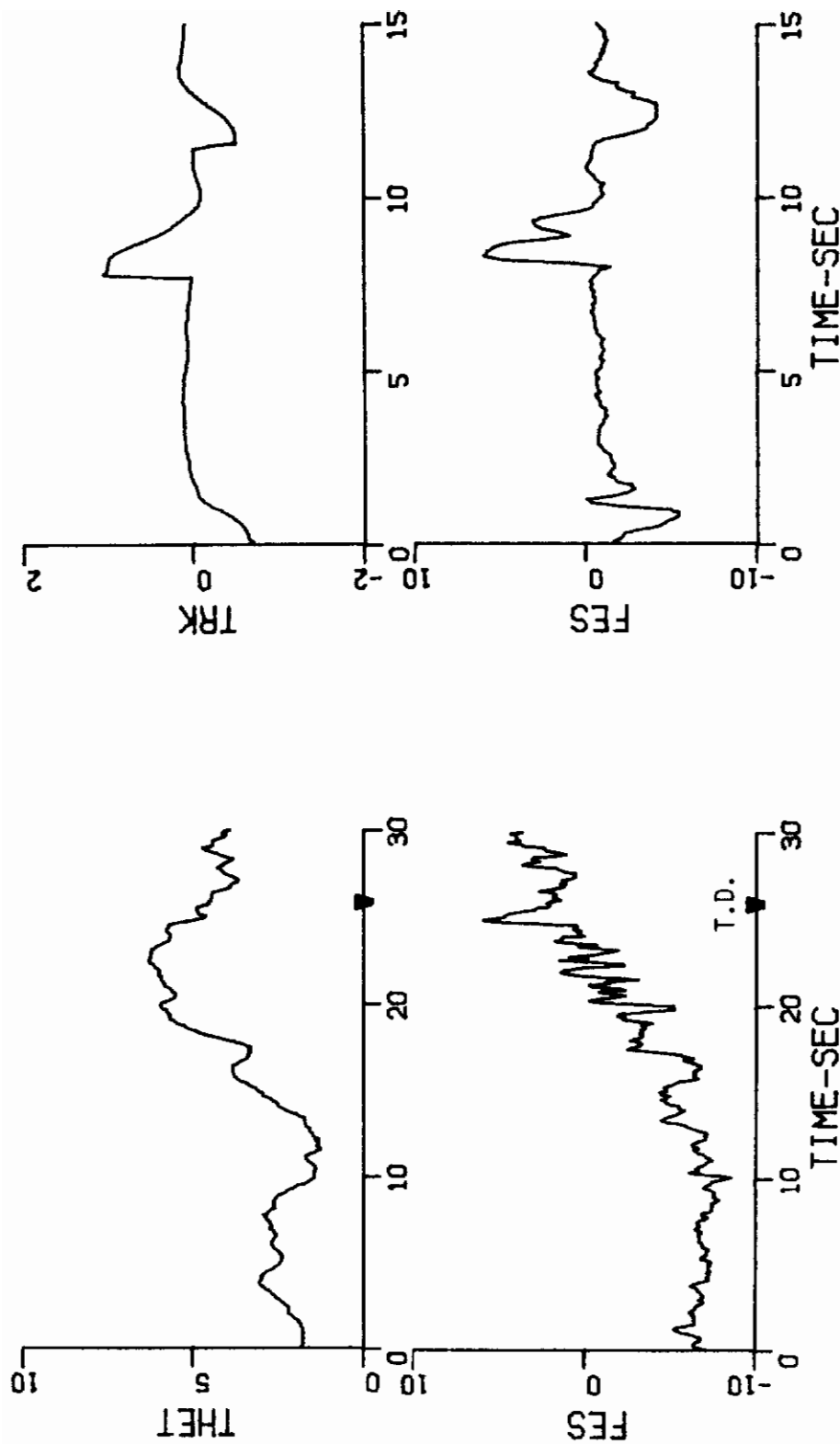


CONFIG. 2-1, PILOT B/1892, PITCH TRACKING TASK (PR = 2)



