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# The Effects of Elevator Rate Limiting and Stick Dynamics on Longitudinal Pilot-Induced Oscillations

Patrick J. Peters

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THESIS

Patrick J. Peters, Captain, USAF

AFIT/GAE/ENY/97M-02



**DEPARTMENT OF THE AIR FORCE**

**AIR UNIVERSITY**

**AIR FORCE INSTITUTE OF TECHNOLOGY**

**Wright-Patterson Air Force Base, Ohio**

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THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

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In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Aeronautical Engineering

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# Preface

The purpose of this thesis was to investigate of the effects of elevator rate limiting and stick dynamics on longitudinal pilot induced oscillations (PIO). The investigation was conducted in two parts. A simulation study was accomplished mainly to prepare for the flight test, but also to gain insight into the rate limiting problem and the effects of stick dynamics. Due to the non-numerical nature of the simulation results, a flexible, three-phase flight test was conducted.

The flight test led to three major conclusions. First, the offset landing task flown was insufficient to consistently uncover handling qualities deficiencies of the aircraft configuration flown. Second, rate limiting did not necessarily cause PIOs. At very low rate limits the problem was the lack of pitch response, not PIO. Any observed oscillations were very low frequency and small in amplitude. Third, for this configuration and task, variations in stick spring constant and natural frequency had negligible effect on the performance of the system with respect to assigned PIO and Cooper-Harper ratings. These conclusions are specific to this system and may not apply to all aircraft, especially aircraft where PIO tendencies are driven by much higher rate limits.

The study was conducted as a thesis under the joint Air Force Institute of Technology (AFIT)/USAF Test Pilot School (TPS) program which was a great opportunity now that it's over. This effort would not have been possible without the help of many others. I would like to thank my advisors: Lt Col Brian Jones (AFIT), who got me started and steered me away from non-linear techniques and complex pilot models; Dr. Brad Liebst (AFIT), who helped me finish this project; and Lt Col Dan Gleason (TPS), who prompted me to keep the project alive while I was busy being a TPS student. I also need to thank Mr. Dave Leggett of Wright Laboratory's

Flight Control Division, who sponsored the project and provided much of the background information required. Many thanks to Mr. Ralph Smith of High Plains Engineering in Mojave, California, without whom the simulation study would not have been possible. He offered his own time to get me started, gave me a simple pilot model, showed me how to simulate a PIO, and showed me a first order rate limited hydraulic actuator model from which I could derive my actuator model. The flight test would not have been possible without the contributions of Mr. Russ Easter and the rest of the CALSPAN team. His experience and willingness to spend long hours implementing our model were critical to the successful completion of the program. I need to give much of the credit for the flight test and report to the rest of the HAVE GRIP test team, which included Captains Duncan Dversdall, Frode Andre Evensen (Royal Norwegian Air Force), Patrick Tom, and Dror Wolf (Israeli Air Force). Duncan deserves a second mention for volunteering to take dictation and proofread parts of this report well after our TPS graduation. Most of all, I want to thank my wife, Rachel, and boys, Paul and Buddy, for putting up with all those late nights, long hours, and times when Daddy just couldn't play.

Patrick J. Peters

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## *List of Abbreviations, Acronyms, and Symbols*

| Abbreviation | Definition | Unit |
|---|---|---|
| A/C | Aircraft | --- |
| AFB | Air Force Base | --- |
| AGL | Above ground level | ft |
| CH | Cooper-Harper | --- |
| CHR | Cooper-Harper rating | --- |
| Delay | Pilot delay in pilot model | |
| de | Elevator deflection | deg |
| dec | Elevator deflection commanded | deg |
| deg | Degree(s) | --- |
| derate | Elevator rate | deg/sec |
| $F_{es}$ | Longitudinal stick force | lb |
| $F_{S\,max}$ | Longitudinal stick force exerted by pilot model | lb |
| ft | foot, feet | --- |
| ILS | Instrument landing system | --- |
| in | inch(es) | --- |
| KIAS | Knots indicated airspeed | --- |
| K | Stick parameter multiplier | --- |
| $K_s$ | Stick spring constant multiplier | --- |
| $K_\omega$, $K_w$ | Stick natural frequency multiplier | --- |
| $K_\zeta$ | Stick damping ratio multiplier | --- |
| kts | Knot(s), nautical air miles per hour | --- |
| Lear II | CALSPAN Variable Stability Learjet Model 25, Registration number N102VS | --- |
| lb | Pound(s) | --- |

## *List of Abbreviations, Acronyms, and Symbols (Continued)*

| Abbreviation | Definition | Unit |
|---|---|---|
| MSL | Mean sea level | ft |
| NM | Nautical mile | --- |
| PIO | Pilot-induced oscillation | --- |
| PIOR | Pilot-induced oscillation rating | --- |
| PTI | Programmed test inputs | --- |
| q | Pitch rate | deg/sec |
| $q_{thresh}$ | Pilot model pitch rate threshold | deg/sec |
| RL | Elevator rate limit | deg/sec |
| rad | Radian | --- |
| s | Laplacian operator | --- |
| sec | Second(s) | --- |
| $T_{last}$ | Simulated PIO duration | sec |
| TPS | Test Pilot School | --- |
| theta | Pitch angle | deg |
| VSS | Variable stability system | --- |
| USAF | United States Air Force | --- |
| $\delta_e$ | Elevator deflection | deg |
| $\delta_{ec}$ | Elevator deflection commanded | deg |
| $\delta_{es}$ | Longitudinal stick deflection | in |

## Abstract

This report presents the results of a limited investigation into the effects of elevator rate limiting and stick dynamics on longitudinal pilot-induced oscillations (PIO). The study was conducted as a thesis under the joint Air Force Institute of Technology (AFIT)/ USAF Test Pilot School (TPS) program and was sponsored by the Flight Control Division of Wright Laboratory.

A simulation study was conducted mainly to prepare for the flight test, but also to gain insight into the rate limiting problem and the effects of stick dynamics. Based on the simulation study, a fairly rapid onset of rate limiting effects was expected for the flight test. An increase in the stick spring constant was expected to significantly improve PIO ratings for rate limits within the range of interest. An increase in the natural frequency of the stick was expected to slightly improve PIO ratings for rate limits within the range of interest. Due to the non-numerical nature of the simulation results, a very flexible flight test plan was required.

To provide the necessary flexibility, the flight test was performed in three phases. The first phase identified the range of elevator rate limits to be used during Phases 2 and 3. The second phase identified the modified stick dynamics to be used in Phase 3. Phase 3 investigated the effects of elevator rate limiting and stick dynamics on PIOs during an offset landing task.

There were three major conclusions. First, the offset landing task flown was insufficient to consistently uncover handling qualities deficiencies of the aircraft

configuration flown. Second, rate limiting did not necessarily cause PIOs. At very low rate limits the problem was the lack of pitch response, not PIO. Any observed oscillations were very low frequency and small in amplitude. Third, for this configuration and task, variations in stick spring constant and natural frequency had negligible effect on the performance of the system with respect to assigned PIO and Cooper-Harper ratings. These conclusions are specific to this system and may not apply to all aircraft, especially aircraft where PIO tendencies are driven by much higher rate limits.

# THE EFFECTS OF ELEVATOR RATE LIMITING AND STICK DYNAMICS ON LONGITUDINAL PILOT-INDUCED OSCILLATIONS

## I. *Introduction*

### General

The purpose of this simulation study and flight test was to investigate the effects of elevator rate limiting and stick dynamics on longitudinal pilot-induced oscillations (PIO). The effects of rate limiting and stick dynamics on the PIO tendency of an aircraft are not fully understood. In order to develop updated standards for the next revision of MIL-STD-1797A (Reference 10), a better understanding of these interactions is required.

This investigation was requested by the Flight Control Division of Wright Laboratory. The simulation study was conducted at the Air Force Institute of Technology (AFIT), Wright-Patterson AFB, Ohio. The flight test was performed in the CALSPAN Variable Stability Learjet Model 25, registration number N102VS (Lear II) under contract to USAF Test Pilot School (TPS) and was conducted under the authority of USAF TPS, Edwards AFB, California. Flights were flown out of Edwards AFB with testing conducted at Air Force Plant 42, Palmdale, California, under USAF TPS Job Order Number

M96J0200. Electronic flight test data is available from the Flight Control Division of Wright Laboratory.

## Background

**Motivation.** PIOs have been experienced throughout the history of aviation, contributing to or causing many accidents and incidents along the way (Reference 26). PIOs are defined by Mil Std 1797A as "sustained or uncontrollable oscillations resulting from efforts of the pilot to control the aircraft" (Reference 10). The oscillation is undesired and occurs when tight control is attempted. We understand how many (mostly linear) causes of PIOs affect aircraft control and can minimize or eliminate them through the proper design of an aircraft's flight control system.

One cause that is not very well understood, but has been the principal nonlinear effect known to contribute to PIO, is control actuator rate limiting (References 29 and 3). Rate limiting has been observed in almost all severe recorded PIOs as was the case in PIOs experienced by the Space Shuttle, the YF-22, and the JAS-39 Grippen (References 13, 27, and 20). Each of these aircraft has experienced at least one documented PIO in the pitch axis, which in the case of the YF-22 and JAS-39 resulted in the loss of the aircraft (Reference 14).

Stick dynamics (damping ratio, natural frequency, displacement response gradients, force displacement gradients, friction, breakout, etc.) also play a large part in PIOs (Reference 28). A better understanding of the interplay between stick dynamics and rate limiting, and their effects on PIOs will help develop flight control systems that are less susceptible to PIOs caused by rate limiting.

**Review of Classical PIO Theory.** PIOs are often encountered suddenly and unexpectedly, ranging in severity from small or just a nuisance to severe or even catastrophic (References 27, 26, and 2). The fact that the pilot is human and adaptive in nature also makes it very difficult to predict PIOs (References 3 and 2). Because of the unpredictability and potential hazards of PIOs, there is certainly a need for aircraft engineers to understand them.

Mr. Ralph Smith developed much of the classical PIO theory and identified three basic types (Reference 37). A Type I PIO occurs when a pilot switches from tracking pitch attitude to tracking pilot-felt normal acceleration. A Type II PIO is initiated by sudden changes in the flight control system or non-tracking abrupt maneuvering (high g maneuvering, turning a stability augmentation system on or off, etc.) and is not likely during the landing phase of flight. A Type III PIO is initiated by pitch attitude tracking only with no relation to pilot-felt acceleration and is probable only when equivalent time delays are large enough to make the pitch angle to stick force ($\theta/F_s$) loop unstable.

Many others in the field have also classified PIOs into similar types such as linear, quasi-linear, and nonlinear (Reference 27). They have also listed many probable causes of PIO including: the linear airplane dynamics, cockpit control design and control/response sensitivity, nonlinear control system phenomena, actuator rate limiting, sluggish response modes, low damped modes, sensitive stick gradients, unstable response modes (that cannot be stabilized by the pilot), and unusual coupling responses (References 29 and 2).

However, "the typical cause of PIO is excessive phase lag and/or time delay in the flight control system that causes the pilot to get out of phase with the aircraft response when making control inputs" (Reference 6). This fact led Roger Hoh and David Mitchell to offer an alternative definition of PIO: "A PIO exists when the airplane attitude, angular rate, or normal acceleration is 180 degrees out of phase with the pilot's control inputs" (Reference 29).

Other researchers focus more on the pilot's role in PIO, claiming that "the most common cause of PIOs are excessive demands on the pilot" (Reference 4). The aircraft is stable, but the pilot closes the loop with an excessive gain causing the instability (Reference 13). "The oscillations can therefore be identified as closed-loop instabilities of a feedback control system" (Reference 26).

**Rate Limiting as a Cause of PIO.** Rate Limiting is hypothesized in this project to be a cause of PIO for two primary reasons. First, it introduces additional phase lag, or delay, between pilot commands and aircraft response. "The response of a rate-limited actuator will lag behind a rapidly changing command. This tends to destabilize the closed-loop system" (Reference 16). Figure 1-1 shows a representative time history of elevator command and elevator position with severe rate limiting from the simulation study. The phase lag can be envisioned by looking at the time difference between peaks of the command and position traces. It is also possible to see the delay by observing the lateral displacement between the two traces for a given elevator position. This time delay can drive the pilot/aircraft system unstable, but more than that, it drives the pilot to make faster inputs to compensate, which worsens the situation.

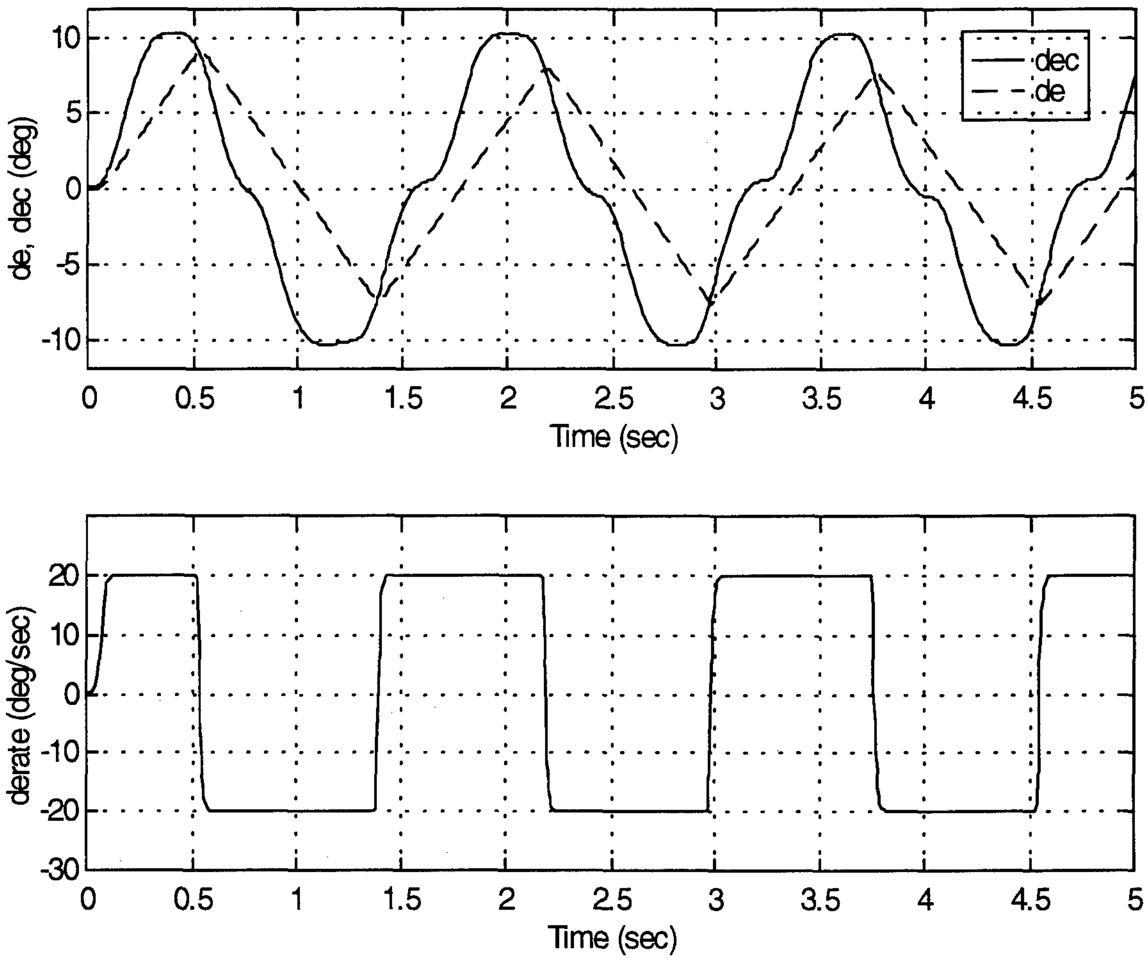


Figure 1-1 Representative Time History of Severe Rate Limiting

The second reason is that the reduction in gain is seen as an apparent loss of control effectiveness. This is also seen in Figure 1-1 by the reduced peak amplitude, and at any given time by the vertical difference between the traces. This effect deceives the pilot into making larger command inputs which further worsens the situation. These two effects combine to make rate limiting a probable cause for PIO.

Notice that both of these effects tend to mislead the pilot. It is common for a pilot in a PIO situation to believe that the aircraft is not responding to his inputs. Specifically, the YF-22 pilot stated that he "was not aware that he was in a PIO and thought the aircraft had malfunctioned" (Reference 13).

Another interesting observation made by some was that "there have been indications that it is possible to PIO an otherwise good airplane simply by saturating the actuator rates, and it appears that the result is almost always a severe PIO" (Reference 29). Although this belief was widely held going into this project, the results of the flight test indicate that this is not the case.

**Objectives**

The overall objective was to investigate the effects of elevator rate limiting and stick dynamics on longitudinal PIO. The specific objectives were to:

1. Investigate the effects of elevator rate limiting on PIOs.
2. Investigate the effects of stick dynamics on PIOs caused by elevator rate limiting.
3. Study the interplay between stick dynamics and elevator rate limiting with respect to longitudinal PIOs.
4. Obtain flight test data for others to use in studying rate limiting as a cause for PIO.

This investigation was performed in two parts. The first was a simulation study to gain a better understanding of the problem and to help develop a plan of action for the flight test (i.e. decide what aspects of the problem on which to focus the flight test, and narrow the size of the test matrix to fit within time and budget constraints). The flight test was then conducted to obtain actual data and evaluate the hypotheses developed during the analytical study.

**Approach**

The following steps were taken to accomplish the objectives of this project:

1. Developed a pilot/aircraft system model which could simulate a PIO.
   A. Used Ralph Smith's bang-bang pilot model.
   B. Capable of simulating a limit cycle by tracking an input signal.

2. Validated the model by matching flight test data from HAVE PIO, a previous AFIT/TPS thesis studying PIO using an offset landing task in the variable stability NT-33A (Reference 7).
   A. Chose three HAVE PIO configurations for detailed investigation.
   B. Matched the amplitude and frequency of time history traces for each of the chosen configurations by varying the pilot model parameters.

3. Modified the hydraulic actuator model to accept elevator rate limiting.

4. Studied Objective 1 by running simulations with a range of rate limits.

5. Developed a metric which showed a measurable degradation of the PIO as the rate limit was decreased.

6. Developed several options for changing the stick dynamics.

7. Studied Objective 2 by running simulations with varying amounts of change in each stick parameter of interest at constant rate limits.

8. Studied Objective 3 by running simulations with a range of rate limits and a 20% change in each stick parameter of interest.

9. Determined aircraft and stick configurations to be used in the flight test based on the simulation results.

10. Conducted the flight test in three phases using an offset landing task.
    A. Phase 1 - Successively decreased the rate limit in order to investigate the effects of rate limiting and establish rate limits of interest.
    B. Phase 2 - At a constant rate limit determined in Phase 1, varied the stick parameters (spring constant and natural frequency) independently in order to investigate the effects of stick dynamics and establish the required amount of change for each.
    C. Phase 3 - Flight tested the matrix of rate limits established in Phase 1 and sticks established in Phase 2.
    D. Collected PIO ratings, Cooper-Harper ratings, pilot comments, and time history data for each offset landing task flown.

**Scope**

This research project was very limited in scope. Some of the areas where the extent of this project were constrained are listed below:

1. The evaluations were limited only to the longitudinal axis of the flight control system.

2. Simulator studies were used rather than shaping functions or other nonlinear techniques to simplify the analysis.

3. Simulations of PIO required the use of a pilot model, however, no effort was made to optimize the pilot model. (See also Shortcomings of the Model/Simulation in Chapter III.)

4. The aircraft configurations evaluated were point designed to the approach and landing phase of flight to allow use of the HAVE PIO flight test results (Reference 7) as a starting point. This followed the established best practice for PIO flight testing which asserted that the offset landing task would provide good PIO data and be more repeatable than "up-and-away" tasks.

5. Due to budget constraints, the flight test was limited to only 15 sorties and 20 hours. The number of sorties and flight time available limited the size of the test matrix, which resulted in limiting the flight test to only one aircraft configuration and only two feel systems in addition to the nominal.

# II. *Theoretical Development*

This section will first present the objectives of the simulation portion of this investigation. Second, it will review some classical PIO theory and explain how rate limiting is a probable cause of PIO. Then it will discuss the development of the pilot/aircraft system model to be used. Next, it will show how the model was used to create a limit cycle and how the model was validated using HAVE PIO flight test data. Finally, this section will explain how the simulations were used to study the effects of rate limiting and identify the aircraft configurations and feel systems to be flight tested.

**Simulation Objectives**

The overall objective was to investigate the effects of elevator rate limiting and stick dynamics on longitudinal PIO. The specific objectives of the simulation study were to:

1. Investigate the effects of elevator rate limiting on PIOs.
   A. Validate that the model produces the classical triangle wave in the elevator position time history at decreased rate limits, noting the apparent delay between the elevator command and elevator position, the decreased amplitude of the elevator movement and the oscillations, and the decreased frequency of the oscillations.
   B. Show a measurable increase in PIO susceptibility with a decrease in rate limit.

2. Investigate the effects of stick dynamics on PIOs caused by elevator rate limiting.
   A. Show a measurable degradation or improvement of PIO tendency measured against the amount of change of different stick parameters for fixed rate limits.
   B. Establish one amount of change to be used for Objective 3.

3. Study the interplay between stick dynamics and elevator rate limiting with respect to longitudinal PIOs. Show a measurable degradation or improvement of PIO tendency at various rate limits for a given amount of change in several stick parameters.

4. Identify and prioritize the aircraft and stick configurations to be used in the flight test.

The overriding focus of the simulation study was to prepare for the flight test.

**Model Development**

The model used in this project started with a normal aircraft model (Figure 2-1) as its baseline and was limited to only the longitudinal axis. This model takes its input from the pilot through a feel system to a control system which sends an elevator position command to the actuator. This actuator command drives the elevator to the commanded position, which works through the aircraft dynamics to generate the aircraft pitch rate (q). Since the objective was to model PIO, the simulation had to include a model of the pilot and an incoming signal to track. As a tracking task, the aircraft was given a set of initial conditions and required to drive the pitch rate to zero. This approach was taken because controlling the pitch rate is normally sufficient to control the aircraft in the longitudinal axis. The remainder of the aircraft model is based upon the HAVE PIO (Reference 7) test configurations in order to have a known starting point. All 18 HAVE PIO configurations were initially evaluated as discussed in the Initial Simulations and Model Validation section of this chapter. Three of these, configurations, 2-1, 2-7, and 3-1, were selected for the full simulator study. Configuration 2-1 was used for the flight test. All

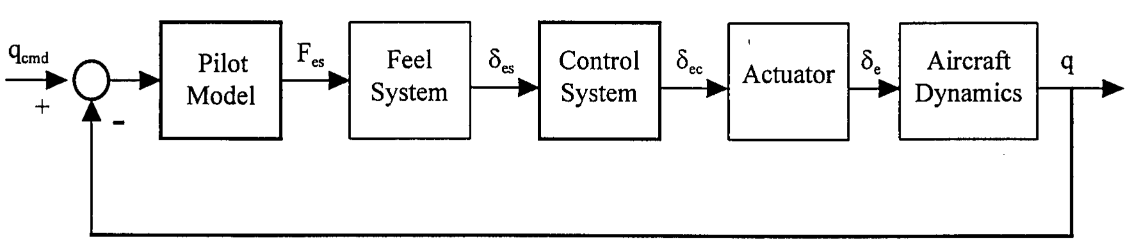


Figure 2-1 Pilot/Aircraft System Model Block Diagram

simulations, including those used in the flight test, were implemented in MATLAB™ using SIMULINK™. For a summary of the simulation configurations and model parameters, see Appendix B.

**Pilot Model.** The pilot model was Ralph Smith's bang-bang pilot model with a threshold (Reference 36 and 35). This model was only a rough approximation of a pilot once he is in a PIO, not during normal flight or the development phase of the PIO, but human pilots do sometimes exhibit this type of behavior (Reference 3). The model is shown in Figure 2-2 and contains three parameters. The first parameter is a time delay to account for pilot reaction time (the time to perceive the pitch rate, make a decision, and apply control inputs). The second parameter, $F_{S\,max}$, is the stick force the pilot uses, both positive and negative, in response to an unacceptable pitch rate. The third parameter, $q_{thresh}$, is the borderline between a pitch rate that is acceptable to the pilot (resulting in zero stick force for this model and normal commands for a real pilot) and one that is not (reacted to with an input of $F_{S\,max}$). In summary, a pitch rate comes into the pilot model and after a delay it exerts a stick force of zero or +/- $F_{S\,max}$ based on whether the pitch rate is within, above, or below the threshold.

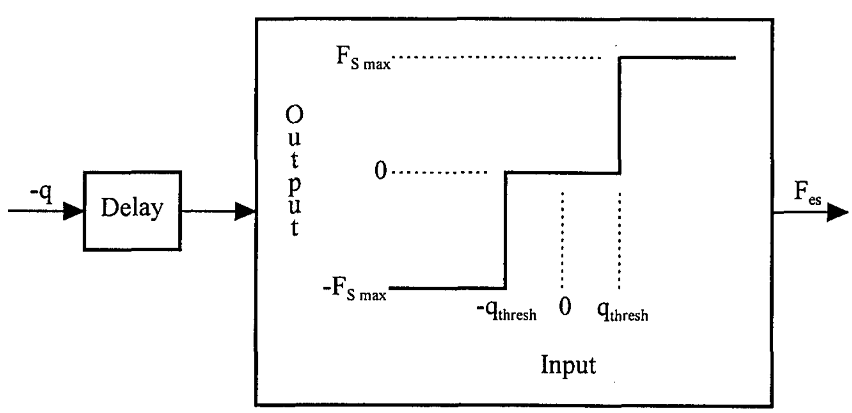


Figure 2-2 Bang-Bang Pilot Model with Threshold

**Feel System.** The stick dynamics (feel systems) were modeled as follows:

$$\frac{\delta_{es}}{F_{es}} = \frac{0.125/K_s}{\left[0.6\,K_\zeta\,,\;26\,K_\omega\right]}\; in\,/\,lb$$

The equation is written in shorthand notation where: $[\zeta,\omega_n] = (s^2 + 2\zeta\omega_n s + \omega_n^2)$

$(a) = (s + a)$

The nominal stick had a spring constant of 8 $^{lb}/_{inch}$, a damping ratio of 0.6, and a natural frequency of 26 $^{rad}/_{sec}$. The parameters $K_S$, $K_\zeta$, and $K_\omega$ were varied to create the various feel systems. A discussion explaining the different feel systems is presented in the Feel System Variation section later in this chapter. Table 2-1 defines the values of $K_S$, $K_\zeta$, and $K_\omega$ for each feel system used in the simulation study. The stick had no breakout force for the simulation study as this would have been equivalent to a change in $F_{S\,max}$.

**Control System.** Two different control systems were used in combination with the aircraft dynamics to create three different aircraft configurations for the modeling and simulation. The control systems for configurations 2-1 and 3-1 was a simple gain of 10 deg/in. The control system for configuration 2-7 had the following transfer function:

$$\frac{\delta_{ec}}{\delta_{es}} = \frac{10}{[0.7, 12]}\,\deg/\,in$$

**Actuator.** The hydraulic actuator used in this investigation is depicted in Figure 2-3. This model implemented the rate limits that were varied during the simulation and flight testing, but not rigorously. The "rate limit" generated by this model differed from a true rate limit by $(1 - e^{-105t}) / 105$, which is very small, but to be strictly correct the model shown in Figure 2-4 should have been used.

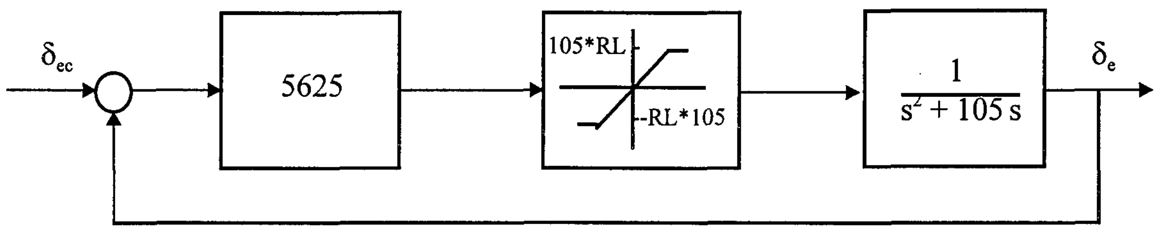


Figure 2-3 Hydraulic Actuator Block Diagram

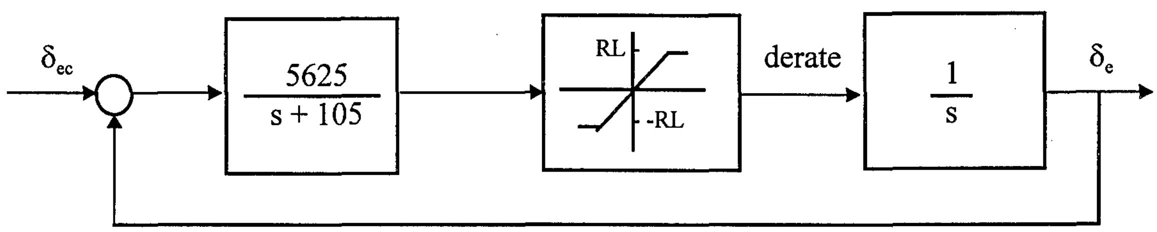


Figure 2-4 Corrected Hydraulic Actuator Block Diagram

The actuator model started off as a standard second order hydraulic actuator, was broken into its effective parts, and was then modified to accept a rate limit. The three components shown in the diagram roughly represent a conversion from elevator position error to hydraulic fluid flow rate, the maximum flow rate that can be generated by the pump, and the ram dynamics. The output of the ram determines the elevator position, which is fed back to match the elevator command. The model with the numerical values shown results in a maximum elevator rate of RL in degrees per second. When the rate is less than RL, the entire hydraulic actuator simplifies to a second order actuator with a damping ratio of 0.7 and a natural frequency of 75 rad/sec.

**Aircraft Dynamics.** Two different sets of aircraft dynamics were used in the simulation study. The first set of dynamics was from HAVE PIO (Reference 7) configuration 3-1 and was used only in the simulation study. The aircraft dynamics for this configuration was:

$$\frac{q}{\delta_e} = \frac{3.3685(0.0847)(0.6987)(0)}{[0.17, 0.16][0.97, 4.22]}$$

The other set of aircraft dynamics was used in both the simulation study and the flight test. This set of dynamics was combined with two different control systems to form the other two aircraft configurations used in the simulation study. This set of dynamics was from HAVE PIO configurations 2-1 and 2-7. The aircraft dynamics for these configurations was:

$$\frac{q}{\delta_e} = \frac{3.3685(0.0845)(0.6990)(0)}{[0.15, 0.17][0.63, 2.41]}$$

**Initial Simulations and Model Validation**

A critical step in developing the working simulations for this analysis was the creation of a limit cycle (or PIO) in the simulation output. This was initially done by running the model with pilot parameters that were estimated to be extreme enough to result in a PIO (Delay = 0.25 sec, $q_{thresh}$ = 4 deg/sec, $F_{S\,max}$ = 50 lbs). Initial conditions were chosen to be q = 10 deg/sec, well outside the pilot's threshold. These parameters did result in a limit cycle for most of the HAVE PIO configurations (Reference 7). Figure 2-5 shows a representative time history from this analysis. Note the closed curve on the q to theta phase plot indicating a limit cycle. The pilot model was refined by reducing the $F_{S\,max}$ to a more reasonable 22 lbs and this time some of the configurations still displayed a limit cycle while some did not. The disturbing reality of this result was

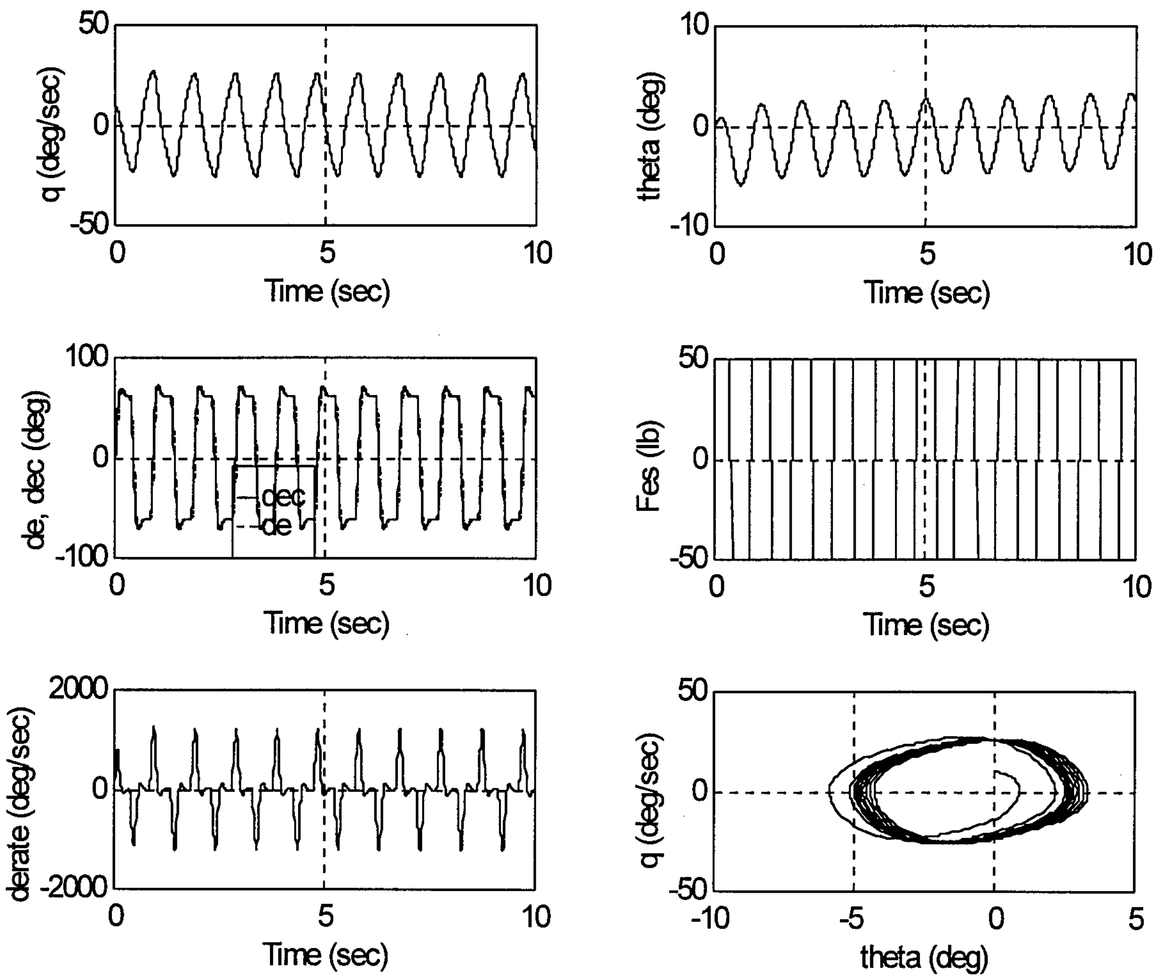


Figure 2-5 Representative Time History: Configuration 2-1, No Rate Limit,

Delay = 0.25 sec, $q_{thresh}$ = 4 deg/sec, $F_{S\ max}$= 50 lbs

that the best HAVE PIO configuration (2-1, with a PIO rating of 1 from the HAVE PIO flight test) still showed a strong limit cycle (PIO) while some of the worst configurations (3-12 for example, with a PIO rating of 4.5 from the HAVE PIO flight test) did not. Figures 2-6 and 2-7 show the time histories from these cases.

An attempt was made to vary all three pilot parameters in such a way that the worst configurations showed a limit cycle while the best did not. This proved to be impossible, and led to the almost obvious conclusion that a single pilot model is not appropriate for all configurations. This makes a lot of sense because pilots fly different airplanes very differently.

In an effort to have appropriate pilot models for each configuration, the pilot model parameters were varied in an effort to roughly match the frequency and amplitude of the most prevalent oscillations seen in the time histories from the HAVE PIO flight test. This was a very time intensive task and therefore the decision was made to cut the number of configurations to be studied from 18 to 3. The three configurations were chosen to provide a range of PIO and Cooper-Harper (CH) ratings that included very good (2-1), good (3-1), and medium (2-7) ratings. Where possible, control system 1 (a simple gain) was chosen to simplify the number of effects that had to be considered in the analysis. Additionally, the two configurations that were somewhat degraded were degraded for different reasons. One (3-1) was too fast or sensitive (high bandwidth) and the other (2-7) was degraded due to phase lag. Finally, for those three configurations, the pilot model parameters were adjusted (as shown in Table B-1) so that the steady state limit cycle matched the most prevalent oscillations seen in the time histories.

