FLIGHT TEST EVALUATION OF TECHNIQUES
TO PREDICT LONGITUDINAL
PILOT INDUCED OSCILLATIONS

THESIS

Eileen A. Bjorkman
Captain, USAF

AFIT/GAE/AA/86J-1

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Aeronautical Engineering

Eileen A. Bjorkman, B.S.
Captain, USAF

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Preface

The purpose of this study was to determine if several proposed pilot induced oscillation (PIO) prediction techniques could predict longitudinal PIO tendency in a variety of aircraft configurations prior to flight test. The techniques were first applied to an existing data base to provide insights into their application and limitations. Based on the analytical results, 18 aircraft/flight control systems were selected for flight testing. Each technique was used to predict the PIO tendencies of the configurations prior to flight.

Although the flight test results were inconclusive due to the limited number of configurations, the results provided some intriguing possibilities for future PIO research. The data base established here is excellent for use in future research; the experiment was tightly controlled and provided extremely consistent results.

The joint AFIT/USAFTPS program under which this research was conducted provided a unique opportunity to apply academic research to an operational test. In performing both my research and the flight test program I was aided by many people. I must especially thank my thesis advisor, Dr. R. A. Calico, for providing me with the topic in the first place. Also, much thanks must be given to Major J. T. Silverthorn, my advisor at TPS, for providing invaluable assistance during the flight test program, particularly the data reduction. I am also deeply idebted to Ralph Smith (now with NASA) for reviewing much of my original research and providing me with some excellent insights to my approach. Much credit must also be given to my test team at TPS. The members included Capt Dave Eidsaune, Capt Rick Bennett, Capt (Japan) Seiichi Miyamoto, and 1Lt Carter Wilkinson. By pulling together, we somehow managed to complete a six week test program in a little over two weeks. Likewise, I must thank all of the Calspan safety pilots involved in the program (Mike Parrag, Bob Harper, and Russ Easter) and the Calspan maintenance crews, who worked many long hours and weekends to allow us to complete the test program on schedule. I owe a special thanks to Mike Parrag and Lou Knotts (also of Calpsan) for their constructive comments and assistance during the planning phase of the flight test program. Their assistance undoubtedly helped us avoid many of the pitfalls which often plague research programs of this nature. Finally, I must thank Lt (USN) Ron "Weasel" Weisbrook for taking the time from his busy schedule to proofread several of my drafts.

Eileen A. Bjorkman

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List of Symbols

a_z	Downward (normal) acceleration of the aircraft center of gravity, g
a_{z_p}	Pilot-felt normal acceleration (normal acceleration at the pilot station), g
$(a_{z_p})_{CR}$	Critical value of Smith's magnitude criterion. Above this value the pilot may switch from tracking pitch to tracking normal acceleration, g/deg/sec
A	Coefficient of s^3 term in aircraft fourth order characteristic equation
A'	Amplitude parameter of the $a_{z_p}(t)$ PSD
$A_{a_{z_p}}$	Coefficient of s^4 term in numerator of pilot-felt normal acceleration transfer function
A_α	Coefficient of s^3 term in numerator of angle of attack transfer function
A_θ	Coefficient of s^2 term in numerator of pitch angle transfer function
$A_{\theta_{w_g}}$	Coefficient of s^3 term in numerator of equivalent gust command transfer function
B	Coefficient of s^2 term in aircraft fourth order characteristic equation
$B_{a_{z_p}}$	Coefficient of s^3 term in numerator of pilot-felt normal acceleration transfer function
B_α	Coefficient of s^2 term in numerator of angle of attack transfer function
B_θ	Coefficient of s term in numerator of pitch angle transfer function
$B_{\theta_{w_g}}$	Coefficient of s^2 term in numerator of equivalent gust command transfer function
C	Coefficient of s term in aircraft fourth order characteristic equation
$C_{a_{z_p}}$	Coefficient of s^2 term in numerator of pilot-felt normal acceleration transfer function

C_α	Coefficient of s term in numerator of angle of attack transfer function
C_θ	Coefficient of s^0 term in numerator of pitch angle transfer function
$C_{\theta w_g}$	Coefficient of s term in numerator of equivalent gust command transfer function
D	Coefficient of s^0 term in aircraft fourth order characteristic equation
$D_{a_{z_p}}$	Coefficient of s term in numerator of pilot-felt normal acceleration transfer function
D_α	Coefficent of s^0 term in numerator of angle of attack transfer function
F_{AS}	Roll control stick force, positive right, lb
F_{ES}	Pitch control stick force, positive aft, lb
F_{RP}	Rudder pedal force, positive right, lb
g	Acceleration of gravity, ft/sec^2
K_a	Pilot gain in the a_{z_p}/F_s loop
K_{a_o}	Value of K_a when $a_{z_p}(t)$ approaches a pure sine wave
K_p	Pilot gain in the θ/F_s loop
K_q	NT-33A pitch rate loop feedback gain
K_α	NT-33A angle of attack loop feedback gain
l_x	Pilot's location forward of the aircraft center of gravity, feet
L_w	Scale of turbulence in Dryden turbulence PSD, feet
m	Average slope of the θ/F_s dynamics from 1 to 6 rad/sec, dB/octave
$M_{(\ )}$	$=[1/I_y][\partial M/\partial(\ )]$, body axis dimensional moment derivative, rad/sec^2 per ( )
M_q'	NT-33A modified M_q derivative
M_w'	NT-33A modified M_w derivative

n_z/α	Steady-state normal acceleration per angle of attack (g/rad)
$N_{\delta_e}^{a_{z_p}}$	Numerator of pilot-felt normal acceleration to elevator deflection transfer function
$N_{\delta_e}^{\alpha}$	Numerator of angle of attack to elevator deflection transfer function
$N_{\delta_e}^{\theta}$	Numerator of pitch angle to elevator deflection transfer function
$N_{w_g}^{\theta}$	Numerator of pitch loop equivalent gust command transfer function
q	Perturbed pitch rate referenced to the vehicle body axis system
s	Laplace transform variable
T_I	Lag equalization time constant in pilot model, sec
T_L	Lead equalization time constant in pilot model, sec
T_N	Neuromuscular time constant in pilot model, sec
u	Perturbed forward speed referenced to the vehicle body axis system, ft/sec
U_o	Equilibrium forward speed, ft/sec
V_o	Reference velocity of aircraft, ft/sec
w	Perturbed downward speed referenced to the vehicle body axis system, ft/sec
W_o	Equilibrium downward speed, ft/sec
$X_{(\ )}$	$=[1/m][\partial X/\partial(\ )]$, body axis dimensional X-force derivative, ft/sec^2 per ( )
$Z_{(\ )}$	$=[1/m][\partial Z/\partial(\ )]$, body axis dimensional Z-force derivative, ft/sec^2 per ( )
Z_w'	NT-33A modified Z_w derivative
α	perturbed angle of attack referenced to the vehicle body axis system
β	perturbed sideslip angle referenced to the vehicle body axis system

δ_e	Elevator deflection input, deg
δ_{AS}	Roll stick deflection at grip, positive right, inches
δ_{ES}	Pitch stick deflection at grip, positive aft, inches
δ_{RP}	Rudder pedal deflection, positive right, iches
Δ	Characteristic equation
Δ'	Width parameter of the $a_{z_p}(t)$ PSD
ν	Index of subjective predictability
ω_{BW}	Bandwidth frequency of θ/F_s, rad/sec
ω_{BWgain}	Frequency at which the gain margin of θ/F_s is 6 dB, rad/sec
$\omega_{BWphase}$	Frequency at which the phase shift of θ/F_s is -135 deg, rad/sec
ω_c	Crossover frequency of θ/F_s loop, rad/sec
ω_d	Dutch roll natural frequency, rad/sec
ω_{n_1}	Natural frequency, second order flight control system, rad/sec
ω_{n_2}	Natural frequency, fourth order flight control system, rad/sec
ω_p	Phugoid mode natural frequency, rad/sec
ω_R	Center frequency of pitch attitude closed loop pilot-vehicle system, rad/sec
ω_{sp}	Short period mode natural frequency, rad/sec
ω_{180}	Frequency at which the phase shift of θ/F_s is -180 deg, rad/sec
$\phi(j\omega)$	Phase angle of a transfer function at frequency ω, deg
ϕ_m	Phase margin of the a_{z_p}/F_s system at the resonant frequency resulting from θ/F_s closure
$\|\phi/\beta\|_d$	Absolute value of controls fixed roll-to-sideslip ratio at ω_d

σ_w	Strength of turbulence in Dryden turbulence PSD, ft/sec
τ	Pilot time delay in the θ/F_s loop, sec
τ_a	Pilot time delay in the a_{z_p}/F_s loop, sec
τ_e	Pilot equivalent time delay in the θ/F_s loop, sec
τ_p	Phase delay, sec
τ_R	Roll mode time constant, sec
τ_s	Spiral mode time constant, sec
τ_{θ_1}	Phugoid mode numerator time constant, sec
τ_{θ_2}	Short period mode numerator time constant, sec
τ_1	Numerator time constant for first order flight control system, sec
τ_2	Denominator time constant for first order flight control system, sec
θ	Perturbed pitch angle referenced to the vehicle body axis system, rad
$\dot{\theta}$	Perturbed derivative of pitch angle (generally pitch rate) referenced to the vehicle body axis system, rad/sec
θ_o	Equilibrium pitch angle
ζ_{cl}	Damping ratio of the dominant mode for closed loop pitch attitude control
ζ_d	Dutch roll mode damping ratio
ζ_p	Phugoid mode damping ratio
ζ_{sp}	Short period mode damping ratio
ζ_1	Damping ratio, second order flight contro system
ζ_2	Damping ratio, fourth order flight control system

Abstract

The purpose of this study was to determine if pilot induced oscillations (PIOs) can be predicted prior to flight using existing PIO prediction techniques. Two techniques to predict longitudinal PIO tendencies (Ralph Smith's theory and Roger Hoh's bandwidth method) were studied analytically using an existing PIO data base. Suggestions were made for both techniques to allow prediction of PIO rating. The two techniques were then applied to 18 aircraft/flight control system landing configurations. The 18 configurations were flight tested using a flared landing task with the USAF/Calspan variable stability NT-33A. Smith's theory correctly predicted the PIO tendencies and frequencies provided the configuration was not sensitive to the pilot model used. A suggested modification to Smith's theory correctly predicted PIO ratings within an average of 0.6 rating. A suggested modification to Hoh's bandwidth method predicted PIO ratings within an average of 0.5 rating.

The limited data base was too small to draw any definite conclusions. Recommendations for further study included collecting more PIO data and using existing data bases and simulator studies to better define the two techniques and to gain physical insights into PIO mechanization.

FLIGHT TEST EVALUATION OF TECHNIQUES TO
PREDICT LONGITUDINAL PILOT INDUCED OSCILLATIONS

I. Introduction

Background

A pilot-induced oscillation (PIO) is an inadvertent, sustained oscillation of a pilot/vehicle system (1:1). Characteristically, a PIO is difficult or impossible for the pilot to stop unless he removes himself from the loop, i.e., the aircraft is stable both stick-fixed and stick free (2:2). PIO's typically occur during tasks for which the pilot is particularly concerned about tight control of the aircraft, such as during landing, takeoff, refueling, and formation flying.

PIO's have been documented since the beginning of manned flight. Although even the Wright Flyer had a mild longitudinal oscillation, PIO did not become a serious problem until high performance jets emerged in the fifties. The high speeds and fully powered control systems of modern aircraft can be potentially lethal; relatively small pilot inputs can cause a rapid buildup to catastrophic loads (1:1). A well documented PIO occurred during the early sixties when an early version of the T-38A sustained a severe PIO (seven cycles of ±4 g's building up to ±8 g's) after the pilot shut down a malfunctioning pitch damper with the elevator mistrimmed (1:1). This PIO is clearly demonstrated by the time histories in Figure 1. The problem was traced to the bobweight in the flight control system, which was subsequently modified to prevent a reoccurrence.

Typically, PIO's have gone undetected until the final flight testing or early production stages of an aircraft when aggressive pilot behavior is more likely. Since fixes to an aircraft at this late stage are difficult and expensive, there have been many attempts to analytically predict PIO tendencies in an aircraft/flight control system before it has been built. Unfortunately, the current military flying qualities specification, MIL-F-8785C (3), provides no guidance for precluding PIO by design. Although two possible PIO prediction techniques, the R. Smith criterion (2) and Hoh's bandwidth method (4), were proposed for inclusion in MIL-F-8785C, the current version simply states that an aircraft will not PIO.

Objectives

The purpose of this study is to evaluate and attempt to refine some of the more recent longitudinal PIO prediction theories. The ultimate goal is to use these theories to predict PIO tendency for a variety of aircraft/flight control system configurations in the approach/landing phase of flight and to verify these predictions using the Calspan/USAFTPS variable stability NT-33. The theories to be examined are R.

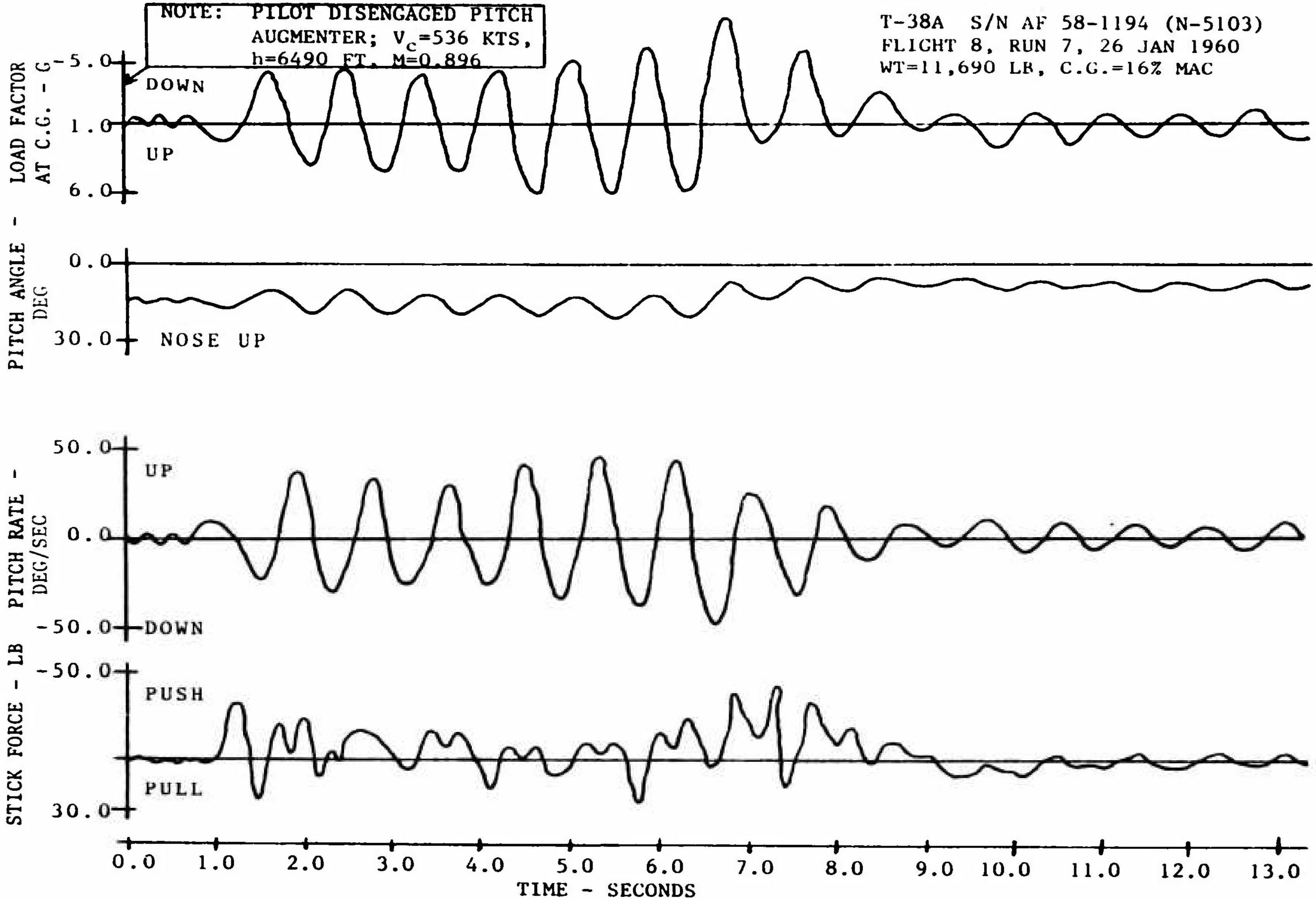


Figure 1. Time History of a PIO

Smith's longitudinal PIO criteria (2,5) and R. Hoh's bandwidth method (4). Although Hoh's method has been proposed as a handling qualities predictor, it will be employed in this study to see if it can be used to predict PIO tendencies.

Specific objectives include:

1. Determine if any parameters obtainable from aircraft/flight control system dynamics can be used to predict PIO ratings and frequencies.

2. Determine if existing PIO prediction techniques need refinement and make suggestions for improvement.

3. Use each technique to predict prior to flight the PIO tendencies of a variety of aircraft/flight control system configurations; determine the percentage of correct PIO predictions made by each technique, including PIO rating and frequency.

Approach

Specifically, the approach taken will be:

1. Study the two techniques and develop or obtain computer programs to ease their implementation.

2. Use the 1978 Calspan Landing Approach Higher Order System (LAHOS) data (6) to see how well the theories predict PIO's noted during this study. Determine if improvements need to be made to any of the techniques.

3. Determine if any parameters obtained from aircraft/flight control system dynamics can predict actual PIO ratings. Also, determine if any of the techniques can predict actual PIO frequency.

4. Determine a set of operationally realistic aircraft/ flight control system configurations for the approach/landing phase which can be simulated on the NT-33. Configurations will be selected to verify and refine the techniques based on insights obtained from examining the LAHOS data.

5. Use the theories to predict which configurations from step 4 will be PIO prone and which will not be PIO prone. Predict PIO ratings and frequencies, if possible.

6. Flight test the configurations using the NT-33. Confirm or refute the predictions.

Scope

It should be noted that this study is not an attempt to develop a new PIO theory. Rather, it will attempt to verify and refine existing theories and to determine whether any of the theories could be useful for inclusion in a future version of MIL-F-8785C. The study will examine only longitudinal PIO and will not attempt to study nonlinear control/feel system dynamics. Also, it is important to point out that the two techniques used in this study are not the only methods currently available which may be useful to predict PIO tendencies. These two theories were selected because they have both been studied previously for inclusion in versions of MIL-F-8785C. In addition, the approach/landing phase of flight was selected for analysis because it is a repeatable, high gain task which provides more consistent PIO data than "up and away" flight. Both the theories examined are directly applicable to "up and away" flight.

More importantly, the intent of this study is not to deal with PIO tendency from only an academic point of view, but to deal with it from an operational perspective. A mild PIO tendency that can be accurately predicted may be of academic interest only. There is little value in predicting a mild PIO if the pilot does not find it objectionable and it does not impair his ability to perform a task. It is more important to find a theory which not only accurately predicts a PIO tendency, but can also tell us something about the impact the resulting PIO tendency will have on the aircraft's mission.

II. Theoretical Development

This section first presents the aircraft equations of motion needed for longitudinal PIO analysis, and then summarizes the R. Smith and bandwidth theories. Finally, an example will be given which applies each theory to the YF-17 as simulated using the NT-33 during the LAHOS study.

Equations of Motion

The equations of motion developed in this section are for the vehicle body axes using "lumped" stability derivatives as described in the parameter identification technique of the LAHOS study (6:211). The "lumped" stability derivatives include the $Z_{\dot{w}}$ and $M_{\dot{w}}$ terms in the appropriate stability derivatives (see Appendix A for further clarification). The general longitudinal equations of motion are presented first; the specific open loop transfer functions necessary for longitudinal PIO analysis are then developed.

The Laplace transformed longitudinal perturbed equations of motion for the airframe, referenced to the vehicle body axis system, using "lumped" stability derivatives, and considering only vertical gusts and elevator deflection as inputs are (7:256)

$$su + W_o q + g\cos\theta_o \theta = X_u u + X_w(w-w_g) + X_q q + X_{\delta_e}\delta_e$$

$$sw - U_o q + g\sin\theta_o \theta = Z_u u + Z_w(w-w_g)$$

$$+ Z_q(q+sw_g/U_o) + Z_{\delta_e}\delta_e \qquad [1]$$

$$sq = M_u u + M_w(w-w_g) + M_q(q+sw_g/U_o) + M_{\delta_e}\delta_e$$

where

u = perturbed forward speed

w = perturbed downward speed

θ = perturbed pitch angle

q = perturbed pitch rate

δ_e = elevator deflection input

w_g = vertical wind gust input

U_o = equilibrium forward speed

W_o = equilibrium downward speed

θ_o = equilibrium pitch angle

Using the two relations $q=s\theta$ and $\alpha=\tan^{-1}(w/U_o)\approx w/U_o$ (valid for small angles) equation [1] becomes

$$su + W_o s\theta + g\cos\theta_o \theta = X_u u + X_w(U_o\alpha-w_g) + X_q s\theta + X_{\delta_e}\delta_e$$

$$s\alpha U_o - U_o s\theta + g\sin\theta_o \theta = Z_u u + Z_w(U_o\alpha-w_g)$$

$$+ Z_q(s\theta+sw_g/U_o) + Z_{\delta_e}\delta_e \qquad [2]$$

$$s^2\theta = M_u u + M_w(U_o\alpha-w_g)$$

$$+ M_q(s\theta+sw_g/U_o) + M_{\delta_e}\delta_e$$

where α = perturbed angle of attack.

Usually, $X_q=Z_q=0$ is a good approximation (7:273-277). Rearranging terms and putting [2] into matrix form yields

$$\begin{bmatrix} (s-X_u) & -X_w U_o & (W_o s+g\cos\theta_o) \\ -Z_u/U_o & (s-Z_w) & (-U_o s+g\sin\theta_o)/U_o \\ -M_u & -M_w U_o & (s^2-M_q s) \end{bmatrix} \begin{bmatrix} u \\ \alpha \\ \theta \end{bmatrix} =$$

$$\begin{bmatrix} X_{\delta_e} \\ Z_{\delta_e}/U_o \\ M_{\delta_e} \end{bmatrix} \delta_e + \begin{bmatrix} -X_w \\ -Z_w/U_o \\ -M_w+sM_q/U_o \end{bmatrix} w_g \qquad [3]$$

In addition, the following transformed kinematic relationships define the normal acceleration at the pilot station:

$$s\theta = q$$

$$a_z = w - U_o s\theta \qquad [4]$$

$$a_{zp} = a_z - l_x s^2\theta$$

where

a_z = downward (normal) acceleration of the aircraft center of gravity

a_{zp} = pilot-felt normal acceleration (normal acceleration at the pilot station)

l_x = pilot's location forward of the c.g.

Selecting one input (set either δ_e or w_g=0) and using Cramer's Rule, the following "generic" transfer function can be developed:

$$\frac{\text{Output}}{\text{Input}} = \frac{\text{Numerator}}{\begin{vmatrix} (s-X_u) & -X_w U_o & (W_o s+g\cos\theta_o) \\ -Z_u/U_o & (s-Z_w) & (-U_o s+g\sin\theta_o)/U_o \\ -M_u & -M_w U_o & (s^2-M_q s) \end{vmatrix}} = \frac{\text{Numerator}}{\Delta}$$

The characteristic equation of the system (Δ) is a fourth order polynomial which factors into two second order polynomials and can be written as

$$\Delta = (s^2+2\zeta_p\omega_p s+\omega_p^2)(s^2+2\zeta_{sp}\omega_{sp}s+\omega_{sp}^2) \qquad [5]$$

These two modes are usually oscillatory and represent the free longitudinal motions of the aircraft. They are called the "short period" and the "phugoid." The short period mode is a relatively well damped, high frequency oscillation, while the phugoid mode is a lightly damped, relatively low frequency oscillation. The short period mode is characterized by small changes in forward velocity, u, and large amplitudes of θ and α.

A two degree of freedom short period approximation to the longitudinal equations of motion can be obtained by assuming constant airspeed (setting u to zero). Both the fourth order dynamics and the short period approximation were initially used in this study and compared; however, for the analysis of landing configurations, the short period approximation in general did not give satisfactory results. The poor results achieved with the short period approximation may be due to the constant airspeed assumption. DiDomenico (8:16) retained the phugoid mode for his landing flare handling qualities study since the phugoid accounts for the airspeed "bleedoff" during the flare. In the following development, the complete dynamics of equation [1] are used.

The fourth order longitudinal characteristic equation is

$$\Delta = s^4 + As^3 + Bs^2 + Cs + D \qquad [6]$$

where

$$A = -M_q - Z_w - Z_u$$

$$B = X_u(M_q + Z_w) + M_q Z_w - U_o M_w - X_w Z_u + W_o M_u$$

$$C = -X_u(Z_w M_q - U_o M_w) + Z_u(X_w M_q + W_o M_w) - M_u(U_o X_w + W_o Z_w - g\cos\theta_o) + gM_w \sin\theta_o$$

$$D = g\cos\theta_o(Z_u M_w - M_u Z_w) - gX_u M_w \sin\theta_o$$

The numerators of the transfer functions important to PIO study will now be developed.