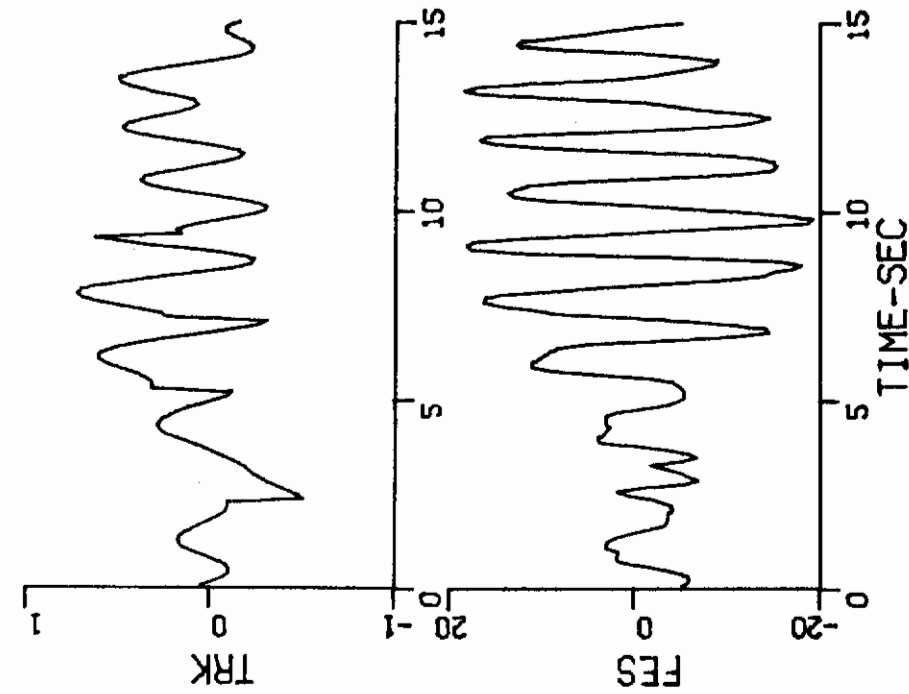
CONFIG. 2-1, PILOT B/1892, VISUAL LANDING TASK (PR = 2)

FIGURE 4-3



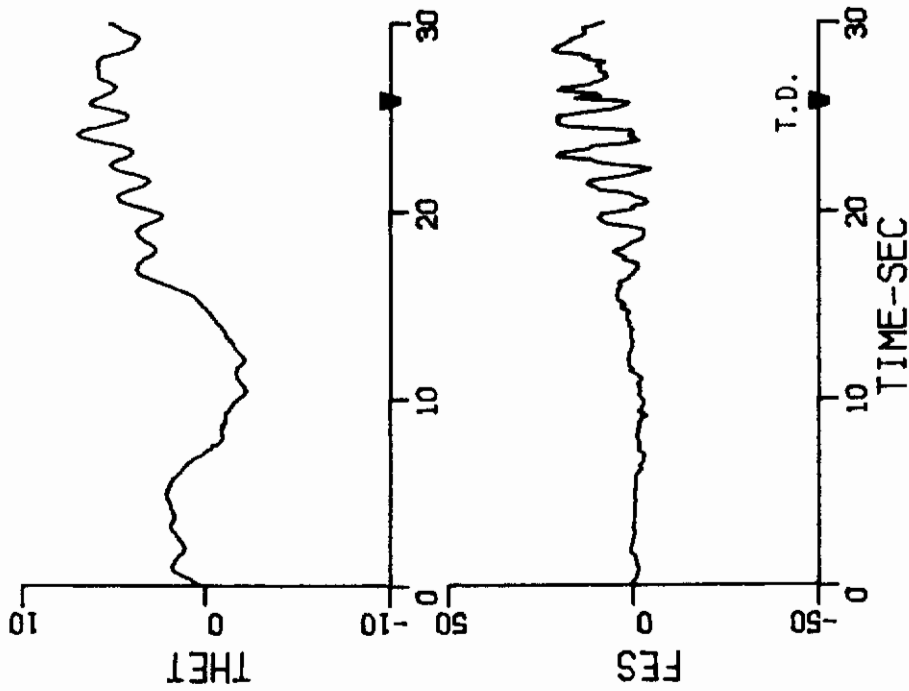
CONFIG. 6-2, PILOT A/1888, VISUAL LANDING TASK (PR = 2) CONFIG. 6-2, PILOT A/1888, PITCH TRACKING TASK (PR = 2)

FIGURE 4-4



CONFIG. 6-1, PILOT A/1888, PITCH

TRACKING TASK (PR = 10)



CONFIG. 6-1, PILOT A/1888, VISUAL LANDING

TASK (PR = 10)

FIGURE 4-5

attitude error on the tracking needle of a discrete error tracking task which the pilot performed after each evaluation, (see Reference 14 for details). Note the scale changes in stick force when comparing configurations.