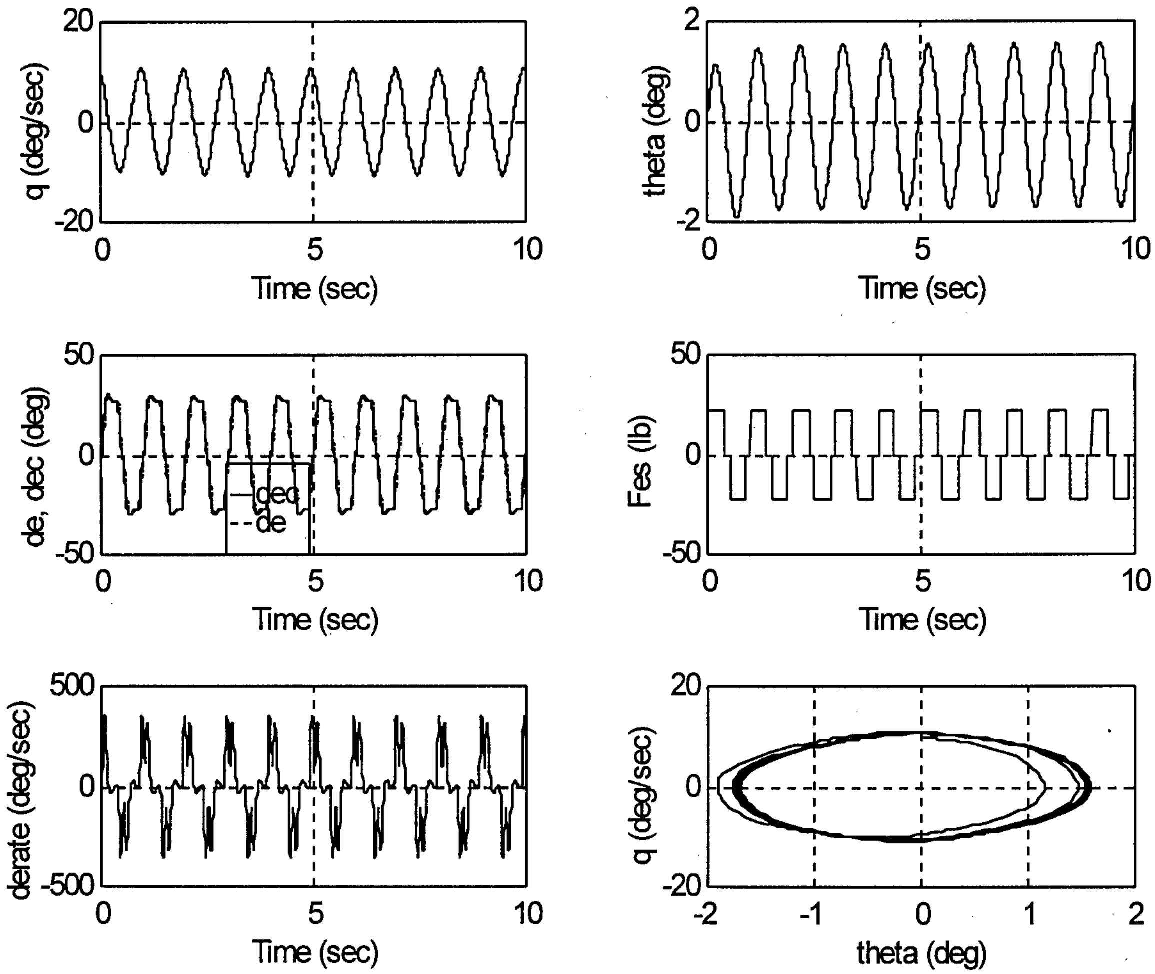


Figure 2-6 Time History: Configuration 2-1, No Rate Limit,

Delay = 0.25 sec, $q_{thresh}$ = 4 deg/sec, $F_{S\ max}$= 22 lbs

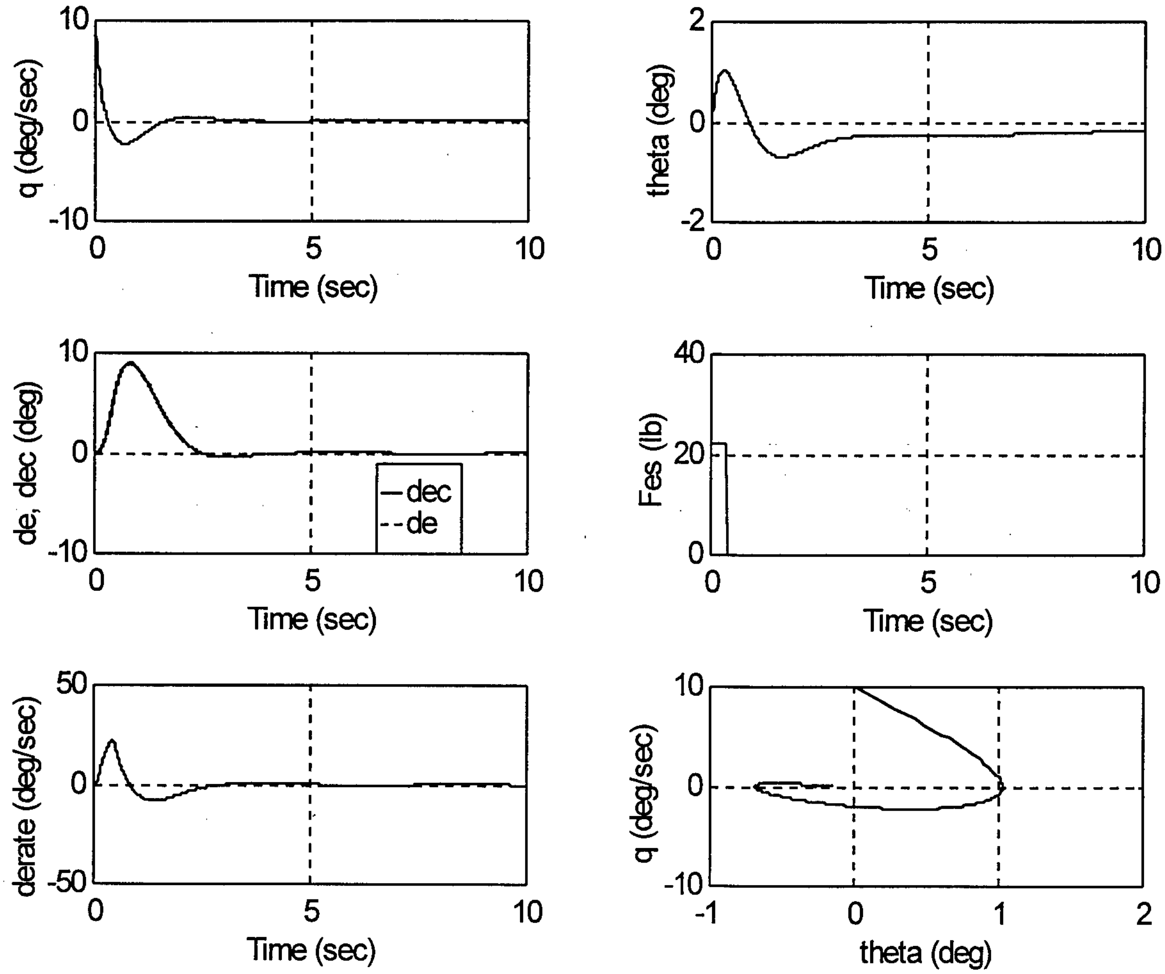


Figure 2-7 Time History: Configuration 3-12, No Rate Limit,

Delay = 0.25 sec, $q_{thresh}$ = 4 deg/sec, $F_{S\ max}$= 50 lbs

**Simulation Study Method**

**Rate Limiting Confirmation.** To develop a preliminary understanding of the effects of rate limiting and stick dynamics on PIO, a simulation study was performed using the HAVE PIO configurations previously identified. First, the model was validated by running the simulation with different rate limits in-order to confirm that rate limiting was having the anticipated effect. The anticipated effect was the classical triangle wave on time history plots of the elevator deflection at decreased rate limits. Also expected were an apparent delay between the elevator command and elevator position, a decrease in the amplitude of the elevator movement and the oscillations, and a decrease in the frequency of the oscillations.

**Metric Development.** The pilot model was adjusted in order to make changes in the PIO simulations measurable. The initial condition for the pitch rate was adjusted to be the peak of the steady state oscillation from the simulations with the nominal pilot parameters needed to match the flight test data. An example of the resultant time history is shown in Figure 2-8. From this baseline, the $q_{thresh}$ parameter was increased very slightly for each configuration in order to suppress the PIO at approximately 5 seconds for each configuration, as shown in Figure 2-9. Measured from the start of the simulation, the last time that the pilot model made a stick force input was defined as $T_{last}$ (the simulated PIO duration) and was used as the metric for evaluating PIO severity in the simulation study. Figures 2-10 through 2-12 show the increase in PIO duration ($T_{last}$) as the rate limit is decreased. Using this metric, each of the three configurations was evaluated with a range of rate limits from 200 deg/sec (essentially unlimited elevator rate) down to zero elevator rate.

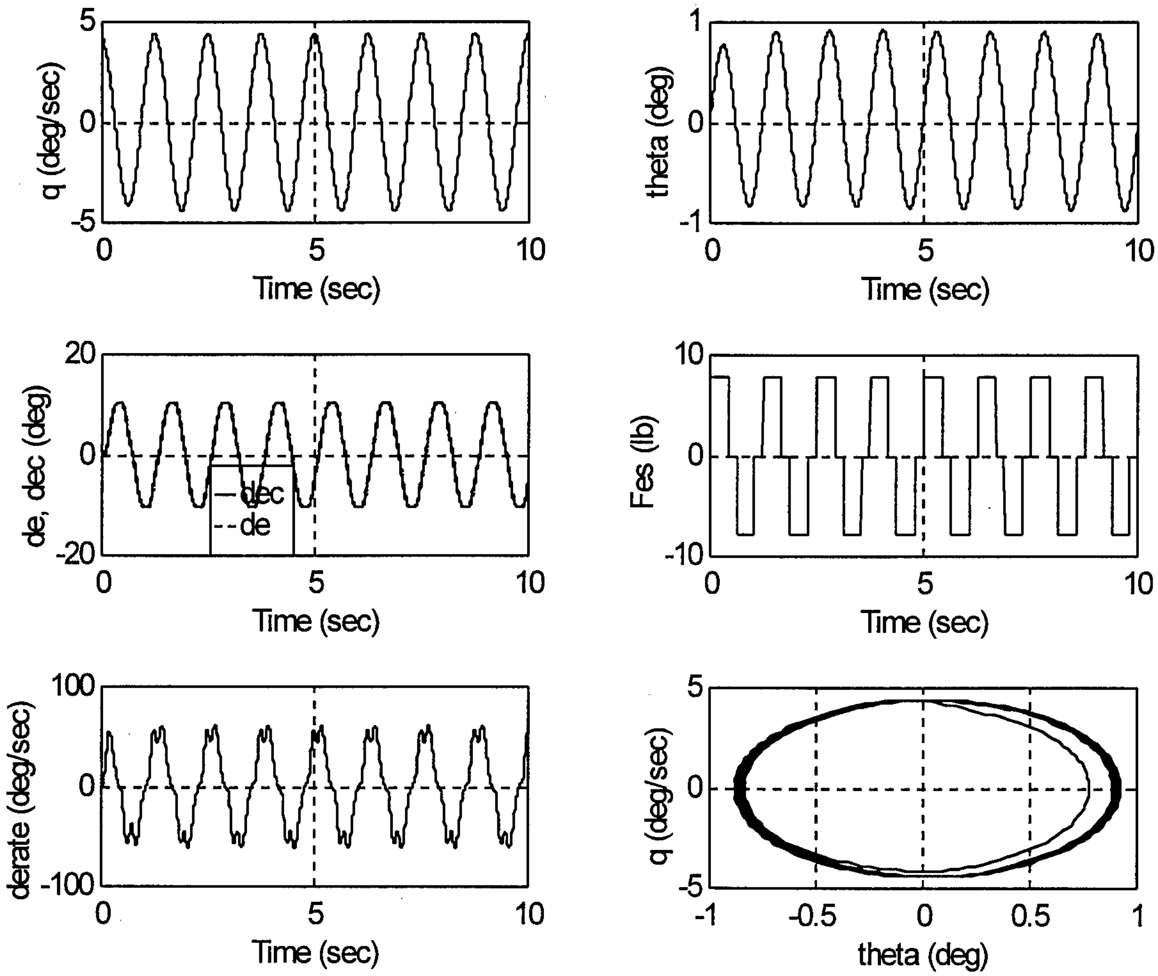


Figure 2-8 Time History: Configuration 2-7, Rate Limit 200 deg/sec,

Delay = 0.23 sec, $q_{thresh}$ = 2.1 deg/sec, $F_{S\,max}$ = 7.9 lbs

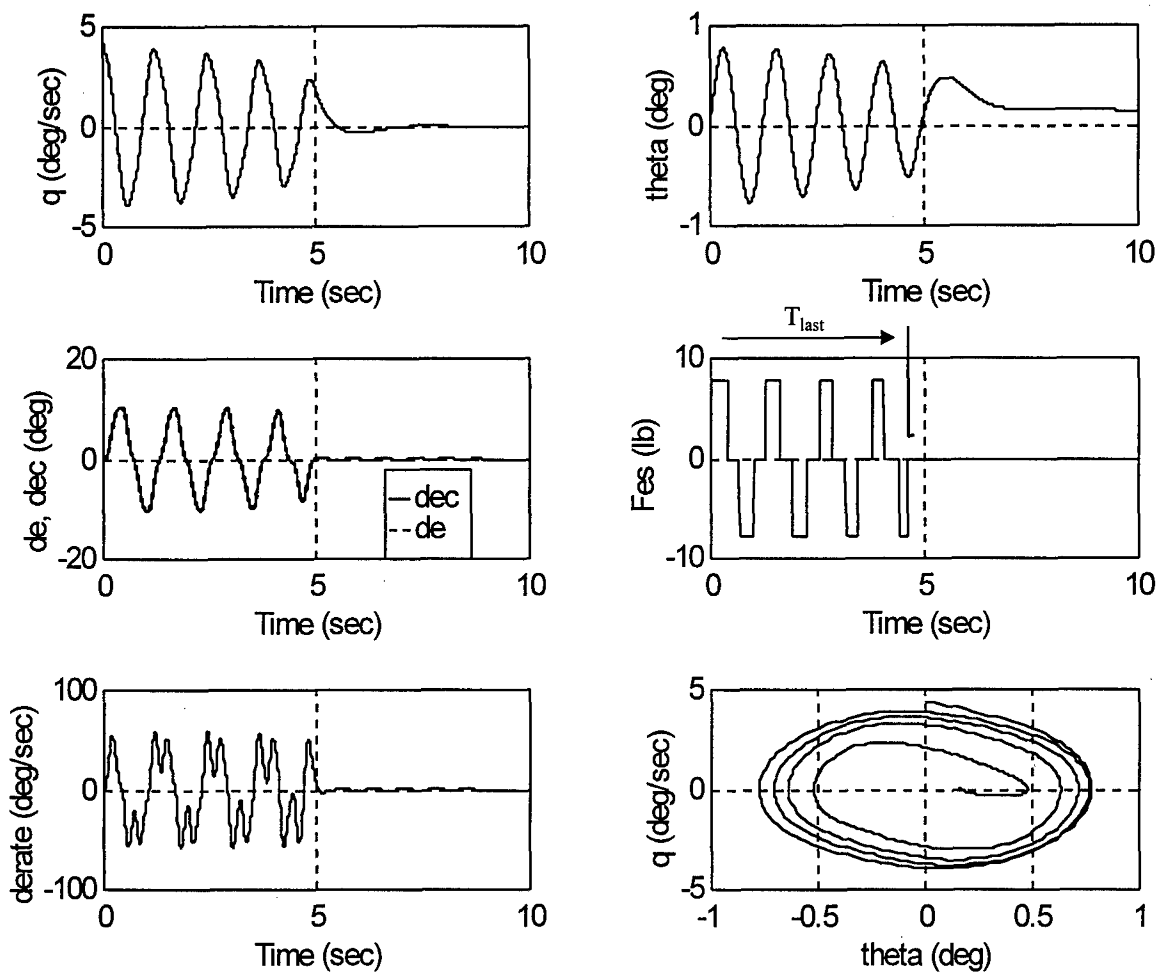


Figure 2-9 Time History: Configuration 2-7, Rate Limit 200 deg/sec,

Delay = 0.23 sec, $q_{thresh}$ = 2.531 deg/sec, $F_{S\ max}$ = 7.9 lbs

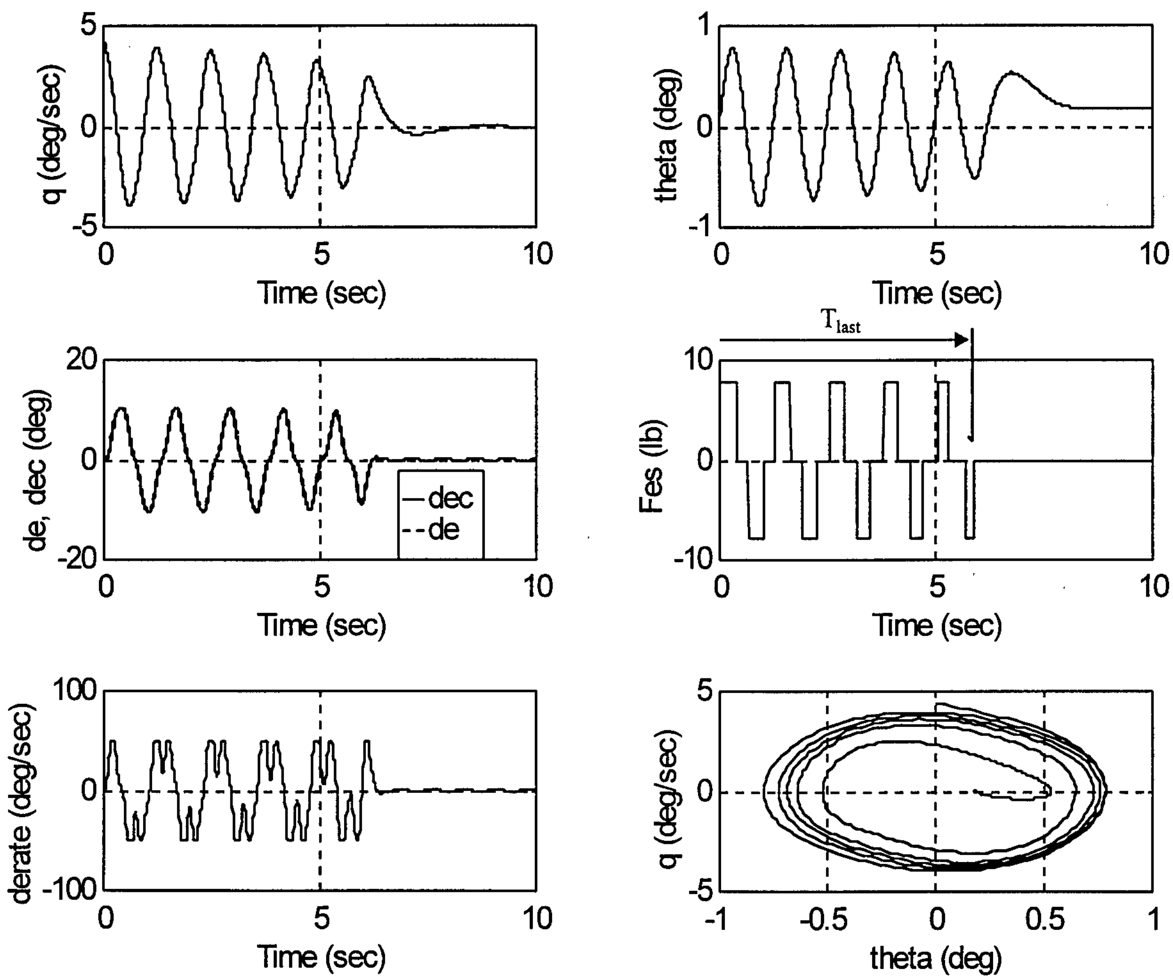


Figure 2-10 Time History: Configuration 2-7, Rate Limit 50 deg/sec,

Delay = 0.23 sec, $q_{thresh}$ = 2.531 deg/sec, $F_{S\ max}$ = 7.9 lbs

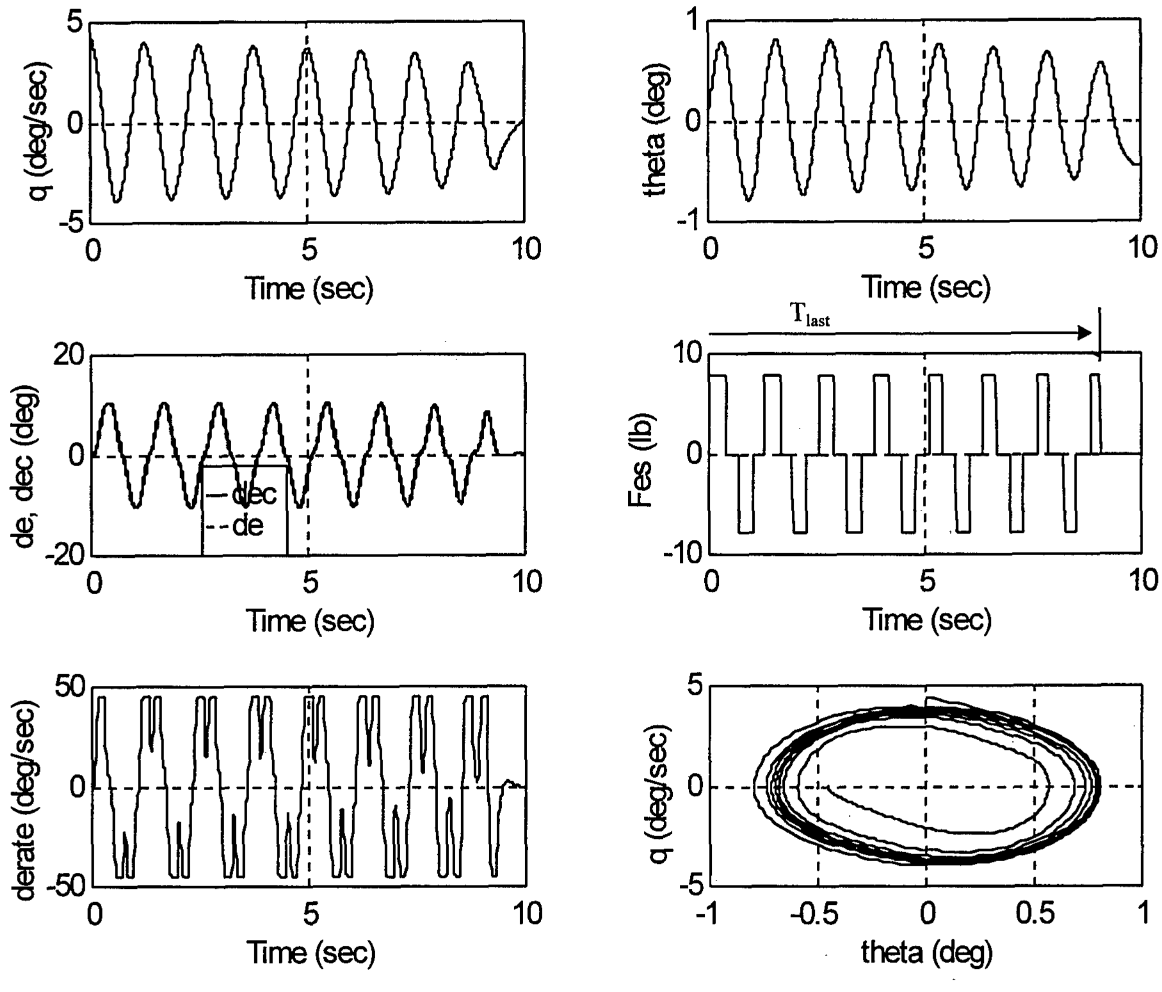


Figure 2-11 Time History: Configuration 2-7, Rate Limit 45 deg/sec,

Delay = 0.23 sec, $q_{thresh}$ = 2.531 deg/sec, $F_{S\ max}$ = 7.9 lbs

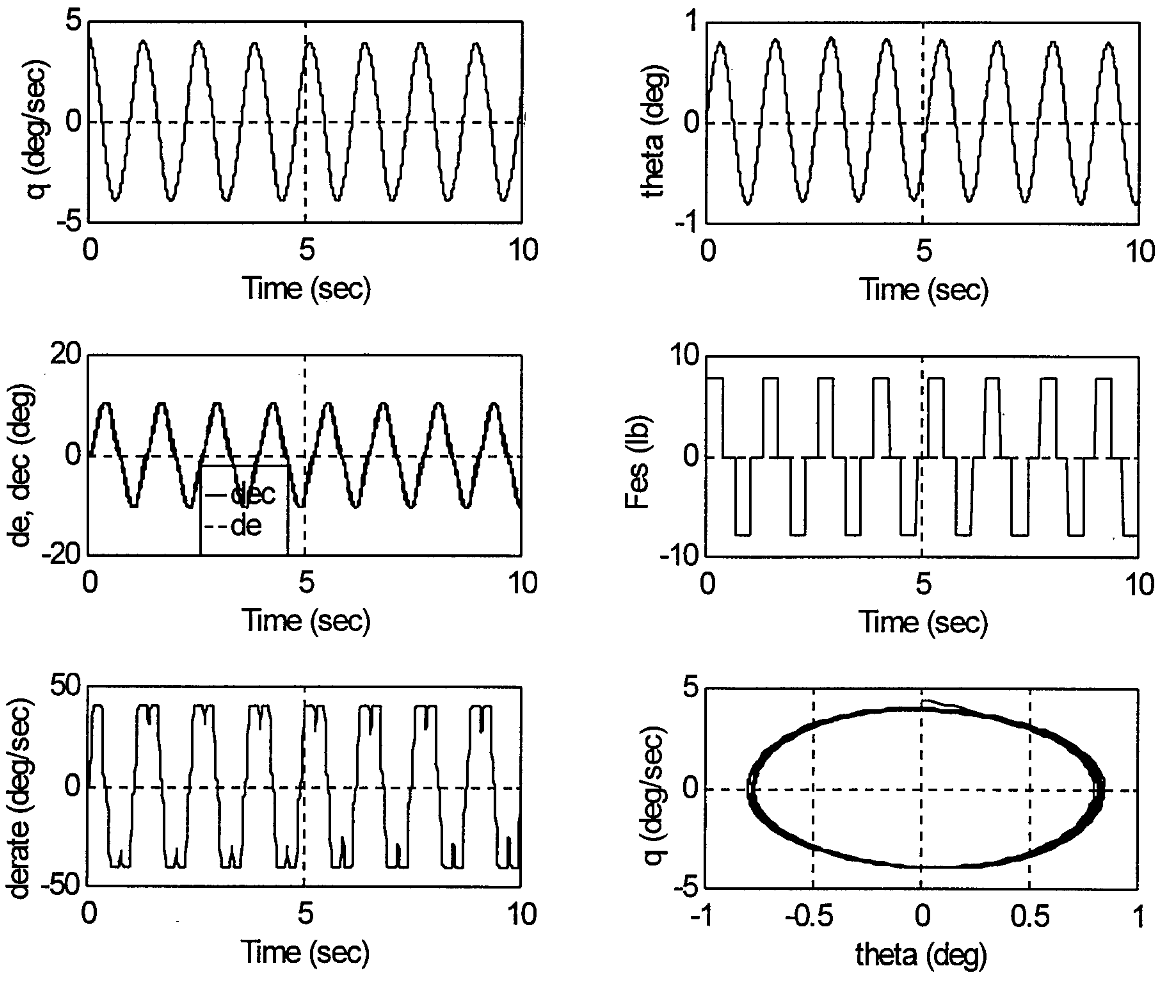


Figure 2-12 Time History: Configuration 2-7, Rate Limit 40 deg/sec,

Delay = 0.23 sec, $q_{thresh}$ = 2.531 deg/sec, $F_{S\,max}$ = 7.9 lbs

**Feel System Variations.** Several options were developed for changing the stick dynamics. The stick was modeled as a spring mass damper system using the following equation:

$$\frac{\delta_{es}}{F_{es}} = \frac{0.125/K_s}{\left[0.6\,K_\zeta\,,\ 26\,K_\omega\right]}\ in\,/\,lb$$

where $[\zeta,\omega_n] = (s^2 + 2\zeta\omega_n s + \omega_n^2)$

$(a) = (s + a)$

The nominal stick, feel system 1, had a damping ratio of 0.6, a natural frequency of 26 rad/sec, and a stick force deflection gradient of 8 lb/in. There were 6 additional sticks used in the study as shown in Table 2-1. Feel system 2 was a pure gain decrease. Feel system 3 was a pure spring constant increase. Both of these feel systems also increased the stick force deflection and force response gradients (i.e. more force required to move the stick the same distance and get the same response). Feel system 4 was a decrease in

Table 2-1 Definition of Feel Systems

| Feel System | Description | Stick Spring Constant Multiplier ($K_S$) | Stick Damping Ratio Multiplier ($K_\zeta$) | Stick Natural Frequency Multiplier ($K_w$) |
|---|---|---|---|---|
| 1 | Nominal | 1 | 1 | 1 |
| 2 | Gain decrease | 1 / K | 1 | 1 |
| 3 | Spring Constant increase | 1 / K | 1 / K^0.5 | K^0.5 |
| 4 | Spring decrease/ Gain increase | 1 | K^0.5 | 1 / K^0.5 |
| 5 | Natural Frequency increase | 1 | 1 | K |
| 6 | Damping Ratio increase | 1 | K | 1 |
| 7 | Inertia increase | 1 | 1 / K^0.5 | 1 / K^0.5 |

the spring constant with an outside decrease in the gain in order to maintain the nominal stick force response gradient, but decrease the deflection response gradient (i.e. the same force required to move the stick a greater distance and get the same response). Feel system 5 was an increase in natural frequency. Feel system 6 had an increased damping ratio. Feel system 7 had a decreased inertia. As a visual representation of these sticks, the deflection response for a one pound step input in stick force is shown in Figure 2-13.

**Final Simulations.** In order to determine how much to change the appropriate parameters for each type of feel system, simulations were run for each configuration at constant rate limits, while the appropriate parameters were varied from half to twice their nominal values. Finally, with a constant amount of change for each feel system, each of the three configurations was evaluated with a range of rate limits from 200 deg/sec (essentially unlimited elevator rate) down to zero elevator rate.

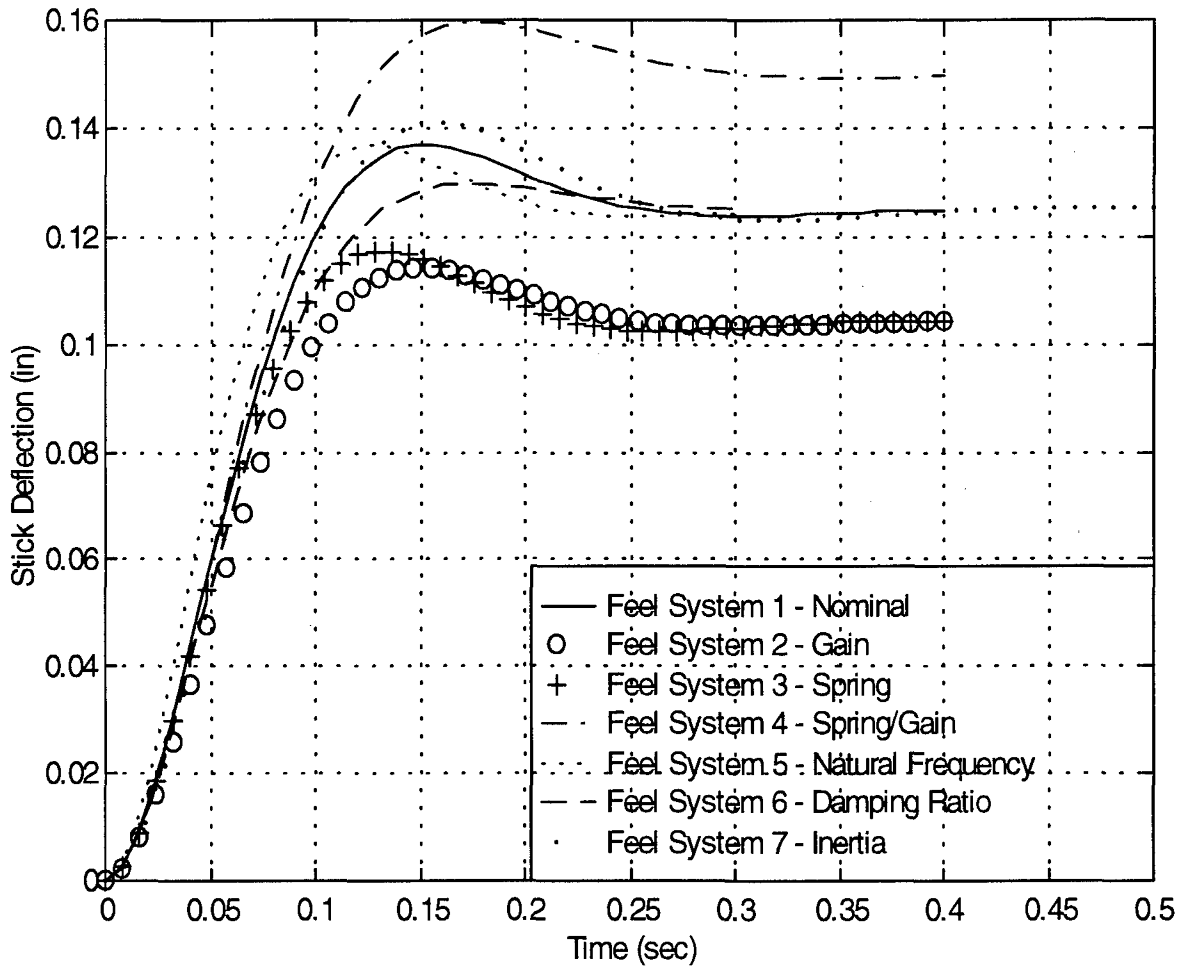


Figure 2-13 Feel System Variations: Stick Deflection Response to One Pound Step Input

# III. *Simulation Results and Analysis*

## Effects of Rate Limiting

First, the model was validated by running the simulation with different rate limits in order to confirm that rate limiting was having the anticipated affect. Partial time histories from three successive rate limits (50, 40, and 30 deg/sec) for configuration 2-7 are shown in Figure 3-1. The familiar triangle wave and the associated delay or phase lag become readily apparent in the 30 deg/sec plot. Also note that with decreased rate limit, the amplitude of the control inputs and the frequency of the oscillation both decrease. Figures 3-2 and 3-3 show the entire set of parameters for this configuration at 50 and 30 deg/sec rate limits. The simulation appeared to show the anticipated effects of rate limiting.

Each of the three configurations were then evaluated, using the metric developed ($T_{last}$), with a range of rate limits from 200 deg/sec (essentially unlimited elevator rate) down to zero elevator rate. This was done in order to show measurable degradation in PIO susceptibility with a decrease in rate limit. Figure 3-4 shows that there is little or no increase in the duration of the PIO until about 29 deg/sec for configuration 2-1, but the PIO becomes infinite in duration by 19 deg/sec. Figure 3-5 shows that there is little or no increase in the duration of the PIO until just above 50 deg/sec for configuration 2-7, but the PIO becomes infinite in duration by 42 deg/sec. Figure 3-6 shows that there is little or no increase in the duration of the PIO until 52 deg/sec for configuration 3-1, but the PIO becomes infinite in duration by 43 deg/sec. For each configuration, the increase in

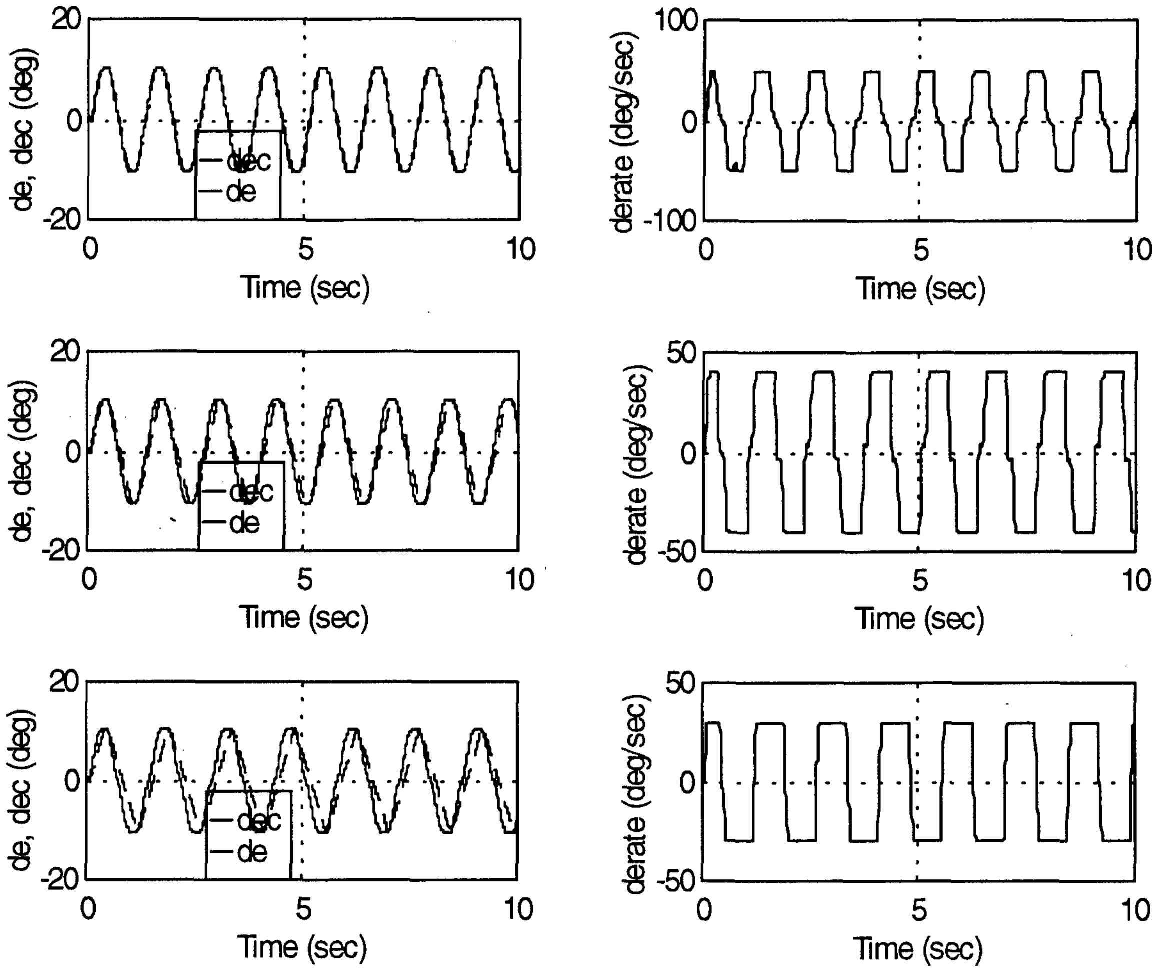


Figure 3-1 Partial Time Histories: Configuration 2-7, Rate Limits 50, 40, and 30 deg/sec