Pitch to Elevator Deflection Numerator.

$$N^{\theta}_{\delta_e}(s) = \begin{vmatrix} (s-X_u) & -X_w U_o & X_{\delta_e} \\ -Z_u/U_o & (s-Z_w) & Z_{\delta_e}/U_o \\ -M_u & -M_w U_o & M_{\delta_e} \end{vmatrix}$$

$$N^{\theta}_{\delta_e}(s) = A_\theta s^2 + B_\theta s + C_\theta \qquad [7]$$

where

$$A_\theta = M_{\delta_e}$$

$$B_\theta = X_{\delta_e} M_u + Z_{\delta_e} M_w - M_{\delta_e}(X_u + Z_w)$$

$$C_\theta = X_{\delta_e}(Z_u M_w - M_u Z_w) + Z_{\delta_e}(X_w M_u - X_u M_w) + M_{\delta_e}(Z_w X_u - X_w Z_u)$$

Angle of Attack to Elevator Deflection Numerator. This transfer function is needed to find the normal acceleration transfer function.

$$N^{\alpha}_{\delta_e}(s) = \begin{vmatrix} (s-X_u) & X_{\delta_e} & (W_o s+g\cos\theta_o) \\ -Z_u/U_o & Z_{\delta_e}/U_o & (-U_o s+g\sin\theta_o)/U_o \\ -M_u & M_{\delta_e} & (s^2-M_q s) \end{vmatrix}$$

$$N^{\alpha}_{\delta_e}(s) = A_\alpha s^3 + B_\alpha s^2 + C_\alpha s + D_\alpha \qquad [8]$$

where

$$A_\alpha = Z_{\delta_e}/U_o$$

$$B_\alpha = [X_{\delta_e}Z_u - Z_{\delta_e}(M_q+X_u)+M_{\delta_e}U_o]/U_o$$

$$C\alpha = [X_{\delta_e}(-Z_uM_q+U_oM_u)+Z_{\delta_e}(X_uM_q+W_oM_u) + M_{\delta_e}(-g\sin\theta_o - X_uU_o - W_oZ_u)]/U_o$$

$$D_\alpha = [g\cos\theta_o(M_uZ_{\delta_e}-Z_uM_{\delta_e})+g\sin\theta_o(M_{\delta_e}X_u-M_uX_{\delta_e})]/U_o$$

Pilot-Felt Normal Acceleration to Elevator Deflection Numerator. From equation [4]

$$a_{z_p} = sw - sU_o\theta - l_x s^2\theta$$
$$= sU_o\alpha - sU_o\theta - s^2 l_x\theta$$

$$N^{a_{z_p}}_{\delta_e}(s) = sU_o N^{\alpha}_{\delta_e}(s) - sU_o N^{\theta}_{\delta_e}(s) - s^2 l_x N^{\theta}_{\delta_e}(s) \qquad [9]$$

$$N^{a_{z_p}}_{\delta_e}(s) = A_{a_{z_p}} s^4 + B_{a_{z_p}} s^3 + C_{a_{z_p}} s^2 + D_{a_{z_p}} s$$

where

$$A_{a_{z_p}} = U_o A_\alpha - 1_x A_\theta$$

$$B_{a_{z_p}} = U_o(B_\alpha - A_\theta) - 1_x B_\theta$$

$$C_{a_{z_p}} = U_o(C_\alpha - B_\theta) - 1_x C_\theta$$

$$D_{a_{z_p}} = U_o(D_\alpha - C_\theta)$$

<u>Pitch Loop Equivalent Command Gust Numerator</u>.

$$N^{\theta}_{w_g}(s) = \begin{vmatrix} (s-X_u) & -X_w U_o & -X_w \\ -Z_u/U_o & (s-Z_w) & -Z_w/U_o \\ -M_u & -U_o M_w & -M_w+M_q s/U_o \end{vmatrix}$$

$$N^{\theta}_{w_g}(s) = A_{\theta_{w_g}} s^3 + B_{\theta_{w_g}} s^2 + C_{\theta_{w_g}} s \qquad [10]$$

where

$$A_{\theta_{w_g}} = M_q/U_o$$

$$B_{\theta_{w_g}} = -[M_w+(Z_w-X_u)M_q]/U_o$$

$$C_{\theta_{w_g}} = X_u(M_w+Z_w M_q/U_o)-X_w(M_u+Z_u M_q/U_o)$$

The primary transfer functions needed for evaluating PIO tendencies are the equivalent gust command transfer function, θ/w_g, the pitch to stick force dynamics, θ/F_s, pilot-felt normal acceleration to stick force dynamics, a_{z_p}/F_s, and pilot-felt normal acceleration to pitch rate, $a_{z_p}/\dot{\theta}$. The last three can be derived by knowing the θ/δ_e and a_{z_p}/δ_e transfer functions and the control, feel, and actuator systems of the aircraft as shown in Figure 2.

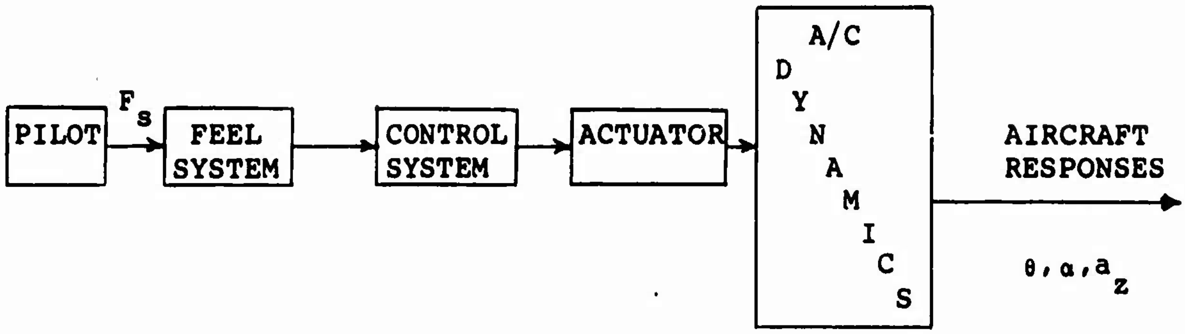


Figure 2. Aircraft/Control System Block Diagram

There is, obviously, no "generic" way of deriving the feel system, control system, and actuator dynamics (δ_e/F_s). Once this transfer function is known, however, the three necessary transfer functions can be derived:

$$\theta/F_s(s) = [\theta/\delta_e(s)][\delta_e/F_s(s)]$$
$$a_{z_p}/F_s(s) = [a_{z_p}/\delta_e(s)][\delta_e/F_s(s)] \quad [12]$$
$$a_{z_p}/\theta(s) = [1/s][a_{z_p}/\delta_e(s)][\delta_e/\theta(s)]$$

Having developed the transfer functions needed for longitudinal PIO analysis, the theoretical development will turn to a discussion of the two PIO theories used in this study.

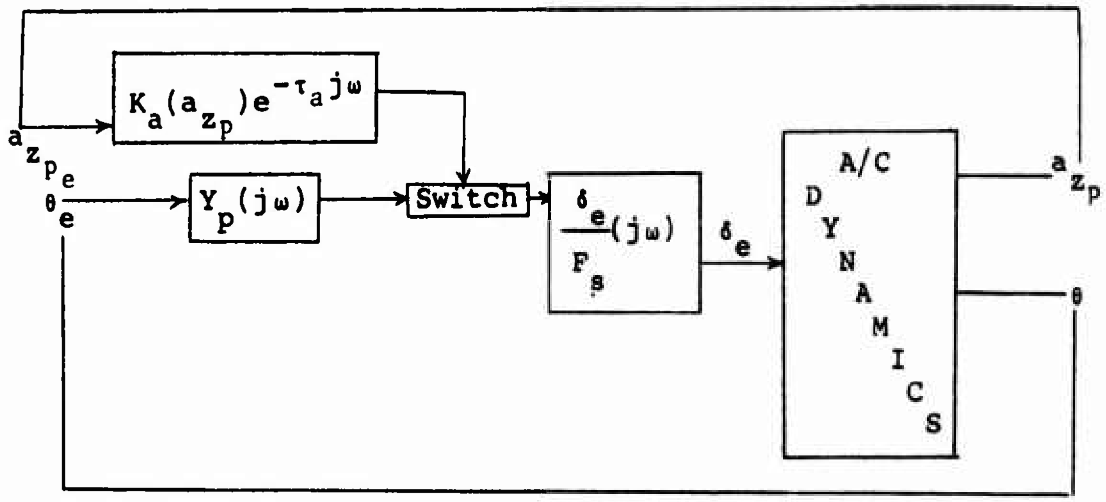
Smith's Theory

Ralph Smith identifies two types of PIO in Reference 2, and a third PIO type in Reference 5. Type I PIO is initiated by pitch attitude control and is postulated to occur in situations where the pilot "switches" control from tracking pitch attitude to tracking pilot-felt normal acceleration. Type II PIO is initiated by abrupt turbulence or nontracking abrupt maneuvering, such as SAS/CAS start-up or shut down or trim malfunction. A third type of PIO, which will be called Type III PIO in this report, was discussed by Smith in Reference 5. This type of PIO is initiated by pitch attitude tracking only; i.e., the pilot's acceleration channel dynamics are irrelevant. To identify an aircraft as being PIO prone or free, all three types of PIO must be examined.

The discussion of Smith's PIO criteria presented below is taken from References 2 and 5. For each type of PIO, the theory is first presented, followed by a summary of the assessment rules. At the end of the section, the results of applying Smith's criteria to the YF-17 as simulated during the LAHOS study are presented.

Type I PIO. Smith's technique may be summarized as follows: There can be a frequency at which the power spectral density of the pilot's normal acceleration due to pitch attitude tracking is "sufficiently" narrowband. If such a frequency exists, there is a high probability during a high gain tracking task the pilot will switch from tracking pitch to tracking normal acceleration. In this case, the frequency is said to be "subjectively predictable." A suggested threshold for the magnitude of normal acceleration the pilot must sense to attempt acceleration tracking is $|a_{zp}/\delta(\omega_R)| \geq$ 0.012 g/deg/sec (2:36). Then, if the phase margin of the pilot-felt normal acceleration to stick force dynamics is less than zero at the subjectively predictable frequency, the aircraft will have a tendency to PIO at that frequency.

To understand how Type I PIO can occur, Smith's pilot model must be presented. The model is shown in Figure 3. The pilot compensation dynamics, $Y_p(j\omega)$, are in the form of the servo model presented in Reference 9. The switch in the diagram is either on or off; i.e., the pilot either tracks pitch angle or normal acceleration. Under normal circumstances the pilot will track pitch, but Smith proposes that if at some point the power spectral density of a_{z_p} due only to closed loop control of pitch attitude (denoted by $\Phi_{a_z a_z}$) is sufficiently narrowband, the pilot will switch to tracking normal acceleration. In order for $\Phi_{a_z a_z}$ to be narrowband the closed loop pilot-vehicle system for pitch tracking must be resonant, as will be discussed later. One of Smith's necessary conditions for PIO is that the pilot at some point begins to track normal acceleration. The theory describing this "switch" is beyond the scope of this study, but a short discussion of the computation is presented below.



$$Y_p(j\omega) = \frac{K_p(T_L j\omega+1)}{(T_I j\omega+1)} e^{-\tau_e j\omega}$$

$K_a(a_{z_p}) \approx 0$ when the PSD of $a_{z_p}(t)$ is broadband

$K_a(a_{z_p}) = K_{ao}$ when the PSD of $a_{z_p}(t)$ is narrowband

$K_a(a_{z_p})e^{-\tau_a j\omega}$ = pilot's acceleration channel dynamics

Figure 3. Smith's Pilot Model

Figure 4 shows a typical $\Phi_{a_z a_z}$ vs ω curve (the computation of $\Phi_{a_z a_z}$ is discussed later). The center frequency (ω_R) and the "width" (Δ') are the important parameters for PIO analysis. Δ' can be computed as

$$\Delta' = \sigma^2_{a_{z_p}} / 2H \qquad [12]$$

where

$$\sigma^2_{a_{z_p}} = 1/(2\pi) \int_{-\infty}^{+\infty} \Phi_{a_z a_z} \, d\omega \qquad [13]$$

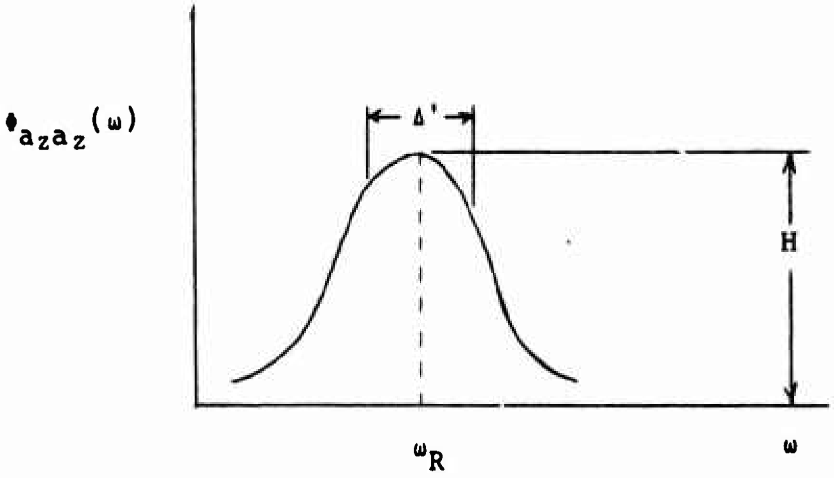


Figure 4. Normal Acceleration Power Spectral Density

The integration can easily be carried out numerically with reasonable values for the limits, since $\Phi_{a_z a_z}$ usually tends toward zero after a finite value of frequency (if it doesn't, $\Phi_{a_z a_z}$ is certainly not narrowband). From the above computations, an "index of subjective predictability" (ν) can be defined, where

$$\nu = \Delta'/\omega_R \qquad [14]$$

Reference 10 suggests that an input stimulus to a pilot-vehicle system may be "subjectively predictable" when $\nu \leq 0.3$; i.e., the pilot may at some point switch to tracking normal acceleration rather than pitch. This is the basis behind the occurrence of Type I PIO.

Smith postulates that Type I PIO begins with highly resonant closed loop pitch attitude dynamics. If a pilot-vehicle system is nonresonant for a reasonable variety of turbulence and pilot model parameters, then Type I PIO is unlikely for that configuration. During normal flight, the pilot model shown in Figure 3 is used with the "switch" set to prevent a_{z_p} feedback control. The servo pilot model is then combined with the aircraft/control system dynamics to determine if the pilot-vehicle system is nonresonant. If $\Phi_{a_z a_z}$ (the acceleration response power spectral density due only to closed loop control of pitch attitude) is determined to be sufficiently narrowband as discussed previously, then Type I PIO is a possibility.

The servo model used in this study is the basic model from Reference 9. The frequency domain definition of the servo model is given by

$$Y_p = \frac{K_p e^{-j\omega\tau}(T_L j\omega+1)}{(T_N j\omega+1)(T_I j\omega+1)} \quad [15]$$

where

K_p = pilot gain

τ = reaction time delay

$\dfrac{(T_L j\omega+1)}{(T_I j\omega+1)}$ = equalization characteristics

$\dfrac{1}{(T_N j\omega+1)}$ = neuromuscular system characteristic

T_N is the first order lag term included to describe the neuromuscular characteristics. It is often combined with τ to give an equivalent $\tau_e = \tau + T_N$, since it is difficult to distinguish between the two. τ varies from about 0.1 to 0.2 seconds and T_N from 0.1 to 0.6 seconds, depending upon the task and the physical state of the pilot. A nominal value of τ_e=0.3 seconds has been successfully used in many studies and will be used here without further comment.

The values of T_L and T_I are selected by the pilot depending on the controlled element. Figure 5 shows the compensatory form selected by the pilot for aircraft dynamics of the form K, K/s, and K/s^2. In general, the pilot chooses his compensation to provide an overall open loop pilot-vehicle system with K/s type dynamics in the region of the crossover frequency. There is good evidence that $T_I = 0$ is often a valid model; i.e., a lead-only model (11). Pilots in general do not like to generate lag terms and will do so only if absolutely necessary to get good low frequency response. Lag terms are usually generated only for aircraft/flight control system combinations which have a relatively flat amplitude response at low frequencies.

Controlled Element	Compensation Chosen	Comments
K	$\frac{K_p(T_L j\omega+1)e^{-\tau e j\omega}}{(T_I j\omega+1)}$	Chosen only if necessary for good low frequency response. Often, however, destabilizing effects introduced by the lag must be overcome at higher frequencies by a lead.
K/s	$K_p e^{-\tau e j\omega}$	
K/s^2	$K_p(T_L j\omega+1)e^{-\tau e j\omega}$	Generally chosen to partially compensate for reaction time and neuromuscular lags or in an attempt to increase system crossover frequency.

Figure 5. Pilot Compensation for Common Controlled Elements

With a first order Pade' approximation, the lead-only pilot model becomes

$$Y_p = -K_p(T_L j\omega+1)\frac{(0.5\tau_e j\omega-1)}{(0.5\tau_e j\omega+1)} \qquad [16]$$

The model can be parameterized by knowing the approximate crossover frequency the pilot chooses for the overall pilot/system dynamics; i.e., where the pilot chooses to close the loop. An estimate of ω_c is given in Reference 5 as

$$\omega_c = 6.0 + 0.24m$$

$$m = 1/5[-|\theta/F_s(j1.0)|-|\theta/F_s(j1.5)|+|\theta/F_s(j4.0)| \qquad [17]$$

$$+|\theta/F_s(j5.0)|-|\theta/F_s(j2.5)|+|\theta/F_s(j6.0)|$$

where "m" is the average slope of the magnitude of the θ/F_s transfer function (in dB/octave) over the region of 1.0 to 6.0 radian/second.

A good representative value of T_L is 0.5 seconds (8,12). Two other values of T_L, 1.5 and 2.5 seconds, were used initially in the study as well, but changing the lead to these higher values had no significant impact on the results. Hence, T_L=0.5 seconds was used throughout the study.

Using the values just discussed for the two parameters, the pilot model becomes

$$Y_p = K_p(\omega_c)(0.5j\omega+1)\frac{(0.5\tau_e j\omega-1)}{(0.5\tau_e j\omega+1)} \qquad [18]$$

This model is plotted with the θ/F_s dynamics ($Y_p[\theta/F_s]$) and K_p is chosen to give the desired crossover frequency, ω_c.

As was previously noted, satisfactory results cannot be achieved for some types of configurations using the lead-only pilot model. Configurations which exhibit a fairly flat amplitude response at low frequencies require a pilot model which provides lag compensation (provided the lag compensation does not make the aircraft/pilot system unstable at the desired crossover frequency). The NT-33 airframe pitch loop dynamics sometimes resulted in a configuration with a fairly flat pitch loop amplitude response in the region of 0.5 to 2.0 radian/second. Figure 6 depicts two

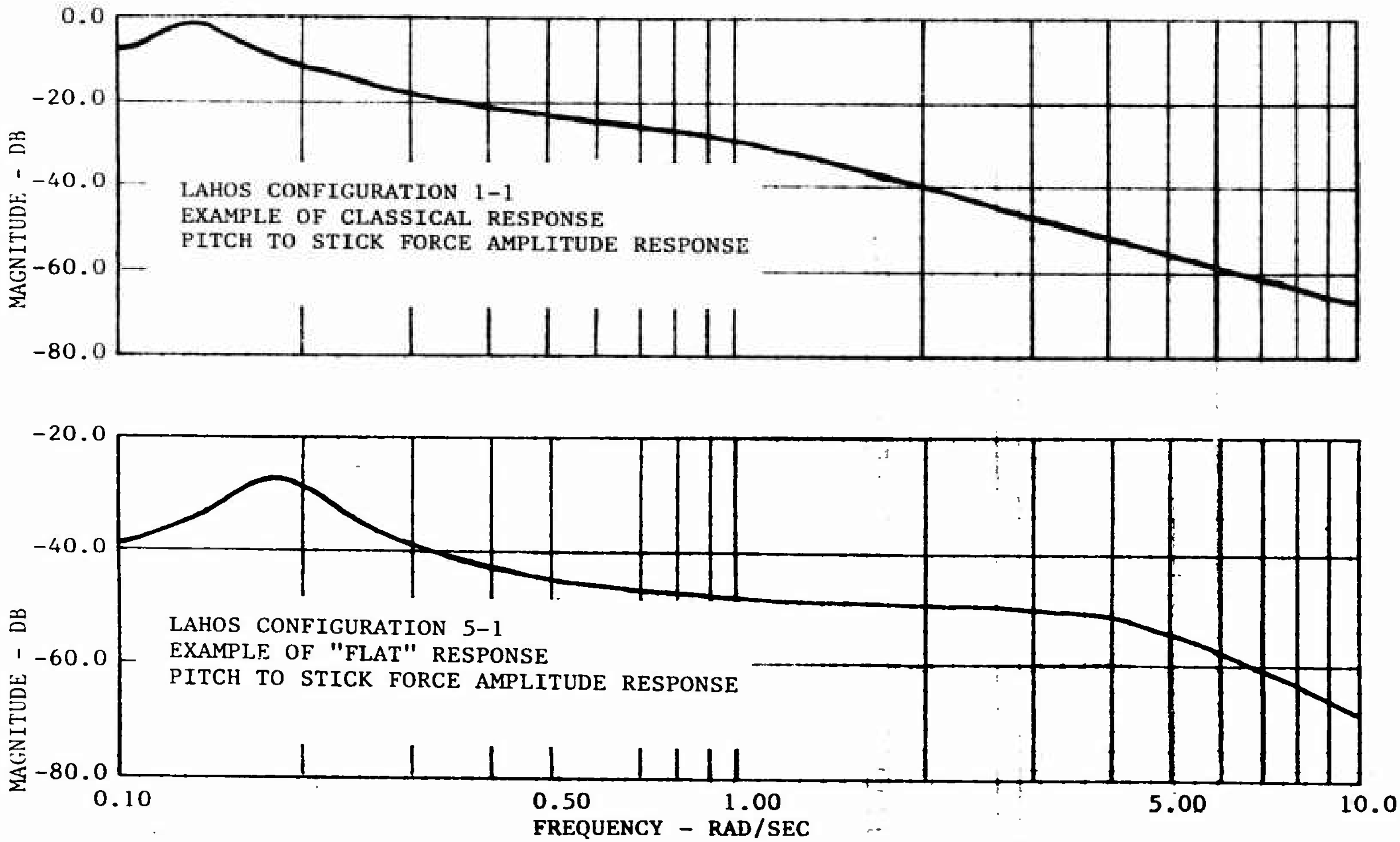


Figure 6. Example of Classical Aircraft Response versus "Flat" Aircraft Response (Pitch to Stick Force)

LAHOS configurations, one with a flat region and one without. For configurations with a flat amplitude response, a lead-lag servo pilot model was used, parameterized as follows:

$$Y_p(j\omega) = \frac{K_p(T_L j\omega+1)e^{-\tau_e j\omega}}{(T_I j\omega+1)} \qquad [19]$$

with T_L = 0.5 seconds, T_I = 1.4 seconds, τ_e = 0.3 seconds, and K_p selected as in equation [17]. The value of T_I was selected to approximately cancel the pitch loop zero which contibuted to the flat response.

Once the pilot model is selected, the closed loop dynamics are computed as:

$$\theta/\theta_c(j\omega) = \frac{[Y_p(j\omega)][\delta e/F_s(j\omega)][\theta/\delta e(j\omega)]}{\{1 + [Y_p(j\omega)][\delta e/F_s(j\omega)][\theta/\delta e(j\omega]\}} \qquad [20]$$

$\theta_c(t)$ is an equivalent command input to Figure 3 due to vertical w-gusts:

$$\theta_c(j\omega) = [-\theta/w_g(j\omega)]w_g(j\omega) \qquad [21]$$

The gust response transfer function θ/w_g was derived in equation [10].

In order to determine the gust response, a turbulence model must be selected. For this study, the Dryden turbulence power spectral density from Reference 3 was chosen:

$$\Phi_{w_g w_g}(\omega) = \sigma_w^2 L_w/\pi \frac{1+3(L_w\omega/V_o)^2}{[1+(L_w\omega/V_o)^2]^2} \qquad [22]$$

where

V_o = reference velocity of aircraft

σ_w = "strength" of turbulence in feet/second

L_w = "scale" of turbulence in feet

From Reference 13, σ_w = 5 feet/second is representative of moderate turbulence, and this value was used throughout the study. A value of L_w = 50 feet is sufficient to represent the landing phase of flight.