Configurations 1-A, 3-0, 3-1, 3-C, 7-1, 7-2 and 7-3 represent exceptions to the observation that the landing task is the more critical task. For these configurations, which are essentially without significant control system dynamics, the pilots often commented that the flare and touchdown task was easier than the approach task. The pilot could fly the aircraft better in the flare than on the approach for reasons which further analysis will hopefully expose. All of these configurations, except 1-A, have a common feature: the basic aircraft has a major problem. Configuration 3 has a lightly damped short period response, while Configuration 7-1 through 3 are statically unstable. It could be that the initial response for these configurations is quick enough to allow the pilot to perform the exacting, fighter closed-loop, landing task more accurately than he can the approach task. During the less demanding approach task, the basic aircraft problems are more apparent and therefore annoy the pilot.

The evidence from this experiment indicates that the landing task is clearly different and generally more difficult than the approach task. In the landing task environment the pilot flies differently than on the approach - the experiment results, in general, show that he has a different standard of performance. The flying qualities of a configuration with a poor combination of dynamics can be degraded significantly by the demands of the landing task.

4.3 EQUIVALENT TRANSPORT TIME DELAYS

Since the use of digital flight control systems is now a reality, it is important to understand the impact on flying qualities of the transport time delays associated with the necessary digital computations. Unfortunately, exact time delays, i.e. not lags but delays during which no response occurs, were not included in this experiment. However, an equivalent time delay can be estimated for the high frequency control system elements evaluated in the

program. These elements, such as "-6" and "-11" for example, introduce phase lag but do not affect the amplitude of the response for frequencies near the relatively lower frequency short period. The effect of these higher frequency prefilters is therefore similar to a pure time delay ($e^{-\tau s}$) for frequencies much lower than the prefilter natural frequency.

For reference, the equivalent time delays, in milliseconds (ms), for the prefilters simulated are:

ω_n	Control System Element	τ_{equiv} (ms)
16	"-6"	90
12	"-7"	120
9	"-8"	160
6	"-9"	230
4	"-10"	250
16(4th)	"-11"	165
26	Feel System	45
75	Elevator Actuator	20

4.4 CONFIGURATION 7: STATICALLY UNSTABLE CASES

These configurations were included in the evaluation matrix as a mini-experiment to gain some insight into the effects of static instabilities on landing flying qualities. The increased capabilities of modern fly-by-wire flight control system designs enable fighter aircraft to operate at more efficient aft c.g. conditions. However, this condition means that the unaugmented aircraft is statically unstable. An obvious question which then arises is: If part of the augmentation system should fail and the pilot is left with a statically unstable vehicle, can he land it safely?

The evaluation results for these configurations are rather startling in that the pilots could perform the landing task with relative ease (PR 3 to 4) even with rapid divergences as severe as 2 seconds to double amplitude. In the tight-control landing task the static instabilities were not a problem and, in fact, were not even noticed by the pilots. Only for the most

unstable case, Configuration 7-3, was a problem evident and then only to Pilot B on the approach task (PR=6). It is reasonable that problems associated with the divergence should surface during the approach task in which the pilots control and attention is not as "tight".

4.5 PRELIMINARY CORRELATION WITH THE NEAL/SMITH CRITERION

Although a detailed analysis of the data from this program using the Neal/Smith closed-loop pitch attitude criterion developed in Reference 4 is beyond the scope of this report, some preliminary findings can be discussed.

The reader is referred to Reference 4 for details of the criterion; the important parameters which come out of the analysis are the closed-loop resonance and the pilot compensation at the bandwidth frequency. Recall that bandwidth can be viewed as the degree of aggressiveness with which the pilot makes changes in pitch attitude. Data for selected configurations from this preliminary analysis are presented below.