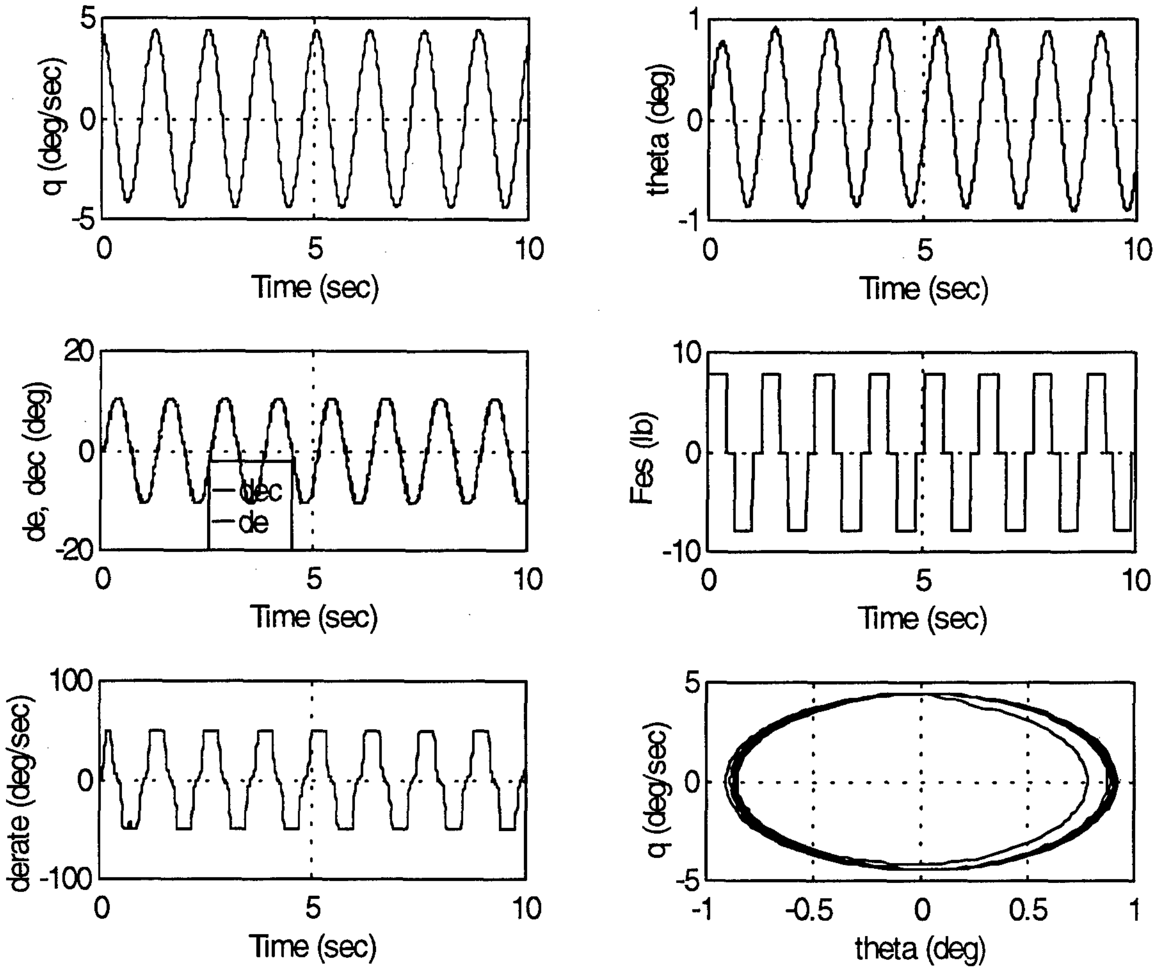


Figure 3-2 Time History: Configuration 2-7, Rate Limit 50 deg/sec

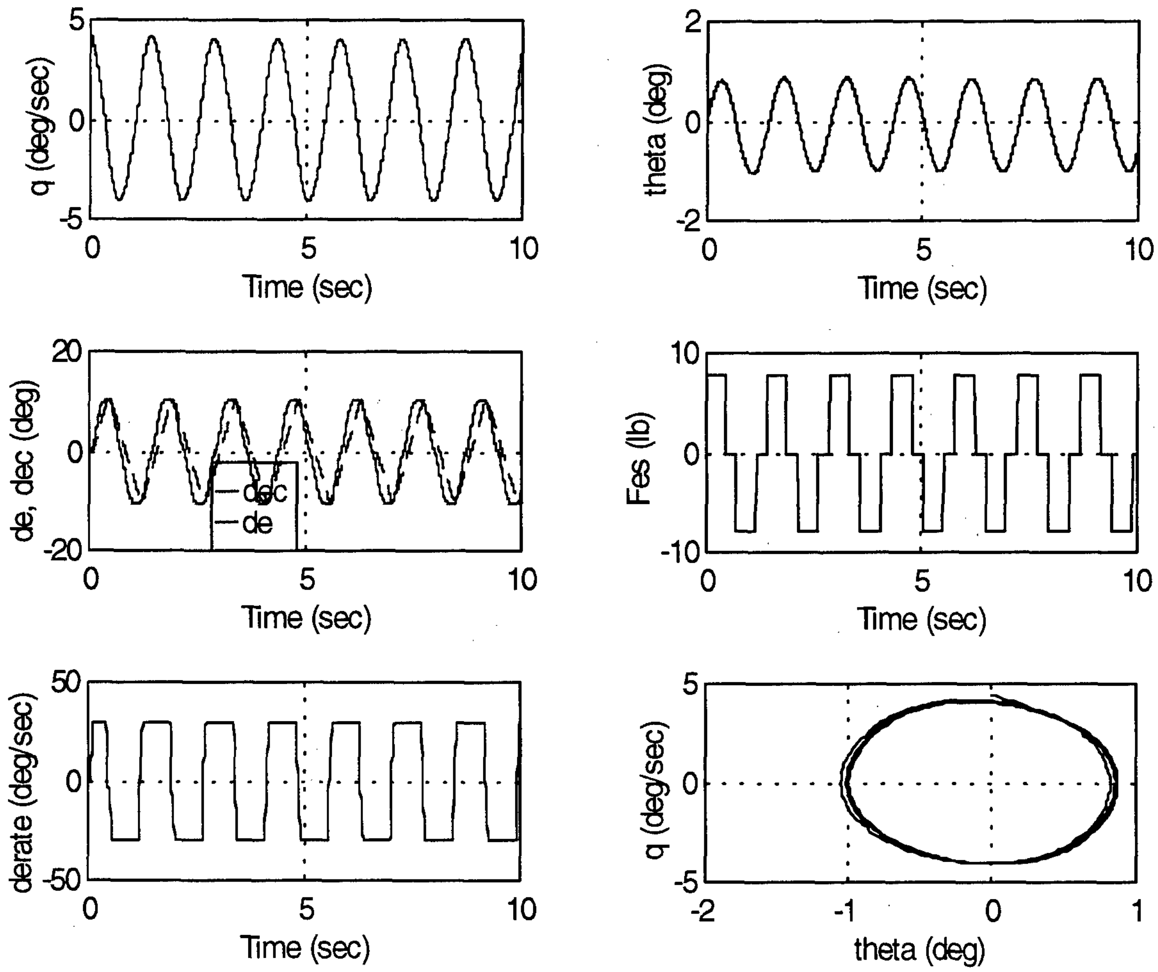


Figure 3-3 Time History: Configuration 2-7, Rate Limit 30 deg/sec

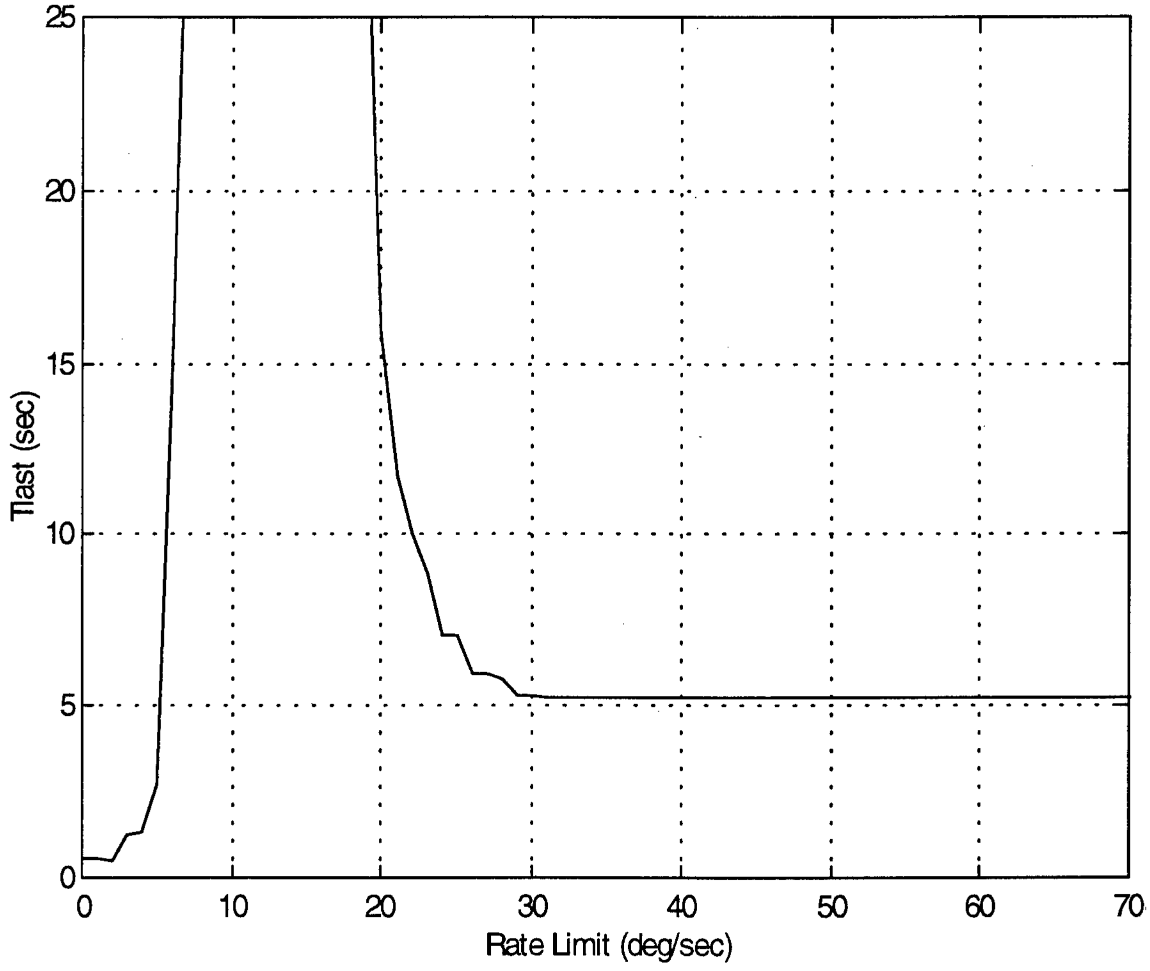


Figure 3-4 $T_{last}$ vs. Rate Limit: Configuration 2-1, Nominal Feel System

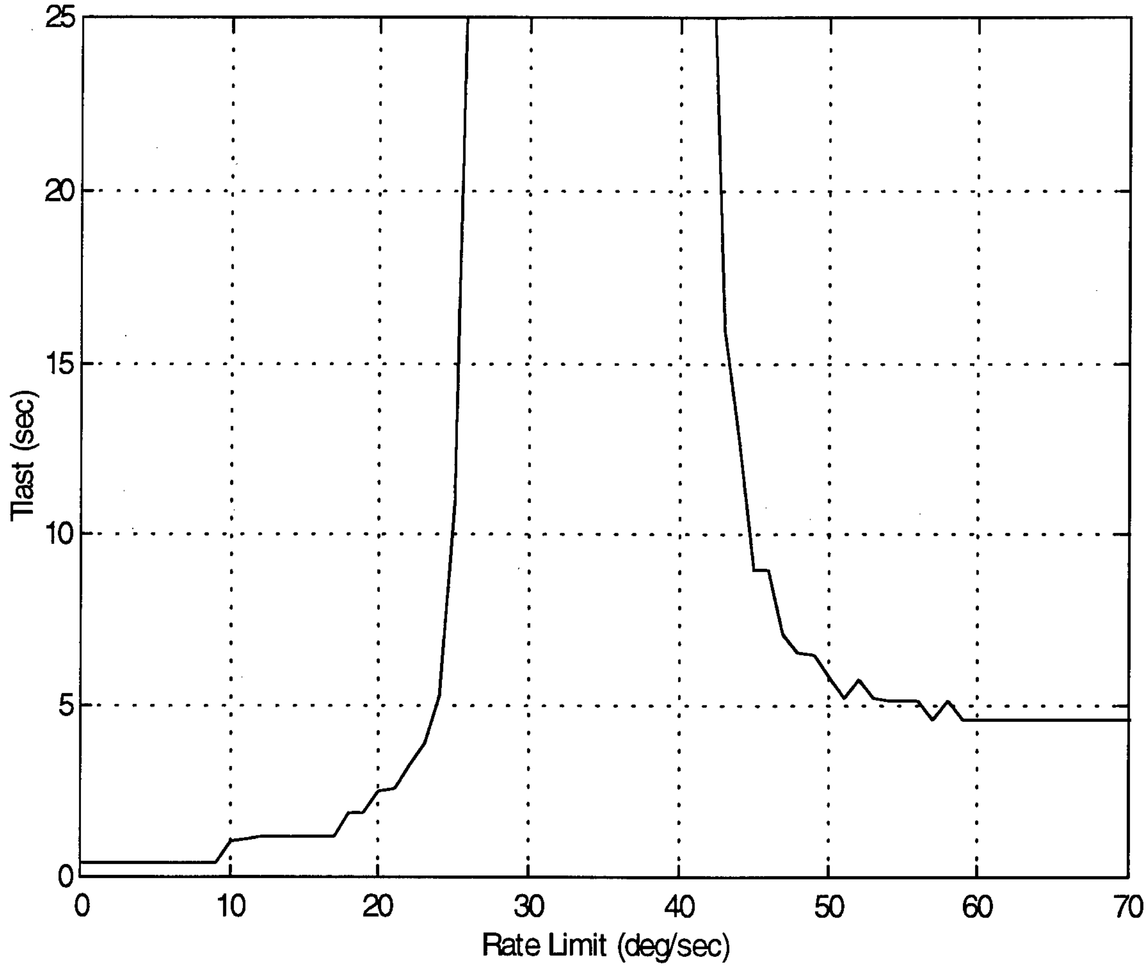


Figure 3-5 $T_{last}$ vs. Rate Limit: Configuration 2-7, Nominal Feel System

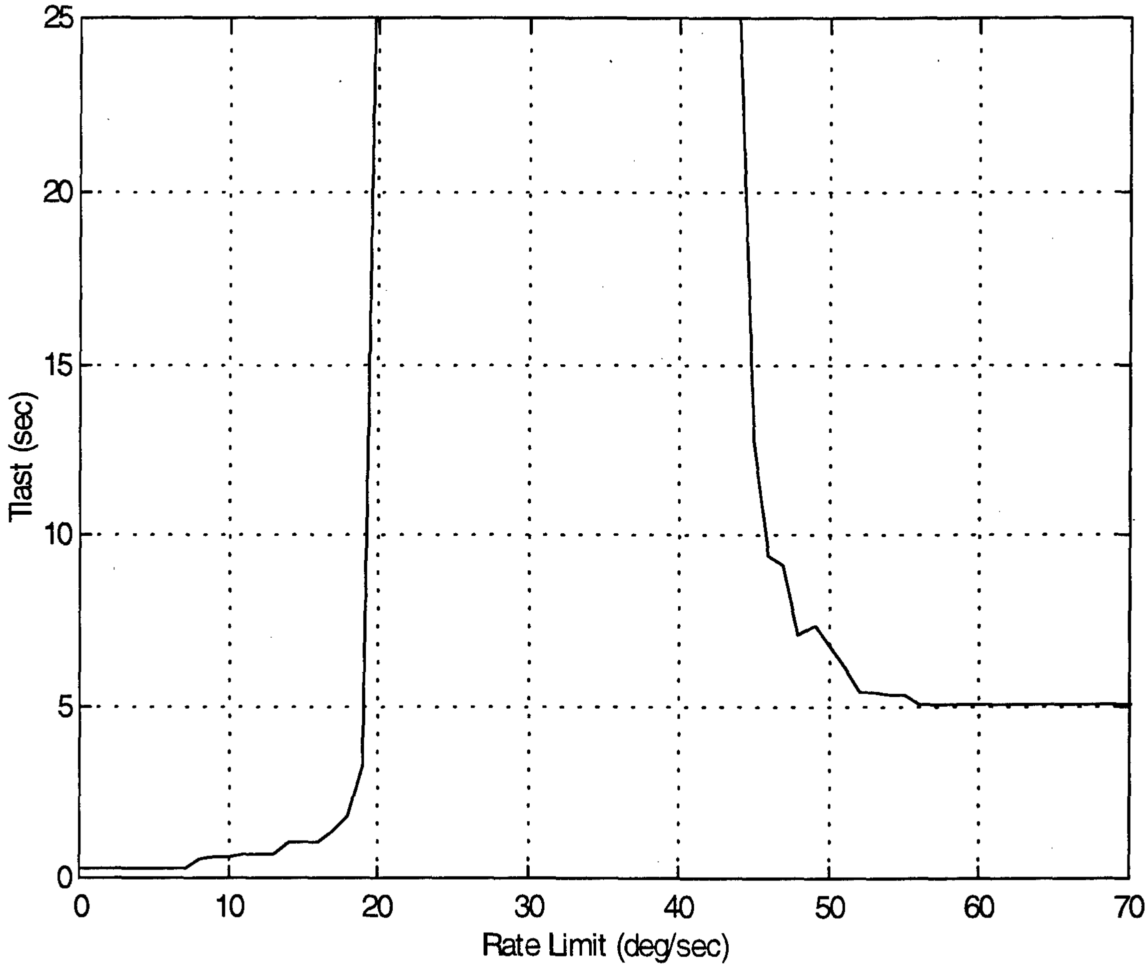


Figure 3-6 $T_{last}$ vs. Rate Limit: Configuration 3-1, Nominal Feel System

PIO duration occurred suddenly and went from five seconds to infinite with a decrease in rate limit of only about 10 deg/sec.

Also note that on the left side of the plots, when the rate limit becomes very small, the PIO was also suppressed very quickly. This result can be explained by the effective diminishing control authority available to the pilot as seen in Figures 3-7 through 3-9. Any oscillations that the pilot caused with this low effective control power were small in amplitude (q remained less than $q_{thresh}$) so the pilot was not drawn into the loop and did not continue to make the full deflection inputs. The left side of these figures was disregarded for this simulation study, because aircraft are not normally equipped with such poor actuators that the pilot is unable to attain at least a reasonable pitch response.

**Effects of Stick Dynamics**

For each of the feel systems, this investigation needed to not only look at what happens when a stick parameter was changed, but also how much that parameter needed to be changed. In order to look at both of these, simulations were run using various multiples of the parameters of interest, from half to twice the nominal values. These simulations were run for each configuration at several rate limits.

Figures C-1 through C-9 show the results of these simulations for the rate limits of most interest (those from where the duration of the PIO begins to increase as the rate limit decreases to where the duration becomes infinite). For most of the feel systems, a 20% change in the stick parameter of interest was sufficient to produce most of the effects noted. For this reason, a 20% change was used to compare all of the different feel

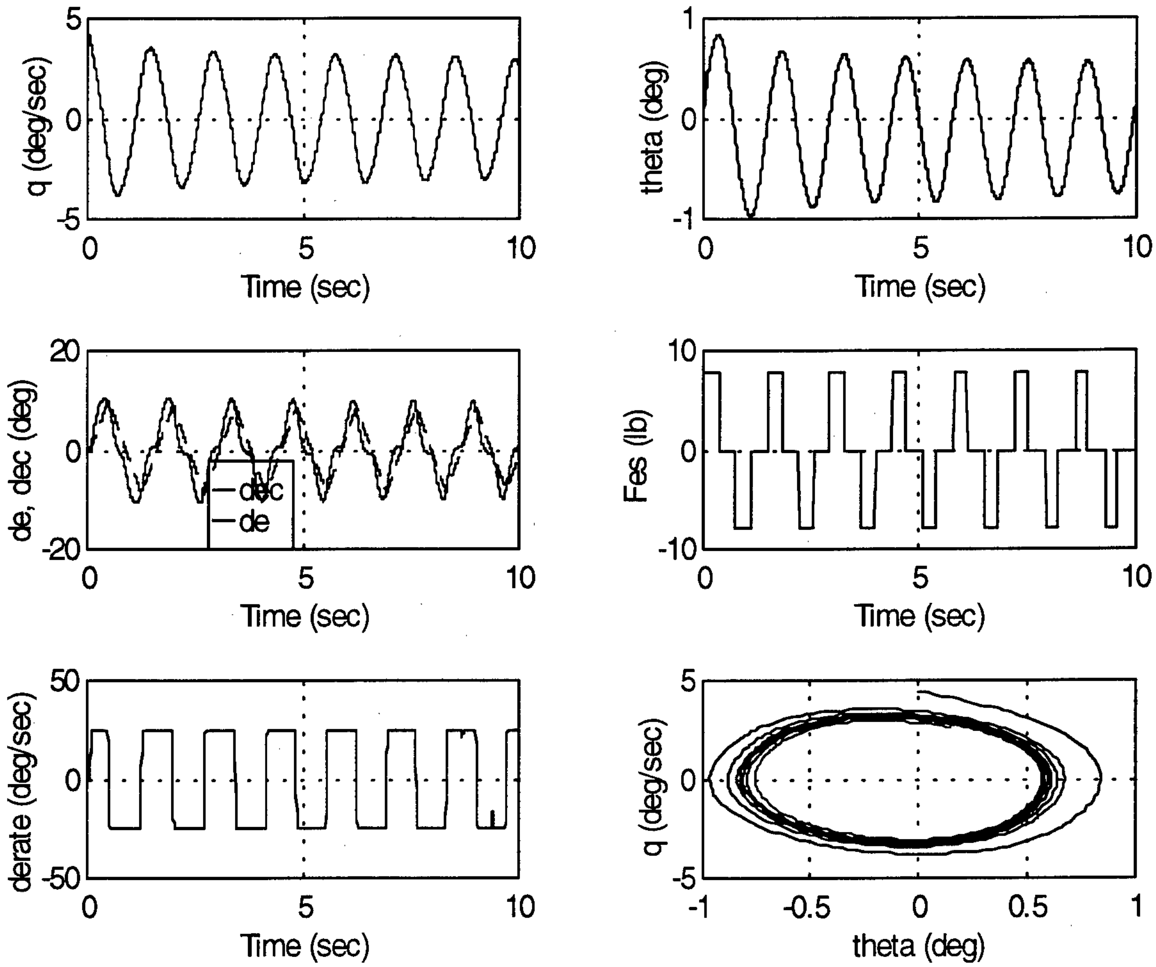


Figure 3-7 Time History: Configuration 2-7, Rate Limit 25 deg/sec,

Delay = 0.23 sec, $q_{thresh}$ = 2.531 deg/sec, $F_{S\,max}$ = 7.9 lbs

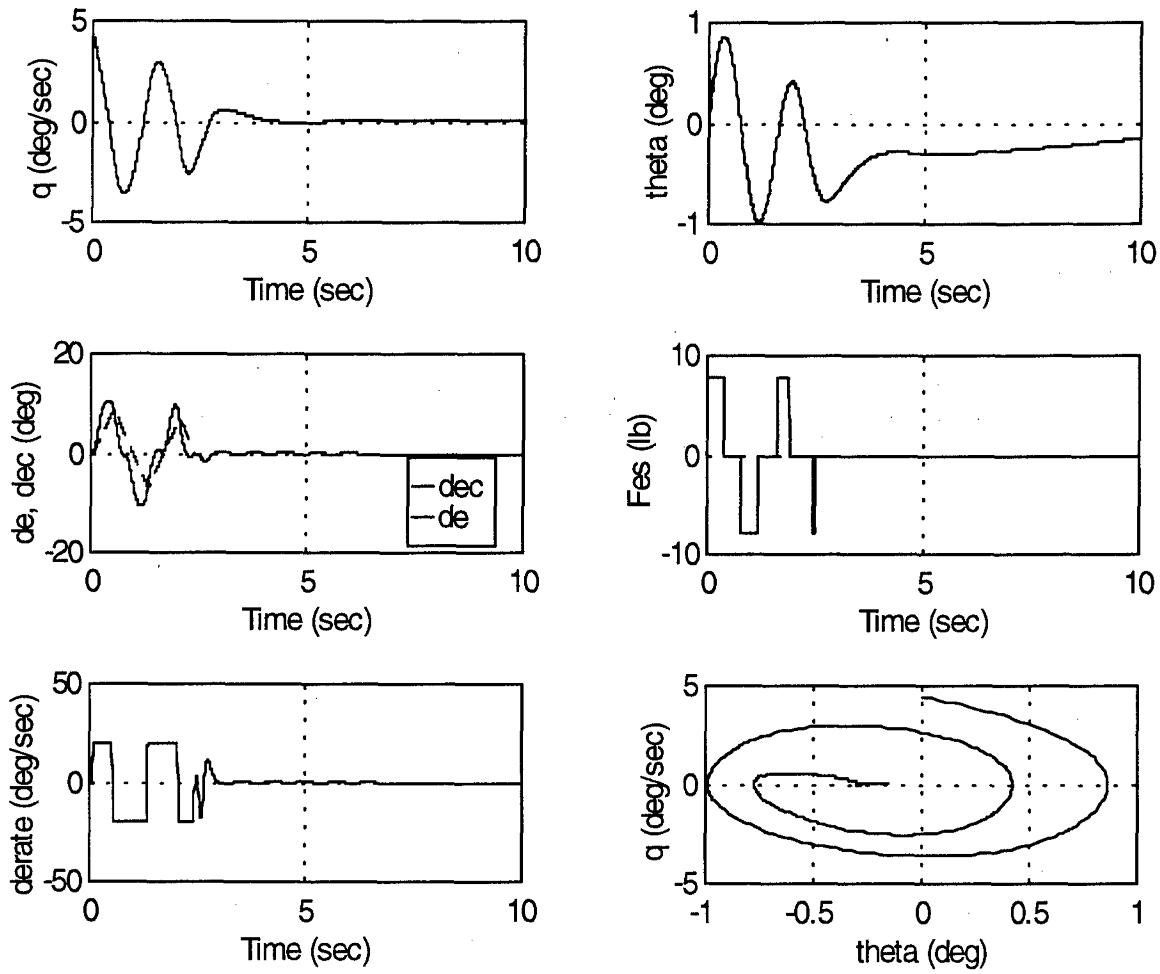


Figure 3-8 Time History: Configuration 2-7, Rate Limit 20 deg/sec,

Delay = 0.23 sec, $q_{thresh}$ = 2.531 deg/sec, $F_{S\,max}$ = 7.9 lbs

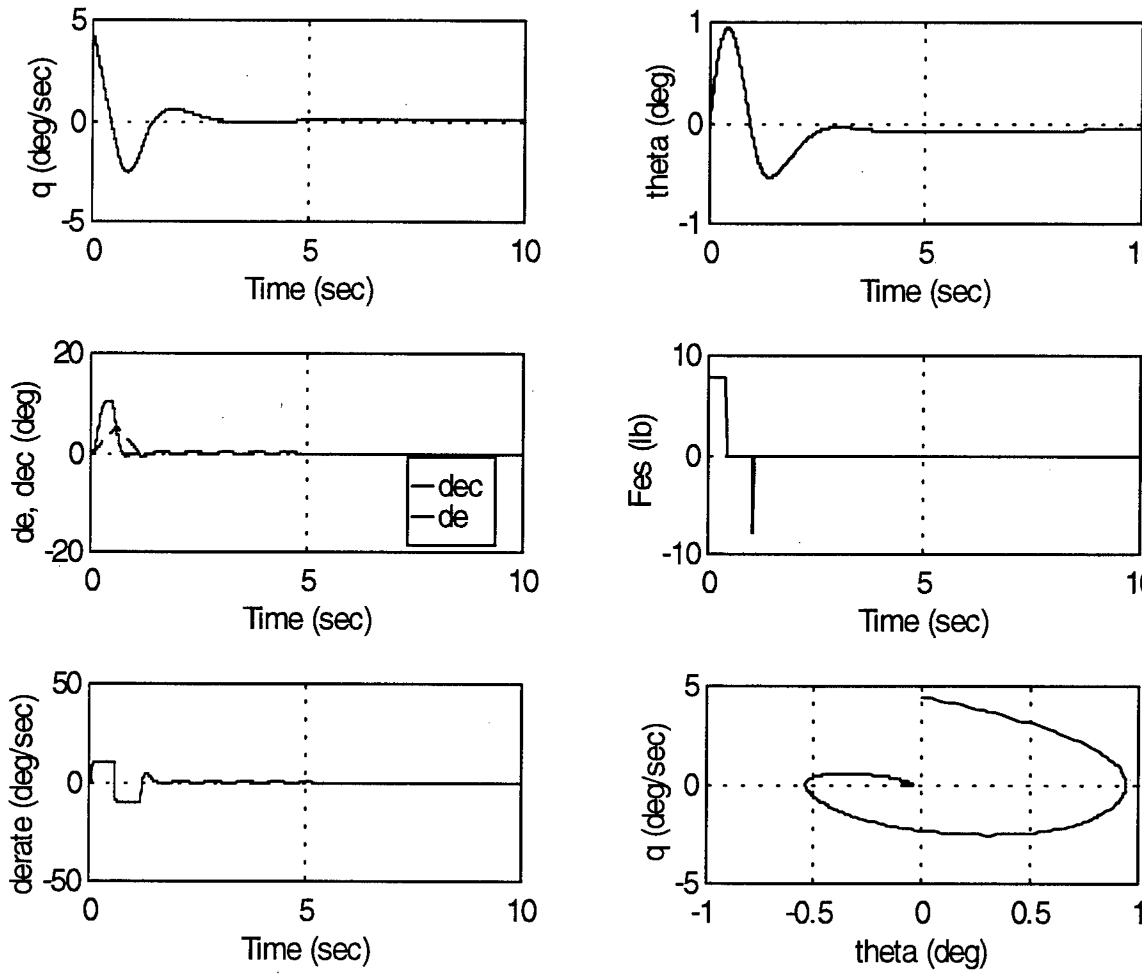


Figure 3-9 Time History: Configuration 2-7, Rate Limit 10 deg/sec,

Delay = 0.23 sec, $q_{thresh}$ = 2.531 deg/sec, $F_{S\ max}$ = 7.9 lbs

systems over the entire range of rate limits. The effects of the different feel systems are more easily seen on the plots of $T_{last}$ vs. Rate Limit (Figures 3-10 through 3-12) and are therefore discussed in the next section.

**Effects of Rate Limiting and Stick Dynamics**

With a 20% change in the stick parameter of interest for each feel system, each of the three configurations were evaluated with a range of elevator rate limits from 200 deg/sec (essentially unlimited) down to zero elevator rate. The results of these simulations are shown in Figures 3-10 through 3-12.

As expected, feel systems 2 (decrease in gain) and 3 (increase in spring constant) were very effective in suppressing the PIO because, using this model, they are effectively the same as decreasing the pilot's input by 20%. A real pilot, however, would be expected to offset this by increasing his inputs to achieve the same aircraft response. Feel system 4 (decrease in spring constant with an outside decrease in gain, i.e. decreased stick deflection response gradient) resulted in slightly degraded system performance because this model did not include its benefit (feedback of stick position to the pilot) and it simply acted as a decrease in natural frequency. Feel system 5 (increase in natural frequency) was effective in limiting the duration of the PIO for all configurations, although not nearly as effective as feel systems 2 and 3. This result is intuitive because the effective delay was reduced. Furthermore, a real pilot would most likely decrease his gain due to increased rate of response, further reducing the probability of PIO. Feel system 6 (increased damping ratio) was good for configuration 3-1 (the high frequency, high damping ratio aircraft), but bad for configuration 2-1. Feel system 7 (increased

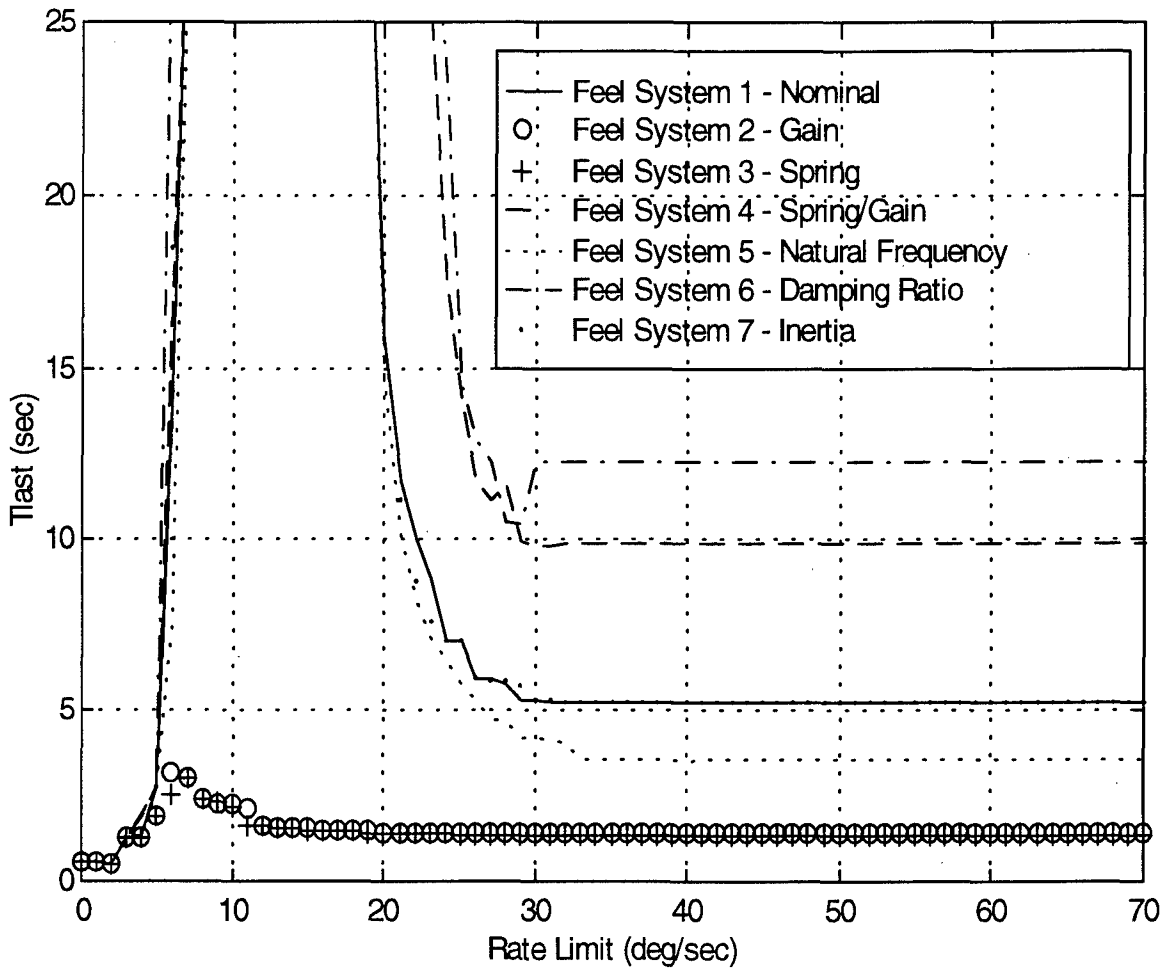


Figure 3-10 $T_{last}$ vs. Rate Limit: Configuration 2-1, All Feel Systems

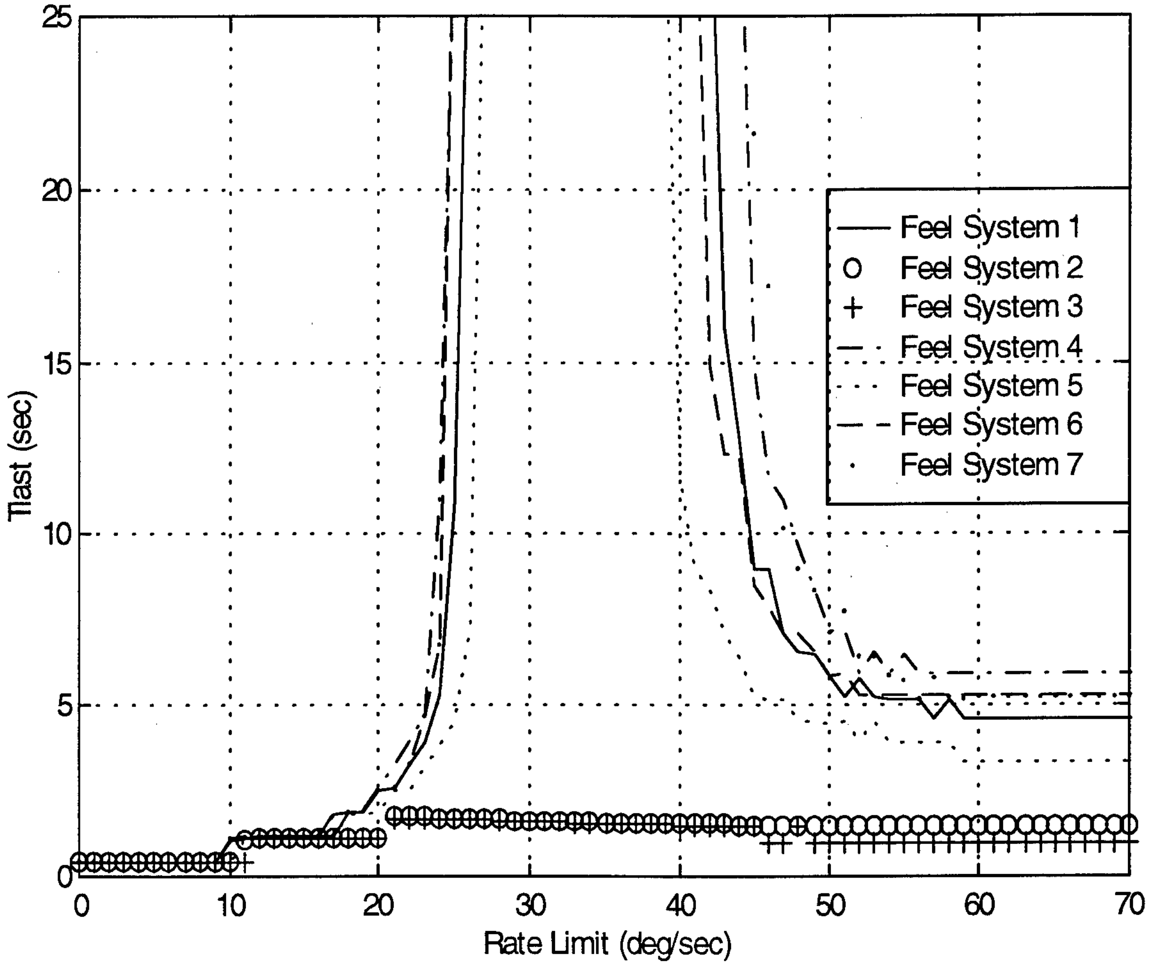


Figure 3-11 $T_{last}$ vs. Rate Limit: Configuration 2-7, All Feel Systems

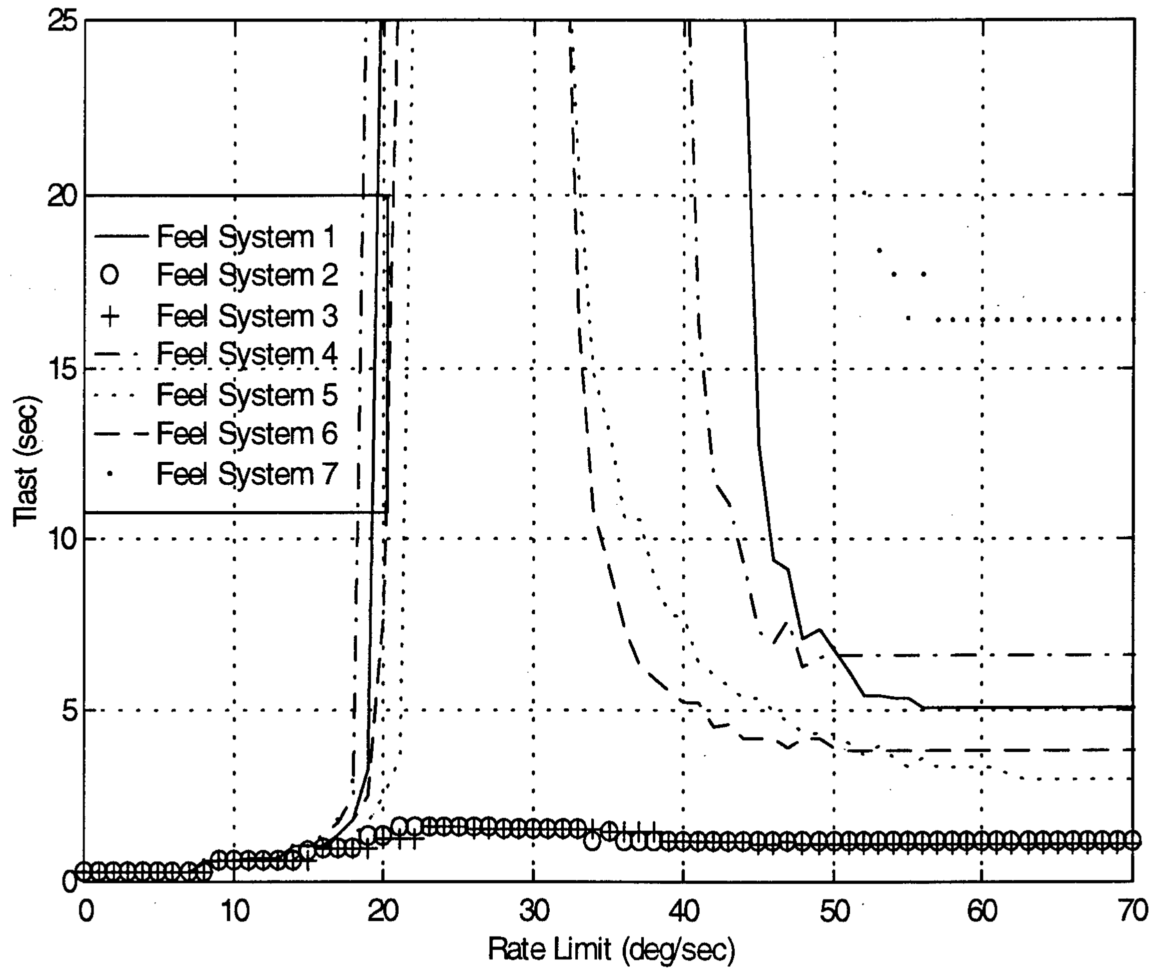


Figure 3-12 $T_{last}$ vs. Rate Limit: Configuration 3-1, All Feel Systems

inertia) had little effect. In addition to the differences between the different feel systems, these three figures still showed a sudden and rapid increase in the duration of the PIO with decreasing rate limit. They also showed that most of the differences between the feel systems were confined to a narrow band of rate limits where the increase in PIO duration occurred (the range of interest).

**Shortcomings of the Model/Simulation**

The simulation study was limited by both the pilot model and its lack of numerical accuracy. Any pilot model has difficulty modeling a human pilot, all of whom are different and possess the ability to learn and adapt. The pilot model used in this study also had some specific deficiencies which affected the results. First, the pilot model always reacted the same, whereas a real pilot would have changed his inputs as the aircraft response changed, as it would with different stick dynamics or rate limits. Second, this pilot model tracked only pitch rate, while a real pilot would have attempted to control many variables. Third, the output of the pilot model was stick force without regard for how far the stick was moved. Although control force is the pilot's most important control reference for flying qualities purposes (Reference 28), a real pilot may not want to make very large stick movements despite the low forces required. Finally, this pilot model approximated a pilot already in a developed PIO, and had no provision to model entry or transition into the PIO.

With the lack of numerical accuracy inherent in these simulations, the $T_{last}$ metric was developed to determine the relative merit of two simulations. This was necessary because the unchanging nature of the pilot model did not allow significant changes in amplitude and frequency of the limit cycle, which are normally the best indicators of the severity of a PIO. With this in mind, there was no way to assign PIO ratings based on these simulations. The rate limits of interest for the different simulations are also only relative and are not an indication of the actual rate limits at which the aircraft was expected to experience PIO. In short, the simulation study was only able to give some indication of what should be flight tested and a general idea of what to expect.

**Summary of the Simulation Results**

The simulation results were limited by the pilot model and were not useful for determining actual rate limits of interest or PIO ratings, but did show the relative merits of different feel systems and the effects of rate limiting. The simulation time histories appeared to show the anticipated effects of rate limiting. For most of the feel systems, a 20% change in the stick parameter of interest was sufficient to produce most of the effects noted. A decrease in gain or increase in spring constant was very effective in decreasing PIO duration; an increase in natural frequency was effective; and an increase in damping ratio helped one configuration but hurt another. For all of the aircraft configuration/feel system combinations, the increase in PIO duration occurred suddenly and went from five seconds to infinite with a decrease in rate limit of only about 10 deg/sec. The simulations also showed that most of the differences between the feel systems were confined to a narrow band of rate limits where the increase in PIO duration occurred (the range of interest).