Now the power spectral density of the pilot's normal acceleration due to pitch attitude tracking can be derived. The closed loop pitch power spectral density is

$$\Phi_{\theta_c\theta_c}(\omega) = |\theta/w_g(j\omega)|^2 \Phi_{w_g w_g}(\omega) \qquad [23]$$

The corresponding normal acceleration due to closed loop pitch attitude tracking is then

$$a_{z_p}/\theta_c(j\omega) = [N_{\delta_e}^{a_{z_p}}(j\omega)/N_{\delta_e}^{\theta}(j\omega)][\theta/\theta_c(\omega)] \qquad [24]$$

and finally, the power spectral density of the normal acceleration due to closed loop control of pitch attitude can be obtained:

$$\Phi_{a_z a_z}(\omega) = |a_{z_p}/\theta_c(j\omega)|^2 \Phi_{\theta_c\theta_c}(\omega) \qquad [25]$$

where the pilot's normal acceleration dynamics were derived previously.

The index of subjective predictability (ν) can then be calculated. If $\nu > 0.3$ or if $\Phi_{a_z a_z}$ has no prominent center frequency for all choices of pilot and turbulence models, then Type I PIO is unlikely. If more than one center frequency exists, then all of those frequencies for which $\nu \leq 0.3$ must be used to evaluate the phase and magnitude criteria presented below. If the center frequency meets the phase and magnitude criteria, then it should be considered a potential PIO frequency.

At this point, Smith suggests that a simpler criterion for subjective predictability may be based on the dominant mode damping ratio ζ_{CL} for closed loop pitch attitude control. He suggests that $a_{z_p}(t)$ is subjectively predictable when $\zeta_{CL} \leq 0.2$ for the closed loop pitch to stick force dynamics. The corresponding center frequency should be set to the dominant mode's undamped natural frequency. Although the more detailed method of determining subjective predictability was used throughout this study, the $\zeta_{CL} \leq 0.2$ criterion was evaluated as well.

If the closed loop control of pitch attitude produces a $\Phi_{a_z a_z}$ which is subjectively predictable, then Smith postulates that the pilot will attempt to track a_{z_p} at some point; i.e. the pilot behaves as in Figure 3 with the switch set to prevent pitch control. He further postulates that when the pilot begins to track a_{z_p}, his crossover frequency will equal the resonant frequency of the $a_{z_p}(j\omega)$ response due to pitch attitude control, and K_a will be selected to establish this crossover frequency. The pilot model then becomes

$$F_s/a_{z_p}\ (j\omega) = K_a e^{-\tau_a j\omega} \qquad [26]$$

with τ_a=0.25 seconds. This value of τ_a was chosen by Smith because of its consistency with actual PIO experiences.

If no important nonlinearities exist (as assumed in this study) then a necessary condition for Type I PIO is that the phase margin of the a_{z_p}/F_s system at the resonant frequency resulting from θ/F_s closure must be negative; i.e.,

$$\phi_m = 180^o + \phi(j\omega_R) \leq 0,$$

where $\phi(j\omega_R)$ is the phase angle of $a_{z_p}/F_s(j\omega_R)$.

If the phase margin is positive, then Type I PIO cannot occur, because a switch to tracking normal acceleration will result in a stable system. To determine the phase margin, $\phi(j\omega)$ is plotted for the open loop a_{z_p}/F_s dynamics including a pilot phase resulting from a 0.25 second delay, as in equation [25]. $\phi(jw)$ will be the sum of phase angles due to the pilot, the feel system dynamics, the control system dynamics, and the airframe dynamics.

Smith's final necessary condition for Type I PIO is that the amplitude of a_{z_p} oscillations due to pitch attitude control must be greater than some "critical" value $(a_{z_p})_{CR}$ to cause the pilot to make the "switch" to acceleration tracking. It is postulated that $(a_{z_p})_{CR} = 0.012$ g/degree/second, i.e.

$$|a_{z_p}/\dot{\theta}(j\omega_R)| > 0.012 \text{ g/degree/second}$$

is necessary for the pilot to sense a subjectively predictable normal acceleration power spectrum due to pitch attitude tracking. This condition will be called "Smith's magnitude criterion."

In summary, for Type I PIO with no significant nonlinearities:

1. Select an appropriate pilot model for the aircraft/flight control system dynamics based on the form of the dynamics and the crossover frequency computation described in Equation [17].

2. Close the pitch attitude loop (θ/F_s).

3. Compute $\phi_{a_z a_z}(\omega)$ using a representative Dryden model of vertical turbulence.

4. Estimate ω_R from $\phi_{a_z a_z}$. If ω_R exists for any pilot/vehicle combination then estimate the subjective predictability index ν. If $\nu>0.3$ then go to step 4a; otherwise, go to step 5.

4a. Estimate the resonant mode damping ratio ζ_R. If $\zeta_R>0.2$ then Type I PIO is unlikely. If $\zeta_R\leq 0.2$ go to step 5.

5. Plot the total open loop system phase angle Bode $\phi(j\omega)$ for the a_{z_p}/F_s loop dynamics. $\phi(j\omega)$ will be the sum of phase angles due to the pilot, the feel system dynamics, the control system dynamics, and the airframe dynamics. The pilot phase should be assumed to result entirely from a 0.25 second delay. If the phase margin $180^o+\phi(j\omega_R)\leq 0$ then go to step 6.

6. If $|a_{z_p}/\dot{\theta}(j\omega_R)|<0.012$ g/degree/second then conclude that Type I PIO is unlikely. If this ratio is $\geq$ 0.012, then conclude that Type I PIO is a possibility.

Type II PIO. Type II PIO is initiated when an abrupt control or disturbance of sufficient amplitude excites the stick-free dynamic modes of the aircraft. This type of control might be due to open loop high g maneuvering, system transients from SAS/CAS shutdown or start-up, and so on. Although by definition Type II PIO is not likely to occur during the landing phase of flight, it is presented here for completeness of Smith's theory.

Type II PIO is analyzed similarly to Type I PIO, except that only open loop dynamics are considered. The procedure is essentially the same, but there is no loop closure to determine $\Phi_{a_z a_z}$. Instead, $\Phi_{a_z a_z}$ is computed using a normalized, broadband noise representation for $F_s(j\omega)$ to simulate the required "abrupt" character, i.e.

$$\Phi_{a_z a_z}(\omega) = |a_{z_p}/F_s(s)|^2_{s=j\omega} \times 1$$

The procedure then follows the same steps as Type I PIO.

Smith also proposes that a simpler criterion for Type II PIO may be to determine whether any stick-free dynamic mode exists with damping ratio $\zeta_R \leq 0.2$ which significantly contributes to $\Phi_{a_z a_z}(\omega)$. The criterion for "significant contribution" is that the modal frequency is less than about 10 radian/second (the pilot's bandwidth of control limit). Again, if such a mode exists, the response is subjectively predictable, ω_R is then set to the modal frequency, and the additional criteria are examined at ω_R.

In summary, for Type II PIO,

1. Compute the power spectral density (PSD) of a_{z_p} for the stick-free airplane dynamics; assume that the airplane is excited by a wideband noise with PSD=1 (to simulate abrupt inputs). That is, assume

$$\Phi_{a_z a_z}(\omega) = |a_{z_p}/F_s(s)|^2_{s=j\omega} \times 1$$

2. Continue with the analysis as described above for Type I PIO, starting at step 4 and replacing "Type I" with "Type II."

3. Simplified alternative procedure: if the damping ratio of the dominant, resonant mode of a_{z_p}/F_s is ≤ 0.2, then Type II PIO is possible. Call this damping ratio ζ_R and continue the analysis as described above for Type I PIO, starting with Step 5 and replacing "Type I" with "Type II." If the damping ratio is >0.2, then conclude that Type II PIO is unlikely. For conservatism, one could define ω_R as the dominant mode's damped frequency and proceed to step 5 of the Type I PIO analysis above.

Type III PIO. Type III PIO of Reference 5 is postulated to appear during the single loop tracking of pitch attitude; i.e., the pilot's normal acceleration dynamics are irrelevant. This mode will probably only be seen when control system or equivalent time delays induce significant phase lag within the bandwidth of the pilot's control (about 10 radian/second). The time delay must be sufficient to make the θ/F_s loop unstable at ω_c (the crossover frequency predicted by Equation [17]); i.e., the necessary condition for attitude only PIO is

$$\angle \theta/F_s(j\omega_c) < -180^\circ$$

To get PIO, something has to excite the pilot to adapt the form of a pure gain. Smith assumes that this follows the development of substantial aircraft resonance in attitude response, as for Type I PIO, except now the pilot's time delay, shown in Figure 3, is assumed to be zero (this seems to be for lack of a better value). The pilot also either feels no normal acceleration (as in a fixed-base simulator) or does not attempt to track the normal acceleration he feels.

The technique for Type III PIO analysis is to use a pure gain pilot model and look for locus crossings of the $j\omega$-axis on a root locus plot. When the frequency at axis crossing is less than ω_c, then the crossing conditions (the pilot gain at the crossing and the corresponding resonant frequency) represent a potential PIO state; i.e., the pilot may adopt the pure gain model and cause PIO.

In summary, for Type III PIO:

1. Plot the root locus of θ/F_s.

2. If there are no imaginary axis crossings of the root locus, then Type III PIO is not a possibility.

3. If the root locus crosses the imaginary axis, determine the frequency of crossing (ω_R). If $\omega_R<\omega_c$, where ω_c is determined from Equation [17], then Type III PIO is a possibility. The gain of the root locus at the axis crossing determines the gain the pilot must generate to cause PIO.

Bandwidth Method

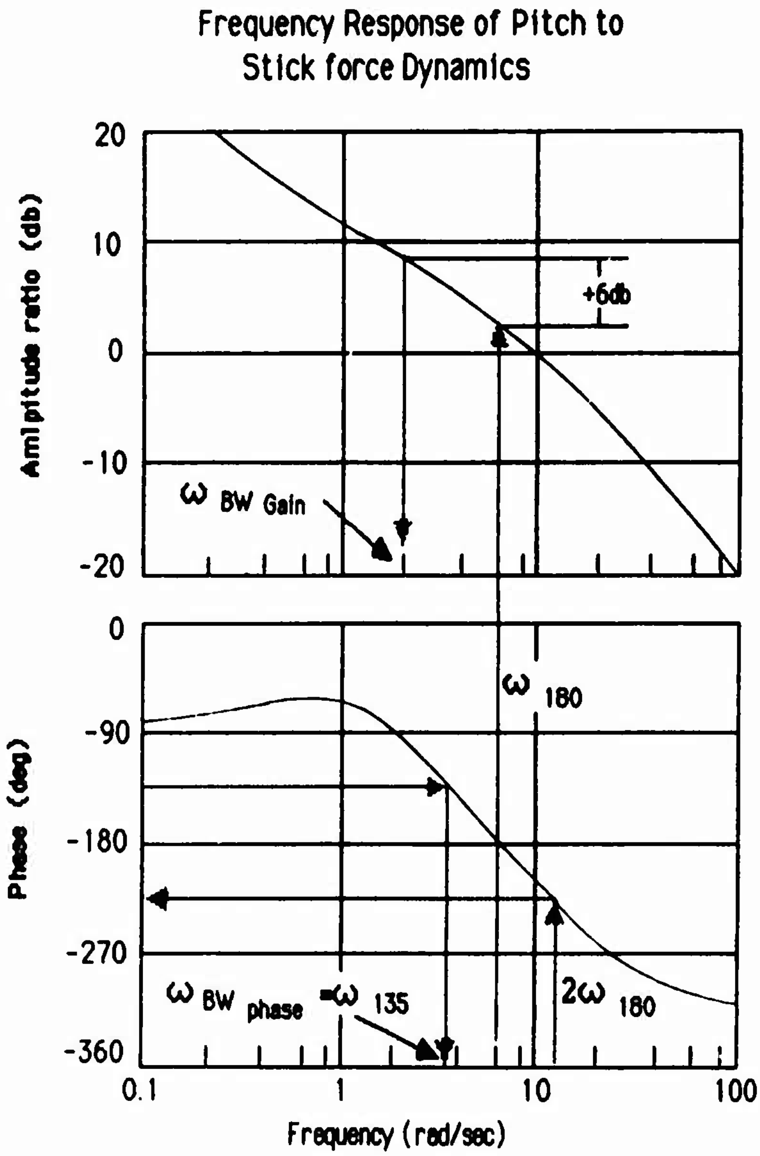
The bandwidth method of Reference 4 was proposed as a handling qualities requirement for MIL-F-8785C. The bandwidth method is particularly attractive because it assumes a "gain-only" pilot model and involves only the use of open loop pitch to stick force (θ/F_s) Bode plots.

"Bandwidth" can be loosely defined as the maximum frequency at which closed loop compensatory tracking can take place without threatening the stability of the aircraft; i.e. the maximum open loop crossover frequency. Hence, a large value of bandwidth is generally desirable to achieve superior tracking performance.

The reason for including bandwidth in this study was to determine if the simple bandwidth method alone could be used to separate PIO prone aircraft from those which are not. The bandwidth criterion sets up boundaries for Level 1, 2, and 3 handling qualities for both Category A and C requirements, based on maximum crossover frequency and system phase delay. The approach taken in this study was to see how well the boundaries and the phase delay parameter correlated with PIO tendencies noted during the LAHOS study.

The following discussion of the bandwidth theory is taken from reference 4. Crossover frequency, directly determined by pilot gain, is a rough measure of the rapidity of a closed loop response. Physically, the pilot will increase his gain (and hence, crossover frequency) to track more rapidly moving targets with acceptable error. However, the pilot cannot indefinitely increase crossover frequency by increasing gain, because he will eventually lose closed loop stability (when the phase margin of the open loop system becomes negative). The pilot would like to choose a value which allows him to double his gain and provide plently of phase margin. A reasonable crossover frequency would then be one which provides at least 6 dB of gain margin and 45° of phase margin.

The above crossover frequency is the bandwidth frequency (ω_{BW}) and is shown in Figure 7. ω_{BW} is defined to be the smaller of two values, $\omega_{BWphase}$ and $\omega_{BWphase}$. These two frequencies are determined as shown in Figure 7.



$$\tau_p = -(\phi_{2\omega_{180}} + 180^o)/(57.3 x 2\omega_{180})$$

Figure 7. Definition of Bandwidth and Phase Delay Parameters

Handling qualities and pilot ratings are not dependent on bandwidth alone; the shape of the phase curve at frequencies above ω_{BW} becomes important as well. If the phase curve drops off rapidly at frequencies above ω_{BW}, the aircraft will generally receive poor pilot ratings, since an abrupt loss in stability margin is produced when the pilot attempts to increase the crossover frequency. One measure of rapid phase rolloff is equivalent system time delay. However, equivalent system time delay, unlike ω_{BW}, is not easily measured. Phase delay, τ_p, a parameter which is easily measured, is defined in Figure 7. Usually, τ_p is numerically similar to equivalent time delay.

The bandwidth criterion suggests that systems with high attainable crossover frequencies and without rapid phase rolloffs should have good handling qualities. Figure 8, from Reference 4, shows flying qualities boundaries based on bandwidth frequency and τ_p. The boundaries of Figure 8 are referred to as the "bandwidth criterion."

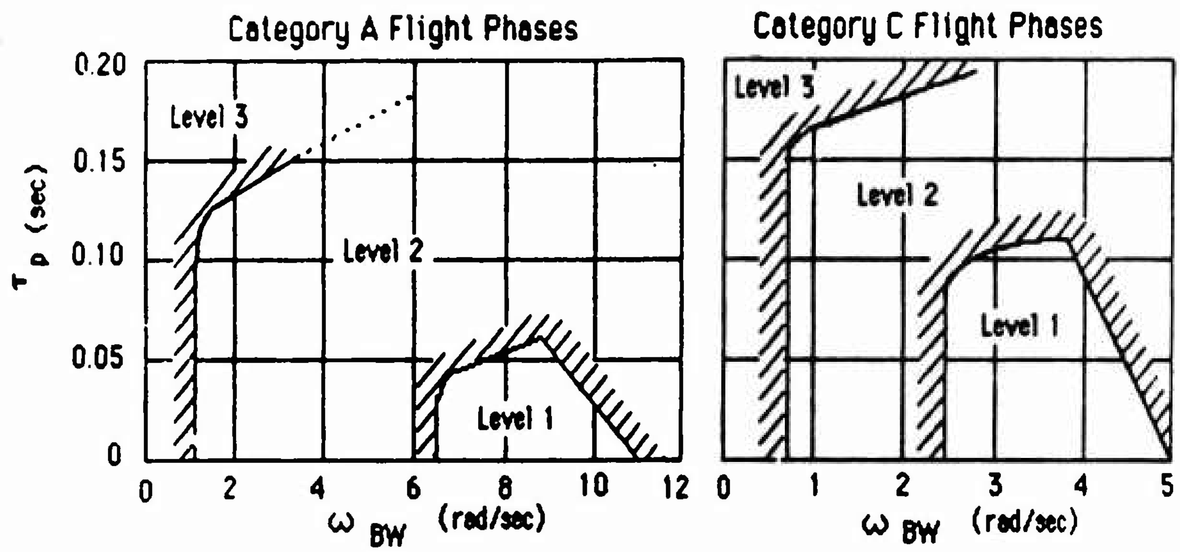


Figure 8. Hoh's Bandwidth Criterion for Handling Qualities

The bandwidth method can then be summarized as follows:

1. Determine ω_{180} from the Bode plot of θ/F_s.

2. Find $\omega_{BWphase}$=frequency where the phase margin is 45^o.

3. Find $|\theta/F_s|$ at ω_{180} and add 6dB. Call this value Z.

4. Find ω_{BWgain}=frequency where Z occurs.

5. $\omega_{BW} = \min(\omega_{BWphase}, \omega_{BWgain})$.

6. $\tau_p = [\phi(2\omega_{180})+180^o]/[57.3x2\omega_{180}]$.

7. Find τ_p and ω_{BW} on the τ_p vs ω_{BW} plot to determine the predicted level of handling qualities.

YF-17 Example

An example will now be presented which applies the two theories to the YF-17 as simulated using the NT-33 during the LAHOS study. The original YF-17 (as simulated on the NT-33) sustained a severe PIO during the landing flare; a modified version was PIO free.

The transfer functions for the YF-17 are:

$$\frac{\theta}{\delta_e} = \frac{0.3369(0.0853)(0.6870)}{[0.15,0.16][0.65,1.94]}$$

where

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

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

$$\frac{a_{z_p}}{\delta_e} = \frac{-1.066(0)(0.0258)[-0.02,6.80]}{[0.15,0.16][0.65,1.94]}$$

$$\frac{\theta}{w_g} = \frac{-0.0085(0)(-0.0051)(-0.06528)}{[0.15,0.16][0.65,1.94]}$$

Actuator Dynamics: $\dfrac{5625.0}{[0.07,75.0]}$

Feel System: $\dfrac{84.5}{[0.6,26.0]}$

Unmodified Control System: $\dfrac{16.37(2.0)(2.3)}{(0.9)(5.0)[0.7,4.0]}$

Modified Control System: $\dfrac{4.26(2.0)(2.3)(16.7)}{(0.9)(5.0)(10.0)}$

Smith's Theory. Tables 1 and 2 summarize the results of applying the Type I PIO theory to the YF-17 data. Table 1 shows the results using the $\nu \leq 0.3$ criterion and Table 2 shows the results using the $\zeta \leq 0.2$ criterion.

Table 1

Results of Type I PIO, YF-17, Using Index of Subjective Predictablity

Aircraft	ω_R(rad/sec)	ν	Phase[1] Margin(deg)	$\lvert a_{z_p}/\dot{\theta}(\omega_R)\rvert$ (g/deg/sec)
Original YF-17	0.17	125.88	-	-
	0.85	0.13	104.76	-
	2.69	0.03	-40.61	0.0241
	9.24	1283.18	-	-
Modified YF-17	0.17	23.62	-	-
	4.22	0.06	-38.22	0.0114

[1]Phase Margin = phase margin of a_{z_p}/F_s evaluated at ω_R using pure gain plus time delay (τ_a=0.25 seconds) for pilot model

Table 2

Results of Type I PIO, YF-17, Using Dominant Closed Loop Resonant Frequency

Aircraft	ω_R(rad/sec)	ζ_{cl}	Phase Margin(deg)	$\lvert a_{z_p}/\dot{\theta}(\omega_R)\rvert$ (g/deg/sec)
Original	0.84	-0.12	105.63	-
	2.73	-0.08	-43.05	0.0236
Modified	4.60	0.14	-49.10	0.0092

The original YF-17 has two subjectively predictable resonant frequencies, one at about 0.85 radian/second, and another at about 2.7 radian/second. The frequencies predicted by both the $\nu \leq 0.3$ criterion and the $\zeta_{cl} \leq 0.2$ criterion are very close. a_{z_p}/F_s has a positive phase margin at $\omega_R=0.85$ radian/second, but is negative at $\omega_R=2.7$ radian/second. The magnitude criterion at this frequency is about twice the value needed for PIO when evaluated at $\omega_R=2.7$ radian/second. Hence, the original YF-17 should have a high probability of being prone to Type I PIO.

The modified YF-17 has a subjectively predictable resonant frequency at $\omega_R=4.22$ radian/second using the $\nu \leq 0.3$ criterion. The $\zeta_{cl} \leq 0.2$ criterion predicts a frequency of 4.6 radian/second. These values are within 10 percent of each other. Using either frequency, the phase margin criterion is negative, but the magnitude criterion is not met. Therefore, Type I PIO is unlikely for the modified YF-17.

Table 3 summarizes the results of applying the Type II PIO theory to the YF-17 data. This table summarizes only the $\nu \leq 0.3$ criterion, since no frequencies were predicted using the $\zeta_{cl} \leq 0.2$ criterion.

Table 3

Results of Type II PIO, YF-17,
Using Index of Subjective Predictability

Aircraft	ω_R(rad/sec)	ν	Phase[1] Margin(deg)	$\lvert a_{z_p}/\dot{\theta}(\omega_R)\rvert$ (g/deg/sec)
Original YF-17	0.17	0.09	225.91	-
	9.91	371.34	-	-
Modified	0.17	0.10	228.92	-

[1]Phase Margin = phase margin of a_{zp}/F_s evaluated at ω_R using pure gain plus time delay (τ_a=0.25 seconds) for pilot model

Although each configuration has a subjectively predictable resonant frequency at 0.17 radian/second, both have large positive phase margins. Hence, Type II PIO is unlikely for either configuration.

The root loci of both the original and modified YF-17 are shown in Figure 9. The $j\omega$-axis crossing is annoted on each diagram. The predicted crossover frequency from equation [17] and the $j\omega$-axis crossing are compared in Table 4.