CLOSED-LOOP RESONANCE (dB)/PHASE ANGLE OF PILOT COMPENSATION (Deg)					
Config. No.	BANDWIDTH (rad/sec)				Average PR
	1.5	2.0	2.5	3.0	
2-1	3/-25	3/-6	5/20	6/42	2
2-C	-2/-25	3/-11	5/8	5/30	2½
4-1	-3/6	-3/27	-3/45	-1/59	2
6-2	-1/2	-1/27	0/48	3/61	2
2-9	3/-5	8/17	15/40	40/55	10
2-11	2/-17	7/11	11/40	19/52	8
4-2	-3/27	-2/50	3/65	8/74	6½
4-10	-2/37	4/57	12/71	32/77	9
5-1	-3/-43	0/-30	3/-18	12/-13	6
5-5	-3/-35	2/-23	9/-14	20/-8	7
6-1	0/27	6/53	16/67	30/80	10

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Assuming that the application of a closed-loop pitch attitude criterion is valid - a point which must be demonstrated with more detailed analysis - the following points can be made:

- No single bandwidth yields reasonable correlation with the flying qualities boundaries of Reference 4.
- Lower bandwidths (1.5 to 2.0) are required for the satisfactory aircraft ($PR < 3.5$) to correlate with the 3 db Level 1 boundary of Reference 4. The boundary may indeed be different for the landing task where it is reasonable that the pilot is more tolerant of attitude oscillations than in the air-to-air tracking situation.
- Higher bandwidths (2.5 to 3.0) are required to produce closed loop pitch tracking performance consistent with the pilot ratings and comments for the unacceptable aircraft ($PR > 6.5$).
- Although not listed, the results for Configuration 1 indicate that there must be a limit on pilot lead capability (time constant less than about 1.0 sec for acceptable ratings, $PR < 6.5$) to yield reasonable correlation.
- The sensitivity of the configuration to bandwidth appears to be a very important parameter. Note that all the satisfactory configurations show small changes in closed-loop resonance while each of the unacceptable aircraft show sharp changes in closed-loop resonance as bandwidth is increased.

Obviously, this brief discussion is incomplete but it does indicate that higher bandwidths than previously estimated (Reference 6) must be used for the landing task and that the sensitivity of the aircraft to a range of bandwidths may be an important correlation parameter.

Section 5 CONCLUSIONS

The experiment described in this paper utilized the NT-33 variable stability aircraft which is capable of reproducing a wide range of aircraft and control system characteristics. Therefore, the results are largely independent of the actual aircraft employed and are restricted only by the task, range of dynamics, flight conditions and aircraft and control system parameters realized in the experiment. Conclusions which may be drawn from this experiment on the effects of control system dynamics on longitudinal approach and landing flying qualities are:

- For aircraft with significant control system dynamics, the landing task, or flare and touchdown, is the critical piloting task.
- The critical area is the last 50 feet of the landing task; landing approach flying qualities evaluations must therefore include actual touchdowns, in a realistic environment, to be valid.
- Significant control system lags create PIO's in the landing task but not in the approach task; basic aircraft problems such as low short period damping or low static stability do not create PIO's in the landing task.
- For the landing approach task (Flight Phase Category C), the longitudinal flying qualities requirements of MIL-F-8785B(ASG) and suggested revisions are not applicable to aircraft with significant control system dynamics.
- Pilot could perform the landing task with relative ease (PR 3 to 4) even with rapid longitudinal divergencies as severe as 2 seconds time to double amplitude.

Contrails

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Jerry Lockenour, Northrop: The time histories you presented indicate that the pilot aggressiveness was clearly different in the landing as contrasted with the tracking task. Also, the aerial refueling task experiment in the NT-33 indicated a large change in aggressiveness, or gain, between the last five feet and the approach to the basket much like the difference you have shown between the landing and the approach. Would you compare the level of aggressiveness in the landing tasks with the tracking tasks?