Based on the simulation study, a fairly rapid onset of rate limiting effects was expected for the flight test. An increase in spring constant was expected to significantly improve PIO ratings for rate limits within the range of interest. An increase in natural frequency was expected to slightly improve PIO ratings for rate limits within the range of interest. Due to the non-numerical nature of the simulation results, the flight test plan needed to be very flexible in order to allow the test team to determine the rate limit range of interest and the amount of change needed for both the spring constant and the natural frequency of the stick.

# IV. *Flight Test Method*

## General

The primary objective of this effort was to investigate the effects of elevator rate limiting and stick dynamics on longitudinal PIO. Specifically, the hypothesis of the test was that, for a given pilot and flight condition, the difference between the elevator rate limit that caused divergent PIOs and that which caused undesired motions would be small (less than 10 degrees/second). It was also hypothesized that the PIO tendency caused by elevator rate limiting would decrease significantly with an increased stick spring force constant and would decrease slightly with an increased natural frequency of the stick. This test program was designed to test these hypotheses by evaluating PIOs in the offset landing task for a range of rate limits and stick characteristics. A portion of the test program was used to verify that the Lear II adequately simulated the desired aircraft dynamics (Appendix D).

The test program was conducted in three phases. The phases were defined as:

**Phase 1.** A single set of aircraft dynamics with the nominal stick defined in Appendix F was incorporated in the Lear II and flown with successively decreased elevator rate limits to determine which rate limits to use in the Phases 2 and 3. These rate limits were on the simulated aircraft's elevator, not the Lear II's elevator (Appendix D).

**Phase 2.** The spring constant and natural frequency of the stick were varied independently and flown with a single elevator rate limit determined in Phase 1in order to identify the two stick configurations to be used in Phase 3.

**Phase 3.** Four elevator rate limits (200 degrees/second and the three rate limits determined in Phase 1) were flown with three stick configurations (nominal plus the two identified in Phase 2) to investigate the effects of elevator rate limiting and stick dynamics on longitudinal PIOs.

**Test Item Description**

**Test Aircraft.** The test aircraft was a Variable Stability Learjet Model 25, registration number N102VS (Lear II), operated by CALSPAN Corporation under contract with USAF TPS. The aircraft had been modified to serve as a three axis in-flight simulator. The center stick and side stick controllers replaced the standard right seat controls and controlled the aircraft through a fly-by-wire system. The aircraft's variable stability system (VSS), working through the fly-by-wire controls, enabled in-flight changes to the aircraft's stability and handling qualities. The VSS sensed the pilot's control inputs, summed these with the aircraft response signals, and, based on the programmed test flight control configuration, computed a signal that was sent to the hydraulic actuators that operated each control surface independently and in parallel with the normal Learjet actuating mechanisms. A detailed description of Lear II's VSS is contained in *Learjet Flight Syllabus and Background Material for the U.S Air Force/U.S. Navy Test Pilot School Variable Stability Programs* (Reference 5).

The left seat (safety pilot) controls were the original Learjet flight controls and allowed the left seat pilot to serve as a safety observer. Control inputs from the left controls were sent to the control surfaces through the normal Learjet mechanical flight control system, completely bypassing the VSS. Because the mechanical flight controls were reversible, the safety pilot could see the actual control surface movement by watching the yoke. The safety pilot could take control of the aircraft at any time by manually disengaging the VSS by pressing any of the disengage buttons located on the yoke, glare shield, and throttle quadrant, or by making a large force input on the yoke. Additionally, the VSS had embedded safety trips that would automatically disengage the VSS when the computer sensed aircraft motions and rates outside the predefined limits.

**Test Flight Control System.** The system under test was various combinations of elevator rate limits and stick dynamics programmed into the Lear II, referred to later in this report as the simulated aircraft. The basic aircraft dynamics for the test program were identified during the Initial Simulations and Model Validation as discussed in Chapter II and were the same dynamics used in the HAVE PIO flight test program (Reference 7). Appendix D contains a detailed description of the aircraft dynamics. These dynamics were programmed into the Lear II and flown with successively decreased elevator rate limits and varied stick dynamics.

## Flight Test Objectives

The overall test objective was to investigate the effects of elevator rate limiting and stick dynamics on longitudinal PIO. The test was conducted in three phases as discussed in the General section of this chapter. The specific test objectives were to:

1. Establish the elevator rate limit to be used in Phase 2 and the three elevator rate limits to be used in Phase 3.

2. Establish two changes from the nominal stick dynamics to be used in Phase 3. One was a change in the spring constant and the other was a change in natural frequency.

3. Investigate the effects of stick dynamics on longitudinal PIO caused by elevator rate limiting.
4. Obtain flight test data for others to use in studying rate limiting as a cause for PIO.

**Procedures**

Prior to the test missions, two T-38 and two F-16 practice sorties were flown against a marked runway (Figure 4-1) to acquaint the pilots with the offset landing task in a variety of aircraft with different landing handling qualities. These flights increased pilot proficiency in the offset landing task and thereby increased the quality of the test results.

The actual test missions were flown in the Lear II. When necessary, the stick natural frequency and force gradients were verified on the ground prior to taxiing. The test aircraft was flown directly from Edwards AFB to Air Force Plant 42, Palmdale, California. At 5,000 feet mean sea level (MSL) the control system was engaged and several programmed test inputs (PTI) were input to verify the model. Two offset landing tasks were then flown as a warm-up for the pilots. After the warm-up landings were complete, the test configurations were set on downwind by the CALSPAN engineer onboard as directed by the test director. The rate limits were then verified by the real time elevator rate trace available in the aircraft. All offset landing tasks were set up visually with a 300 feet lateral offset, following the instrument landing system (ILS) glideslope down to 200 feet above ground level (AGL), at which point a correction was made to land inside the desired box painted on Runway 25 at Palmdale, on speed and with no lateral drift across the runway. Appendix E contains a complete description of the landing task and associated performance standards.

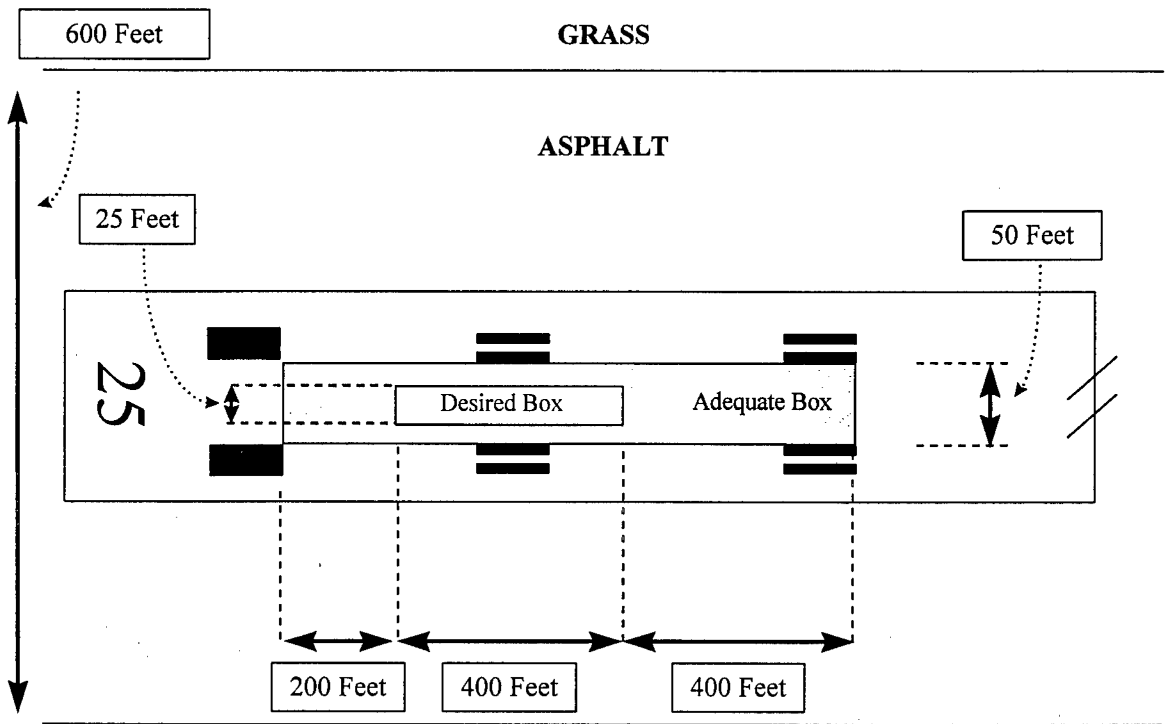


Figure 4-1 Runway Markings for the Offset Landing Task

# V. *Flight Test Results and Analysis*

During the test, the offset landing task was insufficient to consistently uncover handling qualities deficiencies of the aircraft configuration flown. Despite elevator rate limits as low as 5 degree/second, the pilots were able to routinely achieve desired task performance without significant workload. Following through the Cooper-Harper (CH) rating scale decision tree (Appendix F), these combinations of task performance and pilot workload resulted in Level 1 and 2 handling qualities (CH ratings of 6 or lower). However, these ratings did not truly reflect the pilots' perceptions of the handling qualities of the configuration. The pilots commented that the handling qualities were worse than the CH ratings indicated. They realized that the configuration had severely limited elevator control and it would have been difficult to recover from steep glideslopes. In the conditions flown, the pilots were able to compensate for the lack of elevator control by making many small corrections long before big errors in glideslope developed. Because of this, large longitudinal corrections were not usually required. With a more demanding task or in more turbulent conditions, pilots would likely need to make large longitudinal corrections and the deficiencies of this configuration would be more evident.

**Phase 1**

During this phase, the aircraft configuration (with the nominal stick) was flown with decreasing elevator rate limits to investigate the effects of rate limiting on longitudinal PIOs. Rate limiting did not necessarily cause longitudinal PIOs as indicated by PIO ratings of 4 or 5. The PIO and CH ratings (Appendix F) for the three Phase 1 flights are shown in Figures G-1 and G-2, respectively. Two of the three project pilots commented that the aircraft began to show some degradation in handling qualities with elevator rate limits starting at 20 degrees/second. The last project pilot did not notice any degradation until the elevator rate limit was 5 degrees/second. Typical comments from these pilots were that the aircraft felt "sluggish" and there was a noticeable "time delay" in aircraft response. Time histories of the elevator command, elevator position, and elevator rate with 50 and 20 degree/second rate limits are shown in Figures G-3 and G-4. As the rate limits were decreased even further, pilots commented that the aircraft responsiveness seemed to decrease and the apparent time delay between stick input and aircraft response became significant. One pilot gave a PIO rating of 5 with a 10 degree/second elevator rate limit. The time histories for this offset landing are shown in Figure G-5. The PIO was a low frequency, small amplitude oscillation with a period of approximately four seconds. The other two pilots had PIO ratings ranging from 2 to 4 with a 5 degree/second elevator rate limit. Based on these results, 7.5 degree/second was chosen as the elevator rate limits for the stick investigation (Phase 2). Five, 10, and 15 degree/second elevator rate limits were chosen for the investigation of stick dynamics and rate limits (Phase 3).

During Phase 1, PIO ratings, CH ratings, and pilot comments were influenced by factors other than changes in rate limits. Some of these factors were the initial and final set up for the landing task (i.e., the conditions just prior to and just after the offset correction), winds, gusts, and turbulence. As an example, one pilot flew six consecutive offset landings tasks with the same aircraft configuration (including rate limit) and assigned widely varying PIO and CH ratings for that same configuration (Table J-2, Flight 2, 1 Oct 1996). The rate limit for these tasks was 5 degrees/second. On four of the six offset landing tasks, the pilot assigned PIO ratings of 2 and CH ratings of 3 and 4 indicating Level 1 and 2 handling qualities. On the other two landings, the pilot assigned PIO ratings of 4 and CH ratings of 8 and 10 indicating Level 3 and uncontrollable handling qualities. The time histories for the third and fourth of these six landings are shown in Figures G-6 and G-7. Clearly, the perceived handling qualities of a particular configuration varied greatly from one landing task to another due to factors other than the rate limit.

A summary of the pilot comments and observations from Phase 1 is listed below. A complete listing of the pilot comments is listed in Appendix J.

1. Any oscillations observed were low frequency and low amplitude. Pilot estimated the period of the oscillations to be approximately 4 seconds. One pilot commented that although he felt small oscillations in the stick, he could not feel or see any oscillation in the aircraft motion.

2. The project pilots tended to compensate for the low elevator rate limits by flying the aircraft more open loop.

3. Some oscillations were described as glideslope or vertical velocity oscillations.

4. Any oscillations that did develop tended to develop near the end of the task. Because of this, there was not enough time before touchdown to determine if the oscillations were divergent or not.

**Phase 2**

During this phase, the spring constant and natural frequency of the stick were varied independently with a single elevator rate limit determined in Phase 1 in order to identify the two stick configurations to be used in Phase 3.

**Spring Constant Variation.** The PIO ratings and CH ratings for the three pilots with 7.5 degree/second elevator rate limits and stick spring constants ($K_s$) ranging from 0.6 to 2.2 times the nominal are shown in Figures H-1 and H-2. There was no definitive trend relating PIO or CH ratings and the stick spring constant. Different pilots liked different sticks. Qualitatively, pilots tended to describe the stiffer stick ($K_s > 1$) as heavy and the aircraft as sluggish and slow to respond. The stick with $K_s < 1$ was described as light or loose. As in Phase 1, oscillations were low frequency and small amplitude. Two of the three pilots commented that the stiffer stick was worse in terms of task performance and controllability. The stiffer sticks made the oscillations more pronounced, while the lighter sticks seemed to make the oscillations harder to detect. One pilot felt that he had less control with the stiffer stick. The other pilot commented that with the stiffer stick, it was easier to maintain desired landing conditions. However, if a gust or pilot distraction got the aircraft off conditions, then it was harder to correct to proper glideslope with the stiffer stick. For these two pilots, workload definitely increased with the heavier stick. The third pilot felt that with the stiffer stick, he was less likely to put in large control inputs and thus less likely to be on the rate limit. For really stiff sticks, delays became more evident. Again, with the stiffer stick, this pilot was less willing to put in large control inputs making the aircraft appear more sluggish. Since the pilots preferred different sticks and none provided significant handling qualities improvements, a spring constant ($K_s$ = 1.4) was chosen for Phase 3 testing to provide a reasonable stick force gradient.

**Natural Frequency Variation.** The PIO ratings and CH ratings for the three pilots with 7.5 degree/second and 5 degree/second elevator rate limits and natural frequencies of the stick ($K_\omega$) ranging from 0.4 to 2.2 times the nominal are shown in Figures H-3 and H-4. There was no definitive trend relating PIO or CH ratings and the natural frequency of the stick. Different pilots liked different sticks. All three project pilots commented that sticks with higher natural frequencies were more responsive and sensitive. However, this increase in responsiveness led to very little differences in PIO susceptibility or ability to perform CH task. At $K_\omega$ = 1.8, one pilot commented that the stick was too sensitive and felt "jerky." Pilots tended to compensate for the sensitive stick by "backing out of the loop." The project pilots tended to describe the lower frequency sticks ($K_\omega$<1) as heavy with some time delay. In addition, these sticks seemed to "float" or "bounce" due to the higher stick inertia needed to reduce the natural frequency. One pilot thought that the stick with a slightly higher natural frequency ($K_\omega$ = 1.4) had slightly better handling qualities. Another pilot thought the higher frequency stick had marginally worse handling qualities and felt the lower frequency stick had better handling qualities. The third pilot saw little difference with varying stick natural frequencies. Since the pilots preferred different sticks and none provided significant handling qualities improvements, a natural frequency ($K_\omega$ = 1.4) was chosen for Phase 3 testing to provide a reasonable change from the nominal.

During Phase 2, the team discovered that environmental conditions played a large role in the effect of elevator rate limits on PIO and CH ratings. Based on Phase 1 results, the elevator rate limit chosen for the Phase 2 investigation was 7.5 degrees/second. This rate limit was based on flights flown primarily during the mid-morning with low turbulence. During Phase 2, early morning results showed that the 7.5 degree/second rate limit did not produce any oscillations. Because of this, the last two flights in this phase were flown with a 5 degree/second rate limit. For the remainder of the test, it became evident that the gust and turbulence level greatly influenced the development of PIOs. The pilots commented that the gusts and turbulence had a greater effect on the PIO and CH ratings than the variations in the natural frequencies of the stick. In addition, the differences between sticks were not significant enough to be reflected on the PIO or CH ratings.

**Phase 3**

In Phase 3, the four elevator rate limits determined in Phase 1 were flown with the three stick configurations determined in Phase 2 to investigate the effects of elevator rate limiting and stick dynamics on longitudinal PIO. The elevator rate limits used were 5, 10, 15 and 200 degrees/second. The stick dynamics used were the nominal stick, a stick with 40% higher spring constant, and a stick with 40% higher natural frequency. The pilots did not know the order of the test points (different elevator rates and stick configurations). Table F-1 details the configurations flown.

Figures I-1 through I-8 present the PIO and CH ratings for the different rate limits and stick configurations. Pilot comments for Phase 3 are given in Appendix J. This phase confirmed the results of the previous phases.

Changing the spring constant or natural frequency of the stick had little effect on the PIO or CH ratings for this combination of aircraft dynamics and task. Based on their comments, the pilots could feel the differences between the different sticks, but the differences were not significant, especially in task performance. In addition, the pilots did not agree with regard to which stick configuration reduced the PIO tendency without reducing performance.

The offset landing task was insufficient to consistently uncover handling qualities deficiencies of the aircraft configuration flown. At very low rate limits the problem was the lack of pitch response, not PIO. Any observed oscillations were very low frequency and small in amplitude. These results indicate that the task flown may not have been optimal to investigate the effects of stick dynamics and elevator rate limits on longitudinal PIOs. A detailed discussion of the choice of task and configuration for studying PIOs is contained in the Lesson Learned section (Appendix A).

# VI. *Conclusions*

The overall objective was to investigate the effects of elevator rate limiting and stick dynamics on longitudinal PIOs. This objective was met, but not with the expected results. The results of this test led to three major conclusions:

1. The fact that CH ratings were not consistent with the pilot perceptions of the handling qualities of the aircraft indicated that the offset landing task flown was insufficient to consistently uncover handling qualities deficiencies of the aircraft configuration flown. A detailed discussion of the choice of task and configuration for studying PIOs is contained in the Lessons Learned section (Appendix A).
2. Rate limiting does not necessarily cause PIOs. At very low rate limits the problem was the lack of pitch response, not PIO. Any observed oscillations were very low frequency and small in amplitude.
3. Changing the spring constant or natural frequency of the stick had little effect on the PIO or CH ratings for this combination of aircraft dynamics and task. For this test, PIO ratings, CH ratings, and pilot comments were more influenced by the environmental conditions and differences between approach setups than variations in the stick.

These conclusions are specific to this system and may not apply to all aircraft, especially aircraft where PIO tendencies are driven by much higher rate limits.

## *Appendix A - Lessons Learned*

During the course of this flight test, there were several lessons learned which need to be passed on to any who wish to do additional testing in this area (PIO caused by rate limiting). They are as follows:

1. Most of the offset landing tasks were flown early in the morning to avoid gusty winds and provide consistent, repeatable results. However, because of the calm winds, the pilots were able to fly the offset landing task almost open loop, thereby not experiencing PIO. The few flights flown later in the day when the winds were more gusty, showed that pilots had to use higher elevator rates, and thereby experienced more PIOs. However, whether or not a PIO was experienced on a given approach was very dependent upon the amount of gusty winds and turbulence. This makes any results difficult to duplicate. A better way of forcing the pilot into higher gains would be to incorporate a "gust generator" into the variable stability system. This way, if flown in the early morning, the task would be repeatable and still generate the increased pilot gain required to facilitate PIO.
2. Possible solutions to the low rate limit problem include: the "gust generator" mentioned above; an up-and-away close formation task on a maneuvering target (or any other higher gain, operationally representative task); using a simulated aircraft without such good dynamics; using a higher order flight control system so that the elevator actuators will still be working hard even if

the pilot is relatively low gain. The idea is to get the degradation in handling qualities to occur at a much higher rate limit.

3. With the very small differences between test points, neither the PIO nor the Cooper-Harper rating scale was fine enough to make any distinctions between test points. Well documented pilot comments were the best discriminator between test configurations. These worked best when comparisons were made between consecutive test points.

4. All tests should have been blind to the pilot. All project pilots were involved with the test planning and, knowing that rate limiting was involved in the testing, may have altered their compensation accordingly. Preconceived notions about the test points could have affected comments or comparisons. When the pilot knew what to look for, it was easier to tailor the findings and comments to what was expected. Even in Phase 3, the pilots knew what test points were in the test point matrix.

## *Appendix B - Simulation Configurations and Model Parameters*

Table B-1 Simulation Configurations and Model Parameters

| Configuration | q0 (deg/sec) | Aircraft Dynamics | Control System | Pilot Model Parameters | | | | Feel System | Rate Limit (deg/sec) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Delay (sec) | $F_{S\,max}$ (lbs) | $q_{thresh}$ (deg/sec) | $q_{thresh}$ for Metric (deg/sec) | | |
| initial simulations | 10 | All | All | 0.25 | 50, 22 | 4.00 | N/A | Nominal | Various |
| 2-1 | 1.125 | 2 | 1 | 0.30 | 2.0 | 0.30 | 0.5728 | All | Various |
| 2-7 | 4.440 | 2 | 7 | 0.23 | 7.9 | 2.10 | 2.5310 | All | Various |
| 3-1 | 0.845 | 3 | 1 | 0.18 | 3.2 | 0.30 | 0.4335 | All | Various |

# *Appendix C - $T_{last}$ vs. Stick Parameter Multiplier Plots*

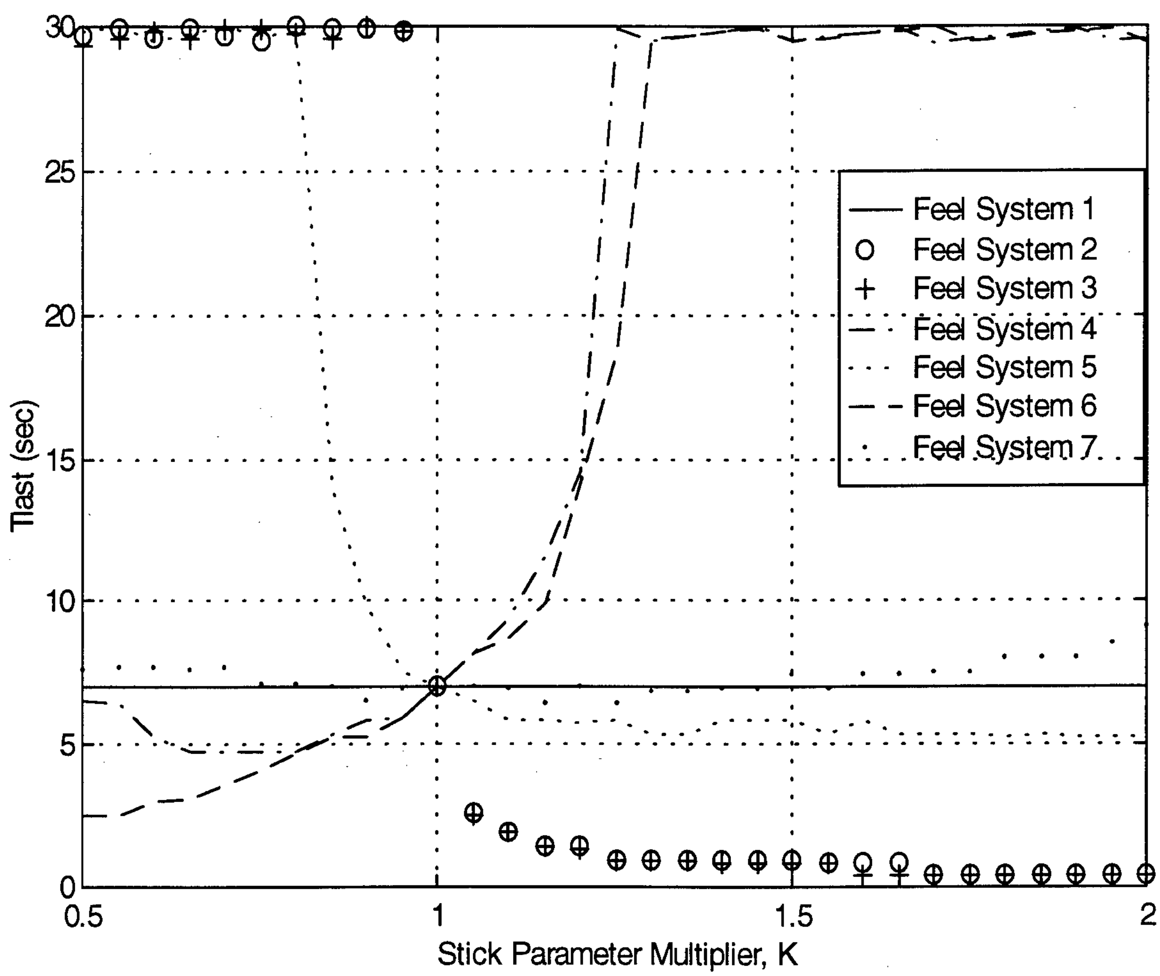


Figure C-1 $T_{last}$ vs. Stick Parameter Multiplier: Configuration 2-1, Rate Limit 25 deg/sec

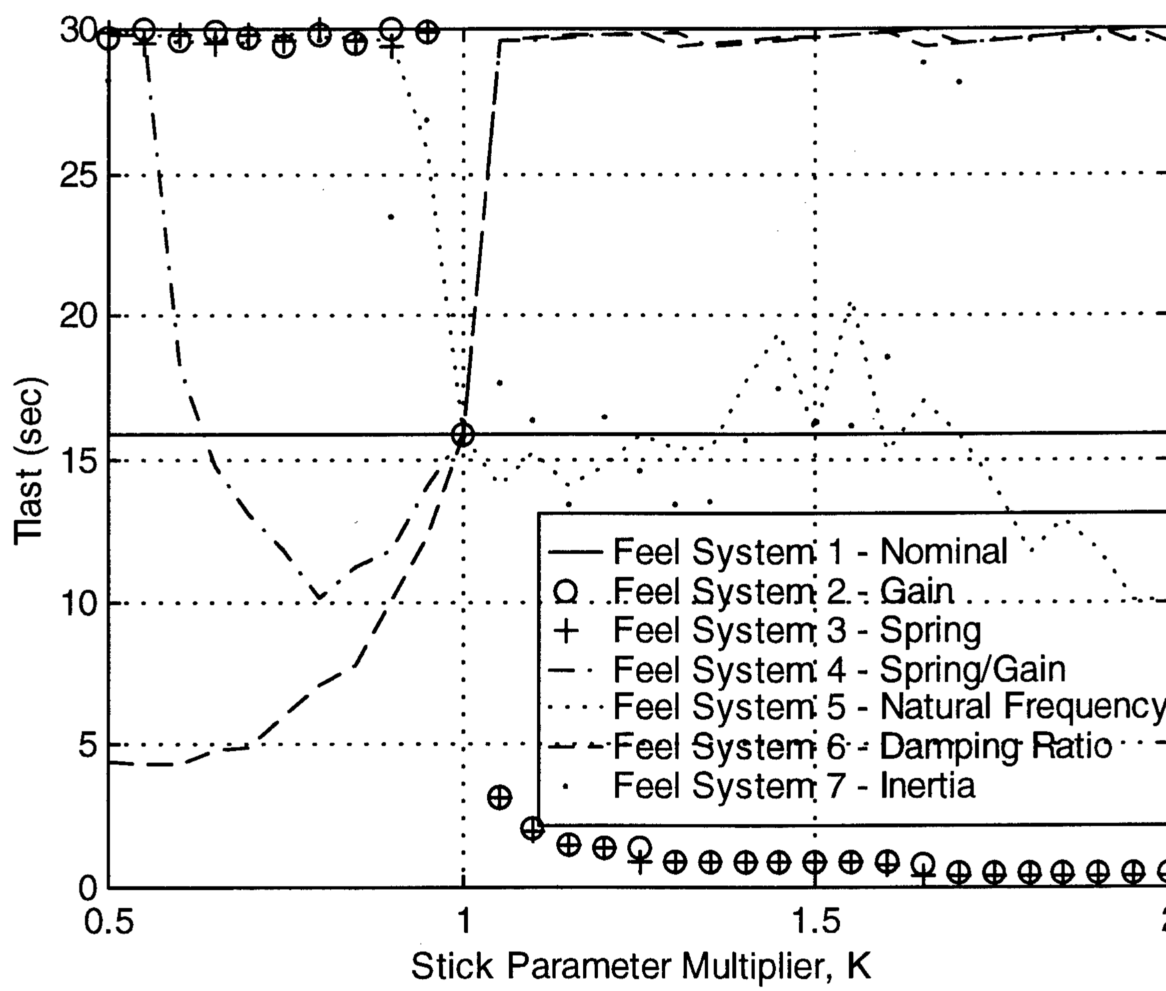


Figure C-2 $T_{last}$ vs. Stick Parameter Multiplier: Configuration 2-1, Rate Limit 20 deg/sec

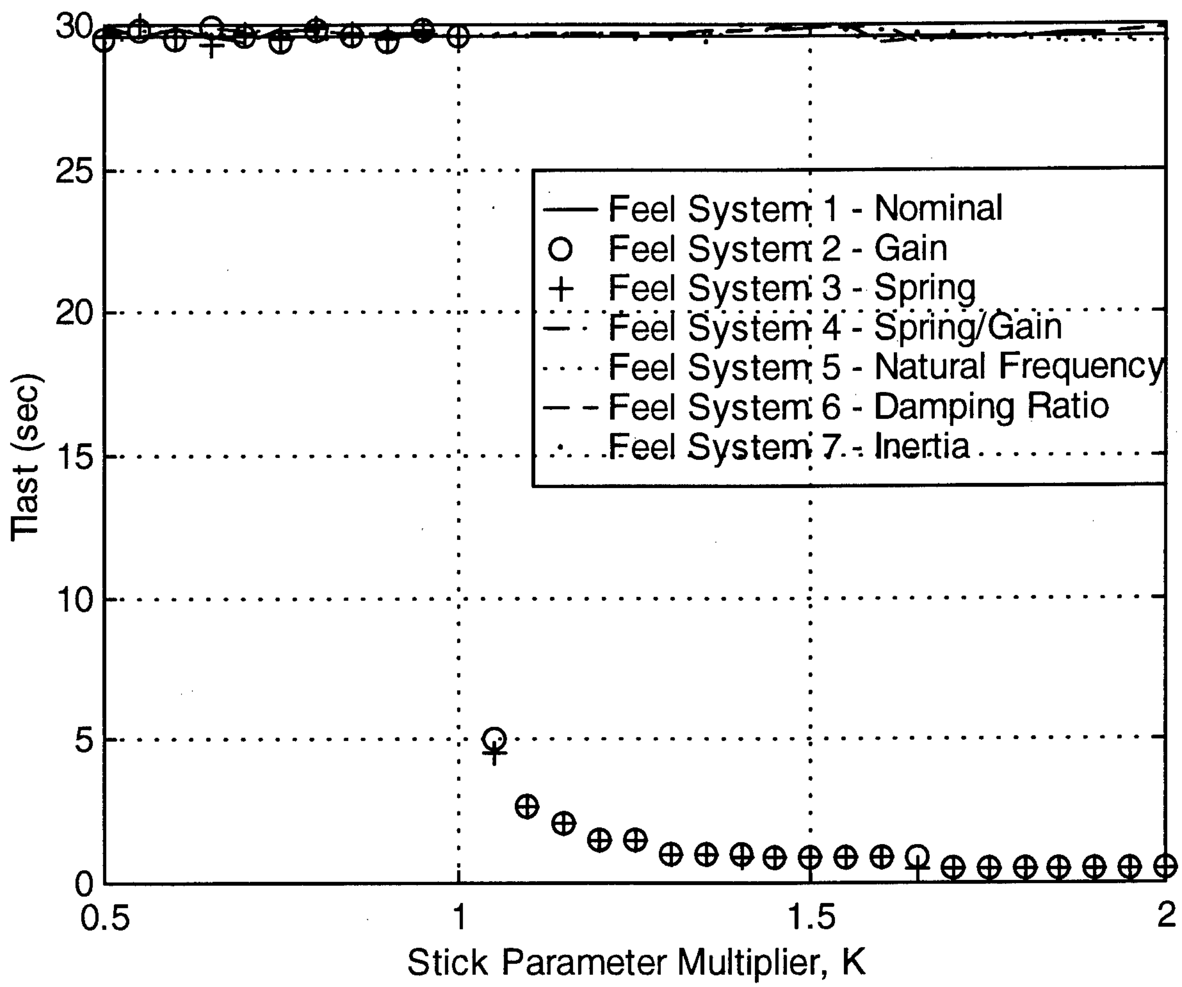


Figure C-3 $T_{last}$ vs. Stick Parameter Multiplier: Configuration 2-1, Rate Limit 15 deg/sec

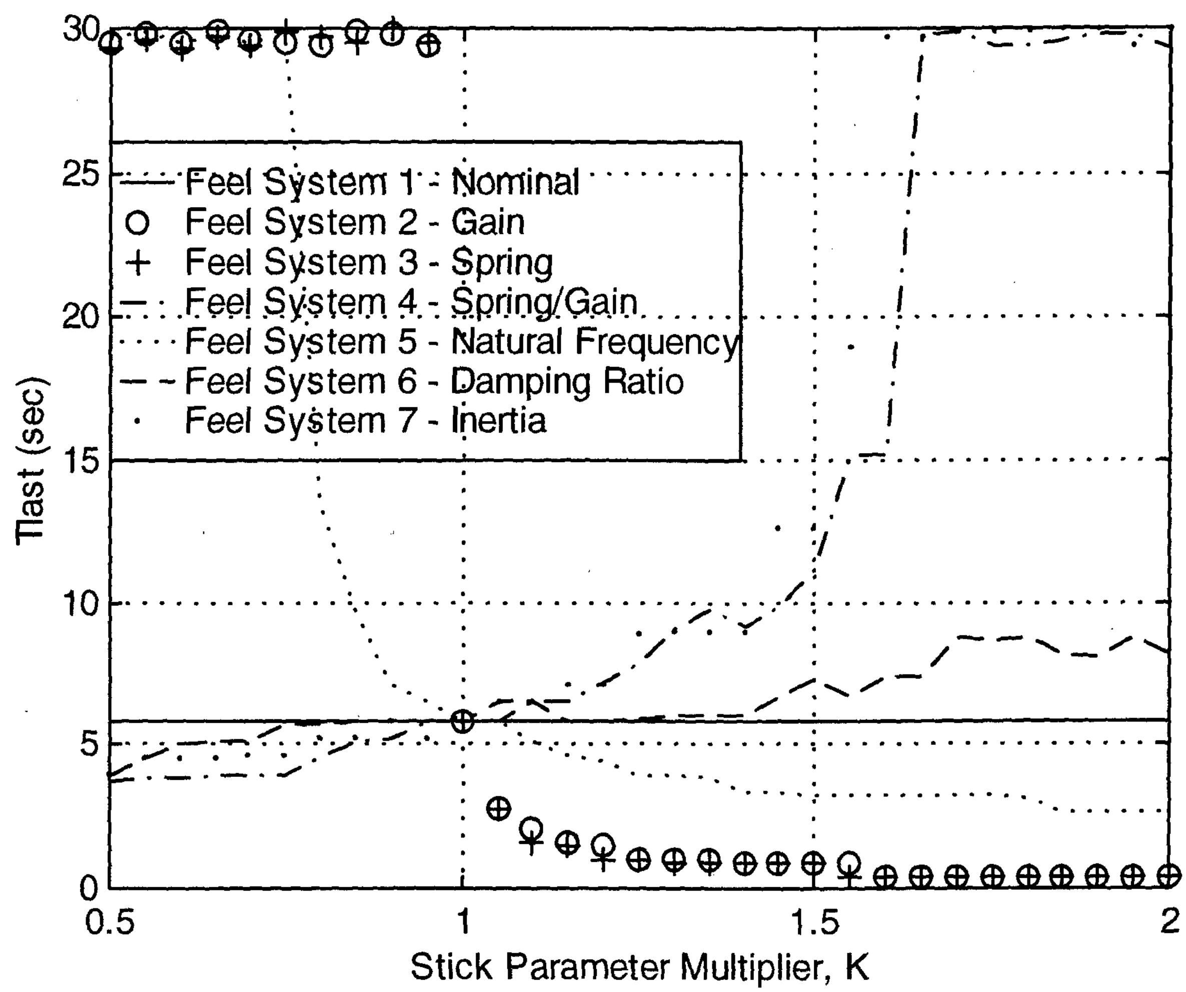


Figure C-4 $T_{last}$ vs. Stick Parameter Multiplier: Configuration 2-7, Rate Limit 50 deg/sec

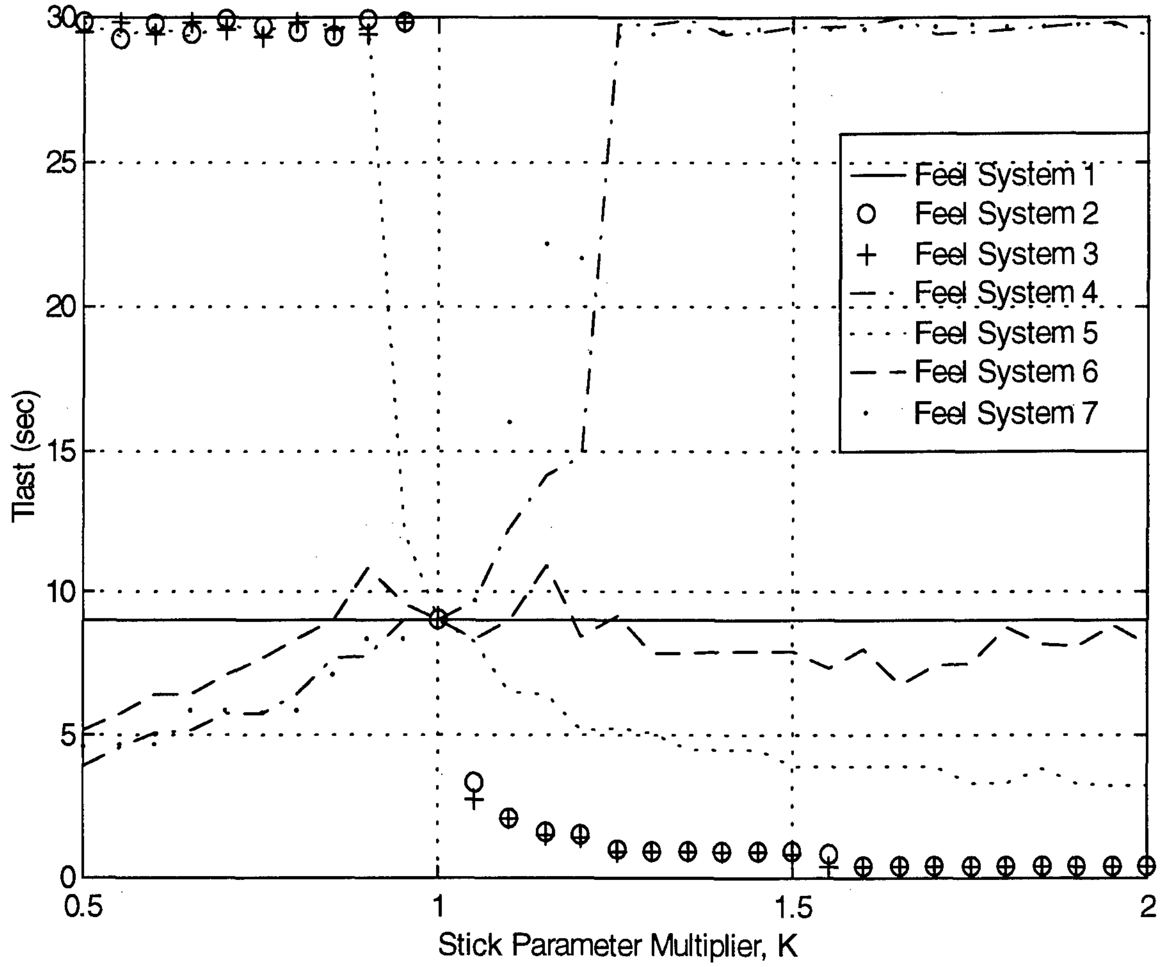


Figure C-5 $T_{last}$ vs. Stick Parameter Multiplier: Configuration 2-7, Rate Limit 45 deg/sec