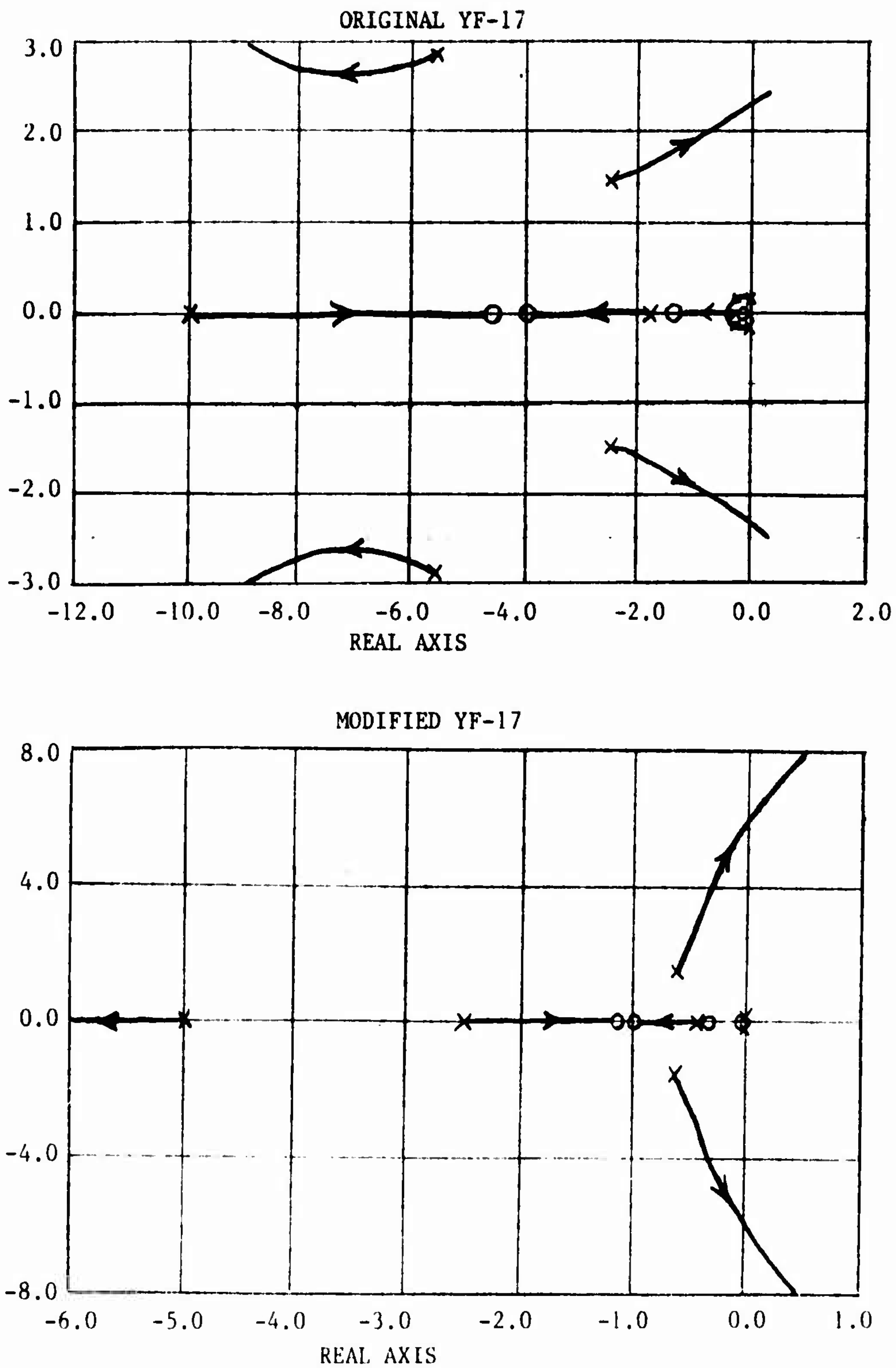


Figure 9. Root Loci for Original and Modified YF-17

Table 4

Predicted Crossover Frequency and jω-axis Crossing, YF-17

Aircraft	Predicted ω_c [1] (rad/sec)	jω-axis crossing (rad/sec)
Original YF-17	3.18	2.34
Modified YF-17	3.84	5.86

[1] Predicted ω_c = crossover frequency predicted by Smith's formula, based on average slope of the pitch to stick force magnitude curve

Type III PIO would be unlikely for the modified YF-17. For the modified YF-17, the frequency at the jω-axis crossing is less than the predicted crossover frequency. Hence, the unmodified YF-17 should also be suspected of being prone to Type III PIO (caused by excessive time delay in the system). How to determine which type of PIO was actually experienced during the flight test is unclear, but it may be related to the actual PIO frequency. Type I PIO theory predicts a PIO frequency of about 2.7 radian/second; Type III PIO theory predicts a PIO frequency of about 2.3 radian/second. The actual PIO value was about 3.0 radian/second; hence, the original YF-17 configuration probably experienced a Type I PIO.

Bandwidth Method. Bode plots for both the original and modified YF-17 are shown in Figures 10 and 11. The critical values needed for the bandwidth method are shown on the diagrams. Figure 12 depicts the bandwidth criterion for both configurations. The modified YF-17 (with no PIO tendency) is very close to the Level 1 boundary and is predicted to have good handling qualities. The original YF-17 (which experienced a PIO) is predicted to have Level 3 handling qualities. This single data point suggests the bandwidth criterion boundaries might be useful as PIO predictors.

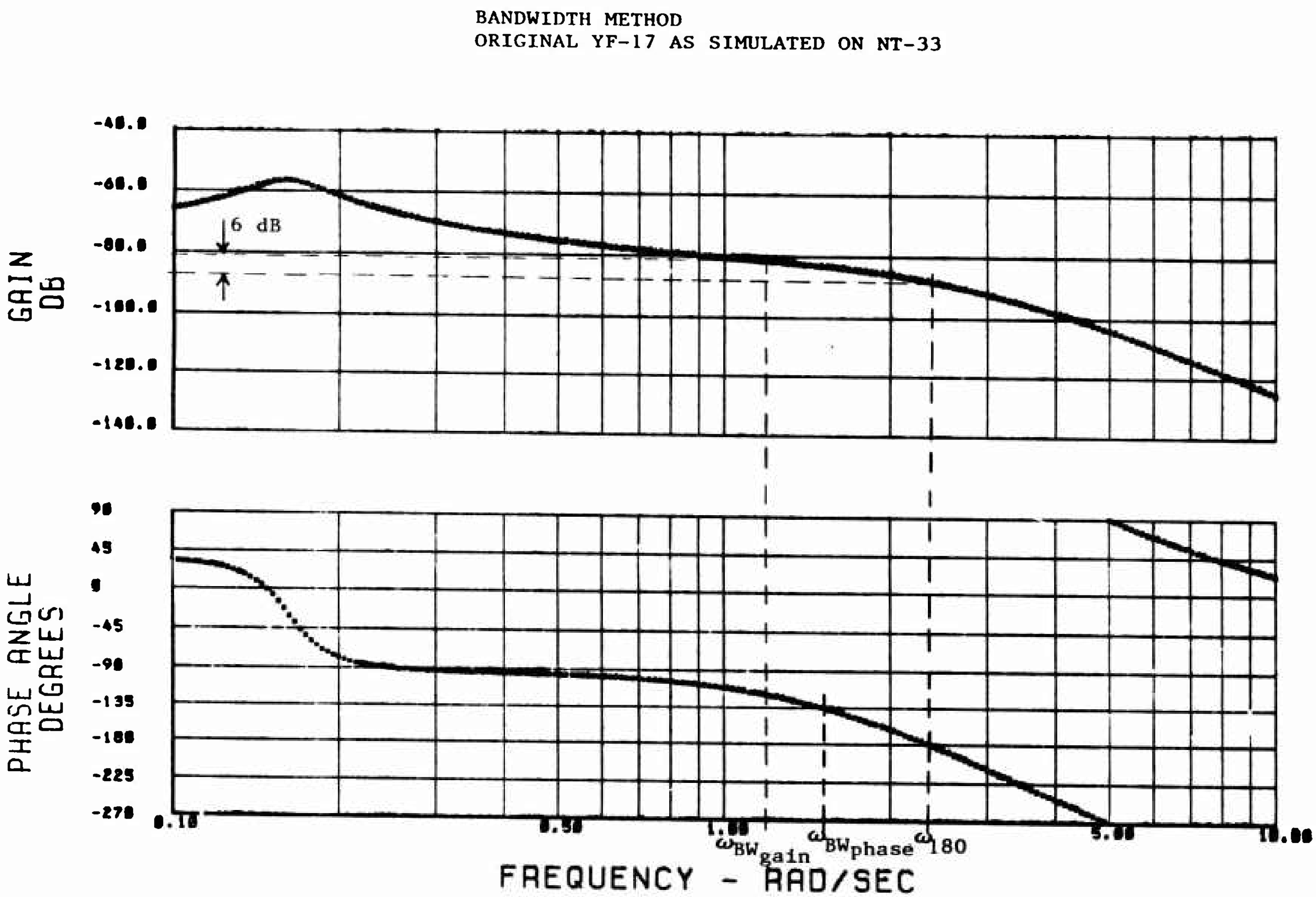


Figure 10. Critical Values used for Bandwidth Method, Original YF-17

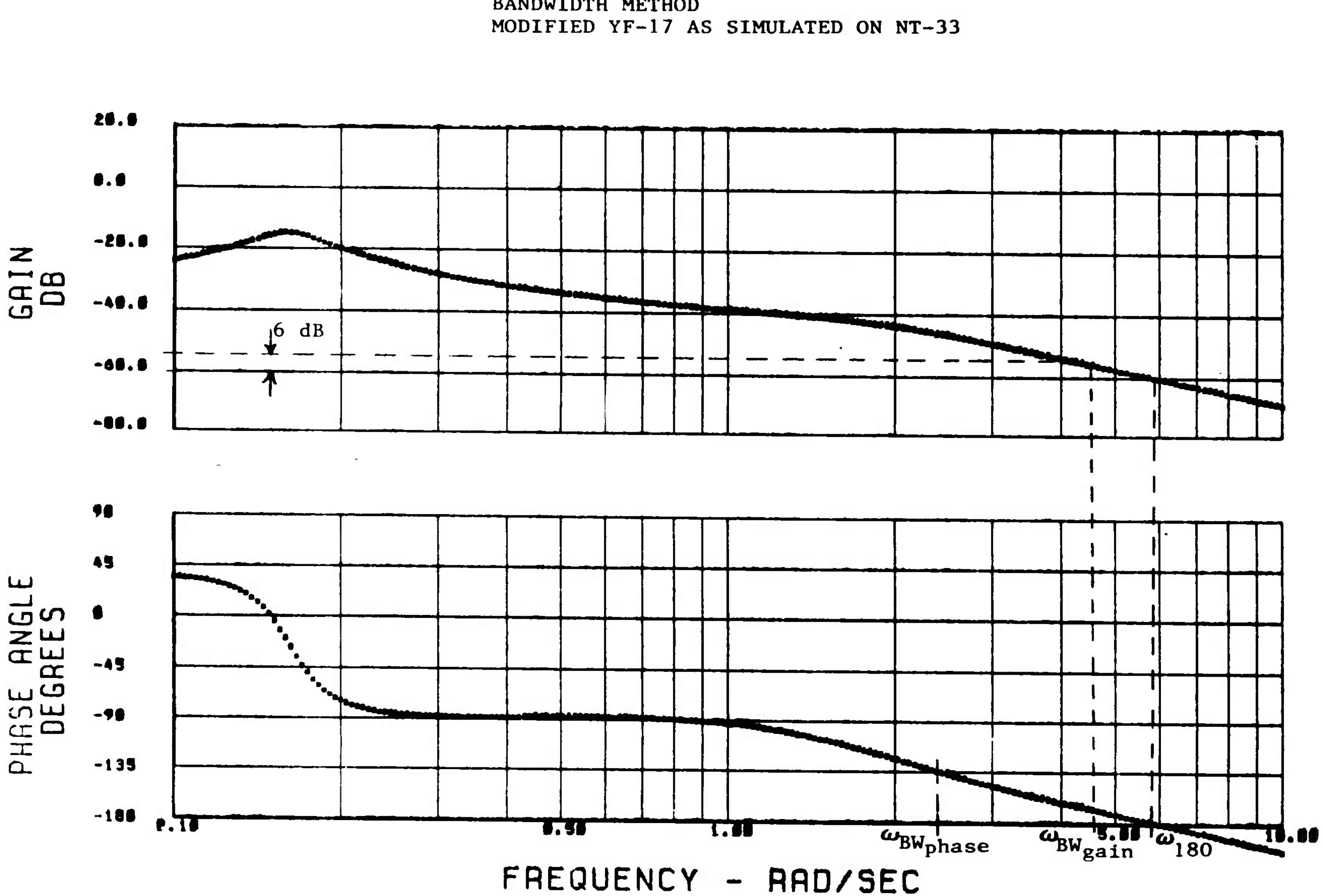


Figure 11. Critical Values used for Bandwidth Method, Modified YF-17

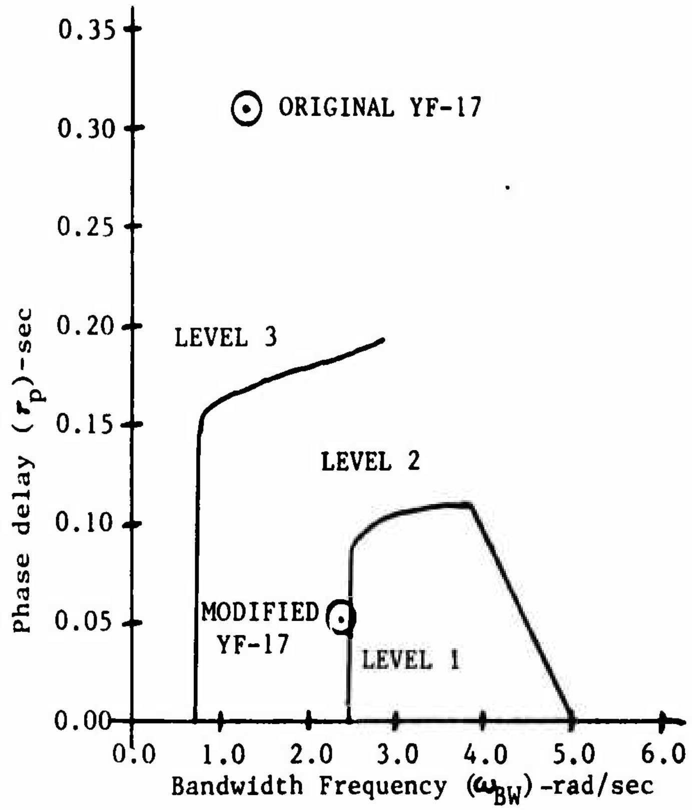


Figure 12. Bandwidth Criterion for Original and Modified YF-17

III. Analytical Results and Analysis

To perform a preliminary analysis, the techniques were applied to the Calspan LAHOS data base (6). This data base was the result of a 1978 Calspan study using the variable stability NT-33A to determine the effects of higher order control system dynamics on fighter approach and landing handling qualities. This was an ideal data base to use because many PIOs were experienced during the flight tests. Appendix A contains a complete description of the LAHOS configurations.

Before beginning an analysis of the data, it is necessary first to define what is meant by a "PIO tendency" and develop a method to determine if a PIO tendency has been experienced in flight. Figure 13 contains both the PIO rating scale and a flowchart which is commonly used in-flight by pilots to determine PIO rating. From the definitions on the scale, there is no doubt that a rating of 4, 5, or 6 can be classified as a PIO tendency. Likewise, a rating of 1 indicates no PIO tendency. The question then arises as to whether or not the "undesirable motions" necessary for a PIO rating of 2 or 3 ought to be considered a PIO tendency. A full-blown PIO, by definition, implies the existence of a sustained oscillation; however, undesirable motions such as a bobble or a tendency to overcontrol usually precede a PIO. What prevents these undesirable motions from becoming PIOs is that the pilot is able to provide enough compensation to keep

DESCRIPTION	NUMERICAL RATING
NO TENDENCY FOR PILOT TO INDUCE UNDESIRABLE MOTIONS	1
UNDESIRABLE MOTIONS TEND TO OCCUR WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. THESE MOTIONS CAN BE PREVENTED OR ELIMINATED BY PILOT TECHNIQUE.	2
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.	3
OSCILLATIONS TEND TO DEVELOP WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. PILOT MUST REDUCE GAIN OR ABANDON TASK TO RECOVER.	4
DIVERGENT OSCILLATIONS TEND TO DEVELOP WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. PILOT MUST OPEN LOOP BY RELEASING OR FREEZING THE STICK.	5
DISTURBANCE OR NORMAL PILOT CONTROL MAY CAUSE DIVERGENT OSCILLATION. PILOT MUST OPEN CONTROL LOOP BY RELEASING OR FREEZING THE STICK.	6

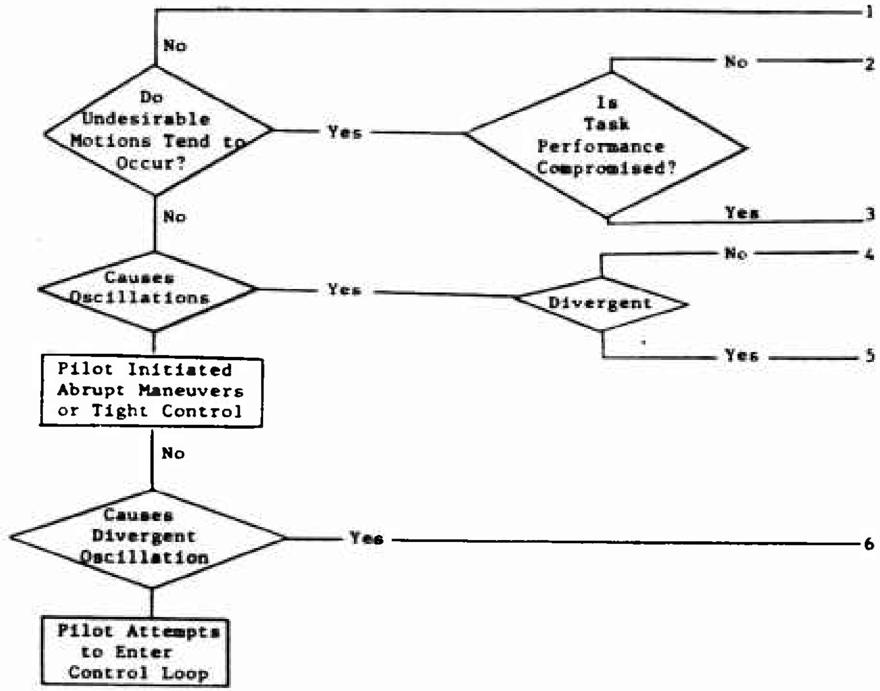


Figure 13. PIO Rating Scale and Flowchart

the motion down to a nuisance level. Thus, for this study, a PIO tendency was defined to be a PIO rating of 2 or greater.

Simply defining a PIO tendency is not enough to determine if a PIO tendency actually existed, however. If a configuration is flown several times, it is possible that ratings may be averaged, with an average PIO rating 2 or greater indicating a PIO frequency.

There are two problems associated with averaging PIO ratings. The first problem is that the PIO rating scale is not necessarily linear in the sense that the severity of the PIO may not increase linearly with increasing PIO rating. Since there is no present means of quantifying PIO severity, there is no way to know if the relationship is linear or not. For this reason, although the ratings used in this study were averaged, the spread of actual ratings for each configuration is included for completeness.

The second problem arises with configurations which are flown only once or twice, as many of the LAHOS configurations were. Particularly poor aircraft (aircraft which receive PIO ratings of 3 or greater) tend to provide repeatable results; i.e., virtually everyone who flies the configuration will give it the same rating. Therefore, even if a particularly poor configuration is flown only once, there can be a fairly high level of confidence that the PIO rating is correct. The problem exists with the ratings of 1 and 2. In general, one data point is insufficient to distinguish between a 1 and a 2. The LAHOS data had several configurations which received ratings of 1 or 2 or both which were flown only once or twice. Table 5 summarizes the number of flights and the PIO ratings for the LAHOS configurations. Each configuration is classified as PIO prone, not PIO prone, or unsure. However, despite the uncertainty in some of the data, all the LAHOS configurations were included in the preliminary analysis.

It must also be pointed out that the argument presented above is really of academic interest only, since an aircraft which receives a PIO rating of 2 is unlikely to be considered in need of modification. It is more important to be able to determine if a theory can separate a PIO rating of 1 or 2 from a 3, since a PIO rating of 3 indicates a problem probably requiring correction.

Table 5

Summary of PIO Ratings, LAHOS Configurations

Configuration	Number Flights	Actual PIO Rating	Average [illegible]	Consider PIO Prone
1-A	1	1	[illegible]	UNSURE
1-B	1	2		UNSURE
1-C	2	1/1	1	NO
1-1	2	2/1	1.5	UNSURE
1-2	1	2	2	UNSURE
1-3	4	4/4/2/3	3.25	YES
1-4	1	4	4	YES
1-6	2	2/2	2	YES
1-8	1	3	3	YES
1-11	1	3.5	3.5	YES
2-A	2	2/2.5	2.25	YES
2-C	4	2/1/1/1	1.25	NO
2-1	3	1/1/1	1	NO
2-2	2	2/1	1.5	UNSURE
2-3	1	3	3	YES
2-4	3	3/2/1	2	YES
2-6	1	2.5	2.5	YES
2-7	2	3/3	3	YES
2-9	1	3	3	YES
2-10	1	4	4	YES
2-11	1	3	3	YES
3-C	2	1/1.5	1.25	NO
3-1	3	2/3/2	2.33	YES
3-2	2	3/3	3	YES
3-3	2	4/3.5	3.75	YES
3-6	2	3/3	3	YES
3-7	1	4	4	YES
4-C	2	1.5/2	1.75	UNSURE
4-1	1	1	1	UNSURE
4-3	3	2/3/3	2.67	YES
4-4	3	3/3/2	2.67	YES
4-6	1	2	2	UNSURE
4-7	1	1	1	UNSURE
4-10	1	4	4	YES
4-11	1	4	4	YES
5-1	2	3/3	3	YES
5-3	5	3/3/2.5/1/1	2.83	YES
5-4	1	2.5	2.5	YES
5-5	1	3	3	YES
5-6	1	3	3	YES
5-7	1	3	3	YES
5-11	1	3.5	3.5	YES
6-1	1	4	4	YES
6-2	1	1	1	UNSURE

Smith's Theory

To use Smith's theory, all three types of PIO must be examined before concluding whether or not a PIO tendency is predicted. Type II PIO was not predicted for any of the LAHOS configurations, so it will not be included in the discussion below.

Tables 6 and 7 summarize Smith's Type I PIO theory as applied to the LAHOS data. The lead-only pilot model was applied to all configurations, except as noted. Table 6 summarizes the results using the $\nu \leq 0.3$ criterion for predicting subjectively predictable resonant frequency, and Table 7 summarizes the results using the $\zeta \leq 0.2$ criterion. The two criterion will hereafter be referred to as the "ν criterion" and the "ζ criterion," respectively.

The two criteria are in very close agreement, for the most part, concerning subjectively predictable resonant frequency and PIO tendency predictions. However, there are a few notable exceptions.

The ν criterion predicts resonant frequencies for several configurations which the ζ criterion does not. These configurations are summarized in Table 8. All the extra frequencies, except one, have values of ν greater than 0.09. Therefore, $\nu \leq 0.09$ may be a better cutoff for subjective predictability. The only configuration which would have any difficulty with this value of ν would be 4-C. This

Table 6

Smith's Type I PIO Predictions Using ν Criterion, LAHOS Data

Configuration	ν	ω_R[1] (rad/sec)	Phase[2] Margin	Magnitude[3] Criterion	Predict[4] PIO?
1-A	0.1455	1.30	71.82	-	NO
1-B	0.1493	1.36	61.97	-	NO
1-C	0.1651	1.47	48.93	-	NO
1-1	0.0390	3.34	-26.39	0.0180	YES
1-2	0.0069	3.03	-35.61	0.0209	YES
1-3	0.0293	2.48	-34.96	0.0272	YES
1-4	0.0392	2.02	-32.16	0.0344	YES
1-6	0.0691	1.57	26.58	-	NO
1-8	0.0309	2.78	-37.59	0.0235	YES
1-11	0.0338	2.78	-37.94	0.0235	YES
2-A*	0.0058	1.08	145.11	-	NO
2-C*	0.0644	2.77	36.92	-	NO
2-1	0.0578	4.37	-38.19	0.0107	NO
2-2	0.0197	4.04	-49.81	0.0127	YES
2-3	0.0091	3.43	-46.75	0.0171	YES
2-4	0.0135	2.97	-42.47	0.0213	YES
2-6	0.0027	4.09	-50.37	0.0124	YES
2-7	0.0048	3.88	-49.31	0.0138	YES
2-9	0.0218	3.24	-45.30	0.0187	YES
2-10	0.0252	2.62	-26.66	0.0252	YES

*Configuration which used lead/lag pilot model; all others use lead only pilot model

[1] Resonant frequency, also predicted PIO frequency

[2] Phase margin of a_{z_p}/F_s evaluated at ω_R, units in degrees

[3] Magnitude of $a_{z_p}/\dot{\theta}$ evaluated at ω_R, units in g/deg/sec

[4] Yes if phase margin <0 degrees and magnitude criterion >0.012 g/deg/sec

Table 6, cont

Configu-ration	ν	ω_R [1] (rad/sec)	Phase [2] Margin	Magnitude [3] Criterion	Predict [4] PIO?
2-11	0.0063	1.21	108.91	-	NO
	0.0006	3.01	-16.66	0.0209	YES
3-C	0.0612	2.20	67.2[illegible]	-	NO
3-1	0.0962	2.23	52.32	-	NO
	0.0243	3.69	-30.45	0.0152	YES
3-2	0.1037	2.31	30.12	-	NO
	0.0171	3.36	-39.56	0.0177	YES
3-3	0.0249	2.88	-37.31	0.0222	YES
3-6	0.0943	2.29	33.81	-	NO
	0.0224	3.42	-40.28	0.0172	YES
3-7	0.0749	2.31	27.49	-	NO
	0.0344	3.27	-40.38	0.0185	YES
4-C	0.2432	2.19	53.31	-	NO
	0.1776	7.93	-221.71	0.0050	NO
4-1	0.1380	3.06	5.90	-	NO
	0.0892	4.63	-51.59	0.0099	NO
4-3	0.0009	3.62	-57.09	0.0160	YES
4-4	0.0116	3.05	-50.46	0.0207	YES
4-6	0.0122	4.51	-70.33	0.0105	NO
4-7	0.0013	4.24	-86.77	0.0120	NO

*Configuration which used lead/lag pilot model; all others use lead only pilot model