Answer: Although a detailed analysis of the data has not yet been undertaken, it is clear that the last 50 feet to touchdown is where the action is. The degree of aggressiveness - the pilot gain, if you like - in this portion of the task appears to be similar to the gain used in tight up-and-away tracking tasks. In fact, it appears that the Flight Phase Category A boundaries would be more appropriate for the landing task than are the present Category C boundaries. Remember that the majority, if not all, of the existing back-up data in MIL-F-8785B for Flight Phase Category C doesn't include the critical landing task - the flare and touchdown.

In looking at the time histories for Configuration 6-1, it appears that the PIO frequency is quite different in the landing task as compared with the tracking task; therefore, the aggressiveness or gain is quite different. Not the case, observe the factor of two differences in the time scales (which I failed to point out at the time); both cases have approximately the same PIO frequency (between 4 and 4.5 rad(sec)).

Wayne Thor, ASD: The degradation of response characteristics (and pilot ability to do a task) with increasing criticality of the task... doesn't this reflect the change in pilot gain and frequency bandwidth with which the pilot attempts to perform these tasks? And therefore, couldn't we, (or has it been done) determine a human factors type limit on lag frequency and gain (separately or in combination) for a 5th through 95th percentile pilot which could then be examined over a range of expected values for a given task including the worst case combination for a given higher order system, to see if instability or some other dangerous or undesirable characteristic can be precipitated and identified?

Answer: We have been trying to model the pilot for years and I do not hold out much hope of actually measuring the pilot gain characteristics in a real task environment as opposed to a laboratory test situation. Special care is therefore required in interpreting pilot rating data for aircraft which have significant dynamic anomalies in the form of delays or lags.

Hans Stegall, NASA JSC: What is the required bandwidth for landing?

Answer: Extrapolations of the Neal-Smith criterion to the landing approach task suggested a bandwidth of 1.2 rad/sec. Although no definitive answer is available at this time since detailed analysis of the data has not been undertaken, it is clear that the appropriate

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bandwidth is much higher than 1.2 rad/sec. The bandwidth is likely of the same order as suggested for up-and-away pitch tracking, about 3 rad/sec.

Of more significance than the exact bandwidth is the rate of change of resonance - tendency to oscillate - with changes in bandwidth. Good aircraft have an orderly, linear increase of resonance with increasing bandwidth. In contrast, poor aircraft (Level 3) show sudden increases of resonance as bandwidth is increased - they have flying qualities "cliffs". In my view the aircraft should be free of these sudden degradations in closed-loop performance up to 3.5 rad/sec for acceptable flying qualities (Level 2).

J.E. Buckley, McAir: Having applied the method to all of the LAHOS configurations at B.W.'s ranging from 1.0 to 5.0 rad/sec, it was found that the variation of pilot compensation with increasing B.W. provided a clearer picture of pilot opinion problem areas than any fixed bandwidth, but that the LAHOS data correlated reasonably well at the originally recommended bandwidth of 3 to 3.5 rad/sec. Pilot time delay was 0.2 sec.

Tom Twisdale, Edwards FTC: We have found that there is no deficiency that is not uncovered in tracking even if the pilot compensates.

John Schuler, Boeing: Do you think that there are other variables to be considered close to the ground?

Answer: Yes, we have really been dealing directly with the inner loop problems in this experiment. Good control of the inner loop is clearly a necessary but perhaps not sufficient condition for good approach and landing flying qualities. We would like to establish requirements or criteria to guarantee good inner loop control as a first step.

John Hodgkinson, McAir: Why do you think advanced ground simulators don't produce the PIO problems shown in the in-flight simulator?

Answer: I do not know the exact reason but there are obviously some factors missing - because of visual or motion drive problems perhaps - which cause the pilot to fly differently. In PIO prone configurations, these differences can be significant. It would certainly be useful to repeat some of the LAHOS data in an advanced ground simulator and shed some light on this anomaly. For landing tasks, at least, in-flight simulators must be included in the design and development process.

Chick Chalk, Calspan: I tried to model a simple closed-loop problem for Configuration 6-1 using acceleration at the pilot's station, pitch attitude and flight path angle. I could not get close to the PIO frequencies for flight path closures and could not get the PIO frequency with attitude without decreasing the pilot's time delay to 0.2 sec. A more complex model that includes pitch angular acceleration seems to be necessary.