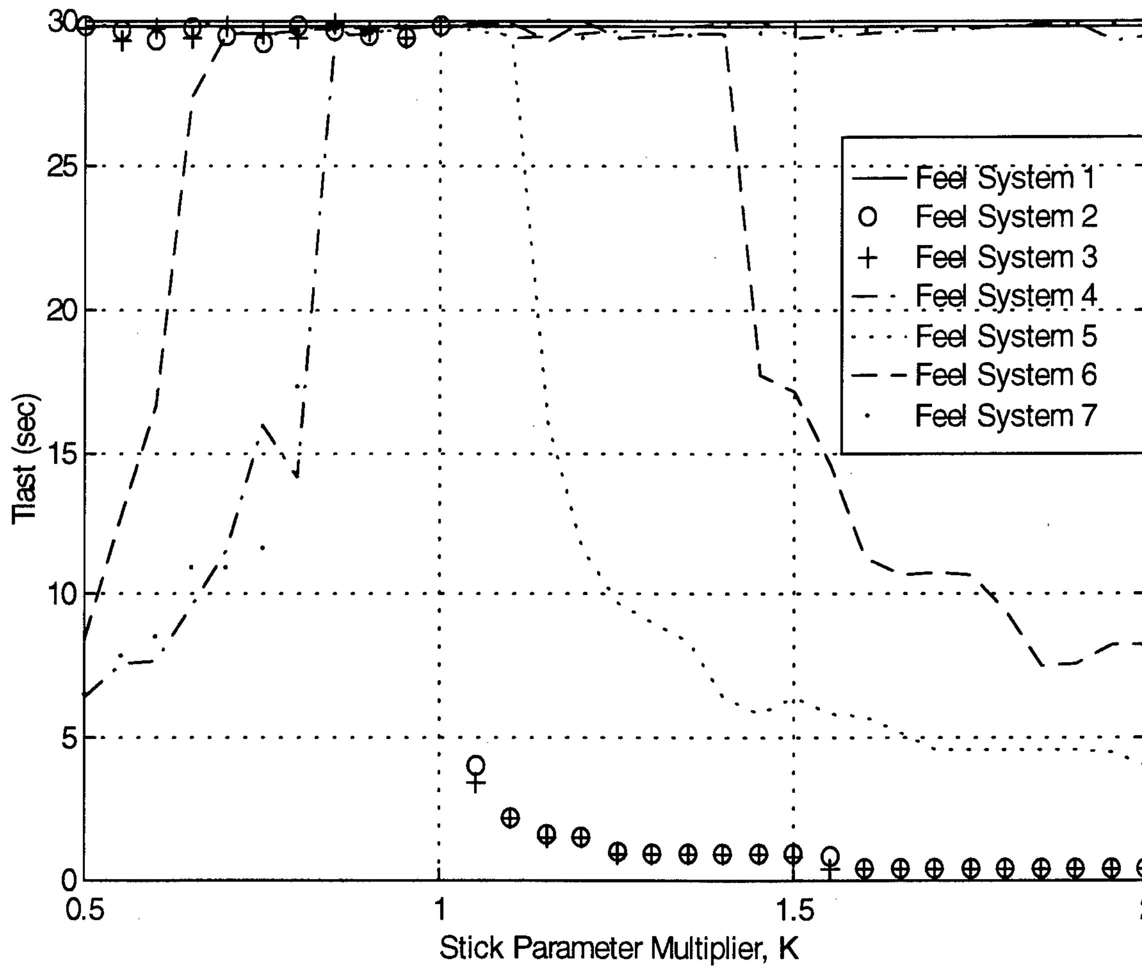


Figure C-6 $T_{last}$ vs. Stick Parameter Multiplier: Configuration 2-7, Rate Limit 40 deg/sec

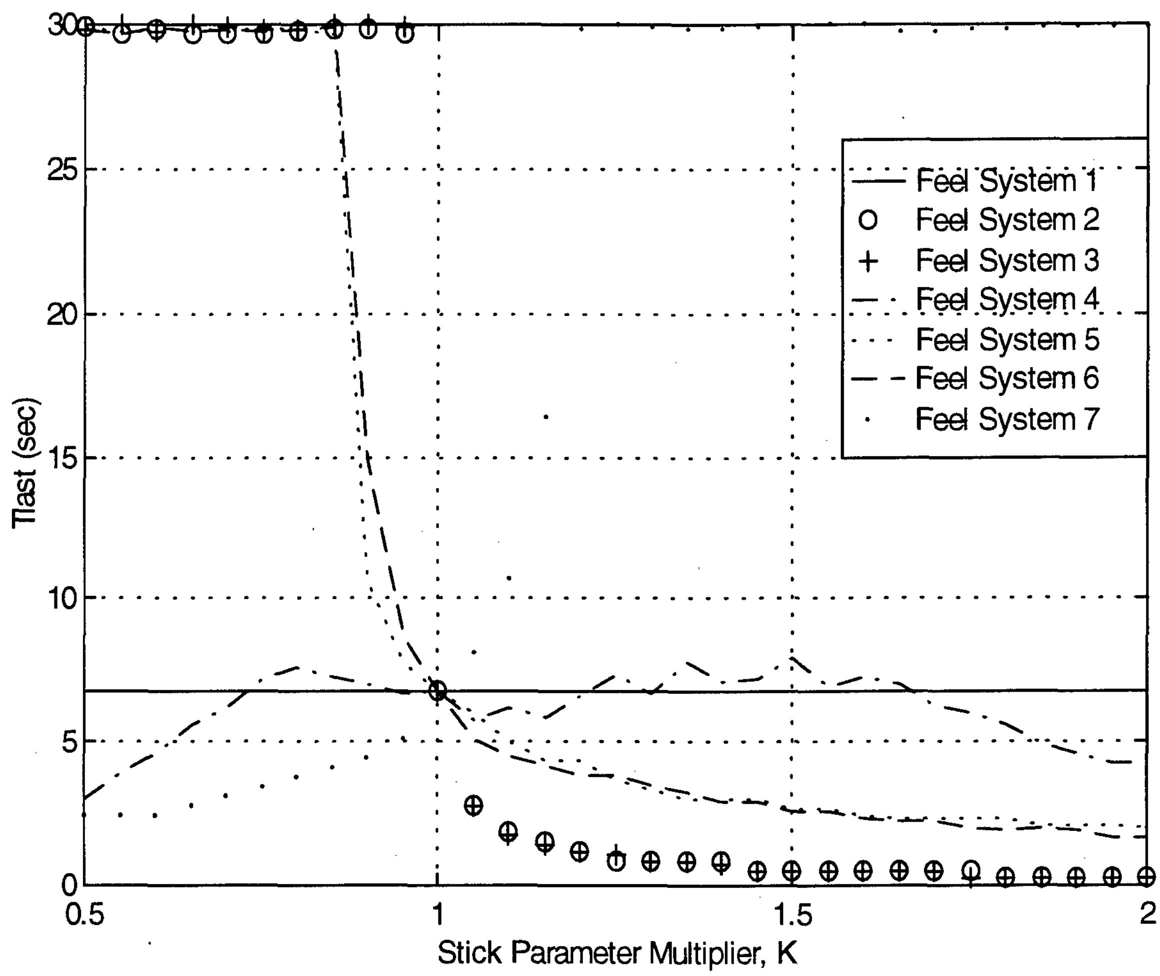


Figure C-7 $T_{last}$ vs. Stick Parameter Multiplier: Configuration 3-1, Rate Limit 50 deg/sec

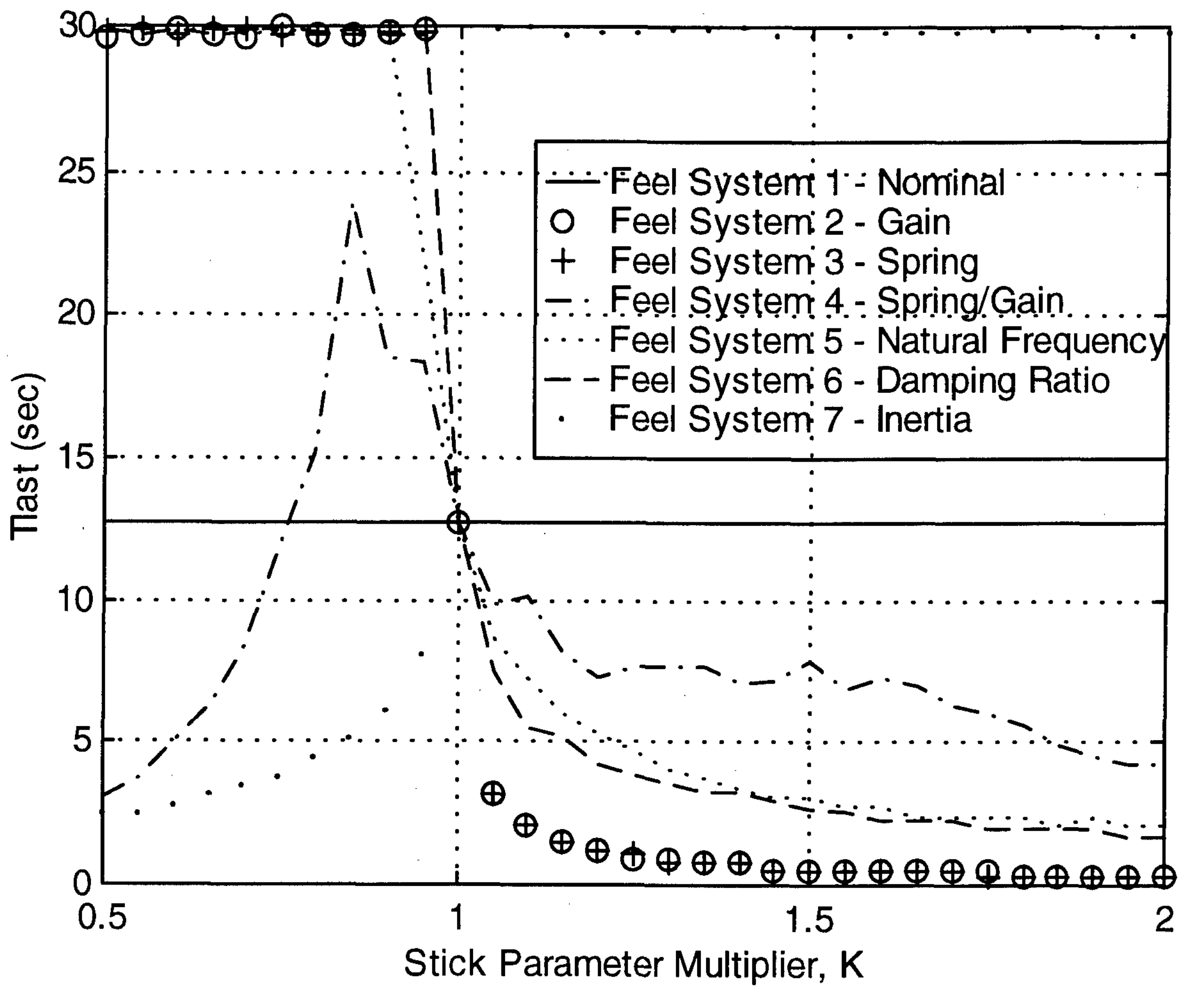


Figure C-8 $T_{last}$ vs. Stick Parameter Multiplier: Configuration 3-1, Rate Limit 45 deg/sec

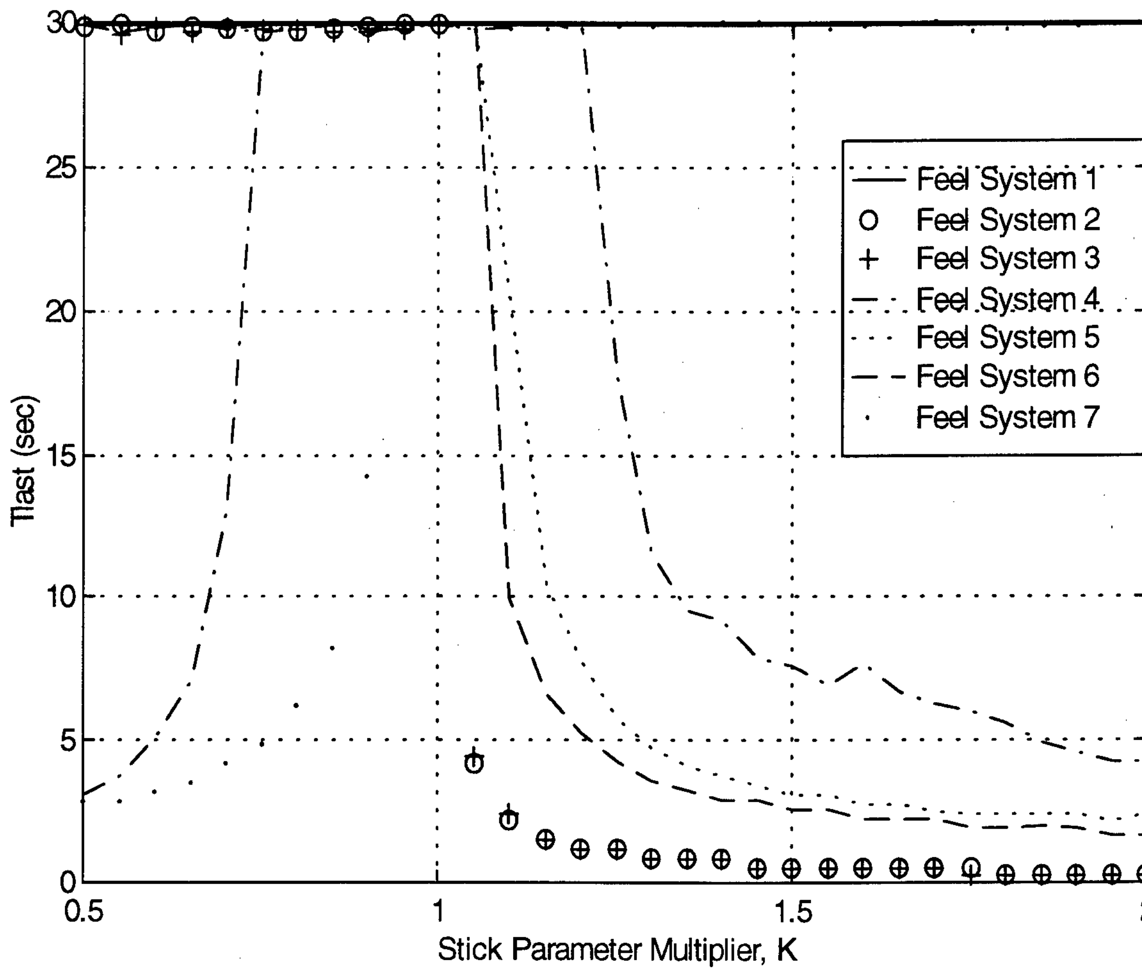


Figure C-9 $T_{last}$ vs. Stick Parameter Multiplier: Configuration 3-1, Rate Limit 40 deg/sec

# *Appendix D - Flight Test Configurations*

The aircraft system model used in the HAVE GRIP flight test is described in the Figure D-1. This figure shows how the Lear II simulates the desired aircraft dynamics and flight control system. The rate limits were imposed on the modeled aircraft's elevator (implemented in the modeled aircraft actuator), not the Lear II's elevator. The Lear II's elevator was always working hard, even to simulate the stick-fixed dynamics of the simulated aircraft. For this project, the diagram could be simplified as shown in Figure D-2. The components of this block diagram are described below.

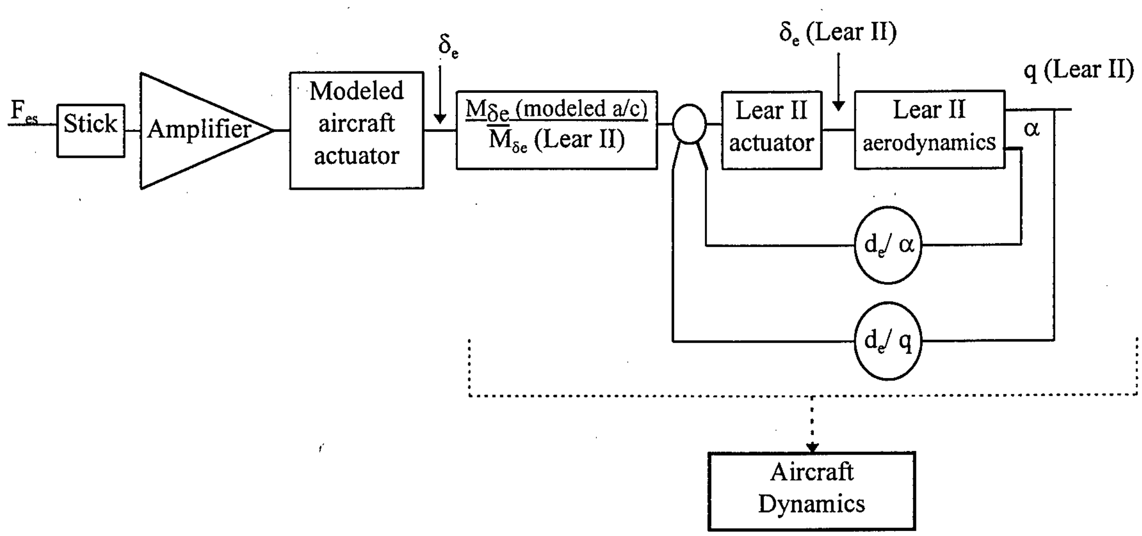


Figure D-1 Lear II Aircraft Block Diagram

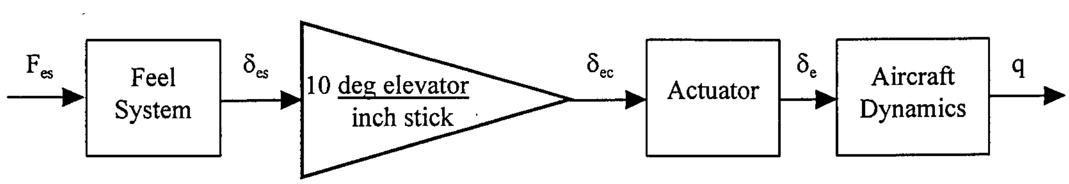


Figure D-2 Simplified Aircraft Block Diagram

**Feel System Description**

The HAVE GRIP stick dynamics (feel system) were modeled by the following equation:

$$\frac{\delta_{es}}{F_{es}} = \frac{0.125 K_S}{[0.6,\ 26 K_\omega]} in / lb$$

The equation is written in shorthand notation where:

$$[\zeta,\omega_n] = (s^2 + 2\zeta\omega_n s + \omega_n^2)$$

and $(a) = (s + a)$

The parameters $K_S$ and $K_\omega$ were varied to make the different stick configurations. Table D-1 defines the rate limiting, $K_S$ and $K_\omega$ for each stick configuration flown during the test

Table D-1 Description of HAVE GRIP Flight Test Configurations

| Phase | Pilot | Rate Limit (deg/sec) | Stick Spring Multiplier ($K_S$) | Stick Frequency Multiplier ($K_\omega$) |
|---|---|---|---|---|
| 1 | 1, 2, 3 | 200 | 1 | 1 |
| | 1 | 50, 40, 30, 20, 15, 10 | 1 | 1 |
| | 2 | 20, 15, 10, 7.5, 5 | 1 | 1 |
| | 3 | 30, 20, 15, 10, 5 | 1 | 1 |
| 2 | 1, 2, 3 | 7.5 | 0.6, 1, 1.4, 1.8, 2.2 | 1 |
| | 1 | 7.5 | 1 | 0.4, 0.6, 1, 1.4, 1.8, 2.2 |
| | 2 | 5 | 1 | 0.4, 0.7, 1, 1.4, 1.8, 2.2 |
| | 3 | 5 | 1 | 0.4, 0.6, 1, 1.4, 1.8 |
| 3 | 1, 2, 3 | 200 | 1, 1.4 | 1 |
| | 1, 2, 3 | 200 | 1 | 1, 1.4 |
| | 1, 2, 3 | 15 | 1, 1.4 | 1 |
| | 1, 2, 3 | 15 | 1 | 1, 1.4 |
| | 1, 2, 3 | 10 | 1, 1.4 | 1 |
| | 1, 2, 3 | 10 | 1 | 1, 1.4 |
| | 1, 2, 3 | 5 | 1, 1.4 | 1 |
| | 1, 2, 3 | 5 | 1 | 1, 1.4 |

program. The nominal stick spring constant was 8 $^{lb}/_{inch}$. A multiplier, $K_s$, of 1.4 resulted in spring constant of 11.2 $^{lb}/_{inch}$. The nominal stick frequency was 26 $^{rad}/_{sec}$. A multiplier, $K_\omega$, of 1.4 resulted in spring frequency of 36.4 $^{rad}/_{sec}$. The stick had a breakout force of 0.75 lb.

**Actuator**

The hydraulic actuator used in the HAVE GRIP simulations are depicted in Figure D-3. Included in this model were the rate limits that were varied during the testing.

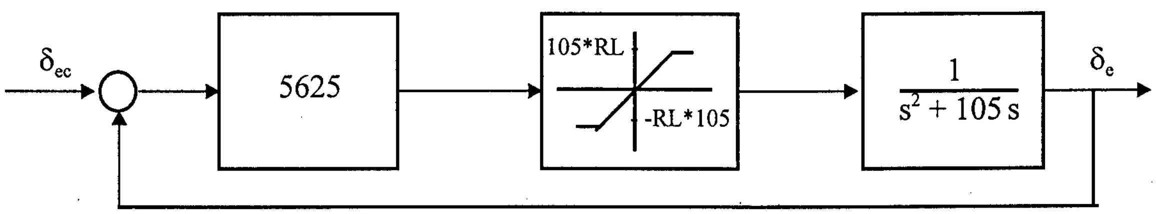


Figure D-3 Hydraulic Actuator Block Diagram

When not rate limited, the actuator dynamics simplify to:

$$\frac{\delta_e}{\delta_{ec}} = \frac{1}{[0.7,\ 75]}$$

The "rate limit" generated by this model differed from a true rate limit by $(1 - e^{-105t}) / 105$, which is very small, but to be strictly correct the model shown in Figure 2-4 should have been used.

**Aircraft Dynamics**

The aircraft configuration used for all HAVE GRIP flight tests was configuration 2-1 from HAVE PIO (Reference 7). The transfer function for this configuration is given below and was simulated by the Lear II except for the phugoid mode:

$$\frac{q}{\delta_e} = \frac{3.3685(0.0845)(0.6990)(0)}{[0.15,0.17][0.63,2.41]}$$

On the next page, a comparison between the model simulation and flight test response to a step input is shown (Figure D-4).

| | | |
|---|---|---|
| A/C: Learjet 25 | Weight: 10,400 lb - 11, 500 lb | Stick Spring Gain: $K_s = 1$ |
| S/N: N102VS | Configuration: 20° Flaps | Stick Frequency Gain: $K_\omega = 1$ |
| Date: 11 Oct 96 | Gear Down | Rate Limit: 20 deg/sec |
| Flight Number: 14 | | |

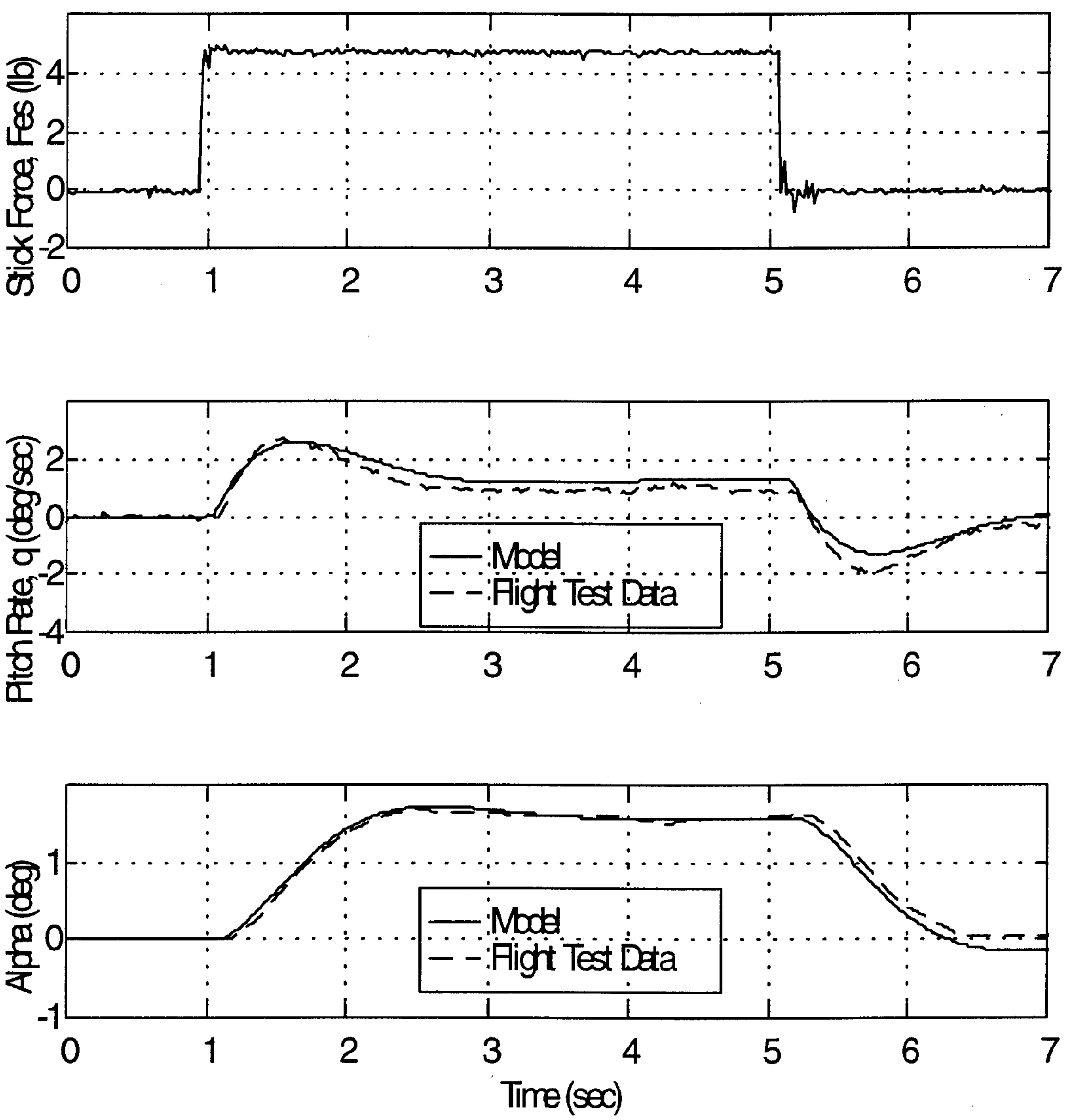


Figure D-4 Model Simulation and Aircraft Response to a Step Input

## *Appendix E - Detailed Flight Test Procedures*

The following steps were performed for each test point:

1. At the beginning of each flight the basic Learjet configuration or the nominal stick with 200 degrees per second rate limit was flown as a warm-up offset landing maneuver. The basic Learjet configuration was used for the warm-up maneuver when the nominal case was tested.

2. Lear II flight control system was configured with the required rate limit/stick dynamic parameters. The test director verified the settings were correct.

3. On downwind at pattern altitude, the variable stability system was engaged and the test pilot took control of the jet.

4. A visual pattern was flown to set up for a lateral offset 300 feet to the left of the runway centerline at a two nautical mile final. The ILS glideslope aimpoint was at the beginning of the adequate box. The test pilot flew 300 feet offset and on ILS glideslope to 200 feet above the runway and, at that point, aggressively corrected to the centerline. The pilot used 30 to 45 degrees of bank for the initial corrections and all gross corrections were completed by 50 feet above the runway. The aim was to flare so as to touch down in the desired box at a touchdown speed 10 kts less than approach speed. The test pilot provided comments for each landing flown, along with PIO and Cooper-Harper ratings against the tasks described below. The task was then be repeated with the same rate limit and stick configuration to collect a second set of comments and ratings. After two landings in a given configuration, the test pilot determined if the landings were representative of the flight control system under test. The test director then determined if the test point was complete and whether or not to proceed with the next test point.

5. The next test block was then be performed or the test mission was called complete.

**Offset Landing Task**

Each offset landing task was set up as follows:

1. Roll out on a 2 NM final to set up for a ILS glideslope (600 feet AGL at 2 NM)

2. Glideslope runway intercept point should be at the beginning of the adequate box
3. Set up offset 300 feet to the left of the centerline when rolling out on final
4. Fly at 125 -135 KIAS (weight dependent) on final
5. Correct to centerline with an aggressive input at 200 feet above the runway
6. Plan to flare so as to touchdown inside the desired box
7. Touchdown speed is 10 kts less than approach speed

Table E-1 Offset Landing Cooper-Harper Task Criteria

| PERFORMANCE LEVEL | CRITERIA |
|---|---|
| DESIRED | Soft landing within the desired box (see below)<br>Touchdown on speed ± 5 kts |
| ADEQUATE | Soft landing within the adequate box (see below)<br>Touchdown on speed +10/-5 kts |

# *Appendix F - Rating Scales*

**Pilot-Induced Oscillation Rating**

A PIO rating was given for each lateral offset landing task. These, combined with the pilots comments, were the primary data in the test program. Figure F-1 was used by the test director to aid the pilot in determining the appropriate PIO rating. PIO ratings are structured pilot comments and were used accordingly. Descriptions for the PIO ratings follow Figure F-1 (Reference 39).

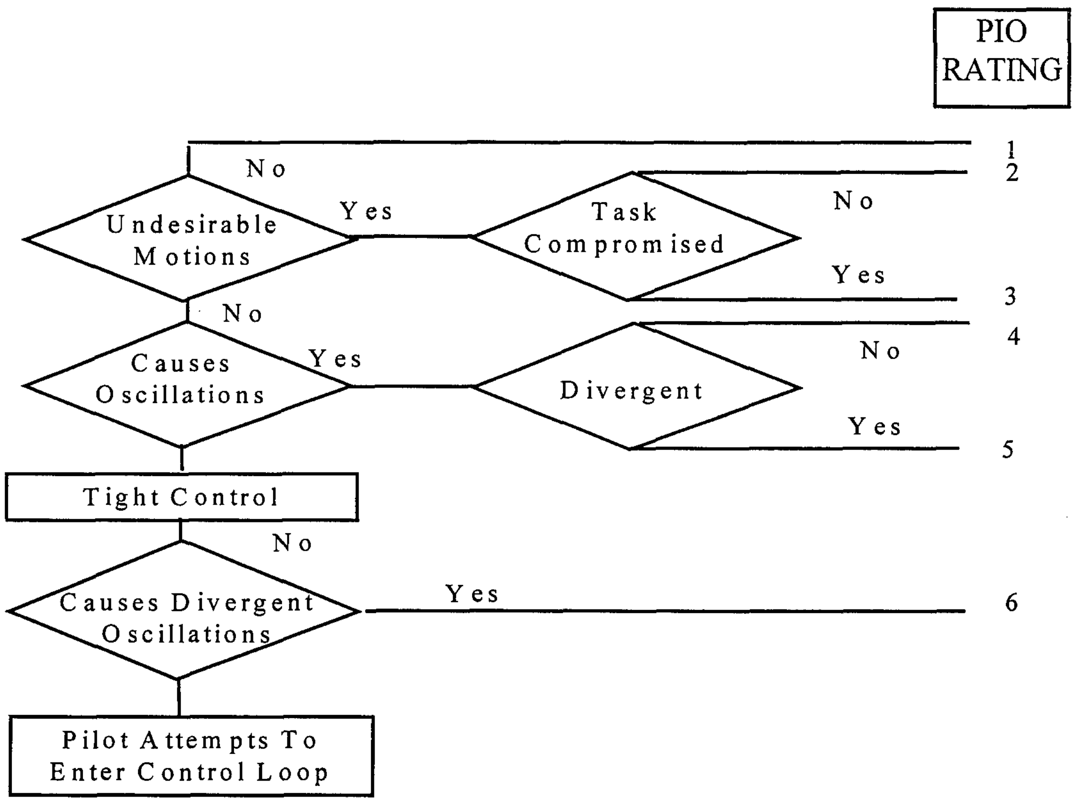


Figure F-1 PIO Rating Scale Decision Tree

<u>**PIO 1**</u> – No tendency for pilot to induce undesirable motion.

<u>**PIO 2**</u> – Undesirable motion tends to occur when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated by pilot technique.

**PIO 3** – Undesirable motions easily induced when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated, but only at sacrifice to task performance or through considerable pilot attention and effort.

**PIO 4** – Oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must reduce gain or abandon task to recover.

**PIO 5** – Divergent oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must reduce gain or abandon task to recover.

**PIO 6** – Disturbance or normal control may cause divergent oscillation. Pilot must open control loop by releasing or freezing the stick.

## Cooper-Harper (CH) Rating

A CH rating was given for each lateral offset landing task as a measure of task performance and pilot workload. The primary purpose of the CH task was to provide a structured, repeatable task which increase the pilots' workload. Figure F-2 was used by the test director to aid the pilot in determining the appropriate CH rating (Reference 9).

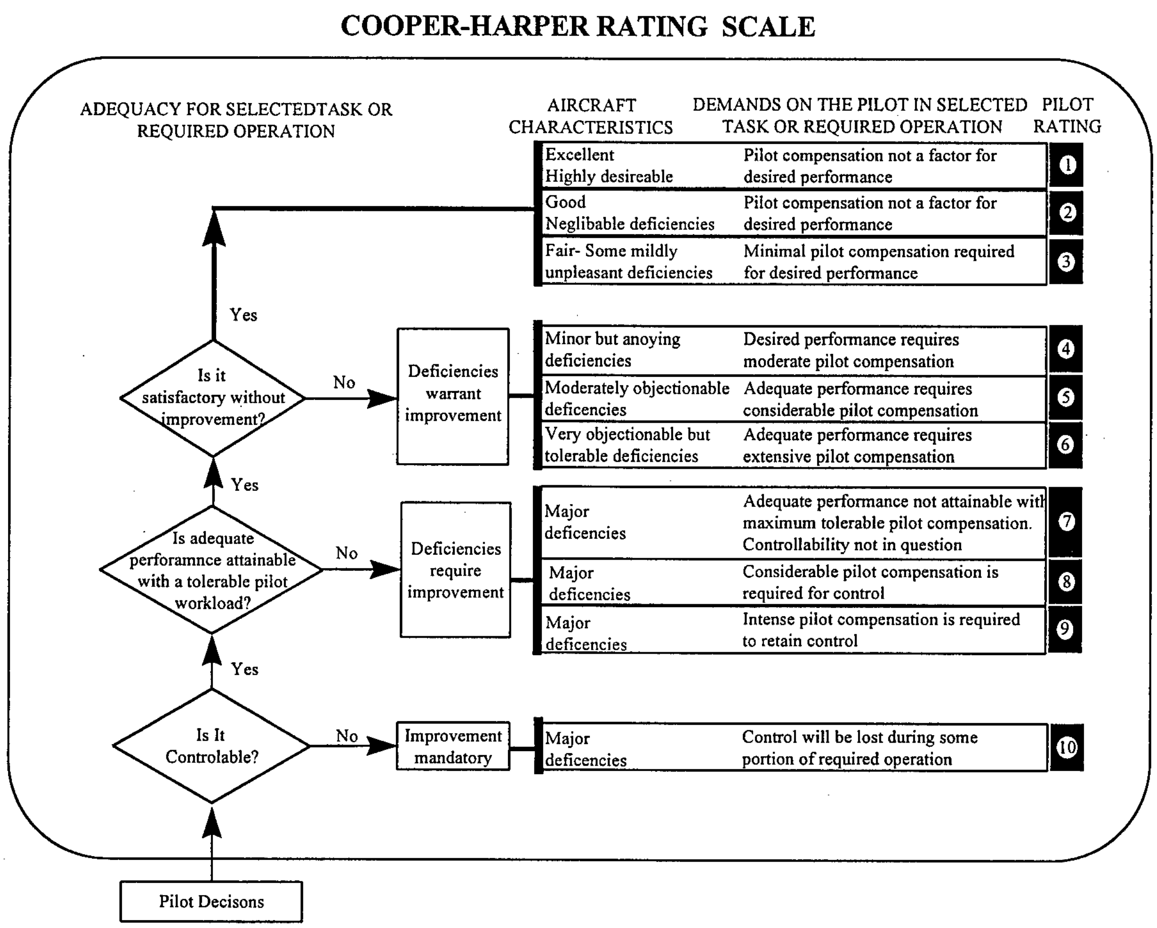


Figure F-2 Cooper-Harper Rating Scale

# *Appendix G - Phase 1 Data Plots*

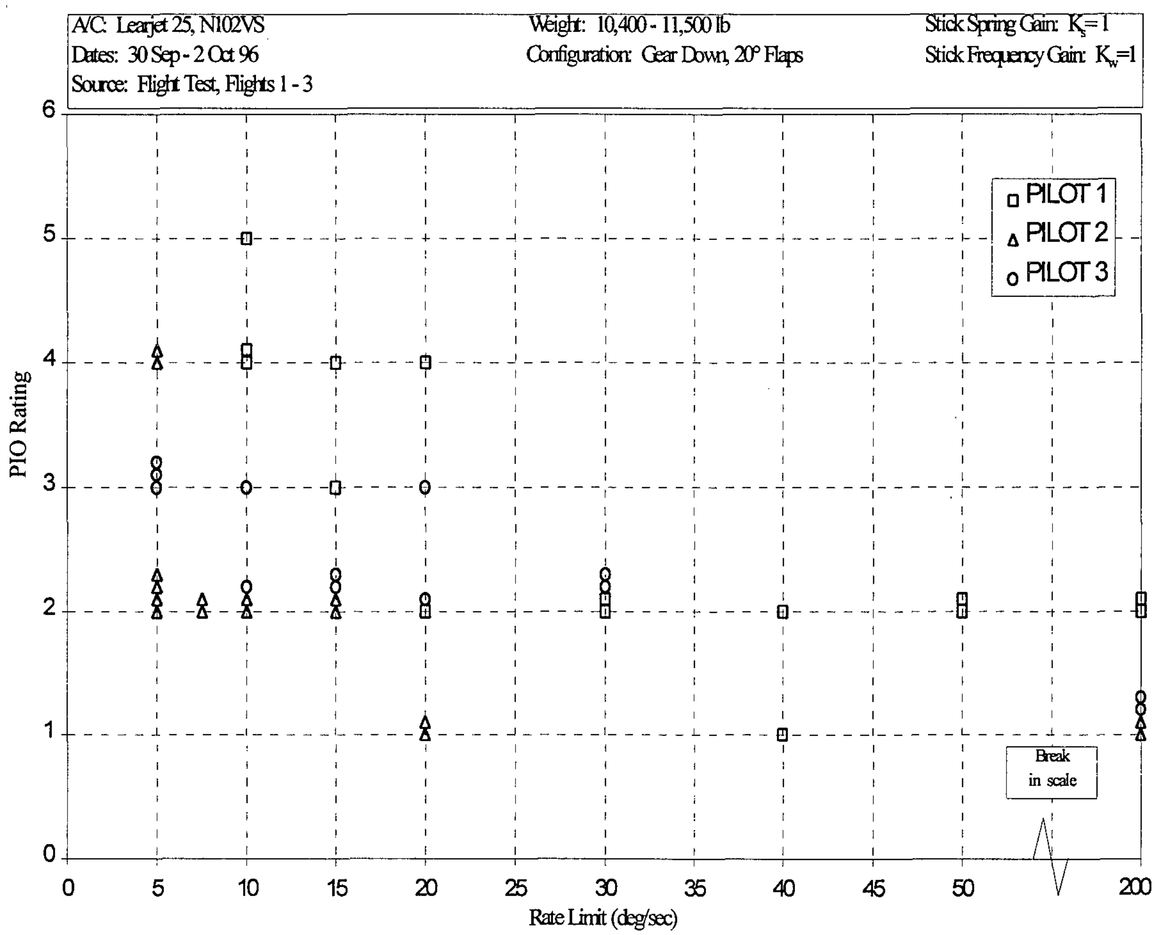


Figure G-1 Phase 1 PIO Ratings

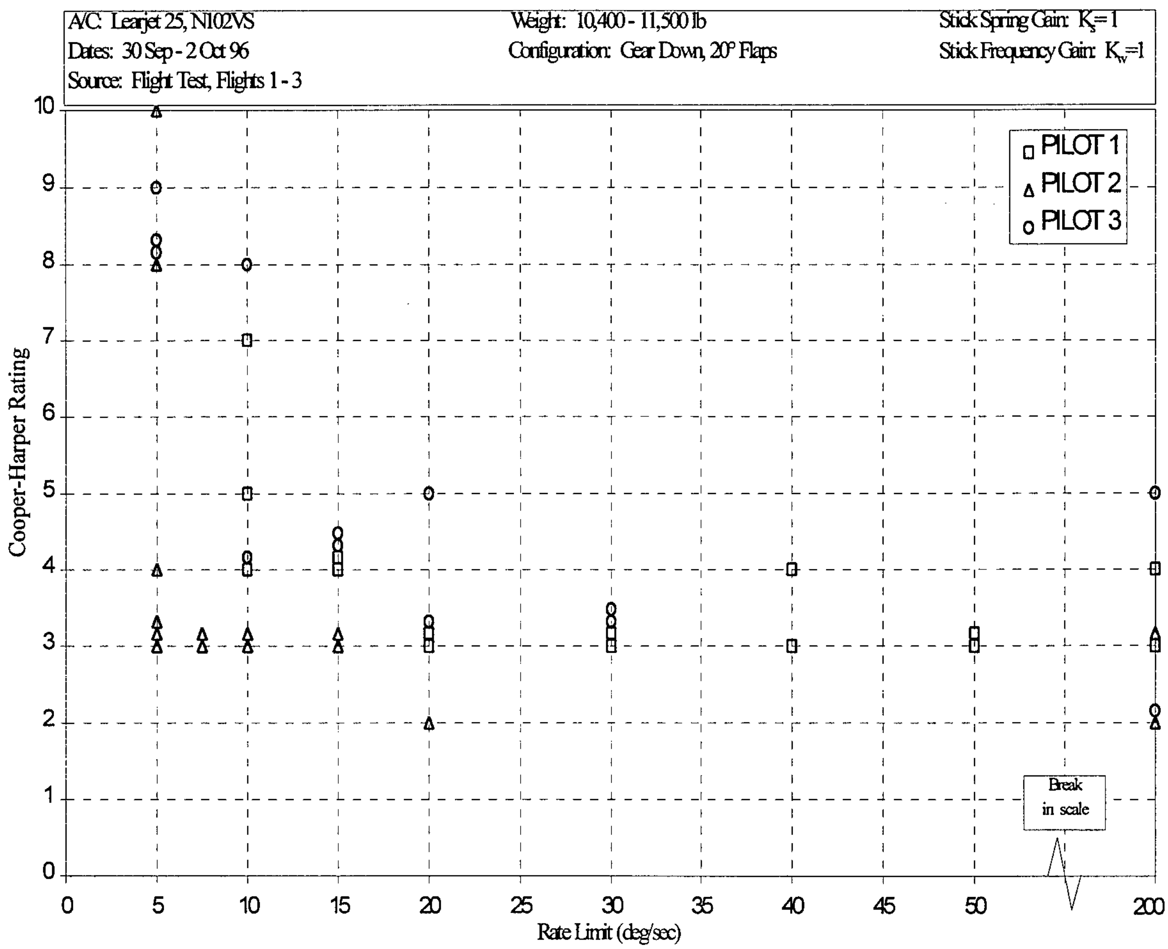


Figure G-2 Phase 1 Cooper-Harper Ratings

| | | |
|---|---|---|
| A/C: Learjet 25 | Weight: 10,400 lb - 11, 500 lb | Stick Spring Gain: $K_s = 1$ |
| S/N: N102VS | Configuration: Gear Down, 20° Flaps | Stick Frequency Gain: $K_\omega = 1$ |
| Date: 30 Sept 96 | Flight Number: 1 | Rate Limit: 50 deg/sec (Landing 2) |
| PIO Rating: 2 | Cooper-Harper Rating: 3 | Pilot Comments: Table J-1, Run 5 |