[1] Resonant frequency, also predicted PIO frequency

[2] Phase margin of a_{z_p}/F_s evaluated at ω_R, units in degrees

[3] Magnitude of $a_{z_p}/\dot{\theta}$ evaluated at ω_R, units in g/deg/sec

[4] Yes if phase margin < 0 degrees and magnitude criterion > 0.012 g/deg/sec

Table 6, cont

Configuration	ν	ω_R [1] (rad/sec)	Phase Margin [2]	Magnitude Criterion [3]	Predict PIO? [4]
4-10	0.0226	2.81	-47.01	0.0232	YES
4-11	0.0008	1.35	72.66	-	NO
	0.0055	3.16	-27.66	0.0197	YES
5-1*	0.0484	3.64	23.40	-	NO
5-3	0.0045	4.60	-74.14	0.0096	NO
5-4	0.0065	4.13	-65.92	0.0122	YES
5-5	0.0068	3.81	-60.71	0.0142	YES
5-6*	0.0508	3.22	29.30	-	NO
5-7*	0.0515	3.11	30.10	-	NO
5-11*	0.0526	2.95	31.77	-	NO
6-1**	0.1300	0.85	104.76	-	NO
	0.0300	2.69	-40.61	0.0241	YES
6-2***	0.0600	4.22	-38.22	0.0114	NO

*Configuration which used lead/lag pilot model; all others use lead only pilot model
**Original YF-17
***Modified YF-17

[1] Resonant frequency, also predicted PIO frequency

[2] Phase margin of a_{z_p}/F_s evaluated at ω_R, units in degrees

[3] Magnitude of $a_{z_p}/\dot{\theta}$ evaluated at ω_R, units in g/deg/sec

[4] Yes if phase margin < 0 degrees and magnitude criterion > 0.012 g/deg/sec

Table 7

Smith's Type I PIO Predictions Using ζ Criterion, LAHOS Data

Configu-ration	ζ_{cl}	ω_R [1] (rad/sec)	Phase [2] Margin	Magnitude [3] Criterion	Predict [4] PIO?
1-A		None	-	-	NO
1-B		None	-	-	NO
1-C		None	-	-	NO
1-1	0.12	3.48	-29.59	0.0169	YES
1-2	-0.03	3.04	-35.77	0.0208	YES
1-3	-0.11	2.54	-37.62	0.0263	YES
1-4	-0.16	2.12	-37.55	0.0326	YES
1-6	-0.64	1.98	5.01	0.0352	YES
1-8	-0.11	2.85	-40.34	0.0227	YES
1-11	-0.12	2.87	-41.24	0.0225	YES
2-A*	-0.02	1.08	145.10	-	NO
	-0.59	5.00	-19.82	0.0074	NO
2-C*	-0.25	3.52	6.14	0.0164	YES
2-1	0.14	4.77	-50.13	0.0085	NO
2-2	-0.08	4.05	-50.04	0.0127	YES
2-3	-0.03	3.44	-47.44	0.0170	YES
2-4	-0.05	2.99	-43.49	0.0211	YES
2-6	-0.01	4.09	-50.44	0.0124	YES
2-7	-0.02	3.88	-49.31	0.0138	YES
2-9	-0.08	3.30	-48.86	0.0182	YES

*Configuration which used lead/lag pilot model; all others use lead only pilot model

[1] Resonant frequency, also predicted PIO frequency

[2] Phase margin of a_{z_p}/F_s evaluated at ω_R, units in degrees

[3] Magnitude of $a_{z_p}/\dot{\theta}$ evaluated at ω_R, units in g/deg/sec

[4] Yes if phase margin $<$ 15 degrees and magnitude criterion $>$ 0.012 g/deg/sec

Table 7, cont

Smith's Type I PIO Predictions Using ζ Criterion, LAHOS Data

Configuration	ζ_{cl}	ω_R[1] (rad/sec)	Phase[2] Margin	Magnitude[3] Criterion	Predict[4] PIO?
2-10	-0.11	2.68	-31.35	0.0245	YES
2-11	0.00	1.21	108.57	-	NO
	0.00	3.01	-16.85	0.0208	YES
3-C	0.18	4.23	-25.11	0.0117	NO
3-1	0.05	3.73	-31.54	0.0149	YES
3-2	-0.04	3.38	-40.46	0.0175	YES
3-3	-0.07	2.95	-41.58	0.0215	YES
3-6	-0.05	3.46	-41.85	0.0169	YES
3-7	-0.08	3.36	-44.16	0.0177	YES
4-C	0.17	7.29	-186.62	0.0039	NO
4-1	0.17	5.62	-93.14	0.0058	NO
4-3	0.00	3.62	-57.07	0.0160	YES
4-4	-0.05	3.06	-51.06	0.0206	YES
4-6	0.04	4.53	-71.20	0.0104	NO
4-7	-0.02	4.24	-66.88	0.0119	NO
4-10	-0.10	2.85	-49.87	0.0227	YES
4-11	0.00	1.35	72.54	-	NO
	0.00	3.16	-27.59	0.0197	YES
5-1*	-0.19	4.05	2.12	0.0127	YES
5-3	-0.02	4.51	-74.60	0.0096	NO

*Configuration which used lead/lag pilot model; all others use lead only pilot model

[1] Resonant frequency, also predicted PIO frequency

[2] Phase margin of a_{zp}/F_s evaluated at ω_R, units in degrees

[3] Magnitude of $a_{z_p}/\dot{\theta}$ evaluated at ω_R, units in g/deg/sec

[4] Yes if phase margin < 15 degrees and magnitude criterion > 0.012 g/deg/sec

Table 7, cont

Smith's Type I PIO Predictions Using ζ Criterion, LAHOS Data

Configuration	ζ_{cl}	ω_R[1] (rad/sec)	Phase[2] Margin	Magnitude[3] Criterion	Predict[4] PIO?
5-4	-0.03	4.14	-66.52	0.0121	YES
5-5	-0.03	3.81	-60.93	0.0142	YES
5-6*	-0.23	3.59	7.92	0.0157	YES
5-7*	-0.24	3.45	9.51	0.0168	YES
5-11*	-0.26	3.26	12.58	0.0183	YES
6-1**	-0.12	0.84	105.63	-	NO
	-0.08	2.73	-43.05	0.0236	YES
6-2***	0.14	4.60	-49.10	0.0092	NO

*Configuration which used lead/lag pilot model; all others use lead only pilot model
**Original YF-17
***Modified YF-17

[1] Resonant frequency, also predicted PIO frequency

[2] Phase margin of a_{z_p}/F_s evaluated at ω_R, units in degrees

[3] Magnitude of $a_{z_p}/\dot{\theta}$ evaluated at ω_R, units in g/deg/sec

[4] Yes if phase margin < 15 degrees and magnitude criterion > 0.012 g/deg/sec

configuration has a subjectively predictable resonant frequency at 7.93 radian/second with ν=0.1776. The ζ criterion predicts a frequency of 7.29 radian/second.

Table 8

Discrepancies Between ν and ζ Criteria
Using Lead-Only Pilot Model

Configu-ration	ω_R (rad/sec)	ν
1-A	1.30	0.1455
1-B	1.36	0.1493
1-C	1.47	0.1651
3-1	2.23	0.0962
3-2	2.31	0.1037
3-6	2.29	0.0943
3-7	2.31	0.0749
4-C	2.19	0.2432
4-1	3.06	0.1380

The other notable exception is the frequency difference predicted by the two criteria when the lead/lag pilot model is used. In addition, the ζ criterion predicted a resonant frequency for 2-A which was not predicted by the ν criterion. These differences are summarized in Table 9.

Table 9

Discrepancies Between ν and ζ Criteria
Using Lead/Lag Pilot Model

Configu-ration	($\nu \leq 0.3$) (rad/sec)	Phase Margin[1]	($\zeta_{CL} \leq 0.2$) (rad/sec)	Phase Margin
2-A	1.08	145.11	1.08	145.10
	--	--	5.00	-19.82
2-C	2.77	36.92	3.52	6.14
5-1	3.71	19.76	4.05	2.12
5-6	3.28	25.51	3.59	7.92
5-7	3.17	26.23	3.45	9.51
5-11	3.01	27.80	3.26	12.58

[1]Phase margin of a_{z_p}/F_s evaluated at ω_R, units in degrees

The frequency difference is enough to make the phase margin criterion only slightly positive for five of the six frequencies predicted by the ζ criterion. Using a slightly positive phase margin criterion ($\geq$15 degrees) to account for uncertainties in the lead/lag pilot model, the ζ criterion would then correctly predict the PIO tendency of four of the above six configurations. The only configurations that now fail are 2-A, which fails the magnitude criterion, but was PIO prone in flight; and 2-C, which is now predicted to be PIO prone, but was not in flight.

One other interesting configuration is 4-C, which has a very high subjectively predictable resonant frequency and very negative phase margin, but which fails the magnitude criterion. There is reason to believe, with PIO ratings of 1.5 and 2, that this aircraft may have had a PIO tendency.

It is possible that the very negative phase margin and/or high frequency may have caused problems with Smith's theory.

Table 10 summarizes Smith's Type III PIO theory. There is only one configuration, 5-3, which is predicted to be Type III PIO prone which was not also predicted to be Type I PIO prone. Since 24 configurations were predicted to be both Type I and Type III PIO prone, the obvious question then arises: which type of PIO is actually seen in flight? Since Type III PIO is dependent only on excessive time delay and not normal acceleration characteristics, a simulator study may be useful in answering this question.

Table 11 summarizes the overall results of using Smith's theory to predict LAHOS PIOs. Only 34 of the 44 PIO tendencies are considered fairly certain; of these, only two, 2-A and 2-C as noted before, were not correctly predicted.

To summarize Smith's results:

1. Smith's method works well as long as the lead only pilot model is applied. Using the lead/lag pilot model produced uncertainty in the data and discrepancies between using the ν and ζ criteria to determine subjectively predictable resonant frequency.

2. There is little difference between the ν and ζ criteria for predicting subjectively predictable resonant frequency. However, the ζ criteria seems to have an edge on the ν criterion when the lead/lag pilot model is used. Moreover, the ζ criterion is much simpler to use.

Table 10

Smith's Type III PIO Predictions, LAHOS Data

Configu-ration	ω_R[1] (rad/sec)	ω_c[2] (rad/sec)	Predict PIO?
1-A	11.11	3.85	NO
1-B	10.30	3.68	NO
1-C	8.44	3.46	NO
1-1	4.06	3.22	NO
1-2	2.41	3.09	YES
1-3	1.78	2.74	YES
1-4	1.40	2.32	YES
1-6	2.49	3.21	YES
1-8	2.06	3.16	YES
1-11	2.03	3.12	YES
2-A	12.15	4.71	NO
2-C	10.04	4.31	NO
2-1	6.48	4.08	NO
2-2	4.06	3.95	NO
2-3	3.17	3.60	YES
2-4	2.65	3.18	YES
2-6	4.12	4.07	NO
2-7	3.79	4.06	YES
2-9	2.99	3.83	YES
2-10	2.55	3.34	YES
2-11	3.44	4.07	YES
3-C	7.87	3.86	NO
3-1	3.98	3.62	NO
3-2	2.98	3.50	YES
3-3	2.59	3.15	YES
3-6	3.02	3.62	YES
3-7	2.88	3.61	YES
4-C	11.50	4.35	NO
4-1	8.21	4.12	NO
4-3	3.42	3.64	YES
4-4	2.62	3.22	YES
4-6	4.80	4.11	NO
4-7	4.30	4.10	NO
4-10	2.49	3.38	YES
4-11	3.78	4.11	YES
5-1	8.82	5.26	NO
5-3	4.66	4.78	YES
5-4	4.07	4.37	YES
5-5	3.67	4.04	YES
5-6	5.74	5.26	NO
5-7	5.28	5.24	NO
5-11	4.83	5.26	YES
6-1	2.34	3.18	YES
6-2	5.86	3.84	NO

[1] Frequency at $j\omega$-axis crossing
[2] Crossover frequency predicted using Smith's formula

Table 11

Summary of Smith's PIO Predictions, LAHOS Data

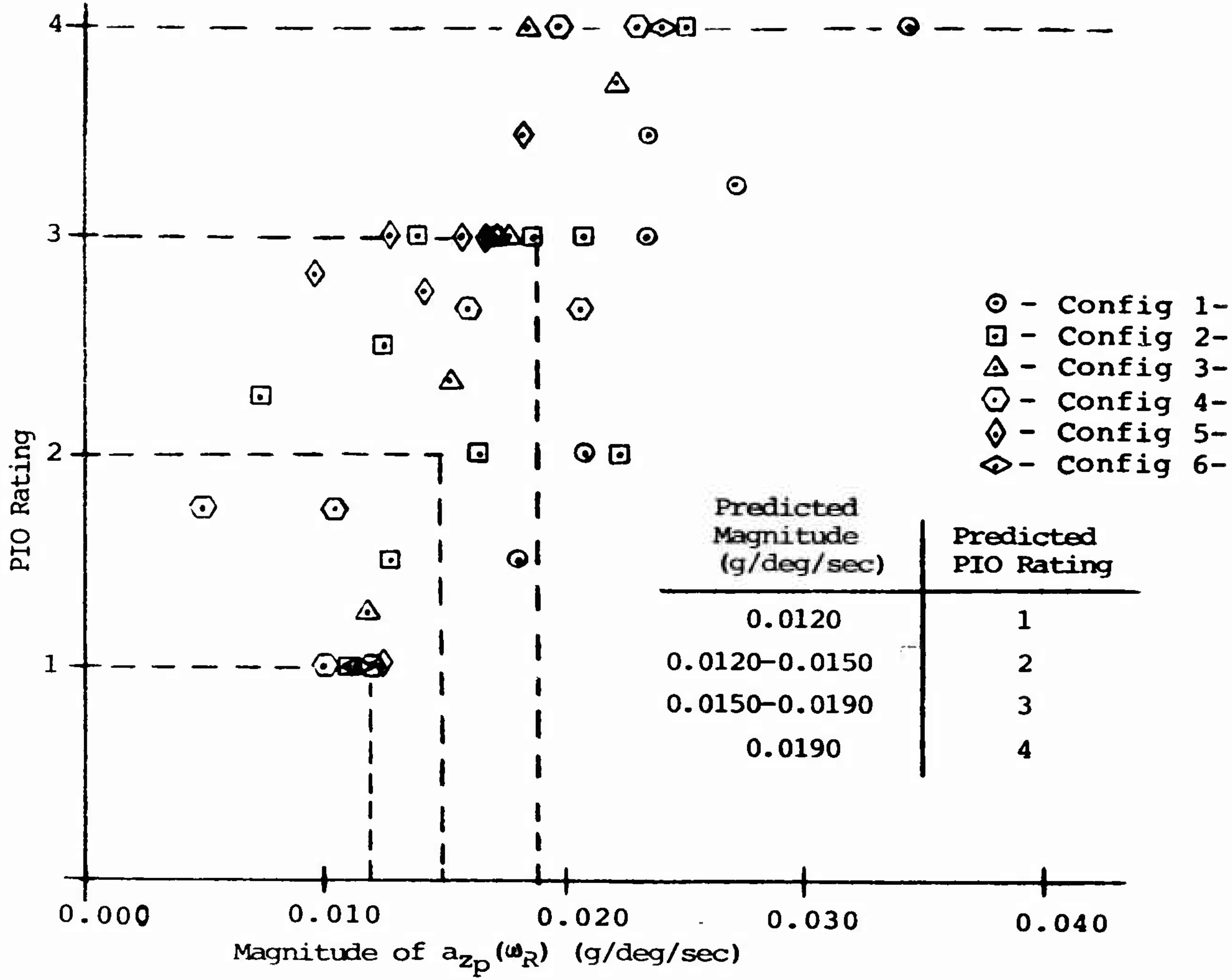
Configu-ration	Predict Type I	Predict Type III	PIO in Flight	Actual[1] PIOR	Average PIOR
1-A	NO	NO	UNSURE	1	1
1-B	NO	NO	UNSURE	2	2
1-C	NO	NO	NO	1/1	1
1-1	YES	NO	UNSURE	2/1	1.5
1-2	YES	YES	UNSURE	2	2
1-3	YES	YES	YES	4/4/2/3	3.25
1-4	YES	YES	YES	4	4
1-6	YES*	YES	YES	2/2	2
1-8	YES	YES	YES	3	3
1-11	YES	YES	YES	3.5	3.5
2-A	NO	NO	YES	2/2.5	2.25
2-C	YES*	NO	NO	2/1/1/1	1.25
2-1	NO	NO	NO	1/1/1	1
2-2	YES	NO	UNSURE	2/1	1.5
2-3	YES	YES	YES	3	3
2-4	YES	YES	YES	3/2/1	2
2-6	YES	NO	YES	2.5	2.5
2-7	YES	YES	YES	3	3/3
2-9	YES	YES	YES	3	3
2-10	YES	YES	YES	4	4
2-11	YES	YES	YES	3	3
3-C	NO	NO	NO	1/1.5	1.25
3-1	YES	NO	YES	2/3/2	2.33
3-2	YES	YES	YES	3/3	3
3-3	YES	YES	YES	4/3.5	3.75
3-6	YES	YES	YES	3/3	3
3-7	YES	YES	YES	4	4
4-C	NO	NO	UNSURE	1.5/2	1.75
4-1	NO	NO	UNSURE	1	1
4-3	YES	YES	YES	2/3/3	2.67
4-4	YES	YES	YES	3/3/2	2.67
4-6	NO	NO	UNSURE	2	2
4-7	NO	NO	UNSURE	1	1
4-10	YES	YES	YES	4	4
4-11	YES	YES	YES	4	4
5-1	YES*	NO	YES	3/3	3
5-3	NO	YES	YES	1/3/3/2.5/1	2.83
5-4	YES	YES	YES	2.5	2.5
5-5	YES	YES	YES	3	3
5-6	YES*	NO	YES	3	3
5-7	YES*	NO	YES	3	3
5-11	YES	YES	YES	3.5	3.5
6-1	YES	YES	YES	4	4
6-2	NO	NO	UNSURE	1	1

*Indicates Type I PIO predicted using criterion only
[1]PIOR = Pilot Induced Oscillation Rating

3. With the exception of one configuration, all the configurations predicted to be Type III PIO prone were also predicted to be Type I PIO prone. What implication does this have on the actual PIO seen in flight?

Overall, the major drawback to Smith's theory appears at this point to be the need for a properly parameterized pilot model. The other problem (although admittedly of academic interest only) is the possible physical discrepancy that may arise by predicting both types of PIO.

Smith's theory predicts only whether or not an aircraft has a tendency to PIO, but says nothing about the severity of the PIO. From the above results, it appeared that Smith's magnitude criterion might be useful as a PIO rating predictor. The magnitude of the pilot-felt normal acceleration to pitch rate at the subjectively predictable resonant frequency (using the ζ criterion) is plotted versus PIO rating is Figure 14. Only those configurations which have a phase margin of less than 15 degrees for the pilot-felt normal acceleration to stick force loop are plotted. Suggested boundaries for PIO ratings of one through four are indicated by the dashed lines and are summarized on the figure. The flight test portion of this project attempted to refine these boundaries, as will be discussed later.



Predicted Magnitude (g/deg/sec)	Predicted PIO Rating
0.0120	1
0.0120–0.0150	2
0.0150–0.0190	3
0.0190	4

Figure 14. Correlation between Smith's magnitude criterion and PIO rating, Lahos data, with suggested PIO rating boundaries

Bandwidth Method

Hoh's proposed theory does not directly predict PIO tendency or rating, but predicts levels of handling qualities. Hoh's proposed bandwidth criterion boundaries for handling qualities levels are shown in Figure 15. Hoh originally used the LAHOS pilot ratings to develop the proposed Category C boundaries in the figure. The flight test data from this study were used to refine the proposed Category C boundaries, as discussed later.

Hoh's bandwidth method was used to see if any correlation existed between PIO ratings from the LAHOS data and the bandwidth criterion. Figure 15 also shows Hoh's bandwidth criterion for the LAHOS configurations. The average PIO rating is noted next to each configuration. In general, high PIO ratings appear to be associated with low bandwidths and large phase delays. Proposed boundaries for PIO ratings of one through four are indicated in Figure 16 by the dashed lines. The flight test data from this study were used to refine these proposed boundaries, as discussed later.

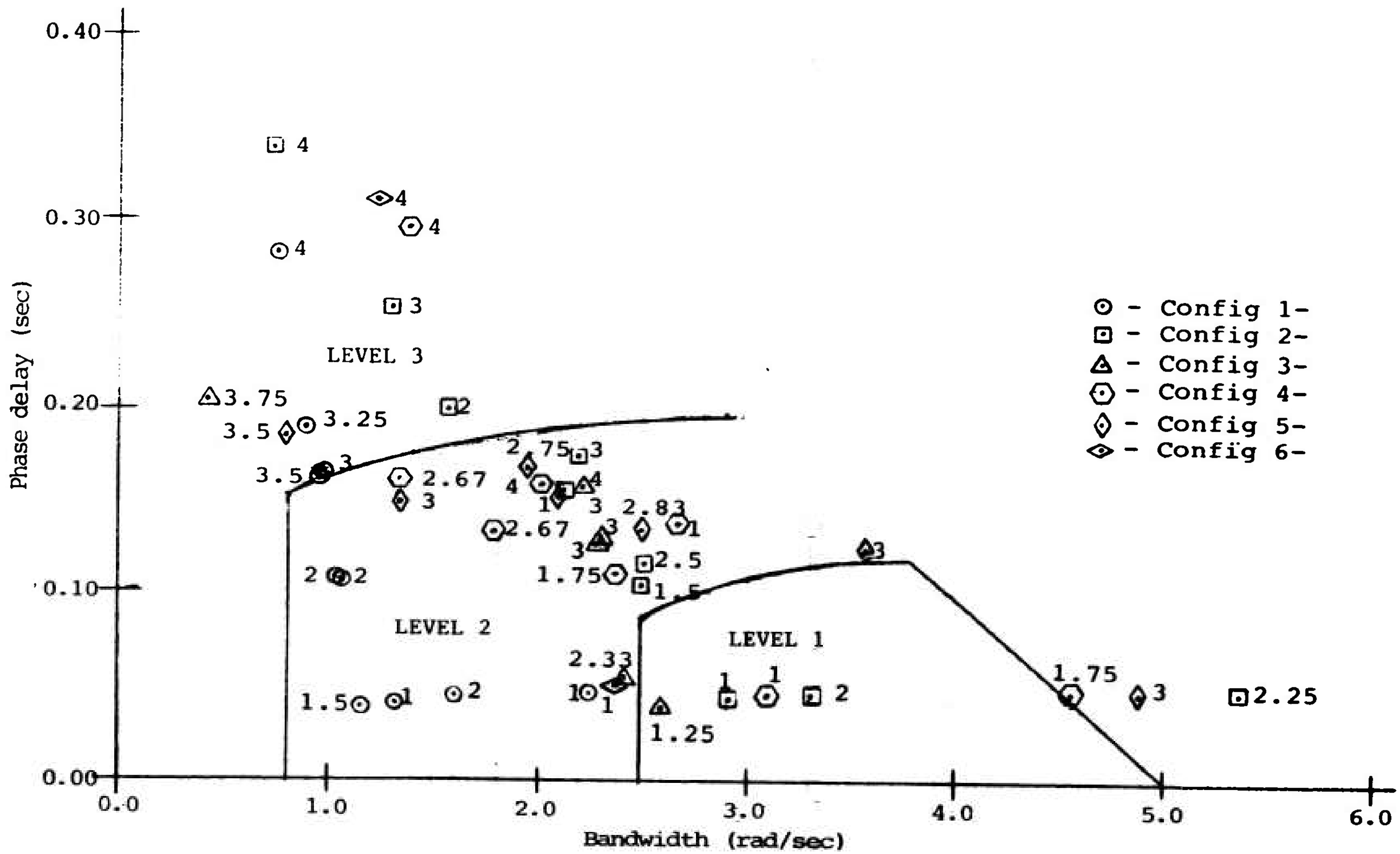


Figure 15. Correlation Between Hoh's Bandwidth Criterion and PIO Ratings, LAHOS Data

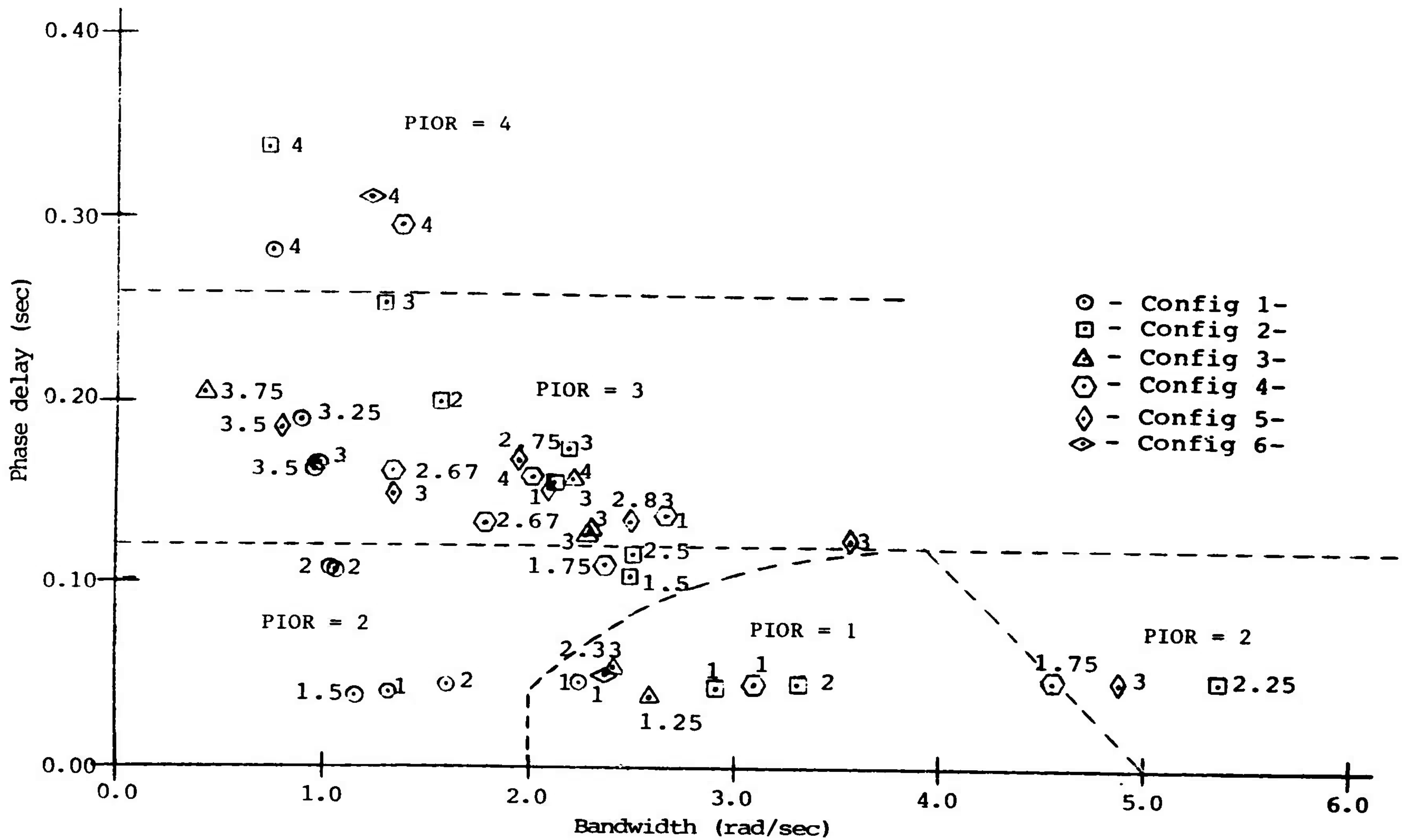


Figure 16. Correlation Between Hoh's Bandwidth Criterion and PIO Ratings, LAHOS Data, with Suggested PIO Rating Boundaries

IV. Flight Test Method

The flight test portion of this project was conducted as part of a USAF Test Pilot School systems project, known as HAVE PIO. The test team consisted of three project pilots and two engineers, including the author. In addition, three Calspan safety/instructor pilots were involved. The previous flying experience of the three project pilots is summarized in Table 12.