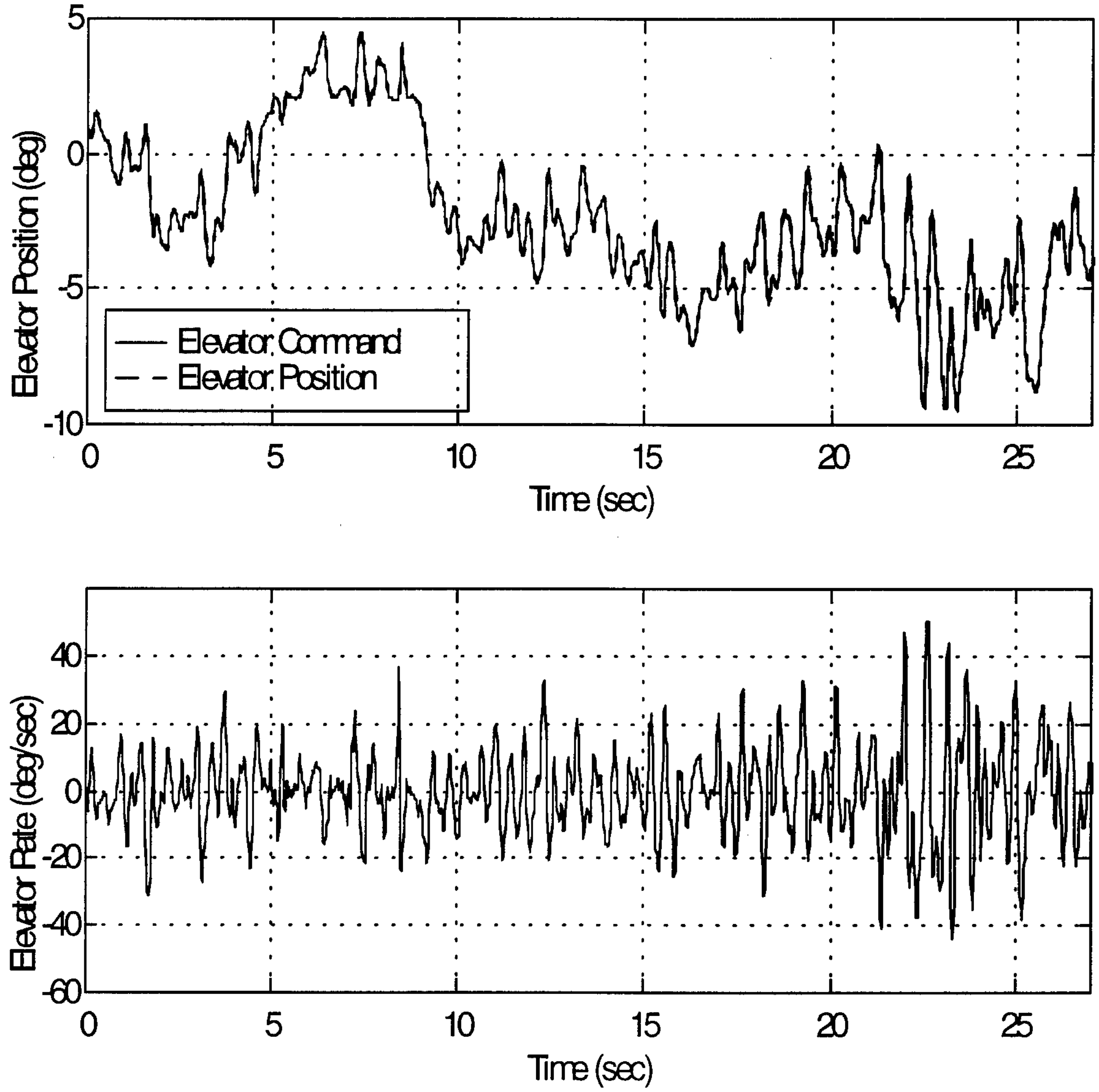


Figure G-3 Sample Data Trace: Flight 1, Rate Limit 50 deg/sec, Landing 2

| | | |
|---|---|---|
| A/C: Learjet 25 | Weight: 10,400 lb - 11, 500 lb | Stick Spring Gain: $K_s = 1$ |
| S/N: N102VS | Configuration: Gear Down, 20° Flaps | Stick Frequency Gain: $K_\omega = 1$ |
| Date: 30 Sept 96 | Flight Number: 1 | Rate Limit: 20 deg/sec (Landing 1) |
| PIO Rating: 4 | Cooper-Harper Rating: 3 | Pilot Comments: Table J-1, Run 10 |

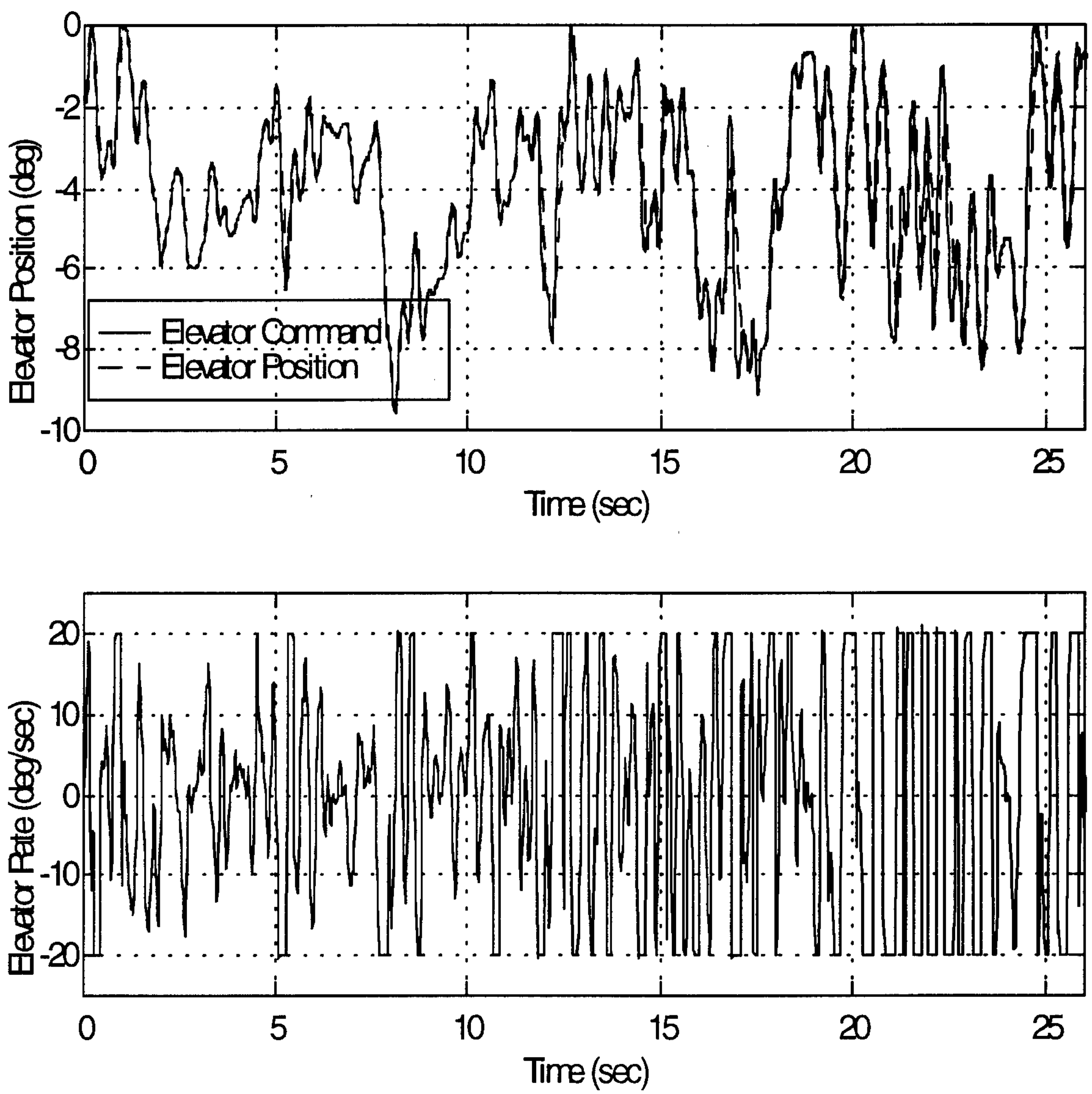


Figure G-4 Sample Data Trace: Flight 1, Rate Limit 20 deg/sec, Landing 1

| | | |
|---|---|---|
| A/C: Learjet 25 | Weight: 10,400 lb - 11, 500 lb | Stick Spring Gain: $K_s = 1$ |
| S/N: N102VS | Configuration: Gear Down, 20° Flaps | Stick Frequency Gain: $K_\omega = 1$ |
| Date: 30 Sept 96 | Flight Number: 1 | Rate Limit: 10 deg/sec (Landing 2) |
| PIO Rating: 5 | Cooper-Harper Rating: 7 | Pilot Comments: Table J-1, Run 15 |

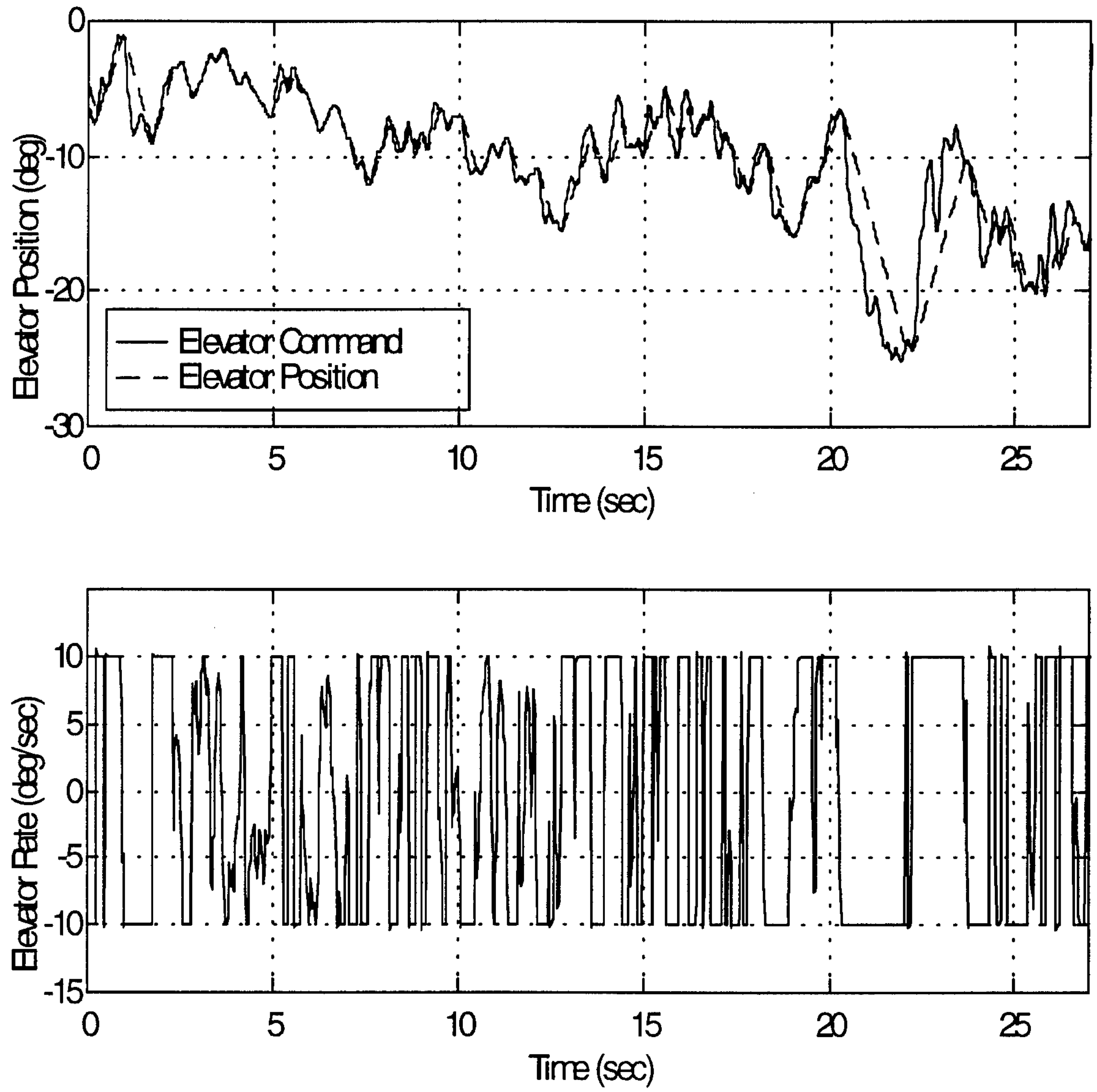


Figure G-5 Sample Data Trace: Flight 1, Rate Limit 10 deg/sec, Landing 2

| | | |
|---|---|---|
| A/C: Learjet 25 | Weight: 10,400 lb - 11, 500 lb | Stick Spring Gain: $K_s = 1$ |
| S/N: N102VS | Configuration: Gear Down, 20° Flaps | Stick Frequency Gain: $K_\omega = 1$ |
| Date: 1 Oct 96 | Flight Number: 2 | Rate Limit: 5 deg/sec (Landing 3) |
| PIO Rating: 2 | Cooper-Harper Rating: 3 | Pilot Comments: Table J-2, Run |

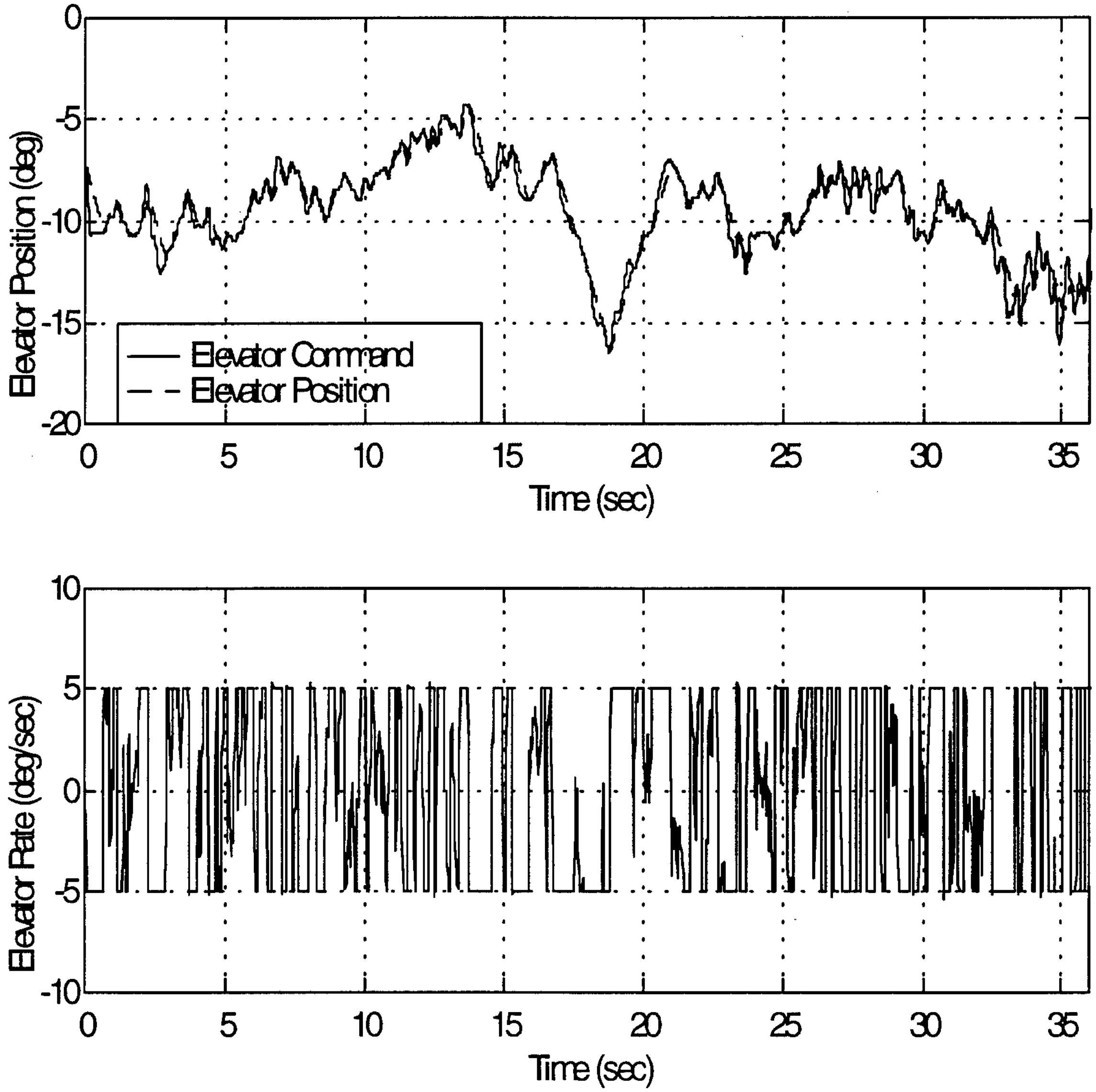


Figure G-6 Sample Data Trace: Flight 2, Rate Limit 5 deg/sec, Landing 3

| | | |
|---|---|---|
| A/C: Learjet 25 | Weight: 10,400 lb - 11, 500 lb | Stick Spring Gain: $K_\delta = 1$ |
| S/N: N102VS | Configuration: Gear Down, 20° Flaps | Stick Frequency Gain: $K_\omega = 1$ |
| Date: 1 Oct 96 | Flight Number: 2 | Rate Limit: 5 deg/sec (Landing 4) |
| PIO Rating: 4 | Cooper-Harper Rating: 8 | Pilot Comments: Table J-2, Run 17 |