Table 12

Project Pilot Experience

Pilot	Aircraft	Hours
A	F-15	1200
	AT-38	40
B	F-111	1050
	AT-38	30
	T-37	60
C	F-4EJ	700
	T-33	200

Based on the previous analytical results, 18 different aircraft/flight control system (FCS) combinations were selected for flight test on the USAF/Calspan variable stability NT-33. These configurations included four sets of Level 1 approach/landing short period dynamics combined with 14 different flight control systems. The PIO tendencies and the frequencies of the configurations were predicted. Each configuration was then flight tested, and the actual PIO tendencies and frequencies were compared to those predicted.

Test Item Description

The test aircraft, NT-33A S/N 51-4120, is a modified, two seat, jet trainer owned by the USAF Flight Dynamics Laboratory and operated by Calspan Corporation, Buffalo, New York. The aircraft is capable of variable dynamic response and control system characteristics (Ref 14). The variable stability system (VSS) modifies the static and dynamic responses of the basic NT-33A by commanding control surface positions through full authority electrohydraulic servos. A programmable analog computer, associated aircraft response sensors, control surface servos, and an electrohydraulic force-feel system provides the total simulation capability. Figures 17 and 18 show a block diagram of the variable stability and a sketch of the flight control system. The instructor/safety pilot varies the computer gains through controls located in the rear cockpit, allowing changes in airplane dynamics and control system characteristics in flight.

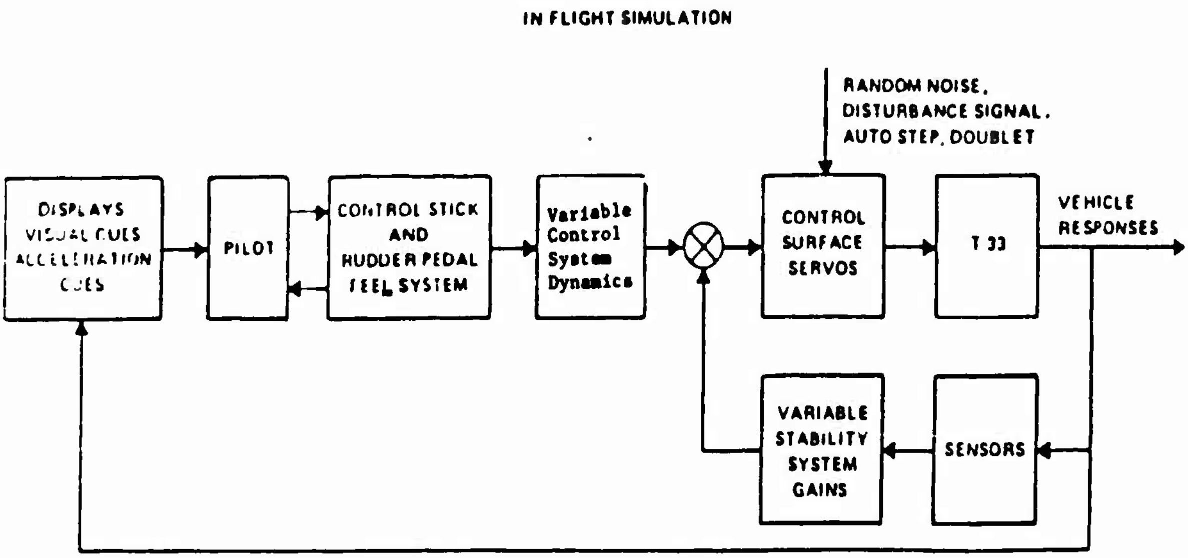


Figure 17. Variable Stability NT-33A Block Diagram

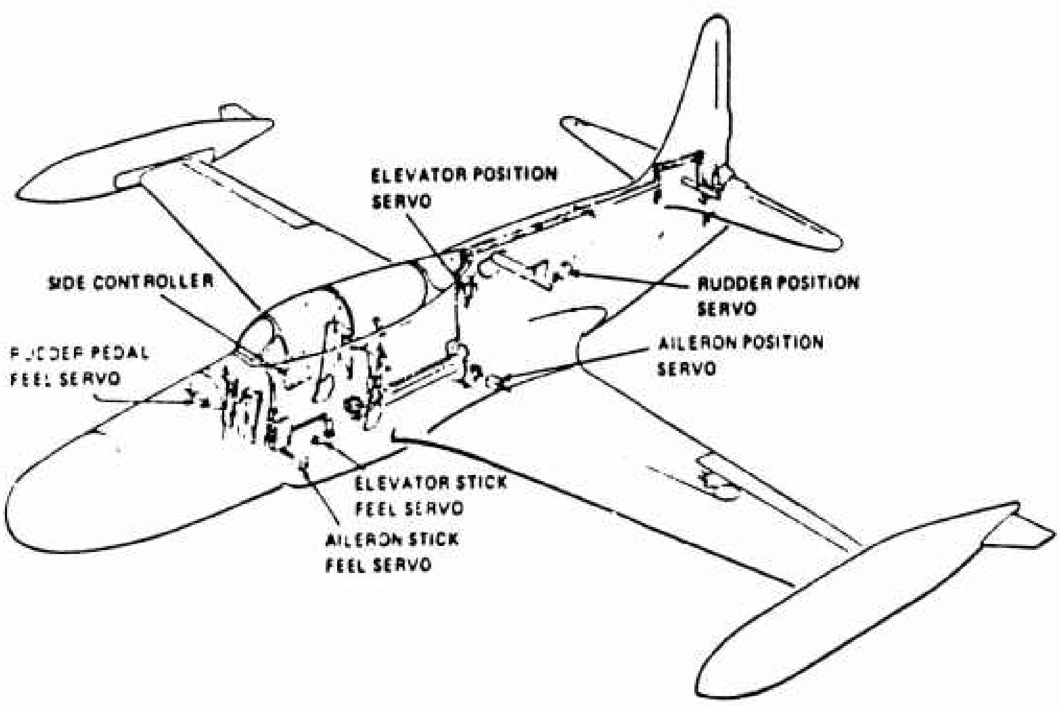


Figure 18. Control System Layout

Test Instrumentation and Data Reduction

The NT-33 instrumentation system consisted of the following items:

1. An on-board Ampex AR 700 magnetic tape recording system with 2.25 hours recording capability was used to record 28 data parameters at 100 samples per second, as listed in Table 13.

2. An AN/ANH-2 voice recorder set manufactured by the Pierce Wire Recorder Corporation provided 45 minutes of recording time for interphone and UHF radio communications.

3. A Head Up Display (HUD) video recorder was used to record the HUD field of view and interphone communications for all approaches and landings.

After each flight project pilots reviewed their HUD video/audio and inflight pilot comment cards and summarized their comments on a mission summary sheet. In addition, individual project pilot Cooper-Harper, PIO, and confidence rating factors were determined and recorded for each configuration. To maintain standardization, these comments and ratings were reviewed to ensure project pilots used similar criteria when assigning PIO and Cooper-Harper ratings. The inflight pilot comment card, Cooper-Harper rating scale, and Confidence ratings are shown in Figures 19, 20, and 21. The PIO rating scale was depicted in Figure 13.

The data were analyzed using several qualitative and quantitative analysis techniques. Project pilot comments were used to qualitatively describe the aircraft PIO

Table 13

Test Instrumentation

NT-33 Digital Tape Parameters

DIGITAL CHANNEL NUMBER	RECORDED VARIABLE	ENGINEERING UNITS
1	Elevator deflection (measured at strut)	degrees
2	Elevator deflection (measured at surface)	degrees
3	Aileron deflection (measured at strut)	degrees
4	Aileron deflection (measured at surface)	degrees
5	Elevator stick deflection	inches
6	Lateral stick deflection	inches
7	Rudder pedal deflection	inches
8	Elevator stick force	pounds
9	Lateral stick force	pounds
10	Rudder pedal force	pounds
11	Event marker	N/A
12	True airspeed	feet/second
13	Roll rate	degrees/second
14	Pitch rate	degrees/second
15	Yaw rate	degrees/second
16	Normal acceleration (measured at c.g.)	g's
17	Angle of attack	degrees
18	Angle of sideslip	degrees
19	Pitch angle	degrees
20	Roll angle	degrees
21	Normal acceleration (measured at pilot's station)	g's
22	Not used	
23	Not used	
24	Not used	
25	Pitch error	degrees
26	Roll error	degrees
27	Not used	
28	Not used	

Feel System Characteristics:

- Forces/Displacements?
- Pitch Sensitivity?

Pitch Attitude Control?

- Initial Response?
- Final Response?
- Predictability?
- Any special piloting techniques/compensation required?
- Tendency toward PIO?

Task Performance:

- Airspeed Control?
- Touchdown Point Accuracy?
- Sink Rate at Touchdown?
- Runway Alignment?
- Level of aggressiveness used to control touchdown point?
- Special control techniques required in flare?
- If approach was abandoned, was it due to poor handling qualities or severe PIO?

Additional Factors:

- Wind/Turbulence
- Lateral-Directional Characteristics

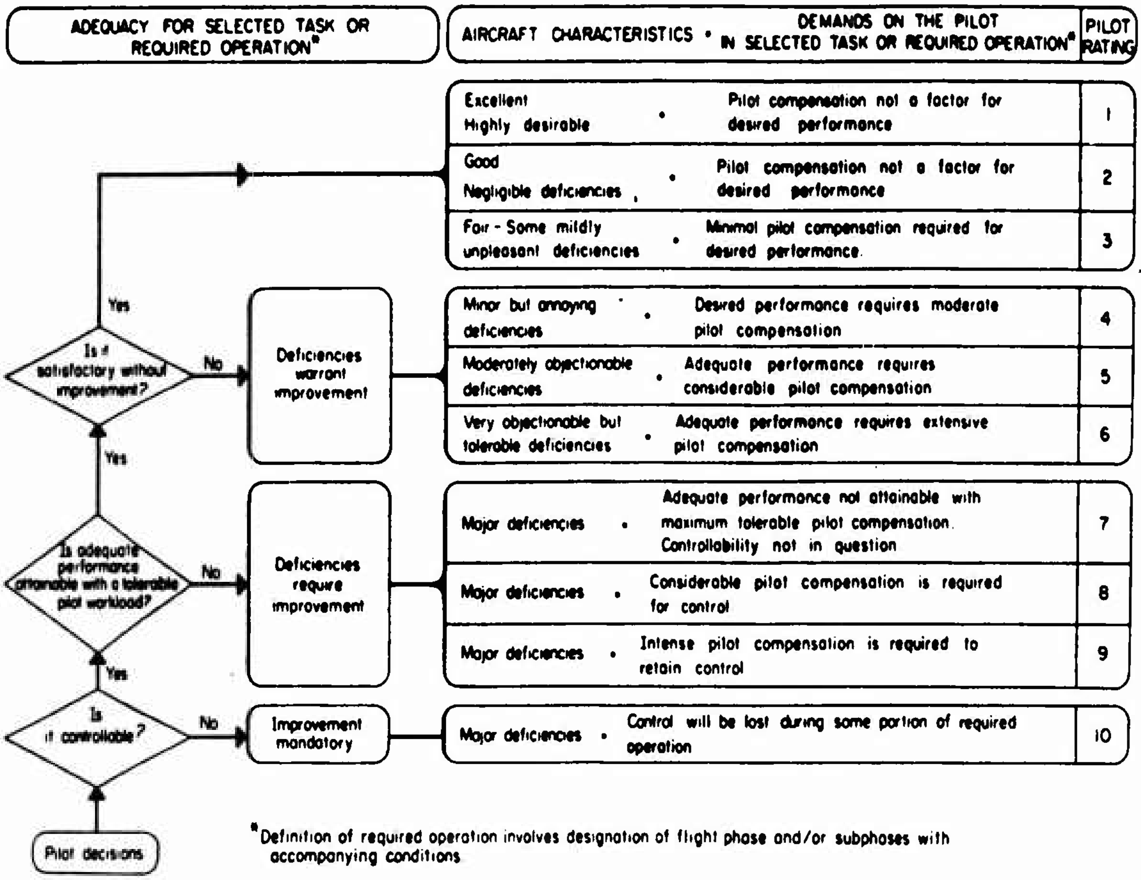
Summarize Evaluation:

- Major problems, good features

Review Ratings:

- PIO Rating, Cooper-Harper Rating, Confidence Factor

Figure 19. In-flight Pilot Comment Card



DEFINITIONS FROM TN-D-5153

COMPENSATION

The measure of additional pilot effort and attention required to maintain a given level of performance in the face of deficient vehicle characteristics.

HANDLING QUALITIES

Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role

MISSION

The composite of pilot-vehicle functions that must be performed to fulfill operational requirements. May be specified for a role complete flight, flight phase or flight subphase

PERFORMANCE

The precision of control with respect to aircraft movement that a pilot is able to achieve in performing a task. (Pilot-vehicle performance is a measure of handling performance. Pilot performance is a measure of the manner or efficiency with which a pilot moves the principal controls in performing a task.)

ROLE

The function or purpose that defines the primary use of an aircraft

TASK

The actual work assigned a pilot to be performed in completion of or as representative of a designated flight segment

WORKLOAD

The integrated physical and mental effort required to perform a specified piloting task

Figure 20. Cooper-Harper Pilot Rating Scale

PILOT CONFIDENCE FACTORS

CLASS A

A pilot may assign a rating with a relatively high degree of confidence, although he may have mild reservations because of incomplete or inadequate simulation of motion cues, disturbances, visual information, or other factors affecting pilot workload.

Supplementary tasks, if needed, can be adequately provided by the pilot.

CLASS B

A pilot can assign a rating with only a moderate level of confidence because of uncertainties introduced by a lack of representative environmental disturbances as well as incomplete or inadequate simulation of motion cues, disturbances, visual information, or other factors affecting pilot workload.

Supplementary tasks may be desired, but are not available.

CLASS C

A pilot can assign a rating with only minimum confidence because considerable pilot extrapolation is required due to an incomplete task, thereby requiring considerable reliance on self-imposed tasks and maneuvers for assessment.

This may also be aggravated by incomplete or very limited simulations of motion cues, disturbances, visual information, or other factors affecting pilot workload.

Figure 21. Pilot Confidence Factors Scale

tendencies and handling qualities during the landing task. Pilot comments, Cooper-Harper and PIO ratings, and strip chart data of stick force, pitch, pitch rate and normal acceleration were used to determine whether or not the aircraft had a PIO tendency during the approach and flare. For data analysis, a PIO was defined as a sustained pitch rate oscillation.

Test Configurations

Landing longitudinal PIO tendencies and flying qualities were evaluated using four pairs of short period natural frequency and damping ratio combined with fourteen different flight control system configurations. All short period dynamics met MIL-F-8785C Level 1 boundaries for the landing approach (Category C). These configurations are depicted in Figure 22 and are also listed in Table 14. Table 14 also gives the dynamic characteristics of the 14 different flight control systems.

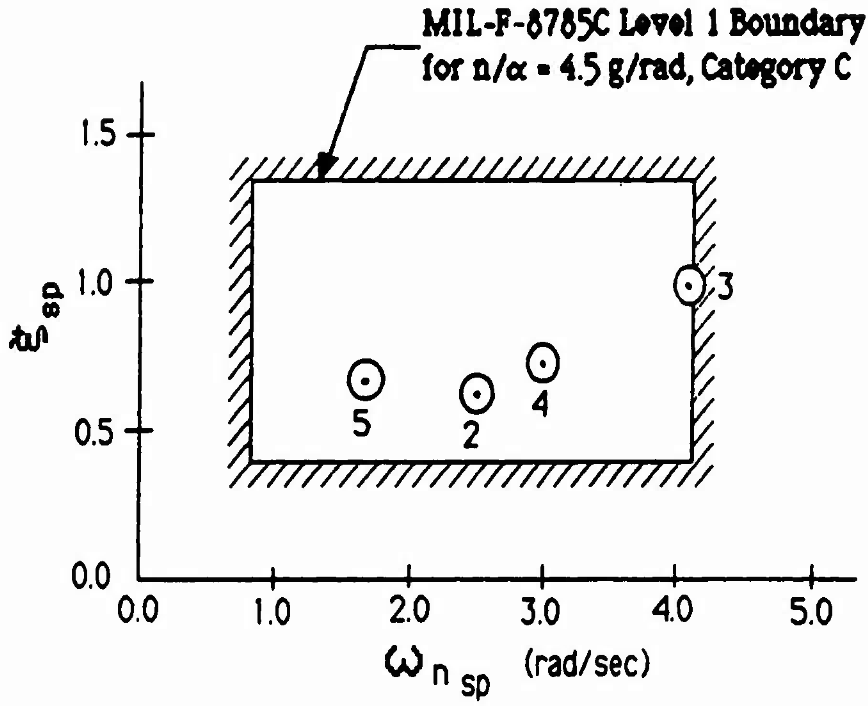


Figure 22. Flight Test Configurations.

Table 15 shows the actual flight control system/aircraft dynamics combinations used. The phugoid and lateral-directional characteristics were held constant and met MIL-F-8785C Level 1 criteria. These characteristics are listed in Appendix A.

Table 14

NT-33A Longitudinal Dynamics and Flight Control Systems

Dynamics

Configuration

	2	3	4	5
$\omega_{n_{sp}}$	2.4	4.1	3.0	1.7
ζ_{sp}	0.64	1.0	0.74	0.68

First Order Filters

	B	D	1	2	3	5
K	3.0	0.5	1.0	10.0	4.0	1.0
τ_1	3.33	20.0	0.0	----	---	---
τ_2	10.0	10.0	0.0	10.0	4.0	1.0

Second and Fourth Order Filters

	6	7	8	9	10	11	12	13
K	256	144	81	36	16	65536	4	9
ζ_1	0.7	0.7	0.7	0.7	0.7	0.93	0.7	0.7
ω_{n_1}	16	12	9	6	4	16	2	3
ζ_2	---	---	---	---	---	0.38	---	---
ω_{n_2}	---	---	---	---	---	16	---	---

First order systems: $$\frac{K(s+\tau_1)}{(s+\tau_2)}$$

Second and fourth order systems: $$\frac{K}{(s^2+2\zeta\omega_{n_1}s+\omega_{n_1}^2)(s^2+2\zeta\omega_{n_2}s+\omega_{n_2}^2)}$$

Table 15

Flight Control System and
Aircraft Dynamics Combinations

Filter	Configuration 2	3	4	5
-B	X			
-D		X		
-1	X	X	X	X
-2			X	
-3		X		
-5	X			
-6		X		
-7	X			
-8	X	X		
-9				X
-10				X
-11				X
-12		X		
-13		X		

The short period dynamics were set by the NT-33A instructor/safety pilot by adjusting the appropriate variable stability gain controls in the rear cockpit. Predetermined flight control system characteristics were also selected by the rear seat pilot. The stick force per inch (gearing) was selected by the first pilot to fly each configuration. From that point on, the gearing for each configuration remained fixed. The gearings for each configuration are listed on the pilot comment cards in Appendix B.

Landing Task

A landing task was defined to allow repeatability of the results. Each pilot flew up to three approaches for each configuration - a straight in approach followed by two offset approaches, one to each side of the runway. After making all three approaches, the project pilots assigned both PIO and Cooper-Harper ratings as a measure of PIO tendency and pilot performance and workload. For the landing task, a PIO was defined as a sustained oscillation which interfered with the accomplishment of the task and required the pilot to reduce his gain or remove himself from the loop. A PIO tendency was defined as an undesirable motion which did not necessarily interfere with the accomlishment of the task.

The offset landing task for this project was a visual approach with a lateral offset and a correction to centerline prior to touchdown. Figure 23 depicts the runway landing task parameters. The size of the lateral offset was approximately 150 feet. Due to runway maintenance, the left 150 feet of the 300 foot wide Runway 22 at Edwards AFB was closed during the test period. The centerline of the remaining 150 foot wide runway was used for touchdown. The aircraft was flown on the desired glidepath using the ILS until the beginning of the overrun, then the correction to the desired touchdown point was initiated. The safety pilot assisted in maintaining a constant offset correction and break point among the three project pilots.

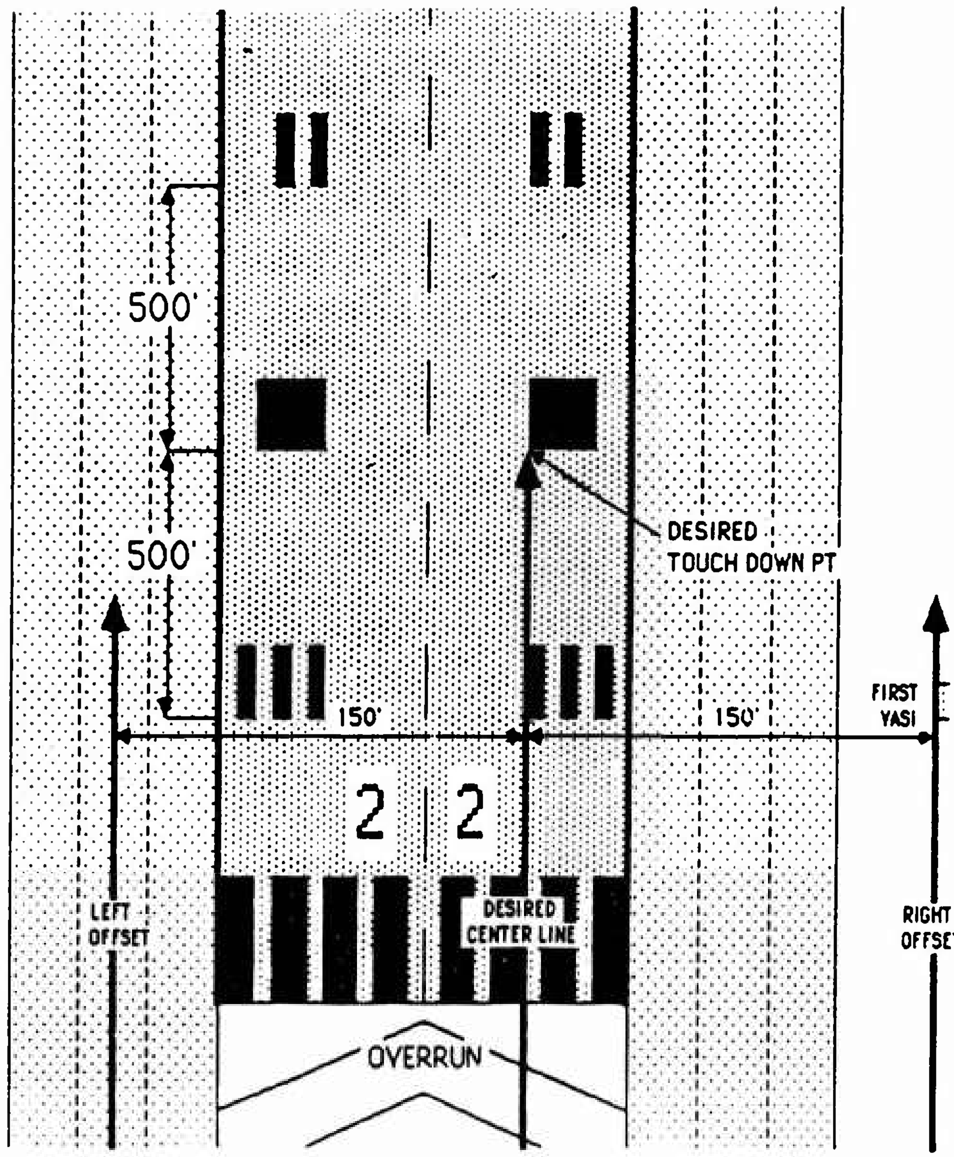


Figure 23. Runway Landing Task Parameters

The touchdown zone was 1000 feet long starting at 500 feet from the threshold and extending to 1500 feet from the threshold. The desired touchdown aimpoint was 1000 feet from the threshold and within 5 feet of centerline. Even though the ILS glidepath intersected the runway at the desired touchdown point, the pilots were still required to make a large longitudinal correction (push over) due to the long flare characteristics of the NT-33A. Each landing was treated as a "must land" situation, unless the instructor/safety pilot or project pilot determined that safety of flight would be compromised in an attempt to land. Table 16 summarizes the evaluation task performance criteria used to assign Cooper-Harper ratings to the visual landing task.

Table 16

Task Performance Standards

Desired	Adequate
No PIOs Tochdown within 5 ft of centerline (main wheels on centerline) Touchdown aimpoint ± 250 ft Approach airspeed ± 5 kts	Touchdown within 25 ft of centerline (tip tank on centerline) Touchdown at aimpoint ± 500ft Approach airapeed -5/+10 kts

An electronic step elevator input was accomplished on downwind before reconfiguring to allow post flight time response verification of the configuration dynamics just flown.

V. Flight Test Results and Analysis

All planned configurations were flown by at least two of the project pilots. PIO ratings, Cooper-Harper pilot ratings, and pilot comments were collected for each configuration. All pilot comments are summarized in Appendix B. Representative time history plots of F_s, θ, q, and a_{z_p} for the last 30 seconds of the approach and landing for each configuration are shown in Appendix C. Table 17 summarizes the Cooper-Harper pilot ratings and the PIO ratings for each configuration.

Table 17

PIO and Cooper-Harper Ratings, HAVE PIO Data

Configu-ration	# of Flights	PIO Ratings	Pilot Ratings
2-B	4	3/2/2/1	7/3/3/3
2-1	3	1/1/1	2/2/3
2-5	3	4/4/5	10/7/10
2-7	3	4/3/2	7/4/4
2-8	3	4/4/4	8/10/8
3-D	2	1/1	2/2
3-1	3	3/2/2	5/3/4
3-3	3	3/1/1	7/2/3
3-6	2	2/2	5/4
3-8	3	4/3/4	8/5/8
3-12	2	4/5	7/9
3-13	2	4/5	10/10
4-1	3	1/1/1	3/2/3
4-2	3	1/1/2	3/3/7
5-1	2	1/1	2/5
5-9	2	4/4	7/7
5-10	2	5/5	10/10
5-11	3	2/4/3	7/7/5

Smith's Theory

Tables 18 and 19 summarize the Type I PIO tendency predicted for each configuration using the ν and ζ criteria, respectively. Table 20 summarizes the Type III PIO tendency predictions, and Table 21 presents an overall summary of the predictions using Smith's theory. All the configurations predicted to be Type III PIO prone were also predicted to be Type I PIO prone. For Type I PIO, the only discrepancy between the two criteria occurred for Configuration 2-B. This configuration used the lead/lag pilot model and was predicted to be PIO prone using the ζ criterion but not the ν criterion.

Table 21 also presents the flight test PIO ratings. Using an average PIO rating of 2 or greater as a basis for PIO tendency, Smith's theory correctly the PIO tendency (or lack of PIO tendency) for 14 of the 18 configurations. Two configurations which were predicted to be not PIO prone had PIO tendencies in flight, and two of the configurations which were predicted to be PIO prone had no PIO tendencies in flight.

Table 22 compares Smith's predicted Type I and Type III PIO frequencies to the actual PIO frequency from flight. The actual PIO frequency was determined from strip chart data as the average PIO frequency from all approaches for a particular configuration. Overall, it is difficult to draw a conclusion about whether a Type I or Type III PIO was experienced because the predicted frequencies for the two

Table 18

Smith's Type I PIO Predictions Using ν Criterion, HAVE PIO Data

Configuration	ν	ω_R [1] (rad/sec)	Phase [2] Margin	Magnitude [3] Criterion	Predict [4] PIO?
2-B*	0.0526	3.41	25.69	-	NO
2-1	0.0615	4.57	-43.18	0.0098	NO
2-5	0.0156	2.75	-41.48	0.0238	YES
2-7	0.0027	4.11	-56.21	0.0124	YES
2-8	0.0098	3.84	-53.80	0.0142	YES
3-D	0.0265	6.81	-158.45	0.0102	NO
3-1	0.0314	7.90	-188.31	0.0108	NO
3-3	0.0090	4.95	-107.81	0.0127	YES
3-6	0.0011	6.18	-146.82	0.0105	NO
3-8	0.0016	5.12	-114.36	0.0123	YES
3-12	0.0223	2.63	-60.59	0.0270	YES
3-13	0.0181	3.21	-71.74	0.0216	YES
4-1	0.0787	5.37	-74.26	0.0068	NO
4-2	0.0109	4.89	-78.61	0.0088	NO
5-1	0.0581	3.88	-29.78	0.0139	YES
5-9	0.0240	2.91	-40.62	0.0220	YES
5-10	0.0246	2.46	-34.72	0.0274	YES
5-11	0.0161	3.32	-44.45	0.0181	YES

*Configuration which used lead/lag pilot model; all others use lead only pilot model

[1] Resonant frequency, also predicted PIO frequency

[2] Phase margin of a_{z_p}/F_s evaluated at ω_R, units in degrees

[3] Magnitude of $a_{z_p}/\dot{\theta}$ evaluated at ω_R, units in g/deg/sec

[4] Yes if phase margin < 0 degrees and magnitude criterion > 0.012 g/deg/sec

Table 19

Smith's Type I PIO Predictions Using ζ Criterion, HAVE PIO Data

Configu-ration	ν	ω_R[1] (rad/sec)	Phase[2] Margin	Magnitude[3] Criterion	Predict[4] PIO?
2-B*	-0.19	3.87	9.46	0.0174	YES
2-1	0.14	5.09	-60.30	0.0072	NO
2-5	-0.07	2.77	-42.80	0.0236	YES
2-7	-0.01	4.11	-56.17	0.0124	YES
2-8	-0.04	3.86	-54.67	0.0141	YES
3-D	0.09	6.84	-159.86	0.0102	NO
3-1	0.11	7.90	-188.13	0.0108	NO
3-3	0.04	4.96	-108.42	0.0127	YES
3-6	0.00	6.18	-147.02	0.0105	NO
3-8	0.01	5.12	-114.34	0.0123	YES
3-12	-0.10	2.65	-61.99	0.0268	YES
3-13	-0.08	3.23	-73.13	0.0214	YES
4-1	0.14	6.07	-112.23	0.0047	NO
4-2	0.04	4.91	-79.59	0.0087	NO
5-1	0.16	4.29	-40.66	0.0113	NO
5-9	-0.09	2.97	-43.77	0.0214	YES
5-10	-0.10	2.51	-38.17	0.0267	YES
5-11	-0.06	3.35	-45.61	0.0179	YES

*Configuration which used lead/lag pilot model; all others use lead only pilot model

[1] Resonant frequency, also predicted PIO frequency

[2] Phase margin of a_{z_p}/F_s evaluated at ω_R, units in degrees

[3] Magnitude of $a_{z_p}/\dot{\theta}$ evaluated at ω_R, units in g/deg/sec

[4] Yes if phase margin < 15 degrees and magnitude criterion > 0.012 g/deg/sec

Table 20

Smith's Type III PIO Predictions, HAVE PIO Data

Configuration	ω_R[1] (rad/sec)	ω_c[2] (rad/sec)	Predict PIO?
2-B	11.86	4.67	NO
2-1	7.07	4.21	NO
2-5	2.39	2.99	YES
2-7	4.05	4.19	YES
2-8	3.66	4.14	YES
3-D	9.09	4.91	NO
3-1	11.68	5.00	NO
3-3	5.36	4.52	NO
3-6	6.90	4.99	NO
3-8	5.40	4.94	NO
3-12	2.27	3.04	YES
3-13	2.95	3.75	YES
4-1	8.70	4.65	NO
4-2	5.33	4.52	NO
5-1	5.79	3.65	NO
5-9	2.53	3.40	YES
5-10	2.14	2.91	YES
5-11	2.93	3.65	YES

[1] Frequency at $j\omega$-axis crossing
[2] Crossover frequency predicted using Smith's formula

Table 21

Smith's Overall PIO Predictions, HAVE PIO Data

Configu-ration	Predict Type I	Predict Type III	PIO in Flight	Actual PIOR[1]	Average PIOR
2-B	YES*	NO	YES	3/2/2/1	2
2-1	NO	NO	NO	1/1/1	1
2-5	YES	YES	YES	4/4/5	4.33
2-7	YES	YES	YES	4/3/2	3
2-8	YES	YES	YES	4/4/4	4
3-D	NO	NO	NO	1/1	1
3-1	NO	NO	YES	3/2/2	2.33
3-3	YES	NO	NO	3/1/1	1.68
3-6	NO	NO	YES	2/2	2
3-8	YES	NO	YES	4/3/4	3.68
3-12	YES	YES	YES	4/5	4.5
3-13	YES	YES	YES	4/5	4.5
4-1	NO	NO	NO	1/1/1	1
4-2	NO	NO	NO	1/1/2	1.33
5-1	NO	NO	NO	1/1	1
5-9	YES	YES	YES	4/4	4
5-10	YES	YES	YES	5/5	5
5-11	YES	YES	YES	2/4/3	3

*Indicates Type I PIO predicted using ζ criterion only
[1]PIOR = Pilot Induced Oscillation Rating

types are too close together. In general, it appears that the flight test frequencies are closer to the Type I predictions. Two of the configurations which were incorrectly predicted for PIO tendency (3-1 and 3-6) have the largest frequency errors. Since the predicted resonant frequency is dependent upon the parameterization of the servo pilot model, a "generic" pilot model as used in this study may not be accurate enough for Smith's theory.

Table 22

Smith's Predicted PIO Frequencies
and Actual Flight Test PIO Frequencies

Configuration	Type I Frequency (rad/sec)	Type III Frequency (rad/sec)	Average PIO Frequency (rad/sec)
2-B	3.9	---	4.8
2-1	4.6	---	---
2-5	2.8	2.4	2.8
2-7	4.1	4.1	4.1
2-8	3.8	3.7	4.3
3-D	6.8	---	---
3-1	7.9	---	10.4
3-3	5.0	---	---
3-6	6.2	---	8.4
3-12	2.6	2.3	2.2
3-13	3.2	3.0	3.2
4-1	5.4	---	---
4-2	4.9	---	---
5-1	3.9	---	---
5-9	2.9	2.5	3.5
5-10	2.5	2.1	2.6
5-11	3.3	2.9	3.6

Table 23 compares the average flight test PIO rating for each configuration to the PIO rating predicted using the magnitude criterion as described previously. The average difference is 0.6 PIO ratings, with a maximum difference of

Table 23

Predicted PIO Ratings from Magnitude Criterion and Flight Test PIO Ratings (PIOR)

Configuration	Predicted PIOR	Actual PIOR	Average PIOR	Δ PIOR[1]
2-B	2	3/2/2/1	2.00	0.00
2-1	1	1/1/1	1.00	0.00
2-5	4	4/4/5	4.33	+0.33
2-7	2	4/3/2	3.00	+1.00
2-8	2	4/4/4	4.00	+2.00
3-D	1	1/1	1.00	0.00
3-1	1	3/2/2	2.33	+1.33
3-3	2	3/1/1	1.68	-0.32
3-6	1	2/2	2.00	+1.00
3-8	2	4/3/4	3.68	+1.68
3-12	4	4/5	4.50	+0.50
3-13	4	4/5	4.50	+0.50
4-1	1	1/1/1	1.00	0.00
4-2	1	1/1/2	1.33	+0.33
5-1	1	1/1	1.00	0.00
5-9	4	4/4	4.00	0.00
5-10	4	5/5	5.00	+1.00
5-11	3	2/4/3	3.00	0.00

[1]Difference in magnitude between average flight test and predicted PIO rating

2.0 PIO ratings. Figure 24 depicts a plot of average PIO rating versus the predicted magnitude criterion. Like the LAHOS data, there is a definite upward trend between the magnitude criterion and flight test PIO rating. However, there is too much scatter in the data at the lower PIO ratings to draw any conclusion about a definite correlation. This scatter is due both to the small sample size (scatter in PIO ratings) and the impreciseness of the pilot model (predicted frequency affects the magnitude criterion). A magnitude criterion of greater than 0.022 g/deg/sec accurately predicts a PIO rating of 4 or 5, but more data are needed to further define the lower PIO rating boundaries.

It also should be noted that one of the configurations with the largest difference between predicted and actual PIO rating (3-1) has a very high predicted resonant frequency associated with a very negative phase margin. This anomaly was discussed previously for one of the LAHOS configurations (4-C). HAVE PIO Configuration 3-1 supports the idea that configurations with very high frequencies which fail the magnitude criterion may still be PIO prone.

An attempt was made to further analyze the flight test data using a frequency response analysis to produce power spectral densities (PSDs) of pitch, pitch rate, and pilot-felt normal acceleration using approximately the last 10 seconds of flight prior to touchdown (or safety pilot assumption of controls). It was hoped that this technique would produce more accurate dominant PIO frequencies than

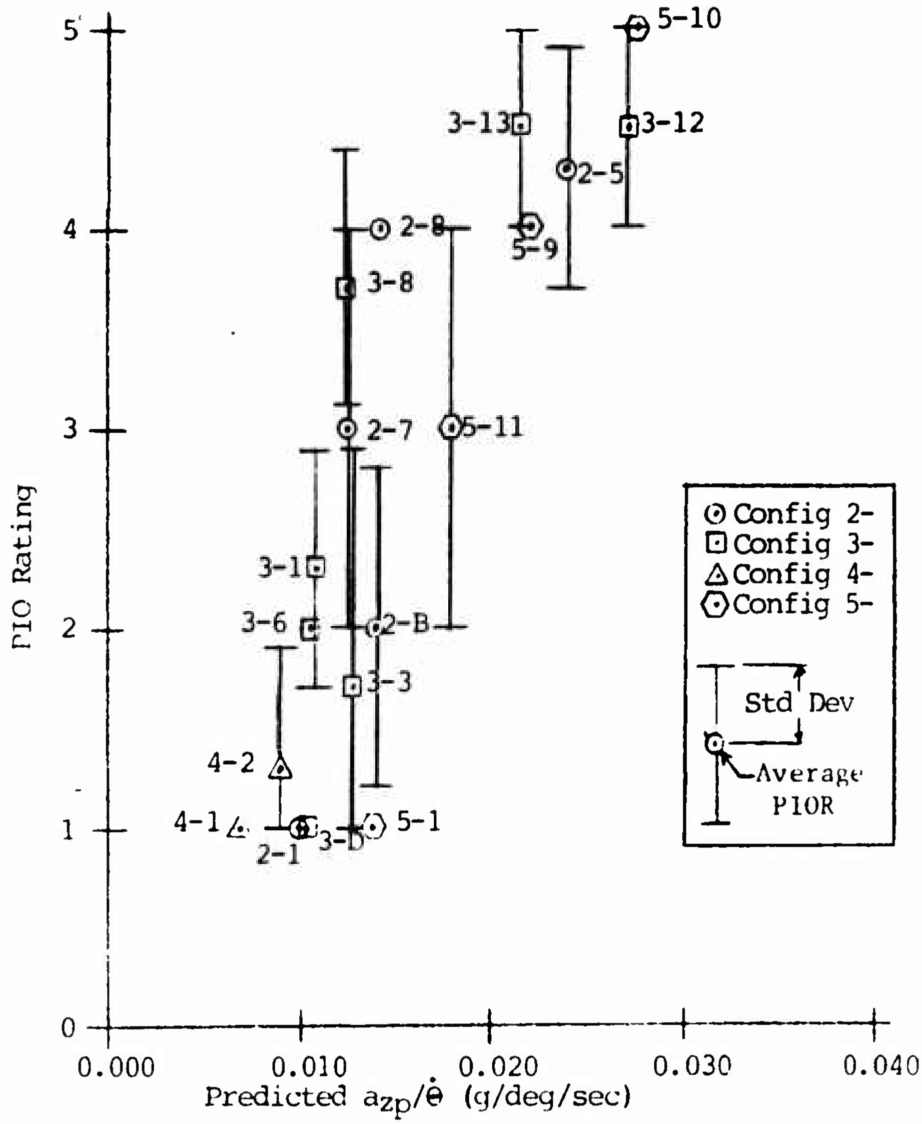


Figure 24. Correlation Between Magnitude Criterion and Flight Test PIO Rating

could be ascertained using strip chart data. A further attempt was made to compare the dominant frequencies to those predicted for both Type I and Type III PIO to determine which type had actually occurred. However, most of the PSDs did not show any particular dominant frequencies. Figure 25 presents typical PSDs for a configuration which received a PIO rating of 3. The only configurations which consistently produced dominant frequencies using the PSD analysis were those which had a sustained PIO; i.e., a PIO rating of 4 or 5. Figure 26 presents typical PSDs for a configuration of this type.

The PSD analysis was an attempt to gain some physical insight into the PIO phenomenon, but was unfortunately inconclusive. A better approach in the future might be to use simulator studies in combination with in-flight simulations. By definition, it should be possible to duplicate a Type III PIO in a simulator but not a Type I (due to the lack of normal acceleration cues). By comparing PIOs experienced in the simulator with those experienced in flight for a given configuration, it may be possible to ascertain which type actually occurred.

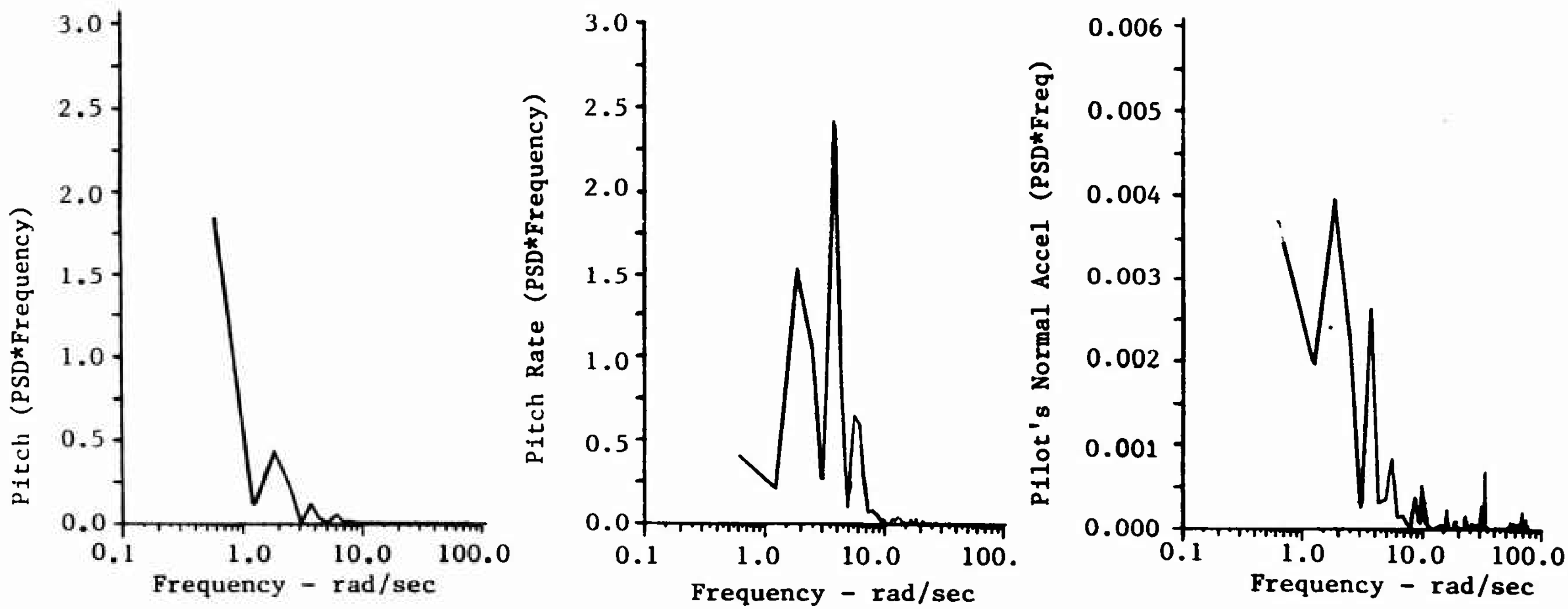


Figure 25. Power Spectral Densities of Selected Parameters, Configuration 2-7, Average PIO Rating = 3.0

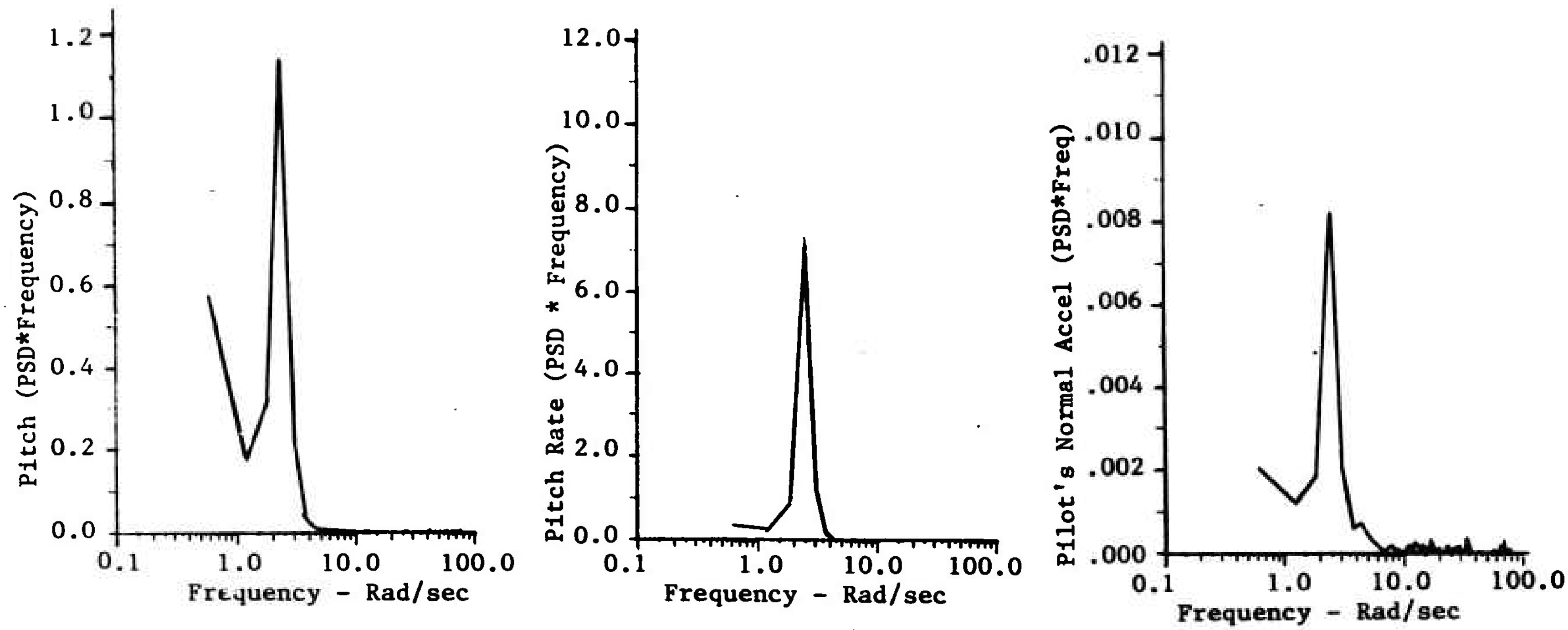


Figure 26. Power Spectral Densities of Selected Parameters, Configuration 2-5, Average PIO Rating = 4.33

Bandwidth Method

Figure 27 presents Hoh's proposed handling qualities level 1, 2, and 3 boundaries. Also shown are the test configurations along with their associated pilot ratings. These data are also summarized in Table 24. Hoh's theory correctly predicted the level of handling qualities for 13 of the 18 configurations. Three of the configurations which were not correctly predicted are very close to the Level 2 boundary (2-8, 3-8, and 5-11). If the boundary were shifted down slightly, these configurations would have been correctly predicted as being Level 3. The other two configurations which were not correctly predicted were 2-B and 3-D. These configurations were both Level 1 in flight, but were predicted to be Level 2. This suggests that Hoh's dashed line for the Level 1 boundary could be drawn to the 6 rad/sec bandwidth point instead of the 5 rad/sec point. Based on this limited flight test data, Figure 28 presents suggested boundary changes for Hoh's bandwidth criterion.