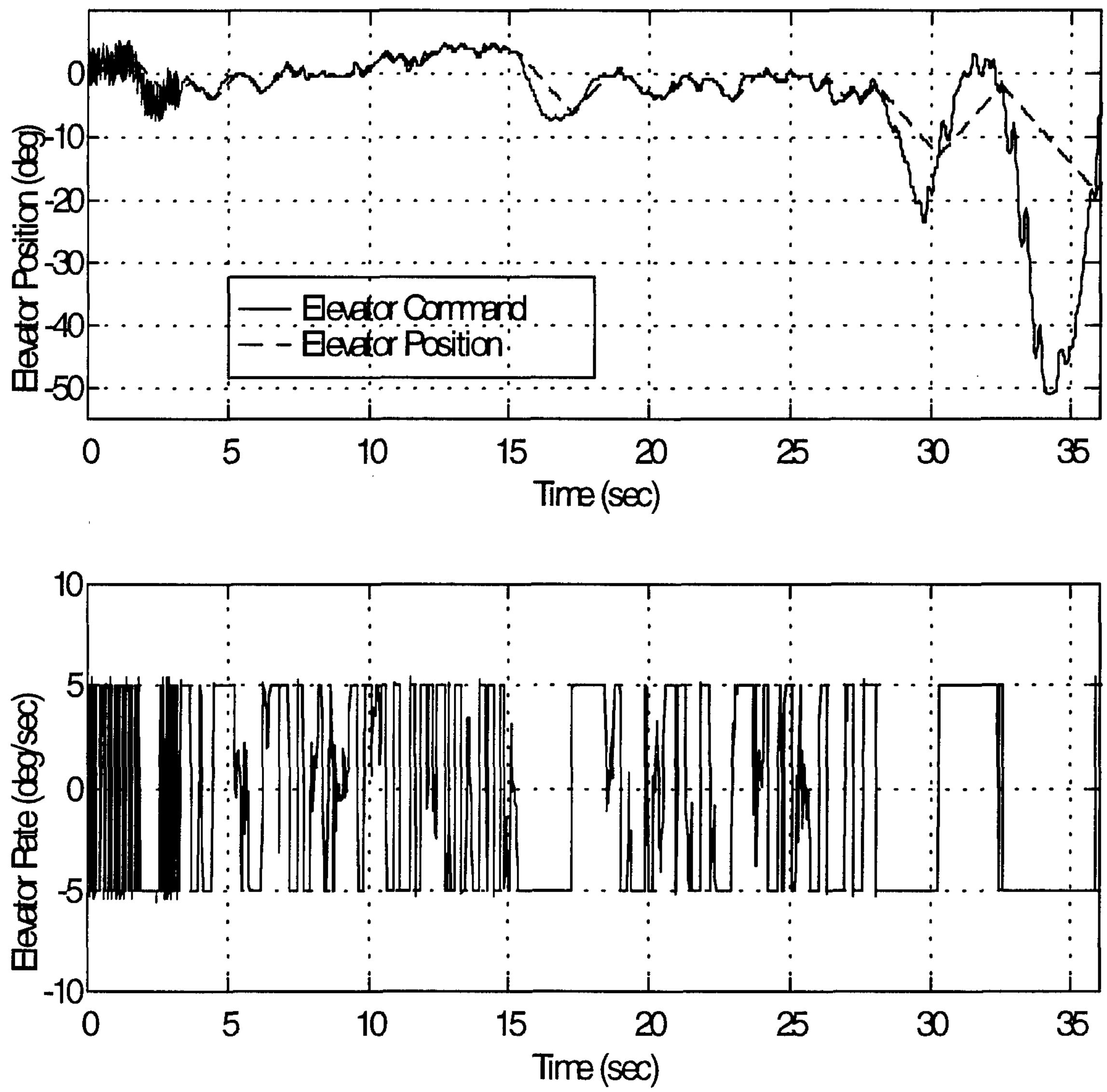


Figure G-7 Sample Data Trace: Flight 2, Rate Limit 5 deg/sec, Landing 4

# *Appendix H - Phase 2 Data Plots*

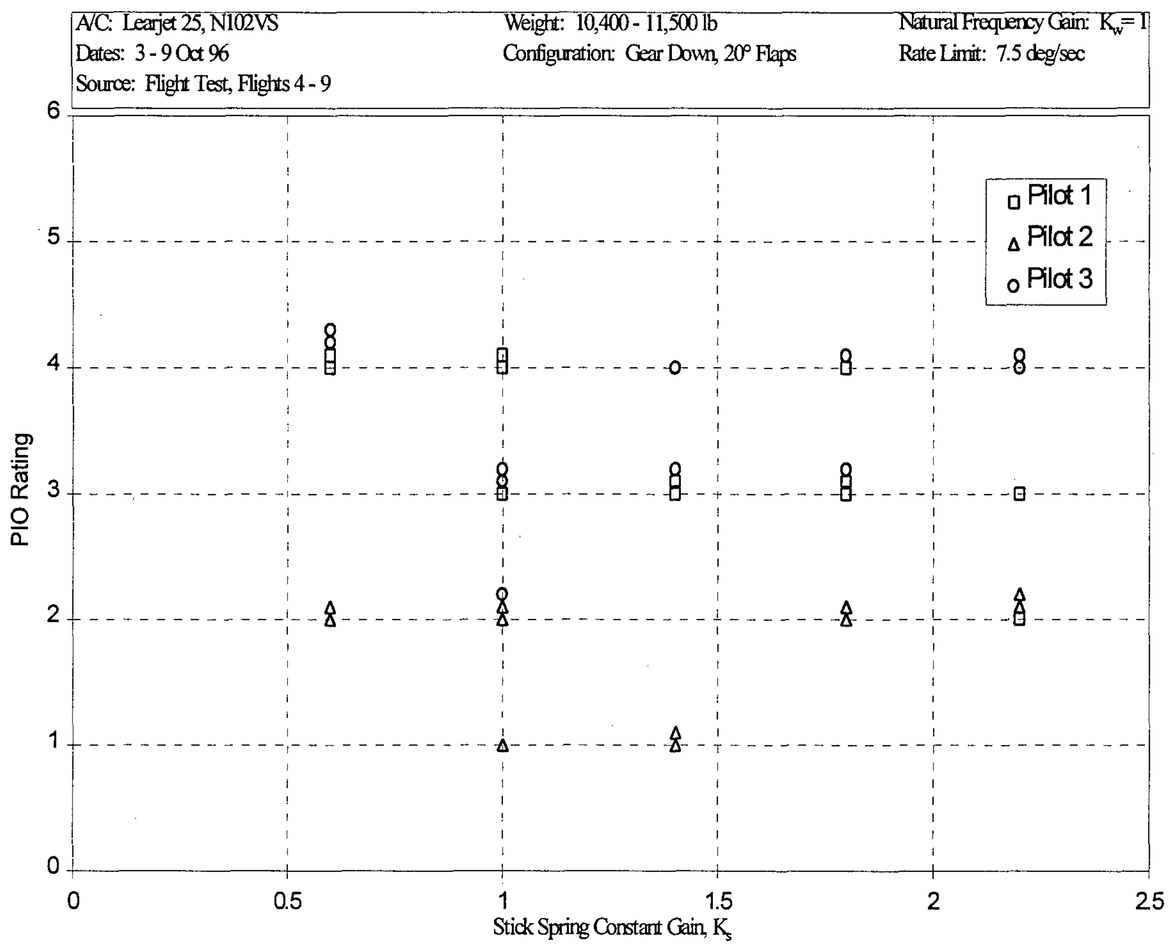


Figure H-1 Phase 2 PIO Ratings for Varying Stick Spring Constant

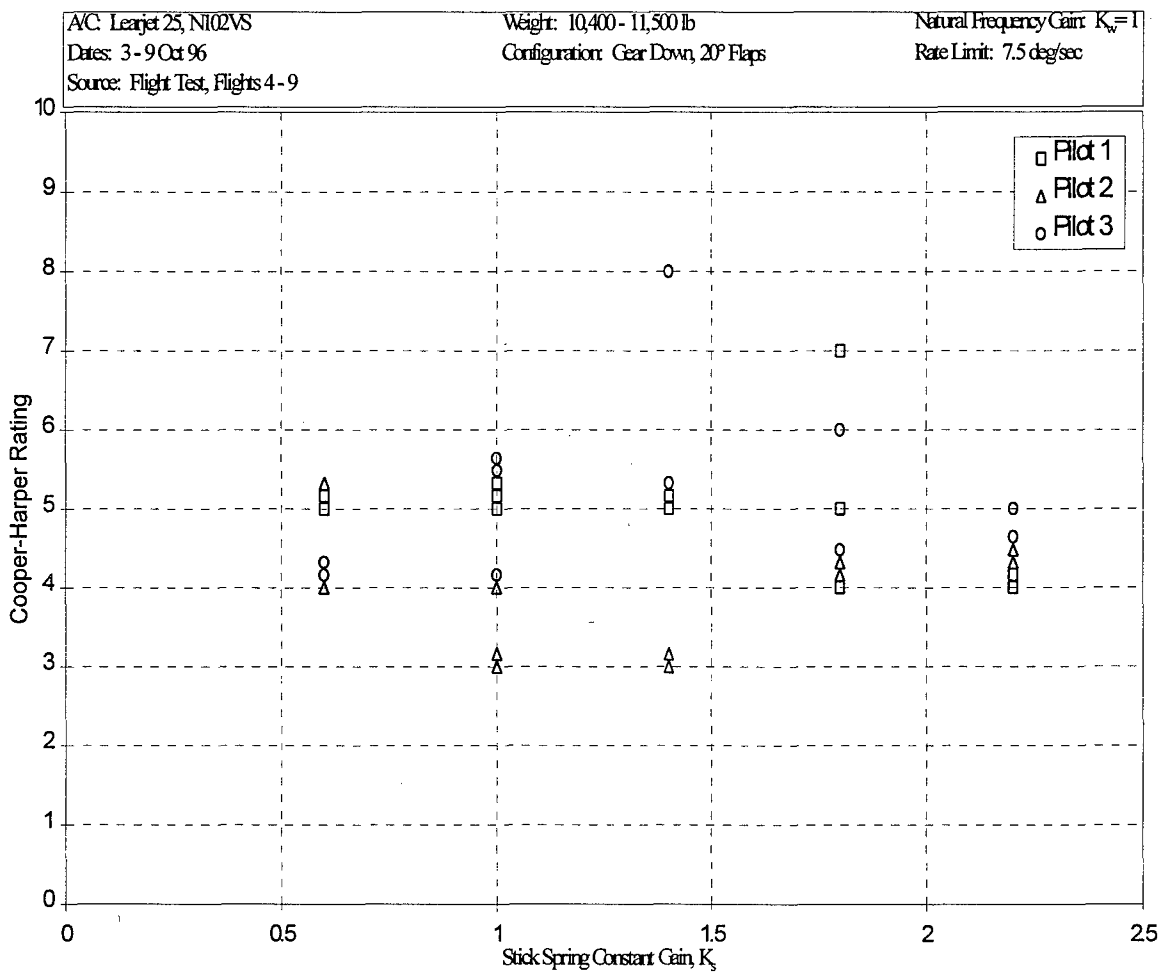


Figure H-2 Phase 2 Cooper-Harper Ratings for Varying Stick Spring Constant

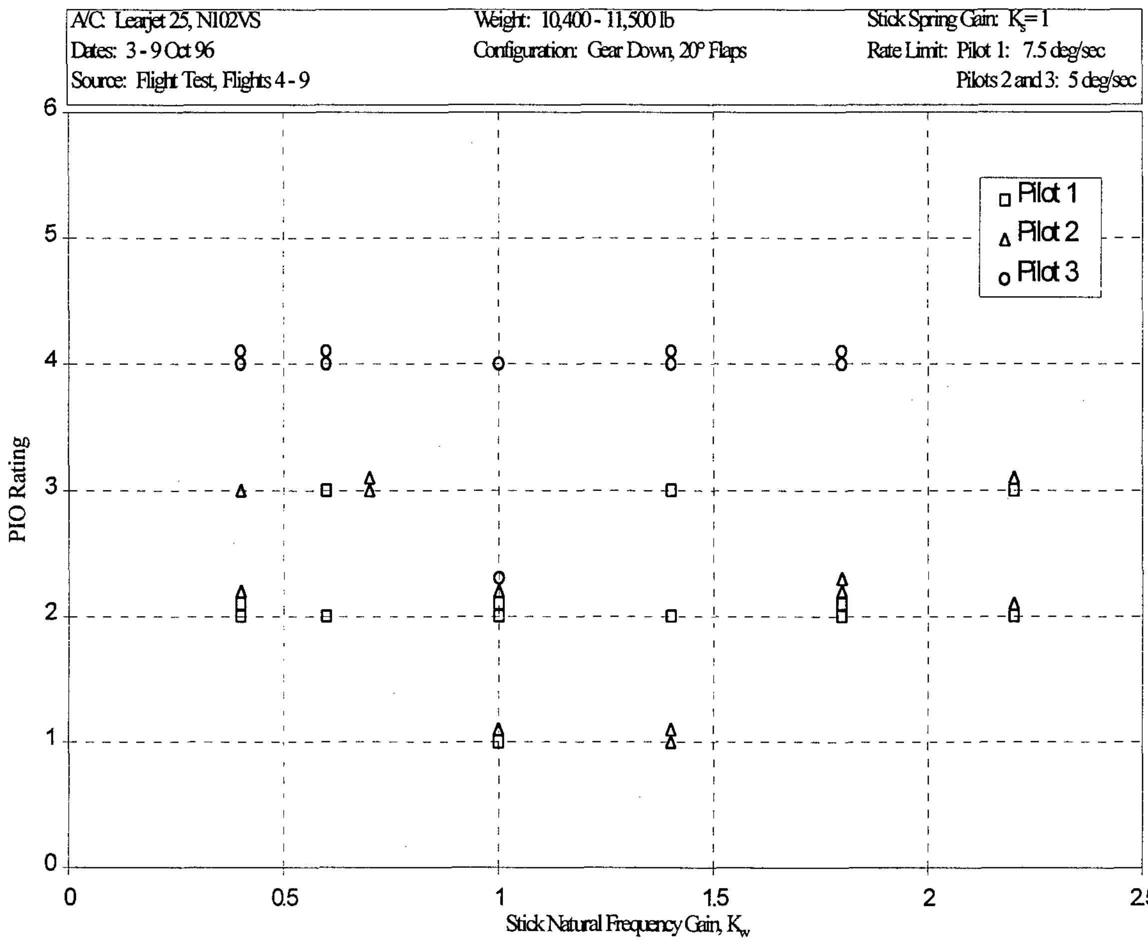


Figure H-3 Phase 2 PIO Ratings for Varying Stick Natural Frequency

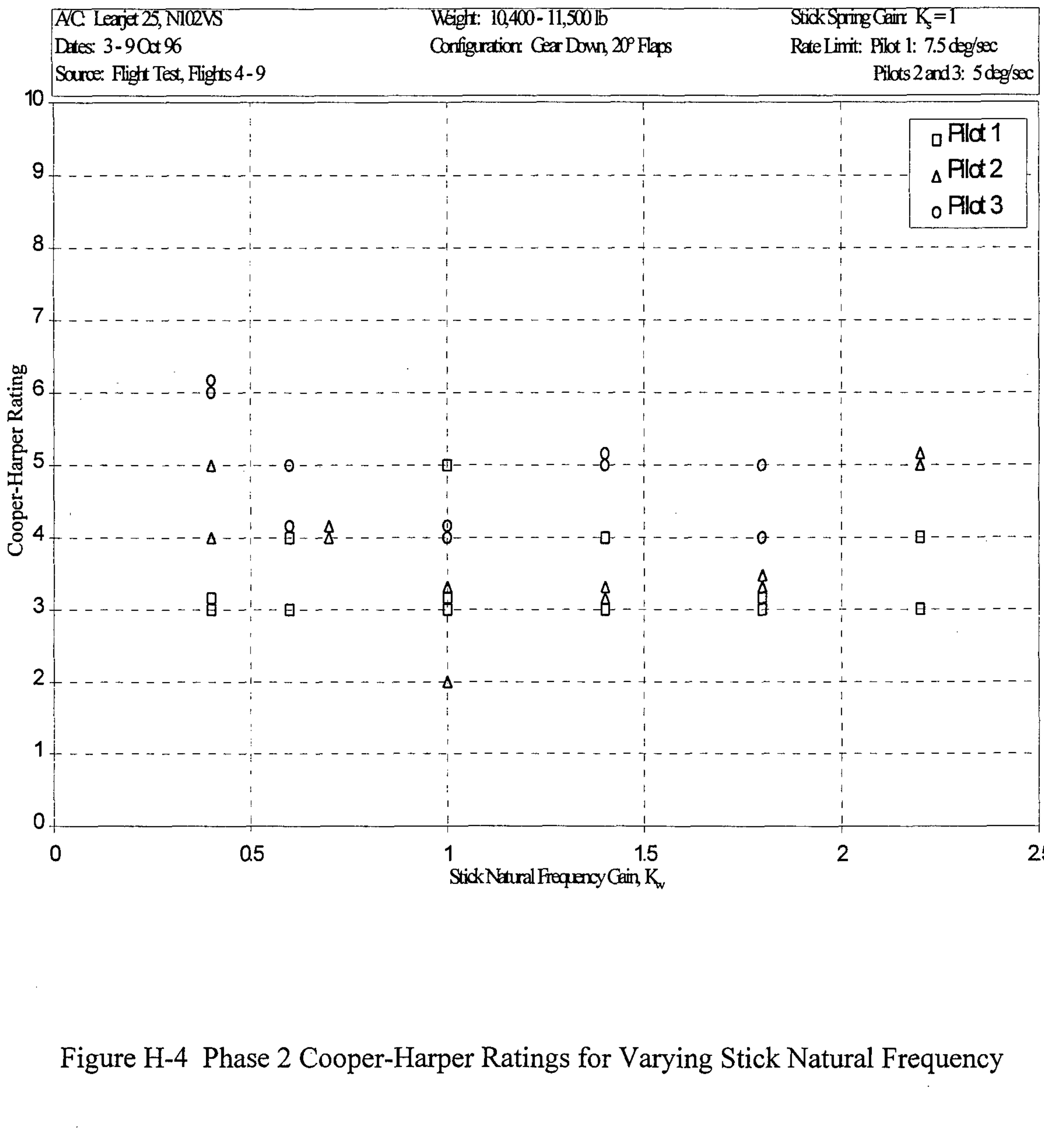


Figure H-4 Phase 2 Cooper-Harper Ratings for Varying Stick Natural Frequency

# *Appendix I - Phase 3 Data Plots*

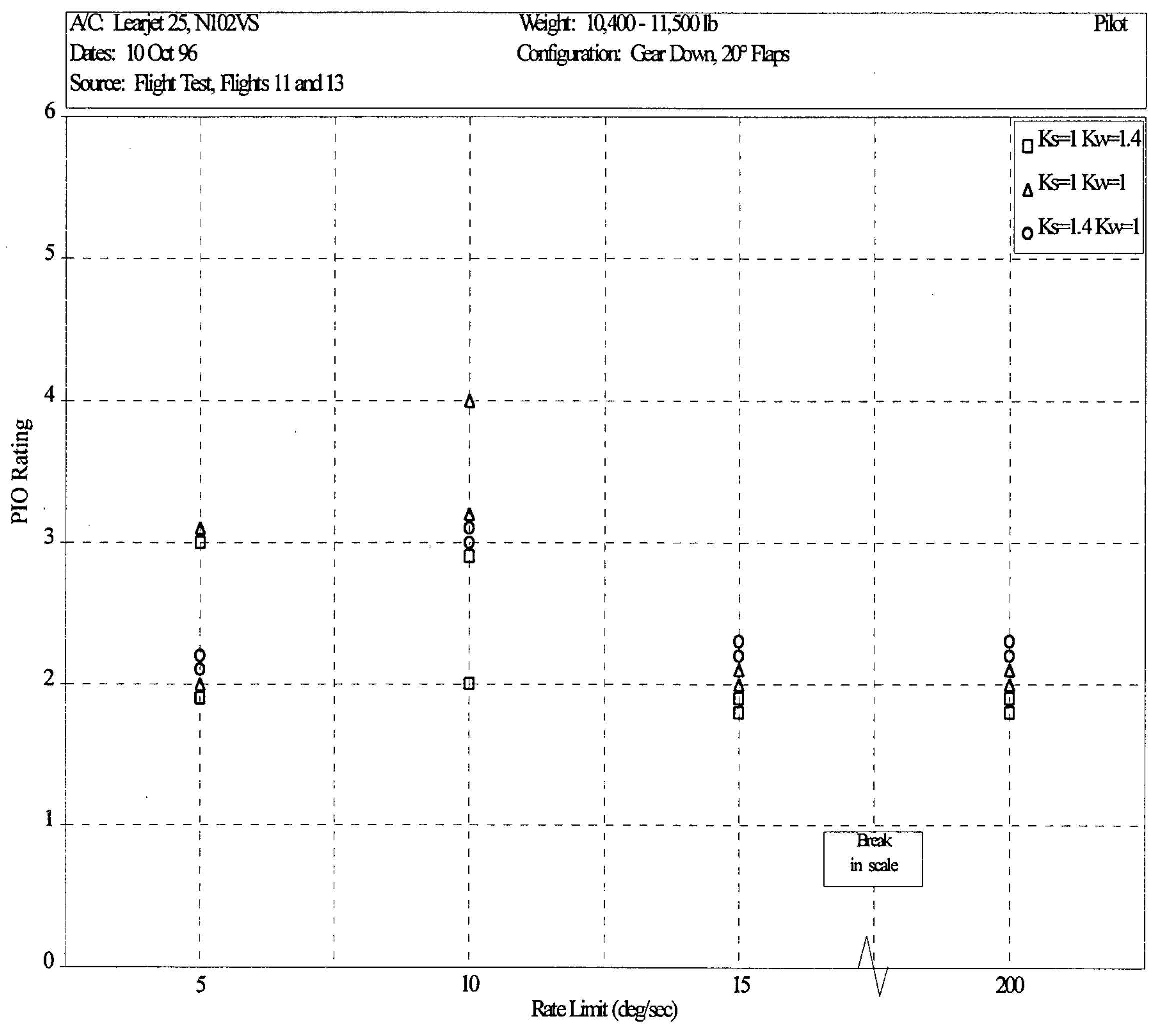


Figure I-1 Phase 3 PIO Ratings for Pilot 1

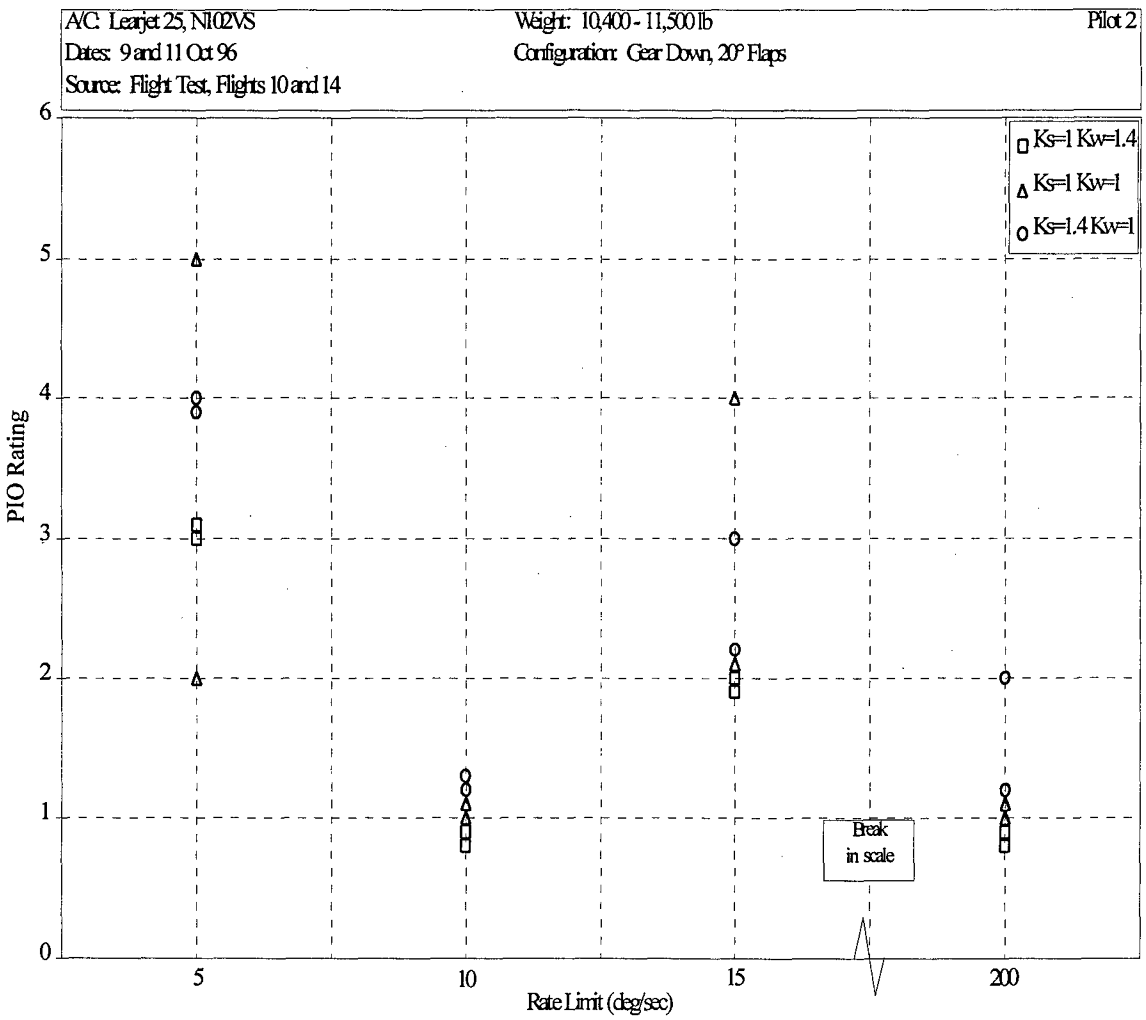


Figure I-2 Phase 3 PIO Ratings for Pilot 2

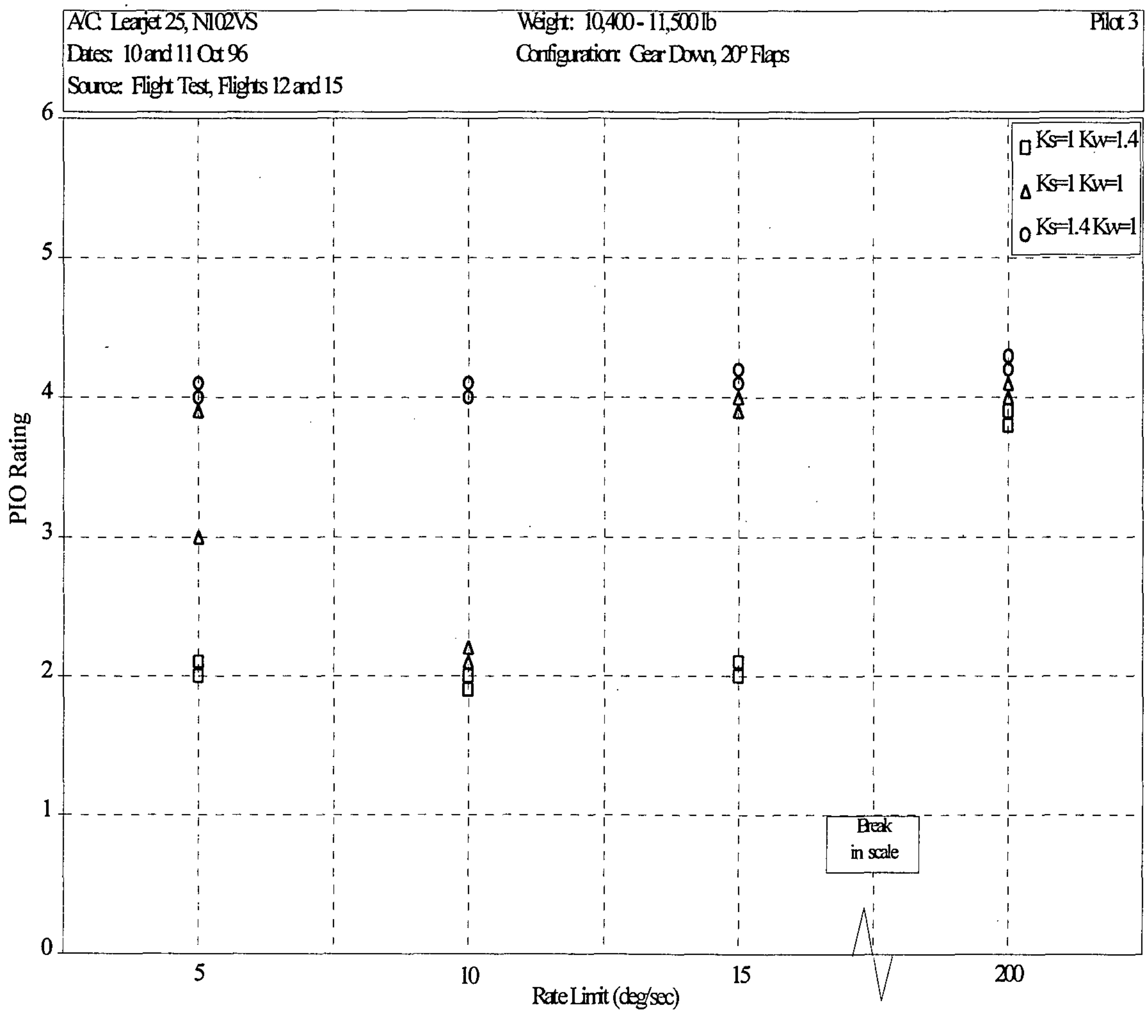


Figure I-3 Phase 3 PIO Ratings for Pilot 3

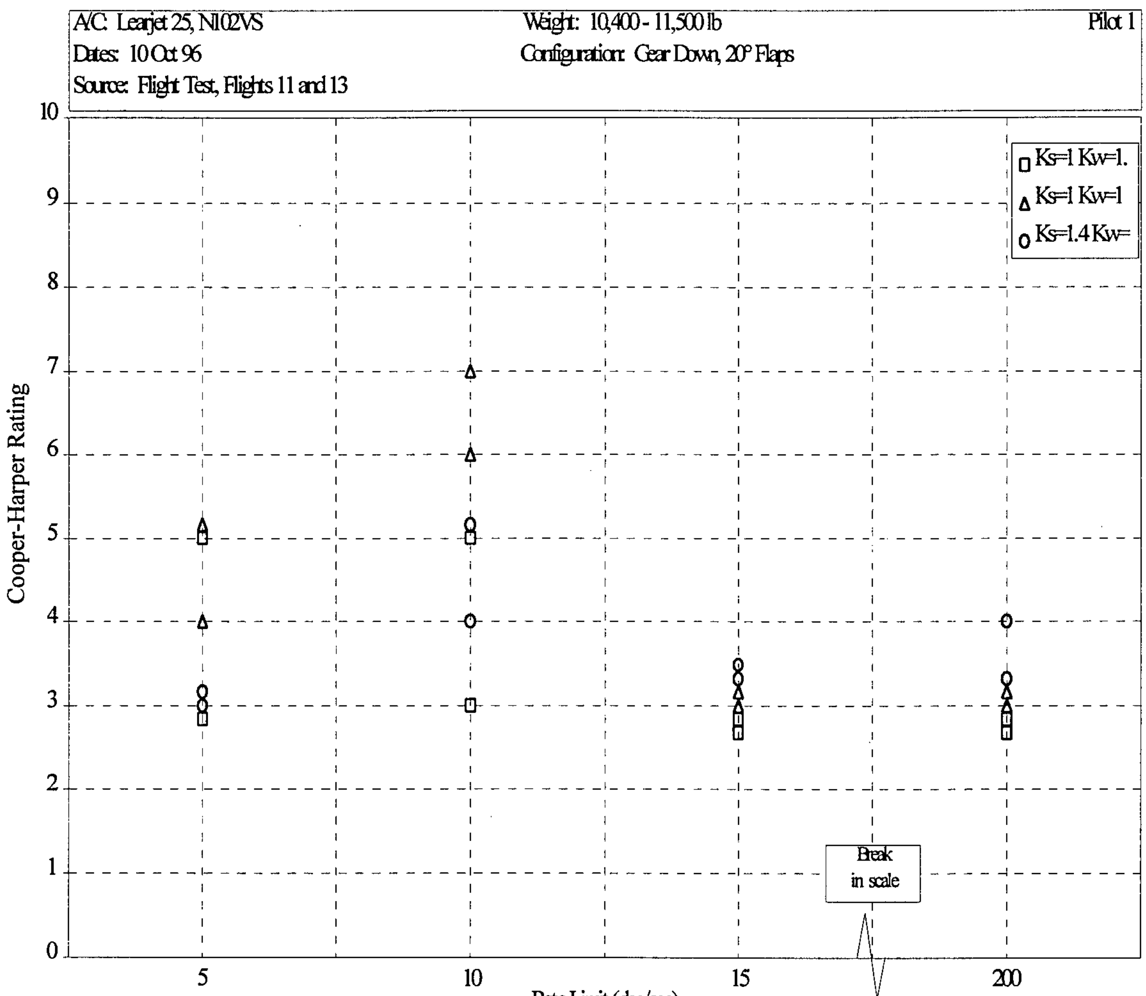


Figure I-4 Phase 3 Cooper-Harper Ratings for Pilot 1

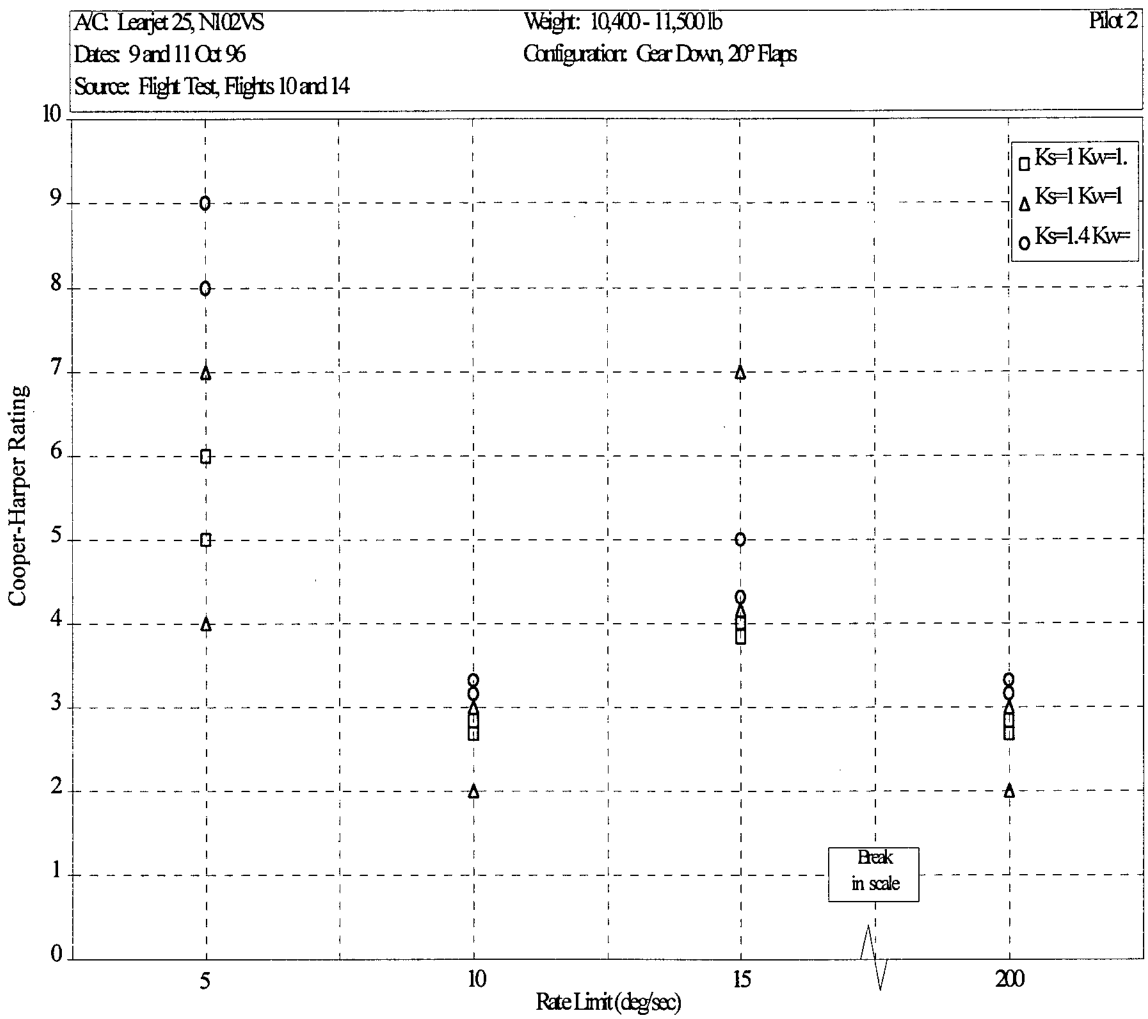


Figure I-5 Phase 3 Cooper-Harper Ratings for Pilot 2

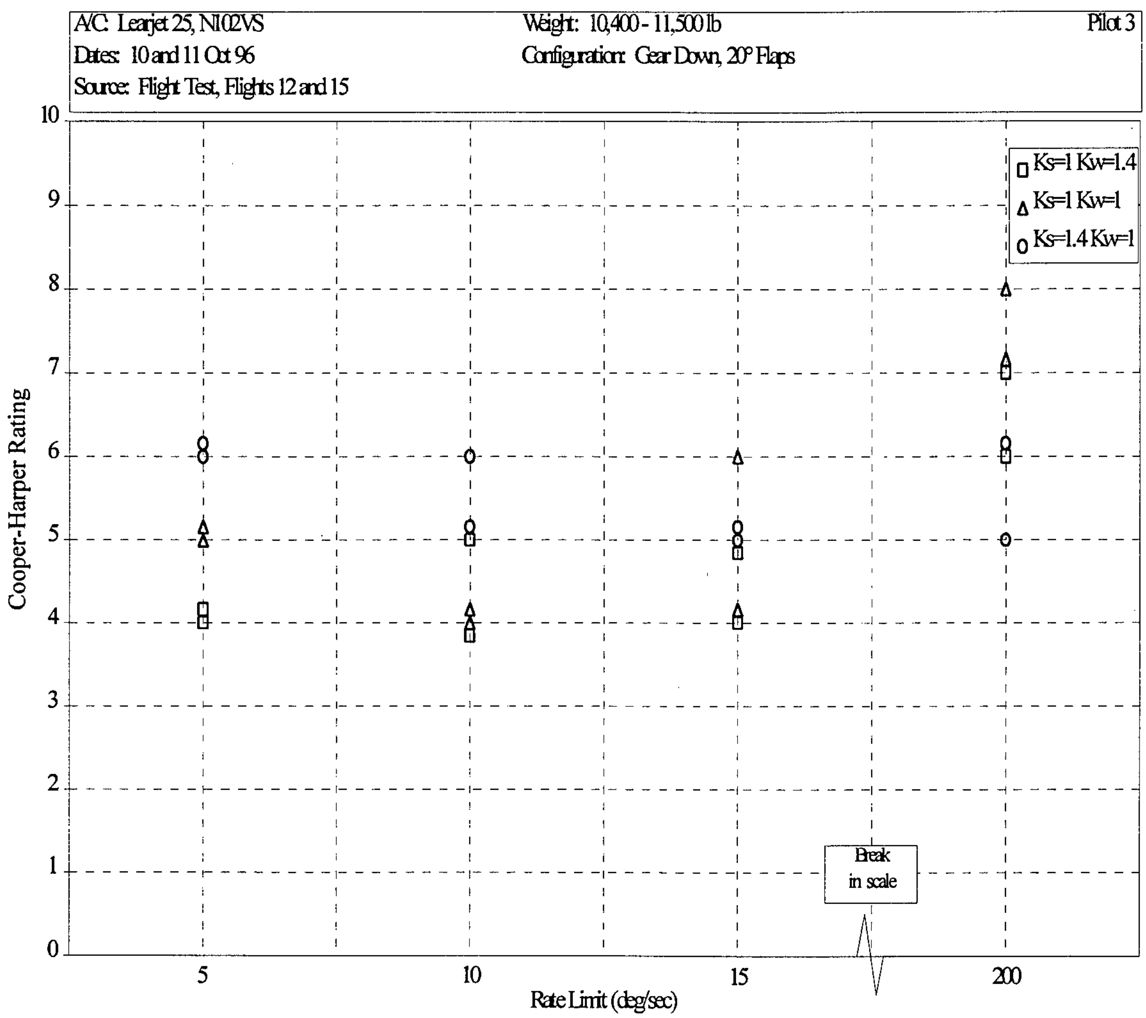


Figure I-6 Phase 3 Cooper-Harper Ratings for Pilot 3

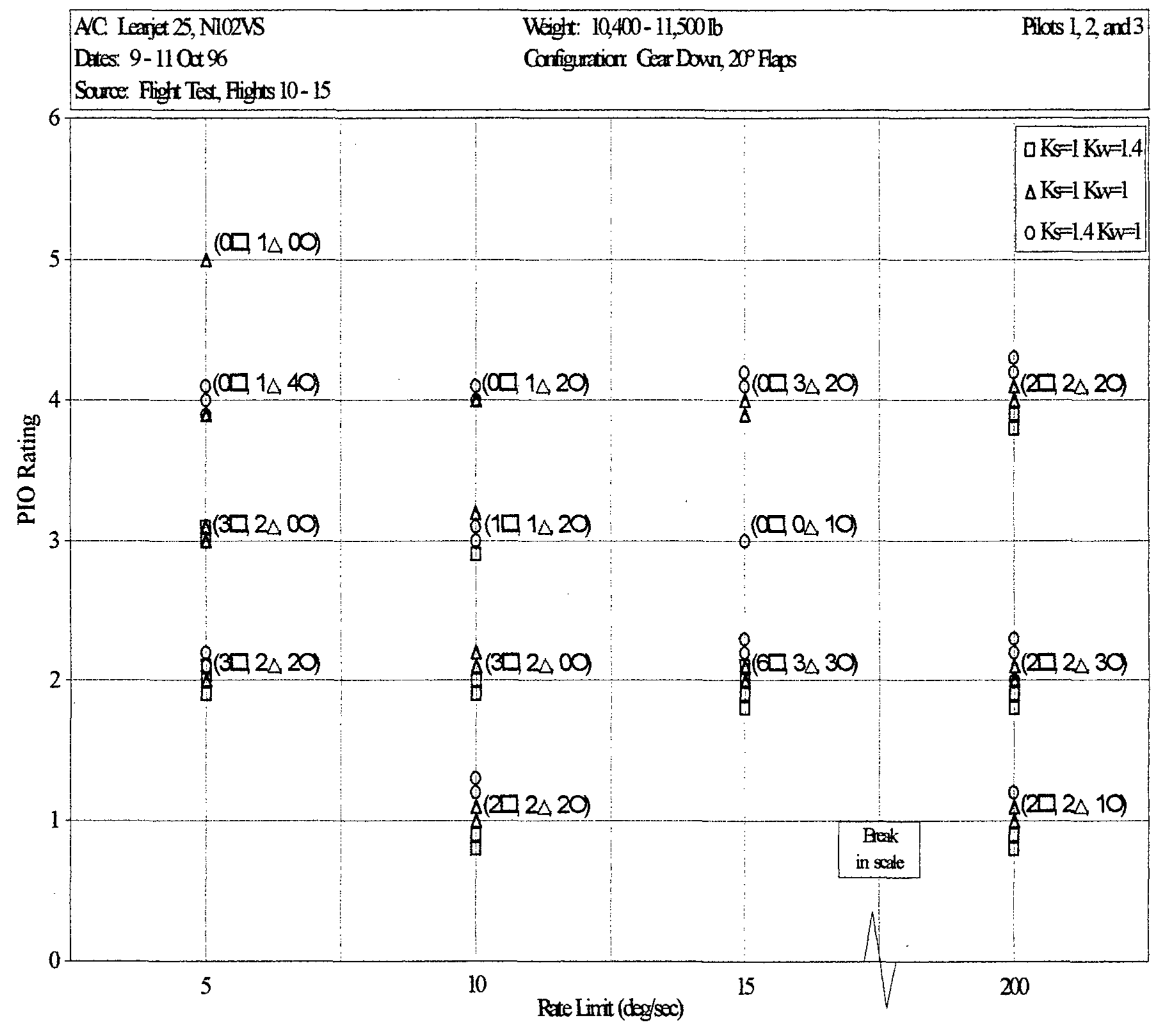


Figure I-7 Phase 3 PIO Ratings for All Pilots

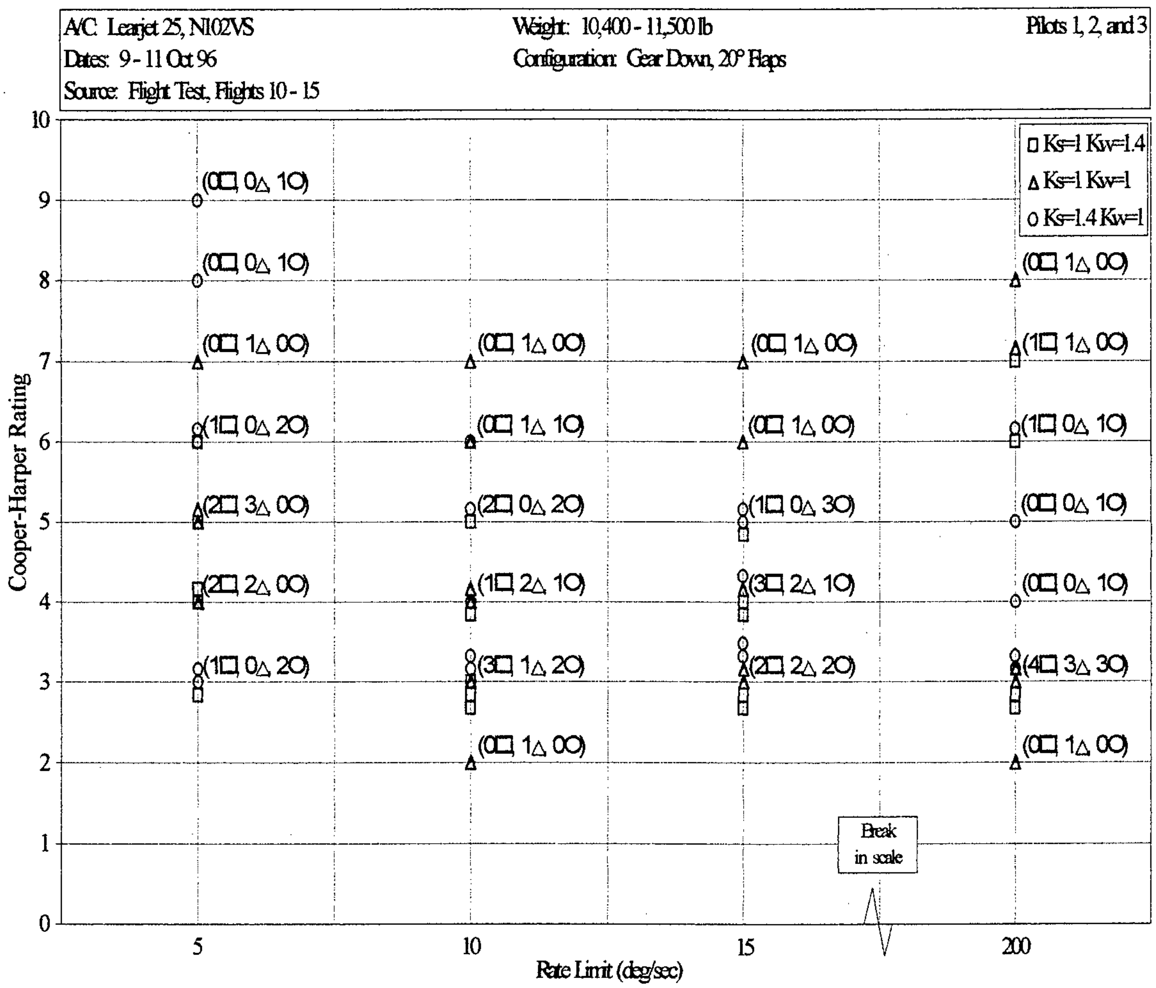


Figure I-8 Phase 3 Cooper-Harper Ratings for All Pilots

# *Appendix J - Summarized Comments from Each Flight*

Table J-1 Summarized Comments: Flight 1

| PILOT: Peters | | | DATE: 30 Sept 96 | | FLIGHT # 1 | Test Phase: 1 |
|---|---|---|---|---|---|---|
| Run # | $K_s$, Spring | $K_\omega$, Freq-uency | Rate Limit (deg/sec) | PIOR | CHR | Comments: |
| 1 | 1 | 1 | Lear Jet | | | Warm Up Landing |
| 2 | 1 | 1 | 200 | 2 | 4 | Sensed small oscillations through stick. Max elevator rate used 55 deg/sec |
| 3 | 1 | 1 | 200 | 2 | 3 | Same as run 2. |
| 4 | 1 | 1 | 50 | 2 | 3 | Max elevator rate used 45 deg/sec |
| 5 | 1 | 1 | 50 | 2 | 3 | Borderline PIO rating of 1 or 2. Touched elevator rate of 50 deg/sec once in flare. |
| 6 | 1 | 1 | 40 | 2 | 4 | Hit rate limit 10 times. Touched 40 deg/sec once. |
| 7 | 1 | 1 | 40 | 1 | 3 | Hit rate limit only 1 time. Touched 40 deg/sec once. |
| 8 | 1 | 1 | 30 | 2 | 3 | Hit rate limit 12 times. Touched 30 deg/sec 17 times. |
| 9 | 1 | 1 | 30 | 2 | 3 | Hit rate limit 5 times. A lot of limit cycle oscillation going on. |
| 10 | 1 | 1 | 20 | 4 | 3 | Pilot was making a lot of small corrections but didn't effect task. Plane not oscillating. On rate limit 20% of time. |
| 11 | 1 | 1 | 20 | 2 | 3 | Touched rate limit 5-10 % of time. |
| 12 | 1 | 1 | 15 | 4 | 4 | Pilot could feel oscillatory motion in aircraft. Felt sluggish, but not bad. On rate limit 5-10% of time. |
| 13 | 1 | 1 | 15 | 3 | 4 | Less pilot compensation this time (hand wasn't moving as much as previous runs). Light Turbulence. Touched rate limit 30% of time. |
| 14 | 1 | 1 | 10 | 4 | 4 | Not as responsive as previous rate. Noticeable drop in elevator effectiveness. Touched rate limit 50% of time. |
| 15 | 1 | 1 | 10 | 5 | 7 | Twice hit rate limit and held there for 1.5 seconds. Touched rate limit 80% of time. |
| 16 | 1 | 1 | 10 | 4 | 5 | Ok control to flare, but not enough to eliminate sink rate and land smoothly. Touched rate limit 50% of time. |

## Additional Comments on Flight 1

**RL=200°/sec.** The next two approaches were flown with RL=200°/sec and the elevator rates (derate) were observed during the approaches and landings. On each approach, the derate had one or two spikes of about 55 and 65°/sec during the flare, with the rest of the peaks around 30-40°/sec. Based on these spikes, the test director decided to use 50°/sec as the next test point. **PIOR: 2/2. CHR: 4/3.**

**RL=50°/sec.** The two approaches flown at 50°/sec showed that the pilot was still improving more based on becoming more familiar with the task than he was being hindered by the rate limiting. No difference was noted by the pilot from the previous (basically unlimited) case. In fact, derate never reached the limit on one of the two approaches. The remaining phase 1 flights should use the predominant peaks in derate rather than the one or two spikes to determine the initial RL. This should allow for more approaches at the lower RLs. **PIOR: 2/2. CHR: 3/3.**

**RL=40°/sec.** Pilot technique was still improving and no degradation in performance was noted. At least two warm-up approaches should be flown prior to any actual test points. This should help keep the pilot's learning curve from affecting the results as much. **PIOR: 2/1. CHR: 4/3.**

**RL=30°/sec.** Pilot technique was still improving and no degradation in performance was noted despite some delay being evident. **PIOR: 2/2. CHR: 3/3.**

**RL=20°/sec.** The pilot noted a small (± ½ inch), slow (1 Hz) oscillation in the stick on the first run at this RL, but could not tell that there was any oscillation by looking outside or by feel (seat of the pants), and no degradation in performance was noted. No oscillations were noticed on the second approach. **PIOR: 4/2. CHR: 3/3.**

**RL=15°/sec.** Another small, slow oscillation was noted in the stick on the first run at this RL. This time, however, the delay was starting to become gross and pilot workload increased to compensate. **PIOR: 4/3. CHR: 4/4.**

**RL=10°/sec.** The small, slow oscillations were still noted in the stick at this RL. In addition, on the second run the flight path angle was slightly steeper than for previous approaches, creating the need for a bigger pitch change at the flare. At this low RL, there was not quite enough pitch authority to make the roundout and a firm touchdown and bounce ensued. The evaluation pilot initiated a go-around and no further touchdowns occurred. A third approach was flown on which pilot made another large pitch up correction and could not take the input out in time. On this approach the aircraft softly skipped out of the desired box into the adequate box. Control was never in question. The major difference noticed on the second (and also, but to a lesser extent, on the third) approach was that the pilot stayed on the RL and for much longer periods (about 1 sec) than on the previous approaches where derate bounced off both sides of the RL continuously. **PIOR: 4/5/4. CHR: 4/7/5.**

Table J-2 Summarized Comments: Flight 2

| PILOT: Evensen | | | DATE: 1 Oct 96 | FLIGHT # 2 | | Test Phase: 1 |
|---|---|---|---|---|---|---|
| Run # | $K_s$, Spring | $K_\omega$, Frequency | Rate Limit (deg/sec) | PIOR | CHR | Comments: |
| 1 | 1 | 1 | Lear Jet | | | Warm Up Landing |
| 2 | 1 | 1 | 200 | 1 | 2 | Warm Up with rate limiting |
| 3 | 1 | 1 | 200 | 1 | 3 | Twice used elevator rate above 30deg/sec, five times above 20 deg/sec elevator rate. |
| 4 | 1 | 1 | 200 | 1 | 2 | ½ dot low on approach.. Four times above 20 deg/sec elevator rate. |
| 5 | 1 | 1 | 20 | 1 | 2 | No turbulence. Hit rate limit 5 times. |
| 6 | 1 | 1 | 20 | 2 | 3 | Hit rate limit 8 times. |
| 7 | 1 | 1 | 15 | 2 | 3 | Sensed slight degradation in control. On rate limit 5% of time. |
| 8 | 1 | 1 | 15 | 2 | 3 | Only two significantly wide peaks on rate limit. |
| 9 | 1 | 1 | 10 | 2 | 3 | Small balloon on landing. On rate limit 15% of time. |
| 10 | 1 | 1 | 10 | 2 | 3 | On rate limit 10% of time. |
| 11 | 1 | 1 | 7.5 | 2 | 3 | On rate limit 30% of time. |
| 12 | 1 | 1 | 7.5 | 2 | 3 | On rate limit 30% of time. |
| 13 | 1 | 1 | 5 | 2 | 3 | On rate limit 50% of time. Pilot sensed rate limit on short final. |
| 14 | 1 | 1 | 5 | 2 | 3 | On rate limit 40% of time. |
| 15 | 1 | 1 | 5 | 2 | 3 | Aggressive roll-in. On rate limit 40% of time. |
| 16 | 1 | 1 | 5 | 4 | 8 | Bounced landing. On rate limit 70% of time. |
| 17 | 1 | 1 | 5 | 4-5 | 10 | Safety trip at 10 feet AGL. Excessive nose low. On rate limit 90% of time. |
| 18 | 1 | 1 | 5 | 2 | 4 | Minor compensation, had to lower gains when pilot felt rate limit. Light turbulence. |

**Additional Comments on Flight 2**

As the rate limits were decreased the most pronounced feeling was given to the pilot in the turn to final. There it could easily be felt that the pitch response was not as it should be. However, rolling out on final and stabilized on the ILS glideslope, very small corrections were made in the longitudinal axis. Even in the correction for the offset, the aircraft was kept on the glideslope with power only, and very little deviation from the glideslope was induced. It should also be noted, that the pilot was told by the Calspan safety pilot not to pull to hard in the offset correction, not to exceed the allowable angle of attack of the Lear 25 system with the test flight control system engaged. As the rate limits were decreased, very little difference in the way the aircraft was flown was made, and hence most of the CH and PIO ratings remain the same throughout the flight. However, on two of the landings (16 & 17) the pilot was distracted in the set up to landing by other aircraft flying in the pattern. This small distraction was enough to not be set up perfectly on glideslope when starting the correction for landing. Hence, when executing the correction for landing from the offset, the pilot also had to make a glideslope correction. This induced a need for more rapid corrections, or higher pilot gains, and as soon as the gains were increased in the longitudinal axis the aircraft did not respond as expected. On landing #16 definite pilot-induced oscillations were encountered in the last portion of the approach, but due to the low frequency of the oscillations the pilot was not able to determine if the PIO was divergent or not. A PIO rating of four was given. On landing #17 the same oscillations were induced, but at a slightly higher altitude. However, the safety pilot took over the aircraft before touchdown due to a too nose low attitude that would not have been possible to correct with the low rate limit (5 degrees per second).

Table J-3 Summarized Comments: Flight 3

| PILOT: Major | | | DATE: 2 Oct 96 | | | FLIGHT # 3 / Test Phase: 1 |
|---|---|---|---|---|---|---|
| Run # | $K_s$, Spring | $K_\omega$, Frequency | Rate Limit (deg/sec) | PIOR | CHR | Comments: |
| 1 | 1 | 1 | Lear Jet | | | Warm up landing |
| 2 | 1 | 1 | 200 | 1 | 5 | |
| 3 | 1 | 1 | 200 | 1 | 2 | On time history, no elevator rate peaks above 50 deg/sec, 7 peaks above 40 deg/sec. |
| 4 | 1 | 1 | 30 | 2 | 3 | Jerky motion. Noticeable limitation on pitch control effectiveness. On rate limit 15% of time. |
| 5 | 1 | 1 | 30 | 2 | 3 | Rate limit noticeable on forward stick motion. On rate limit 5% of time. |
| 6 | 1 | 1 | 20 | 3 | 5 | Adequate control for slow corrections. Hard to correct sink rate and pitch rate control. On rate limit 50% of time. |
| 7 | 1 | 1 | 20 | 2 | 3 | Sluggish in pitch. Bounce on landing. Appeared like there was a time delay in system. On rate limit 80% of time. |
| 8 | 1 | 1 | 15 | 2 | 4 | Sluggish. On rate limit 95% of time. |
| 9 | 1 | 1 | 15 | 2 | 4 | |
| 10 | 1 | 1 | 10 | 3 | 8 | Tripped safeties. Significant delay in pitch. Oscillatory motion noticed. |
| 11 | 1 | 1 | 10 | 2 | 4 | Delay in pitch and decreased responsiveness. On rate limit 98% of time. |
| 12 | 1 | 1 | 5 | 3 | 8 | High workload and landed in adequate box but landing wasn't soft. Safety pilot took for go-around. |
| 13 | 1 | 1 | 5 | 3 | 8 | Go-around executed. Sluggish in pitch. Undesired and uncorrectable sink rate. |
| 14 | 1 | 1 | 5 | 3 | 9 | High compensation in pitch axis due to time delay. Delay in response was too big. Hard landing. |

**Additional Comments on Flight 3**

**Nominal (200 °/sec).** No noticeable deficiencies. Pilot was able to fly the task crisply and precisely. PIOR 1, CHR 2 overall for the combined runs.

**30 °/sec.** Noticed rate limiting immediately when pilot applied nose down trim. When pilot trimmed nose down, he would occasionally bump the stick forward and would see a time delayed jerk in the aircraft response. The time delay was small but perceptible. This led to the aircraft not having as crisp of a response as pilot would have liked. PIOR 2, CHR 3 overall.

**20°/sec.** Time delay getting longer. Controls showed some sluggishness. Setup on run not stable leading to slow airspeed on final, thus landing early. PIOR 2, CHR 3 overall.

**15°/sec.** Time delay getting longer. Now seeing a marked increase in workload. Increased workload included closer analysis of glidepath and more rapid longitudinal inputs. Sluggishness continued to increase. PIOR 2, CHR 4 overall.

**10°/sec.** Getting a little tougher to fly. Run # 9 tripped off on second turn in task. The aircraft was slow and started to exceed the safety AOA limit. Setup was not stable in airspeed/glidepath on the run. Run # 10 seemed to be more representative and repeatable. PIOR 2, CHR 4 overall.

**5°/sec.** All three tries failed to complete task. However, aircraft was controllable. Pilot would have been able to land it from a straight-in. Very sluggish pitch response made precise glidepath control during maneuvering impossible. No tendencies for PIO were seen on runs 11 and 12. The frequency of the response seemed to slow enough to prevent any PIOs. On run 13, the aircraft automatic safety features tripped off during a glideslope correction at 50 feet AGL. The potential for PIO may have been present, however the aircraft kicked itself off after one-half of a cycle. More runs at 5°/sec may help to define its PIO susceptibility. PIOR 3, CHR 8 overall.

**Overall Comments.** The low apparent frequency response of the controls seemed to aid in preventing PIO. A faster apparent frequency response may increase the susceptibility to PIO. Also, a larger longitudinal gain may increase the magnitude of the undesirable motions, thus seeing more pronounced effects as rate limits were lowered.

For the task and control system being tested, we may find the PIO rating scale too course. Since we are not seeing any PIO until the task is undoable, the sale has only three ordinates compared to the CH scale which has six ordinates to describe the doable task.

Table J-4 Summarized Comments: Flight 4

| PILOT: Peters | | | DATE: 3 Oct 96 | FLIGHT # 4 | | Test Phase: 2 |
|---|---|---|---|---|---|---|
| Run # | $K_s$, Spring | $K_\omega$, Frequency | Rate Limit (deg/sec) | PIOR | CHR | Comments: |
| 1 | 1 | 1 | 200 | 2 | 3 | Safety trip occurred prior to touch down. Few rates above 40 deg/sec. |
| 2 | 1 | 1 | 200 | 2 | 3 | Had to control speed through correction. Several rates above 40 deg/sec |
| 3 | 1 | 1 | 200 | 2 | 5 | Adequate performance. Light Turbulence and tail wind present. Above 40 deg/sec elevator rate 8 times. |
| 4 | 1 | 1 | 7.5 | 4 | 5 | Bounced landing. On rate limit 60% of time. |
| 5 | 1 | 1 | 7.5 | | | Safety trip at initial correction of offset. |
| 6 | 1 | 1 | 7.5 | 3 | 5 | Slight bounce. Never cycled stick back and forth. On rate limit 80% of time. |
| 7 | 1.4 | 1 | 7.5 | 3 | 5 | High and fast at start of correction. Did notice oscillations and considered them undesired motion. Stick cycles were faster. |
| 8 | 1.4 | 1 | 7.5 | 3 | 5 | Landed after C-18. Considerable pilot compensation and bounced out of desired box. Heavy stick force noticed turning final. No oscillations noticed. A good size correction was required to get desired box. |
| 9 | 1.8 | 1 | 7.5 | 3 | 4 | Increased turbulence made it difficult to hold speed. Seemed less oscillatory than run 7, but oscillations still present. Desired performance with moderate workload. |
| 10 | 1.8 | 1 | 7.5 | 4 | 7 | Small oscillation. Fast at start of maneuver. "Out of there" PIO 100% prior to touchdown. |
| 11 | 1.8 | 1 | 7.5 | 3 | 5 | Heavy stick force which the pilot commented kept him from putting in lots of stick. |
| 12 | 2.2 | 1 | 7.5 | 2 | 4 | Very high stick force. Oscillatory motions did not get away from pilot. Desired performance and moderate workload. Rate limits mostly in one direction. Stick forces very high. |
| 13 | 2.2 | 1 | 7.5 | 3 | 4 | Bigger bobbles. Delay was bugging pilot. Desired performance with moderate workload. Less time in rate limit. Very heavy stick forces. |
| 14 | 0.6 | 1 | 7.5 | 4 | 5 | Small and higher frequency stick motion. Pilot working harder to keep stick under control. Adequate performance. More time on rate limit. Light to moderate turbulence. |
| 15 | 0.6 | 1 | 7.5 | 4 | 5 | Desired performance with considerable workload. Light to moderate turbulence. |
| 16 | 1.0 | 1 | 7.5 | 4 | 5 | Adequate performance. Slow oscillation noticed in the rate of descent (low amplitude and frequency). PIO prior to touchdown. |

**General Comments on Flight 4**

The ratings showed a very slight improvement for the heavier sticks. Qualitatively, the pilot thought that the heavier the stick, the less tendency he felt he had to cause oscillations. In the turn to final, the stick forces were noticeably heavier or lighter, but on final they were not as noticeable.

Table J-5 Summarized Comments: Flight 5

| PILOT: Peters | | | DATE: 4 Oct 96 | | | FLIGHT # 5 / Test Phase: 2 |
|---|---|---|---|---|---|---|
| Run # | $K_s$, Spring | $K_\omega$, Frequency | Rate Limit (deg/sec) | PIOR | CHR | Comments: |
| 1 | 1 | 1 | 200 | 1 | 3 | Warm up. Smooth as glass air. Max elevator rate used was 25 deg/sec. |
| 2 | 1 | 1 | 200 | 1 | 2 | Warm up |
| 3 | 1 | 1 | 7.5 | 1 | 5 | Low pilot gains because air was so calm. Landed long |
| 4 | 1 | 1 | 7.5 | 2 | 3 | |
| 5 | 1 | 1 | 7.5 | 2 | 3 | Wobble when crossing landing box. |
| 6 | 1 | 1.4 | 7.5 | 3 | 4 | Bigger wobble. |
| 7 | 1 | 1.4 | 7.5 | 2 | 3 | More responsive, but not a big difference. |
| 8 | 1 | 1.8 | 7.5 | 2 | 3 | Firm touch down. Not a noticeable difference |
| 9 | 1 | 1.8 | 7.5 | 3 | 4 | Little more motion. |
| 10 | 1 | 2.2 | 7.5 | 2 | 3 | Workload barely minimal. |
| 11 | 1 | 2.2 | 7.5 | 2 | 3 | Steeper at the end of the landing. Not noticeable change. Light to moderate turbulence. |
| 12 | 1 | 0.6 | 7.5 | 2 | 3 | Heavier, more delay. |
| 13 | 1 | 0.6 | 7.5 | 3 | 4 | Big wobble, affected performance, but not that much. |
| 14 | 1 | 0.4 | 7.5 | 2 | 3 | Stick feels heavier and slower, but not much difference in performance. |
| 15 | 1 | 0.4 | 7.5 | 2 | 3 | |

**General Comments on Flight 5**

The ratings showed no trends. Qualitatively, the pilot thought that the nominal stick was about the best, but changes in stick natural frequency had no effect on the tendency he felt he had to cause oscillations. In the turn to final, the pilot noted that lower stick natural frequencies made the stick forces appear heavier.

Table J-6 Summarized Comments: Flight 6

| PILOT: Major | | | DATE: 4 Oct 96 | | | FLIGHT # 6 / Test Phase: 2 |
|---|---|---|---|---|---|---|
| Run # | $K_s$, Spring | $K_\omega$, Freq-uency | Rate Limit (deg/sec) | PIOR | CHR | Comments: |
| 1 | 1 | 1 | 200 | 3 | 5 | Warm Up. Low on final. 8 elevator rate peaks over 50 deg/sec. |
| 2 | 1 | 1 | 200 | 2 | 4 | Warm Up. Annoying tendency on correction. |
| 3 | 1 | 1 | 7.5 | 3 | 5 | Pulled to limit and held several times. Under corrected on initial turn. Short of desired. |
| 4 | 1 | 1 | 7.5 | | | Tripped the safeties on initial correction. |
| 5 | 1 | 1 | 7.5 | 2 | 4 | Undesirable motions. Definite delay in pitch. Also sluggish in pitch. |
| 6 | 1 | 1 | 7.5 | 3 | 5 | Bounced landing. Sideslip reached 5 degrees. |
| 7 | 1.4 | 1 | 7.5 | 4 | 8 | Convergent oscillation noticed. Stick was more sluggish. |
| 8 | 1.4 | 1 | 7.5 | | | Go around due to C-130 on runway. |
| 9 | 1.4 | 1 | 7.5 | 3 | 5 | Light turbulence. No oscillation. |
| 10 | 1.8 | 1 | 7.5 | 4 | 4 | Light turbulence. Large sink rate correction required. Very low frequency oscillation (PIO) noticed in the rate of descent. Frequency of oscillation was about 8 sec. |
| 11 | 1.8 | 1 | 7.5 | 3 | 6 | Pilot worked very hard on sink rate control. Very sluggish stick. Adequate performance. |
| 12 | 2.2 | 1 | 7.5 | 4 | 5 | Again, low frequency oscillation in rate of descent. |
| 13 | 2.2 | 1 | 7.5 | 4 | 4 | Workload increased due to high stick force and slow response. It was luck that the landing was in the desired zone. Sluggishness makes for considerable workload. |
| 14 | 0.6 | 1 | 7.5 | 4 | 4 | Weird combination of stick force and elevator responsiveness. |
| 15 | 0.6 | 1 | 7.5 | 4 | 4 | Low frequency PIO is still there. |

**Additional Comments on Flight 6**

Saw a gradual decrease in flying qualities as "spring" was increased. From point 6 on, I saw a slow speed PIO in glide path. The oscillation had a period of about 7-10 seconds. As the spring constant got heavier, the oscillation grew in magnitude.

When the spring constant was decreased below the nominal (run 14 & 15), the glide path oscillation was still noticed, however, it was subtle. This leads me to believe the PIO was there for the nominal stick (run 3-5) but went unnoticed.

Workload slowly increased as spring constant increased. It wasn't until point 11 that I would have called the workload extreme. However I noticed that initial conditions for the task affected workload greatly.

Stick inputs for the heavier springs were slow but intense because of the slow aircraft response to a longitudinal control input. Going form the heaviest spring to the lightest spring (pt 13 to 14) showed a dramatic change in compensation techniques. At the light spring, stick input was very jerky. The jerkiness was similar to stick pumps often seen in an aircraft flair, but continuous and intense.

Again, on this flight, the PIO sale wasn't fine enough to break out the gradual decrease in flying qualities. In fact, the CHRatings had a lot of noise in them. To reduce noise in the CHRatings, I plan to call all runs that have undesired control response as adequate or worse, regardless of where and how I touch down. This I believe will lead to a little less noise in the ratings as well as possibly finer detail broken out.

Table J-7 Summarized Comments: Flight 7

| PILOT: Major | | | DATE: 7 Oct 96 | | | FLIGHT # 7 Test Phase: 2 |
|---|---|---|---|---|---|---|
| Run # | $K_s$, Spring | $K_\omega$, Frequency | Rate Limit (deg/sec) | PIOR | CHR | Comments: |
| 1 | 1 | 1 | 200 | 1 | 3 | Warm up. High on glide slope. On oscillatory tendency. |
| 2 | 1 | 1 | 200 | 1 | 3 | Warm up. Little more correction. |
| 3 | 1 | 1 | 7.5 | 2 | 4 | Undesired motions, but didn't compromise task. Moderate work load, desired performance. |
| 4 | 1 | 1 | 7.5 | 4 | 7 | Pilot initiated go around. Little PIO. Set up was high and hard to correct. Go around just prior to touch down. |
| 5 | 1 | 1 | 7.5 | 2 | 4 | Undesirable motions, but didn't compromise task. Little sluggishness. Some delay in system noticed. |
| 6 | 1 | 1 | 5 | 2 | 4 | Worked harder than last time. Undesirable motions, but didn't compromise task. Moderate compensation. |
| 7 | 1 | 1.4 | 5 | 4 | 5 | Large bounce. Some oscillations noticed, though they were hard to see (very small amplitude). Task affect considered/ considerable compensation. Sluggish on stick. |
| 8 | 1 | 1.4 | 5 | 4 | 5 | Oscillations noticed. Desired performance with considerable compensation. |
| 9 | 1 | 1.8 | 5 | 4 | 5 | Stick appeared more sensitive and jerkier. No increase in workload. Pilot lowered his gains. Adequate performance. |
| 10 | 1 | 1.8 | 5 | 4 | 4 | Slight oscillation. |
| 11 | 1 | 0.6 | 5 | 4 | 5 | Considerable pilot compensation. 7-10 second period PIO noticed in the glide slope. |
| 12 | 1 | 0.6 | 5 | 4 | 5 | Again oscillation in the sink rate. Jerky inputs to dampen the motion. No perceptible change in stick. |
| 13 | 1 | 0.4 | 5 | 4 | 6 | Stick seemed to float back and forth with very little pilot input. Increased compensation. Stick forces were a little light. |
| 14 | 1 | 0.4 | 5 | 4 | 6 | Stick PIO, couldn't see the oscillation outside the aircraft. More annoying than anything else. |
| 15 | 1 | 1 | 5 | 4 | 4 | Oscillation in glide slope. No stick oscillation. Between moderate and considerable compensation. |

**Additional Comments on Flight 7**

Both 7.5° and 5°/sec rate limits showed low frequency sink rate oscillations. However 5°/sec showed it more consistently. The 7.5°/sec rate limit was more dependent on initial conditions for the task. Note that the air was smooth today for the entire sortie.

Changes in stick frequency showed no increase in the aircraft PIO frequency and amplitude. The PIO stayed low amplitude at an approximate period of 7-10 seconds. Changes in stick frequency did show a decrease in handling qualities. The higher frequency sticks had marginally higher handling qualities rating. The lower frequency sticks were marginally higher than the nominal stick. Initial condition seemed to greatly affect the ratings, thus 1 radian per second and higher were very close in workload.

At $K_{\omega}$=0.4, a stick PIO was encountered that did not translate to perceivable aircraft motion. The stick seemed to float back and forth with a 1-2 second period. This oscillation was seen in level flight as well as during the maneuvering. This stick PIO greatly increased workload.

Initial conditions were important. If stabilized on airspeed and glideslope at task initiation, the task appeared easier to do. Thus, to see changes in controls configuration, exact initial conditions should be avoided.

Table J-8 Summarized Comments: Flight 8

| PILOT: Evensen | | | DATE: 7 Oct 96 | | FLIGHT # 8 | Test Phase: 2 |
|---|---|---|---|---|---|---|
| Run # | $K_s$, Spring | $K_\omega$, Freq-uency | Rate Limit (deg/sec) | PIOR | CHR | Comments: |
| 1 | 1 | 1 | 200 | 1 | 3 | Warm up. Max elevator rate used was 40 deg/sec. |
| 2 | 1 | 1 | 200 | 1 | 3 | Warm up. Adequate performance, miss-judged the aimpoint. The CHR of 3 was assigned because the pilot felt the failure to achieve desired performance was the result of his miss-judgment, not the aircraft handling qualities. |
| 3 | 1 | 1 | 7.5 | 1 | 3 | Feels like some rate limit, but doesn't compromise task |
| 4 | 1 | 1 | 7.5 | 2 | 3 | Feels more nose heavy |
| 5 | 1.4 | 1 | 7.5 | 1 | 3 | A little better |
| 6 | 1.4 | 1 | 7.5 | 1 | 3 | |
| 7 | 1.8 | 1 | 7.5 | 2 | 4 | Sluggish in pitch and was hard to correct. |
| 8 | 1.8 | 1 | 7.5 | 2 | 4 | Even worse. Hard to make rapid corrections. |
| 9 | 2.2 | 1 | 7.5 | 2 | 4 | Not as stiff a stick. Not a significant difference. |
| 10 | 2.2 | 1 | 7.5 | 2 | 4 | Very stiff stick. Pilot felt he couldn't correct as much. |
| 11 | 0.6 | 1 | 7.5 | 2 | 4 | Light stick. Felt like there was lots of freeplay. Too loose and felt "strange". |
| 12 | 0.6 | 1 | 7.5 | 2 | 5 | Desired performance with more than moderate compensation. |
| 13 | 1 | 1 | 7.5 | 2 | 4 | Undesirable motions. Rate limiting was sensed. |

**Additional Comments on Flight 8**

The best stick to fly, just based on feel of the stick, was the nominal stick. However, with a slight increase in the stick spring constant, slightly better CH ratings were given because the task was performed better. With even more increase in the stick spring constant, the stick felt too stiff and it was difficult to make small rapid corrections to the glideslope.

With the lighter stick spring constants the aircraft felt very loose in the longitudinal axis. It felt like the stick had too much freeplay, and it almost felt like some control of the aircraft was lost.

Table J-9 Summarized Comments: Flight 9

| PILOT: Evensen | | | DATE: 7 Oct 96 | | | FLIGHT # 9 / Test Phase: 2 |
|---|---|---|---|---|---|---|
| Run # | $K_s$, Spring | $K_\omega$, Frequency | Rate Limit (deg/sec) | PIOR | CHR | Comments: |
| 1 | 1 | 1 | 200 | 1 | 2 | Still air. Peak elevator rate used was 15 deg/sec. |
| 2 | 1 | 1 | 200 | 1 | 2 | 30 deg/sec elevator rate used. |
| 3 | 1 | 1 | 5 | 1 | 2 | Felt a little rate limit. Would not realize the difference in available rate limit in a blind test. Only one place just prior to touch down where elevator wasn't within 80 % of rate limit. |
| 4 | 1 | 1 | 5 | 2 | 3 | A little low on initial set up. Data suspect. |
| 5 | 1 | 1.4 | 5 | 1 | 3 | Stick felt a little better than the last run. Less time on rate limit than the two previous runs. |
| 6 | 1 | 1.4 | 5 | 1 | 3 | Felt better than the nominal stick. More time on rate limit than previous run. |
| 7 | 1 | 1.8 | 5 | 2 | 3 | Didn't feel quite as good as the previous run. Spent more time holding the stick on the rate limit. More correction required by the pilot. |
| 8 | 1 | 1.8 | 5 | 2 | 3 | Missjudged altitude. |
| 9 | 1 | 0.7 | 5 | 3 | 4 | Stick felt more sluggish. Didn't like the stick as much as the nominal stick. Consistently on rate limit. |
| 10 | 1 | 0.7 | 5 | 3 | 4 | Not really responsive in flair. Hard to correct for pitch. |
| 11 | 1 | 0.4 | 5 | 2 | 4 | Stick felt "weird", like it was bouncing. Otherwise felt stable. |
| 12 | 1 | 0.4 | 5 | 4 | 7 | Could feel rate limit. Small PIO present. Workload required improvement. Very persistent on rate limit just prior to touch down. |
| 13 | 1 | 2.2 | 5 | 3 | 5 | Felt much better than the lower stick frequencies. Bounced on landing. |
| 14 | 1 | 2.2 | 5 | 2 | 5 | Same comment as 13. No bounce this time. Less persistently on rate limit. |

**Additional Comments on Flight 9**

The best stick was the one where the stick natural frequency was increased slightly (1.4 times nominal). With this stick the aircraft felt more responsive. With increasing stick natural frequency the stick almost felt as if the spring constant was increased.

With a decrease in the stick natural frequency, the stick felt sluggish and it almost amplified the feeling of a slow response from the aircraft.

Table J-10 Summarized Comments: Flight 10

| PILOT: Evensen | | | DATE: 9 Oct 96 | | FLIGHT # 10 | Test Phase: 3 |
|---|---|---|---|---|---|---|
| Run # | $K_s$, Spring | $K_\omega$, Frequency | Rate Limit (deg/sec) | PIOR | CHR | Comments: |
| 1 | 1 | 1 | 200 | 2 | 3 | Warm up. Light turbulence. Two peaks over 40 deg/sec on data traces. |
| 2 | 1 | 1 | 200 | 2 | 3 | Warm up. Light turbulence. Three peaks over 30 deg/sec. |
| 3 | 1.4 | 1 | 15 | 2 | 4 | One dot low on setup. Hit rate limit. Stick felt looser than previous run. Work load moderate |
| 4 | 1.4 | 1 | 15 | 3 | 5 | Light turbulence. Not quite the responsiveness the pilot wanted at end of flare. Adequate performance with considerable workload. |
| 5 | 1 | 1 | 5 | 5 | 7 | Oscillations were present and growing in amplitude. Adequate with max tolerable compensation. |
| 6 | 1 | 1 | 5 | 2 | 4 | Safety pilot took aircraft on final. The oscillation found in run 5 was not present this time. No gross corrections on final. Moderate compensation. |
| 7 | 1 | 1.4 | 5 | 3 | 6 | Definitely could sense the rate limit. Task was compromised. It was hard to tell if there was an oscillation. Stick felt lighter than the previous stick. Adequate performance with extensive compensation. |
| 8 | 1 | 1.4 | 5 | 3 | 6 | Sloppier stick, noticeably worse than previous stick. Workload higher than pervious run. Adequate performance achieved. |
| 9 | 1 | 1 | 15 | 2 | 4 | Elevator rate didn't hit the rate limit as much as on the previous run. Stick felt stiffer. Undesirable motion was not as bad as previous run. |
| 10 | 1 | 1 | 15 | 4 | 7 | Aggressive correction required at end of offset. Oscillation present, but not divergent. |
| 11 | 1 | 1.4 | 15 | 2 | 4 | Not as much rate limiting. Some undesirable motion, but didn't compromise task. No perceived change from run 10. |
| 12 | 1 | 1.4 | 15 | 2 | 4 | Little undesirable motion, didn't compromise task. Moderate compensation. Stick change had no effect in task performance. |
| 13 | 1.4 | 1 | 5 | 4 | 8 | Definitely requires improvement. Considerable compensation required for control. Rate limiting definitely felt. Small stick corrections at the end. Was able to stop the oscillations that occurred. Forces were too heavy. Once in flare, the forces were to heavy to correct. Biggest PIO yet. |
| 14 | 1.4 | 1 | 5 | 4 | 9 | Bounce on landing. Unable to make small rapid corrections. Able to damp out the oscillations that occurred. Major compensation and intense concentration required. |

**Additional Comments on Flight 10**

On this flight the winds were moderate in amplitude and gusting (5-10 kts). The work load on all landings were considerably higher than on any of the other flights due to the winds. The results may not be totally repeatable due to the gusty winds. However, it was seen that noting any difference between a change in the stick natural frequency and stick spring constant was very difficult, and no effort was made to investigate what stick was programmed into the flight control system. Just flying the task, sometimes the increase in stick natural frequency was felt as an increase in the stick spring constant and vice versa.

Table J-11 Summarized Comments: Flight 11

| PILOT: Peters | | | DATE: 10 Oct 96 | | | FLIGHT # 11 / Test Phase: 3 |
|---|---|---|---|---|---|---|
| Run # | $K_s$, Spring | $K_\omega$, Freq-uency | Rate Limit (deg/sec) | PIOR | CHR | Comments: |
| 1 | 1 | 1 | 200 | 2 | 3 | Warm up. A couple of elevator rate peaks over 20 deg/sec. |
| 2 | 1 | 1 | 200 | 1 | 2 | Warm up. A couple of peaks over 30 deg/sec. |
| 3 | 1 | 1.4 | 5 | 3 | 5 | A little bit of delay in stick response. Slow aircraft response. Desired performance, but workload more than moderate. Some long holds on rate limit. |
| 4 | 1 | 1.4 | 5 | 2 | 3 | Quite a delay. Sluggish. A lot worse than the previous. Not as persistently on rate limit as previous run. |
| 5 | 1 | 1 | 5 | 3 | 5 | Pulled power too soon. Landing wasn't smooth. Didn't notice the delay quite so much. |
| 6 | 1 | 1 | 5 | 2 | 4 | Noticed a little delay. Little bobble in airspeed control. Just slightly better than previous configuration. |
| 7 | 1.4 | 1 | 5 | 2 | 3 | A little heavier stick forces on the turn. Slightly better than previous configuration. Slight bobble and slight delay. Wasn't working as hard on this landing as previous ones. |
| 8 | 1.4 | 1 | 5 | 2 | 3 | Worked the flare. Little compensation. Noticeably better than before. Airplane helps to be smooth. |
| 9 | 1.4 | 1 | 15 | 2 | 3 | Noticeably lighter stick forces. Less delay and more responsive. Nicer stick forces. Noticeably better. |
| 10 | 1.4 | 1 | 15 | 2 | 3 | Open loop. Little bobbles and some delay. Lighter stick forces. Generally nicer stick on final. |
| 11 | 1 | 1 | 15 | 2 | 3 | A little heavier stick force. Not quite a good, more bobble. |
| 12 | 1 | 1 | 15 | 2 | 3 | Not much difference from previous stick. Heavier stick force prevents flare. No significant difference vs other configurations. |
| 13 | 1 | 1.4 | 15 | 2 | 3 | Slightly nicer. Lighter stick force and more responsive. Control response was right away. Slight less bobble and better in the flare. |
| 14 | 1 | 1.4 | 15 | 2 | 3 | Got slow and had a firm touch down. Not much difference between last two runs. Didn't flare as much. Not sure it is the stick. |

**Additional Comments on Flight 11**

The rate limit on the first three sets of test points was low enough and caused enough degradation of handling qualities that differences were seen for the different sticks. The last three sets were not degraded enough to have significant differences caused by the sticks.

Table J-12 Summarized Comments: Flight 12

| PILOT: Major | | | DATE: 10 Oct 96 | | | FLIGHT # 12 / Test Phase: 3 |
|---|---|---|---|---|---|---|
| Run # | $K_s$, Spring | $K_\omega$, Frequency | Rate Limit (deg/sec) | PIOR | CHR | Comments: |
| 1 | 1 | 1 | 200 | 1 | 3 | Warm up. A couple of elevator rates over 40 deg/sec. |
| 2 | 1 | 1 | 200 | 1 | 3 | Warm up. Light turbulence in base turn. Landed a little off centerline. Was more aggressive in turn. |
| 3 | 1 | 1.4 | 5 | 2 | 4 | Apparent delay in system made sink rate control harder. Stick felt heavier. May have been a small oscillation. Held stick at rate limit for 1.5 seconds at one point. |
| 4 | 1 | 1.4 | 5 | 2 | 4 | No oscillation. Some undesired motion with the delay. Moderate compensation. Heavier stick than run 1 with some apparent delay. Held stick at rate limit for 1.5 seconds at one point. |
| 5 | 1 | 1 | 5 | 3 | 5 | Small premature oscillation in base turn. Light turbulence. Configuration appeared more oscillatory. Pilot compensation was to be jerky on inputs. Bigger overshoots. Stick felt lighter than runs 3 and 4. Held stick at rate limit for 1.2 seconds at one point. |
| 6 | 1 | 1 | 5 | 4 | 5 | Considerable oscillations in glide slope. Comfortable stick, but jerky. Held stick at rate limit for 1.2 seconds at one point. |
| 7 | 1.4 | 1 | 5 | 4 | 6 | Trouble with oscillations in flare. Big bounce on landing. Gross oscillations were the worst seen so far. Stick felt heavy and there was apparent pitch delay. Held stick at rate limit for 1.8 seconds at one point. |
| 8 | 1.4 | 1 | 5 | 4 | 6 | Same large oscillations. Used throttle to set-up. Extensive compensation ("working hard"). Heavy stick with time delay = oscillations. Held stick at rate limit for 2 seconds at one point. |
| 9 | 1.4 | 1 | 15 | 4 | 5 | Stick felt faster but still heavy. Still some time delay (smaller than before). Slightly heavier on stick forces. Considerable compensation. Some oscillations, but better than last stick. Held stick at rate limit for 0.8 seconds at one point. |
| 10 | 1.4 | 1 | 15 | 4 | 5 | Oscillation on base turn. Desired box, but considerable compensation. Slightly jerky stick. |
| 11 | 1 | 1 | 15 | 4 | 6 | Lighter stick, fast, but more delay. Little more delay than last stick. Working hard on glideslope (extensive) to damp oscillation. One dot high at correction. Held stick at rate limit for 0.5 seconds at one point. |
| 12 | 1 | 1 | 15 | 4 | 6 | Light turbulence, stronger than before. Highest frequency oscillation seen yet. Very objectionable. Worse than stick in runs 7 & 8. Held stick at rate limit for 0.8 seconds at one point. |
| 13 | 1 | 1.4 | 15 | 3 | 5 | Good on stick sensitivity. Little time delay. Crisp, little jerkiness. |
| 14 | 1 | 1.4 | 15 | 2 | 4 | Minor but annoying def. Little delay, but still annoying. Less delay than previous stick. |

Table J-13 Summarized Comments: Flight 13

| PILOT: Peters | | | DATE: 10 Oct 96 | FLIGHT # 13 | | Test Phase: 3 |
|---|---|---|---|---|---|---|
| Run # | $K_s$, Spring | $K_\omega$, Freq-uency | Rate Limit (deg/sec) | PIOR | CHR | Comments: |
| 1 | 1 | 1 | Base learjet | 2 | 5 | Warm up. Small undesired motion. |
| 2 | 1 | 1 | Base learjet | 3 | 5 | Warm up. Sloppy feel. Undesired motion. Hit 60 deg/sec once, 50 deg/sec three times, 40 deg/sec 4 times. |
| 3 | 1 | 1.4 | 10 | 2 | 5 | 3 KIAS off airspeed-adequate performance. Undesired motion, but not oscillatory. Moderate compensation/workload. Delay causes sluggish response. Not as sloppy, but more sluggish. Skipped out of box. |
| 4 | 1 | 1.4 | 10 | 3 | 3 | Minimal compensation. Undesirable motion didn't affect performance. Better performance out of this stick |
| 5 | 1 | 1 | 10 | 4 | 7 | Light-moderate turbulence. Undesired motion requiring pilot compensation. One bounce to a go-around. Pitch control not able to arrest gust effects. Controllable but needed big inputs. Big pitch rate change just prior to touch down. |
| 6 | 1 | 1 | 10 | 3 | 6 | More sensitive stick, but worse performance. Oscillation was large amplitude in pitch but could be damped out. Corrected to the desired box. Extensive compensation. Was on the rate limit more with this stick. |
| 7 | 1.4 | 1 | 10 | 3 | 4 | Some undesirable motion. Worked hard for desired performance. Light to moderate turbulence. Heavier stick slowing down input (limiting). Airplane sluggish to input. Did not push airplane to limit. |
| 8 | 1.4 | 1 | 10 | 3 | 4 | Some undesired motion. Little oscillation on glide slope. Putting input in & taking it out was major form of compensation. Better than last stick. Reduced sensitivity was good. |
| 9 | 1.4 | 1 | 200 | 2 | 3 | Stick still heavy. Minimal-moderate workload. Aircraft responded better. Aircraft less sluggish. Some undesired motion. |
| 10 | 1.4 | 1 | 200 | 2 | 4 | Seemed lighter stick forces (even more so than previous run). Pilot was moving hand faster. Small undesired motion resulted in moderate compensation. Hand jerking around more. |
| 11 | 1 | 1 | 200 | 2 | 3 | Pretty nice configuration. Turbulence induced bobble. Between minimum-moderate compensation to get better performance. Improvement over runs 9/10. |
| 12 | 1 | 1 | 200 | 2 | 3 | Minor undesired motion. Minimal side of work load. Hand not jerking about to fly plane. |
| 13 | 1 | 1.4 | 200 | 2 | 3 | Light to moderate turbulence. No difference in stick from runs 11/12. |
| 14 | 1 | 1.4 | 200 | 2 | 3 | Pretty nice. |

**Additional Comments from Flight 13**

The rate limit on the first three sets of test points was low enough (combined with the afternoon turbulence) to cause degradation in handling qualities, but the problem was really in control power available, not PIO. The last three sets were not degraded enough to have significant differences in performance caused by the sticks.

A discussion with Russ Easter after the flight brought out the fact that, for many of the configurations flown, the pilots knew that there were significant problems with the airplane. The CH ratings do not reflect how bad the pilots really thought the airplane was, but instead were driven by task performance and perceived workload.

Table J-14 Summarized Comments: Flight 14

| PILOT: Evensen | | | DATE: 11 Oct 96 | | | FLIGHT # 14 | Test Phase: 3 |
|---|---|---|---|---|---|---|---|
| Run # | $K_s$, Spring | $K_\omega$, Freq-uency | Rate Limit (deg/sec) | PIOR | CHR | Comments: | |
| 1 | 1 | 1 | Base learjet | 1 | 2 | Warm up. No undesired motion. Could make small abrupt changes without exciting undesired motion. Two elevator rate peaks above 30 deg/sec. | |
| 2 | 1 | 1 | Base learjet | 1 | 2 | Warm up. Easy to make small corrections. One peak above 40 deg/sec, five above 30 deg/sec. | |
| 3 | 1 | 1.4 | 10 | 1 | 3 | Little stiffer stick. Not as responsive. Could make relatively big corrections. Overshot on final. Could not feel rate limit. No tendency to hold stick on rate limit. | |
| 4 | 1 | 1.4 | 10 | 1 | 3 | No sustained rate limit. Corrections at end not quite as easy as first two runs. | |
| 5 | 1 | 1 | 10 | 1 | 3 | Hard to see difference. Stick a litter lighter. Stick feels better, but no real change in performance. Very little time spend holding at rate limits. | |
| 6 | 1 | 1 | 10 | 1 | 2 | Rate limit at flare, not as responsive as first one. Really minor. | |
| 7 | 1.4 | 1 | 10 | 1 | 3 | Little undesired motion if pilot increased gain. Stick heavier, more like runs 3 and 4. | |
| 8 | 1.4 | 1 | 10 | 1 | 3 | Hard time discerning between different runs. | |
| 9 | 1.4 | 1 | 200 | 1 | 3 | Small input at end resulted in undesired motion. Can't tell difference between previous stick. | |
| 10 | 1.4 | 1 | 200 | 2 | 3 | Just outside desired box (still pretty good flying). The CHR 3 was assigned by the pilot because he felt he was the cause of the performance degredation. Stick a bit heavier (need to fly more closed loop than before). "Not quite the responsiveness I wanted." | |
| 11 | 1 | 1 | 200 | 1 | 3 | Small corrections caused the airplane to respond well. Stick more responsive. Still hard to discern differences. | |
| 12 | 1 | 1 | 200 | 1 | 2 | Flies nice. Like stick better than 9/10. Responds nicely all the way down. | |
| 13 | 1 | 1.4 | 200 | 1 | 3 | At flare—make small rapid corrections. Not quite as good as previous configuration. No undesirable motion. | |
| 14 | 1 | 1.4 | 200 | 1 | 3 | No difference. | |

**Additional Comments on Flight 14**

Again it was hard to tell the difference between the changes in the stick constant and changes in the stick natural frequency. Since the test was performed blind to pilot, he tended to fly a litter higher gain in the offset landing task than on the three first flights.

This was to check if there was any undesirable aircraft motions induced by increasing pilot gains. This increase in pilot gain is reflected in the CH ratings. Almost no undesirable aircraft motions were discovered on any of the landings. Specific comments for each combination of rate limiting and stick characteristic is given in the above table.

Table J-15 Summarized Comments: Flight 15

| PILOT: Major | | | DATE: 11 Oct 96 | FLIGHT # 15 | | Test Phase: 3 |
|---|---|---|---|---|---|---|
| Run # | $K_s$, Spring | $K_\omega$, Frequency | Rate Limit (deg/sec) | PIO R | CHR | Comments: |
| 1 | 1 | 1 | Base learjet | 2 | 4 | Warm up. Stick too responsive (light). Predictable, no apparent delay. |
| 2 | 1 | 1 | Base learjet | 2 | 4 | Warm up. No time delay. Good response. Stick high frequency response. Light turbulence. |
| 3 | 1 | 1.4 | 10 | 2 | 4 | Heavier stick + same frequency = better. No delay. Predictable. Longest occurrence of holding at the rate limit was 0.8 sec. |
| 4 | 1 | 1.4 | 10 | 2 | 5 | Heavier stick. Responsive. No time delay. Might have floated trying to flare. Light turbulence. |
| 5 | 1 | 1 | 10 | 2 | 4 | Jerky motion for last three sticks. Light turbulence. Longest occurrence of holding at the rate limit was 0.5 sec. |
| 6 | 1 | 1 | 10 | 2 | 4 | Stick jerky. High flare. Felt in control. Light turbulence. |
| 7 | 1.4 | 1 | 10 | 4 | 5 | Heavier stick, less in control. Not as much jerky motion. Considerable compensation. Longest occurrence of holding at the rate limit was 1.2 sec. |
| 8 | 1.4 | 1 | 10 | 4 | 6 | More aggressive. Heavy sluggish stick. Extensive compensation. |
| 9 | 1.4 | 1 | 200 | 4 | 6 | Light pulsing of stick. More responsive than last stick. Still heavy stick. Extensive compensation. |
| 10 | 1.4 | 1 | 200 | 4 | 7 | Light turbulence. Pitch sensitivity with some delay. |
| 11 | 1 | 1 | 200 | 4 | 8 | Lighter stick than last time. Stick seems to float a little bit. Short period PIO in flare. |
| 12 | 1 | 1 | 200 | 4 | 7 | Not as bad as last time, but still working hard. |
| 13 | 1 | 1.4 | 200 | 4 | 6 | PIO attend. Better than last stick. |
| 14 | 1 | 1.4 | 200 | 4 | 5 | Stick floated. |

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# Vita

Captain Patrick J. Peters was [redacted]. He graduated from Saline High School, Saline, Michigan, in 1981. He then earned a Bachelor of Science degree in Aeronautics and Astronautics from the Massachusetts Institute of Technology, School of Engineering. After graduation, he worked on the 747 Aerodynamics Staff for the Boeing Commercial Airplane Company in Seattle, Washington until joining the Air Force in September 1986. He received a commission from the USAF Officer Training School, then entered Euro-NATO Joint Jet Pilot Training at Sheppard AFB, Texas, where he received his wings in April 1988. After survival training and A-10 RTU, Capt Peters served as an A-10 pilot in the 355th Tactical Fighter Squadron (TFS) at Myrtle Beach AFB, South Carolina. While he was with the 355th TFS at King Fahd AB, Saudi Arabia, he flew missions in support of Operations Desert Shield and Desert Storm. In August 1992, he joined the 357th Fighter Squadron at Davis-Monthan AFB, Arizona, where he served as an A-10/OA-10 RTU instructor pilot and functional check flight OIC. He was selected to enter the joint Air Force Institute of Technology/USAF Test Pilot School program in July 1994. After graduation, he was assigned to the 416th Flight Test Squadron at Edwards AFB, California to fly the F-16.

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**13. ABSTRACT** *(Maximum 200 words)*

This report presents the results of an investigation into the effects of elevator rate limiting and stick dynamics on longitudinal pilot-induced oscillations (PIO). A simulation study was conducted to prepare for the flight test, but also to gain insight into the effects of rate limiting and stick dynamics. Due to the non-numerical nature of the simulation results, a flexible three-phase flight test plan was developed, first varying the rate limits, then varying the stick dynamics, and finally flying a matrix determined in the first two phases.

There were three major conclusions. First, the offset landing task flown was insufficient to consistently uncover handling qualities deficiencies of the aircraft configuration flown. Second, rate limiting did not necessarily cause PIOs. At very low rate limits the problem was lack of pitch response, not PIO. Any oscillations were very low frequency and small in amplitude. Third, for this configuration and task, variations in stick spring constant and natural frequency had negligible effect on the performance of the system with respect to assigned PIO and Cooper-Harper ratings. These conclusions are specific to this system and may not apply to all aircraft, especially aircraft where PIO tendencies are driven by much higher rate limits.

**14. SUBJECT TERMS**
Elevator Rate Limiting, Flight Control Systems, Control Sticks, Handling Qualities, Stick Force Gradients, Pilot-Induced Oscillation (PIO), Control Stick Forces, Rate Limited Actuators, Cooper-Harper Rating Scale.

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