Proposed PIO rating boundaries based on the preliminary research presented earlier are depicted in Figure 29, and each flight test configuration is plotted to predict its PIO rating. The figure also includes the flight test PIO ratings. These data are also summarized in Table 25. The average difference in PIO rating is 0.5 with a maximum difference of 1.3. Using this limited flight test data, the suggested PIO rating boundaries were refined as shown in Figure 30.

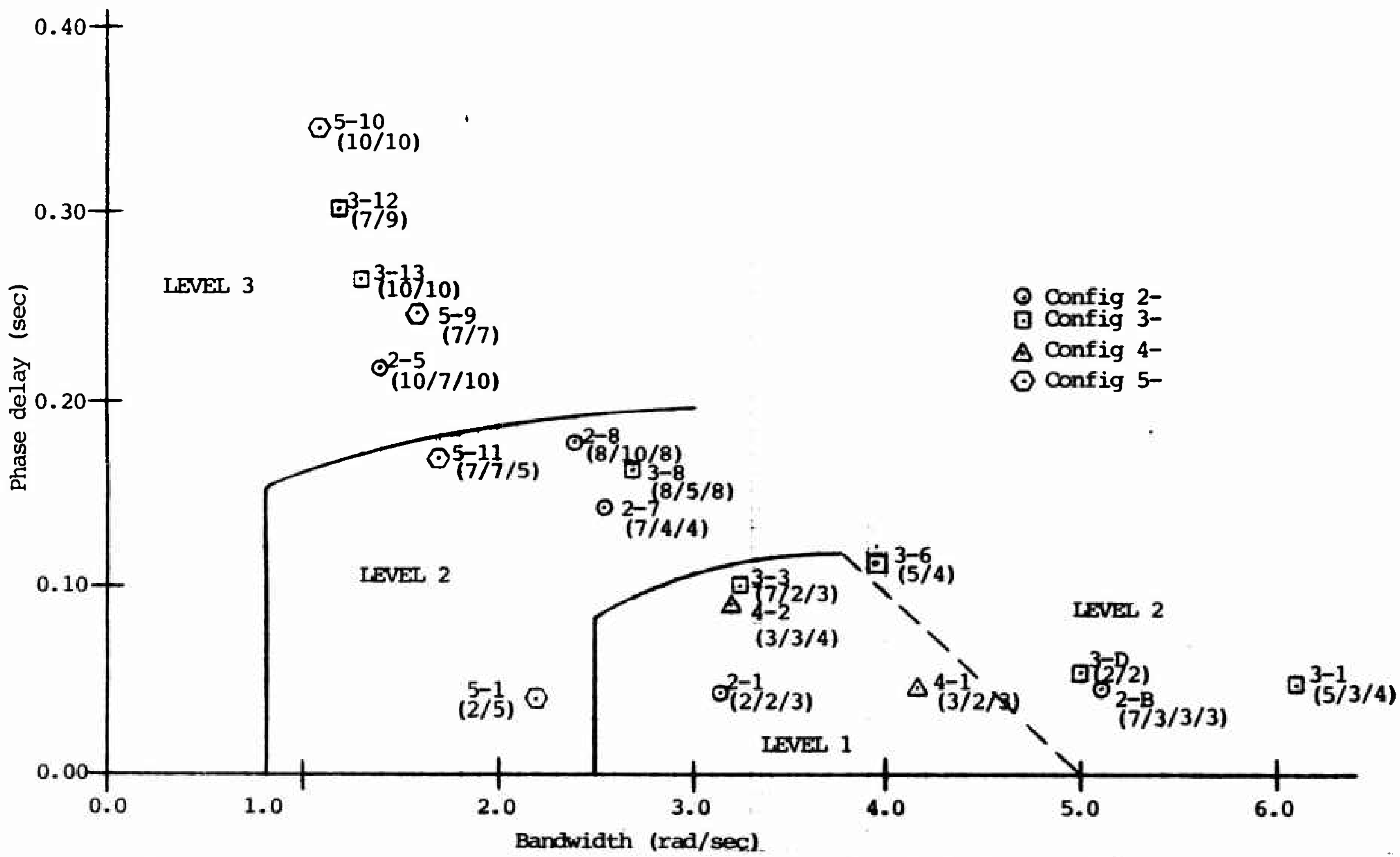


Figure 27. Bandwidth Method Predicted Handling Qualities Levels and Flight Test Pilot Ratings

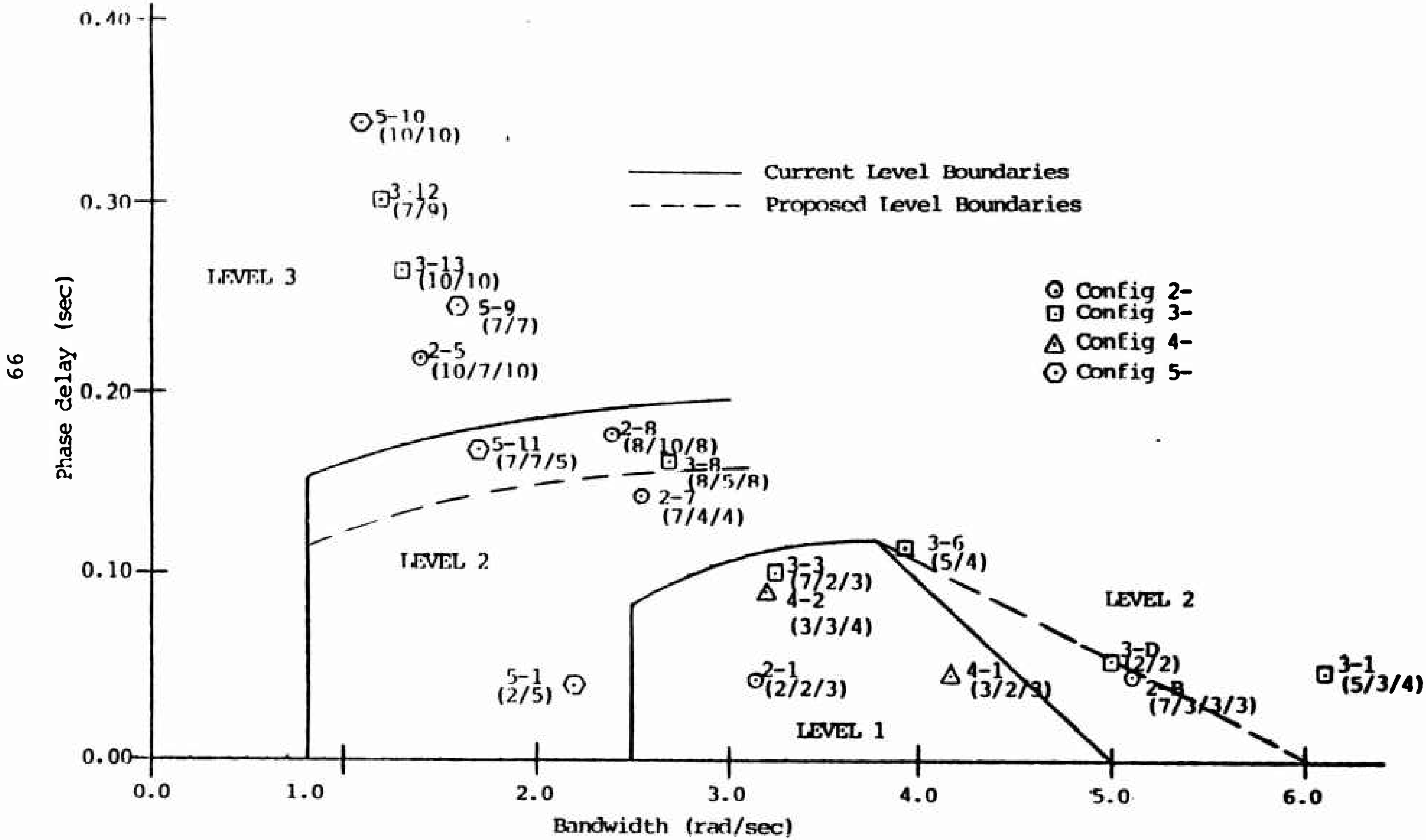


Figure 28. Proposed Boundary Changes for Hoh's Bandwidth Criteria

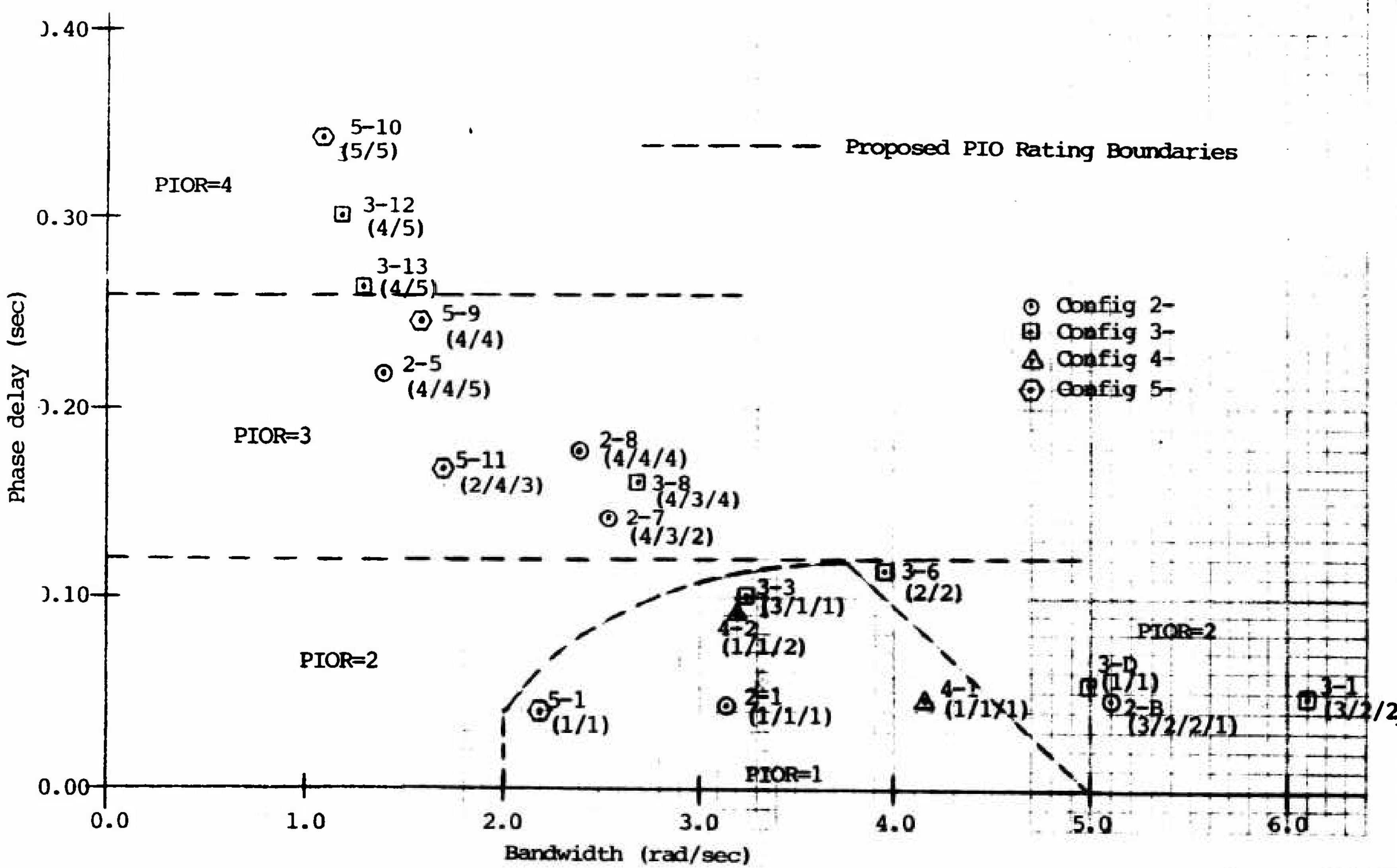


Figure 29. Proposed PIO Rating Boundaries Using LAHOS Data, with HAVE PIO Flight Test PIO Ratings

The major difference between the LAHOS data and the HAVE PIO data was that there were no LAHOS configurations which received a PIO rating of 5, but there were several HAVE PIO configurations which were rated as 5's. Reviewing the LAHOS time histories and pilot comments cards, and discussing the flights with the LAHOS pilots revealed that several of the LAHOS PIOs were, in fact, divergent and should have received 5's. Although the difference is of academic interest only (both a 4 and 5 are unflyable) the difference helps explain disrepancies between the two data bases. Also, the difference between parameters which predict a 4 or a 5 might be helpful in ascertaining whether or not the PIO rating scale can be considered linear.

Table 24

Bandwidth Method Predicted Handling Qualities and Flight Test Pilot Ratings

Configu-ration	Predicted Level	Pilot Ratings	Actual Level
2-B	2	7/3/3/3	1
2-1	1	2/2/3	1
2-5	3	10/7/10	3
2-7	2	7/4/4	2
2-8	2	8/10/8	3
3-D	2	2/2	1
3-1	2	5/3/4	2
3-3	1	7/2/3	1
3-6	2	5/4	2
3-8	2	8/5/8	3
3-12	3	7/9	3
3-13	3	10/10	3
4-1	1	3/2/3	1
4-2	1	3/3/7	1
5-1	2	2/5	2
5-9	3	7/7	3
5-10	3	10/10	3
5-11	2	7/7/5	3

Table 25

Predicted PIO Ratings from Bandwidth Criterion and Flight Test PIO Ratings (PIOR)

Configu-ration	Predicted PIOR	Actual PIOR	Average PIOR	Δ PIOR[1]
2-B	2	3/2/2/1	2.00	0.00
2-1	1	1/1/1	1.00	0.00
2-5	3	4/4/5	4.33	+1.33
2-7	3	4/3/2	3.00	+0.00
2-8	3	4/4/4	4.00	+1.00
3-D	2	1/1	1.00	-1.00
3-1	2	3/2/2	2.33	+0.33
3-3	1	3/1/1	1.68	+0.68
3-6	1	2/2	2.00	+1.00
3-8	3	4/3/4	3.68	+0.68
3-12	4	4/5	4.50	+0.50
3-13	4	4/5	4.50	+0.50
4-1	1	1/1/1	1.00	0.00
4-2	1	1/1/2	1.33	+0.33
5-1	1	1/1	1.00	0.00
5-9	3	4/4	4.00	+1.00
5-10	4	5/5	5.00	+1.00
5-11	3	2/4/3	3.00	0.00

[1]Difference in magnitude between average flight test and predicted PIO rating

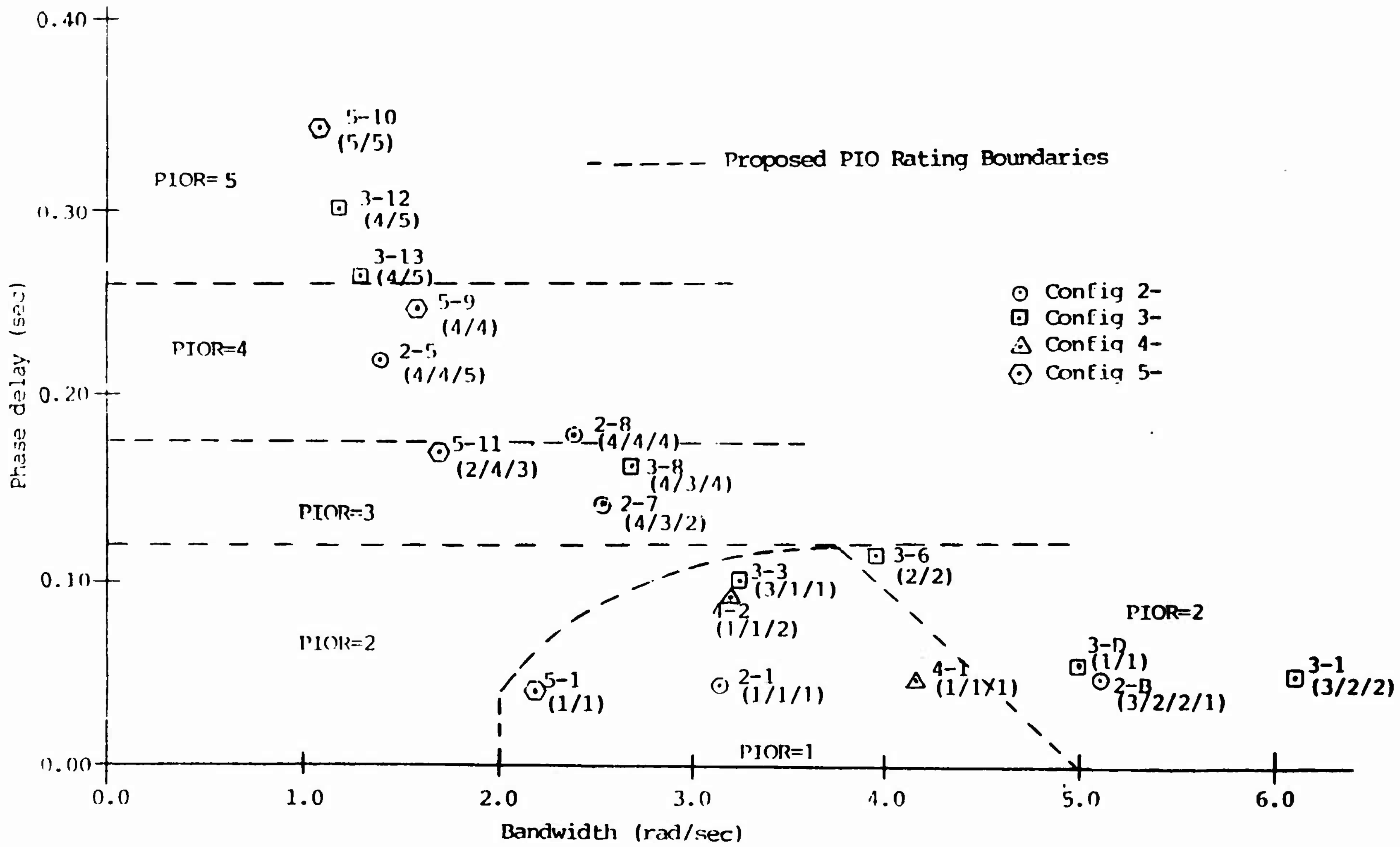


Figure 30. Proposed PIO Rating Boundaries Using the Bandwidth Criteria

VI. Conclusions and Recommendations

Current PIO prediction techniques predict only PIO tendency. This research attempted to determine if existing techniques could be used to determine the severity of the PIO as well; i.e., predict PIO rating.

Smith's theory can accurately predict both PIO tendencies and frequencies with a properly parametreized pilot model. This need for an accurate pilot model is a major drawback to Smith's theory. There appears to be a correlation between Smith's magnitude criterion and actual PIO ratings. Further research needs to be performed using more accurate pilot models along with existing data bases to determine this correlation more precisely.

Hoh's bandwidth method appears promising as both a handling qualities predictor and PIO rating predictor. Hoh's method is particularly attractive because it requires no pilot model. The data collected in this study were used to suggest changes to Hoh's proposed level boundaries and to draw proposed PIO rating boundaries for the Category C phase of flight. Finally, it was pointed out several times that there is uncertainty as to whether or not the PIO rating scale is linear with respect to increasing PIO severity. Defining the relationship between PIO rating and some easily measurable parameter (such as pitch or normal acceleration) would greatly aid PIO research. Such a relationship would help in analyzing PIO ratings, pilot comments, and time history data to determine consistency among pilots. This might also help understand configurations with "clifflike" qualities; i.e., some pilots have no problems, but other pilots behave just slightly more aggressively and have severe problems.

One important question in PIO research remains unanswered, however. What really causes PIO? Are PIOs caused by the switch from tracking pitch to tracking acceleration at certain frequencies, as Smith proposes? The accurate PIO frequency predictions in this study certainly seem to add weight to his theory. Or are PIOs simply caused by large time delays, which can cause the pilot to become out of phase with his inputs, as Hoh's method suggests? This study showed that Hoh's method can predict PIO tendencies as well as Smith's, but with an entirely different premise. It is possible that the real cause is a combination of the two theories. Bandwidth and phase delay may in fact be related somehow to Smith's "switching" frequency. Further research using new and existing PIO data bases and simulator studies is warranted to determine a real understanding of the PIO phenomenon.

APPENDIX A

ESTIMATED STABILITY DERIVATIVES AND TRANSFER FUNCTIONS FOR THE LAHOS AND HAVE PIO CONFIGURATIONS

Overall Aircraft Configuration

The aircraft was always flown in the power approach configuration (gear down, flaps 30 degrees, speed brake extended). The only variation among approaches was the approach airspeed, which varied with aircraft weight (fuel remaining). These varying approach speeds are indicated below:

Fuel Remaining (Gals)	Approach Speed (KIAS)
150	125
250	130
350	135
450	140
550	140

A nominal touchdown speed of 120 KIAS (U_o=205 feet/second and W_o=25 feet/second) was used for defining the dynamic characteristics of both the LAHOS and HAVE PIO configurations. Other nominal aircraft characteristics are listed below.

n_z/α = 4.5 g/radian

τ_{θ_2} = 1.4 second

l_x = 6.43 feet (distance between center of gravity and pilot's station)

Phugoid characteristics:

ω_{ph} = 0.17 radian/second

ζ_{ph} = 0.15

τ_{θ_1} = 12 second

Lateral-directional characteristics:

$\omega_d = 1.3$ radian/second

$\zeta_d = 0.2$

$|\phi/\beta|_d = 1.5$

$\tau_s = 75$ second $\qquad \tau_s = 0.3$ second

Feel system characteristics:

Longitudinal: $\dfrac{\delta_{ES}}{F_{ES}} = \dfrac{0.125}{[0.6,26]}$ in/lb

Lateral: $\dfrac{\delta_{AS}}{F_{AS}} = \dfrac{0.25}{[0.7,26]}$ in/lb

Directional: $\dfrac{\delta_{RP}}{F_{RP}} = \dfrac{0.017}{[0.7,26]}$ in/lb

Actuators: $\dfrac{5625.0}{[0.7,75]}$

where

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

$(s) = (s+a)$

For LAHOS, the gearing ratio between the elevator and the stick position was selected by the pilot for each flight evaluation of a configuration. For HAVE PIO, the gearing ratio was selected for each configuration by the first pilot to fly it; on subsequent evaluations the gearing ratio remained set at the value initially selected.

LAHOS Configurations

The dynamics characteristics for the LAHOS configurations are shown in Table 26.

Table 26

LAHOS Dynamic Characteristics

Parameter	1-1	2-1	3-1	4-1	5-1	6-1 (YF-17)
ω_{sp}	1.03	2.30	2.19	2.00	3.90	1.94
ζ_{sp}	0.73	0.57	0.25	1.06	0.53	0.65
X_u	-0.041	-0.041	-0.041	-0.041	-0.041	-0.041
X_w	0.11	0.11	0.11	0.11	0.11	0.11
X_q	0.0	0.0	0.0	0.0	0.0	0.0
X_{δ_e}	0.0032	0.0032	0.0032	0.0032	0.0032	0.0032
Z_u	-0.25	-0.26	-0.26	-0.26	-0.26	-0.26
Z_w	-0.75	-0.75	-0.75	-0.75	-0.75	-0.75
Z_q	0.0	0.0	0.0	0.0	0.0	0.0
Z_{δ_e}	1.1	1.1	1.1	1.1	1.1	1.1
M_u	0.0	0.0	0.0	0.0	0.0	0.0
M_w	-0.00232	-0.01875	-0.02239	-0.00663	-0.05934	-0.01184
M_q	-0.76	-1.83	-0.29	-3.49	-3.25	-1.75
M_{δ_e}	0.33685	0.33685	0.33685	0.33685	0.33685	0.33685
Θ_0	4.5	4.5	4.5	4.5	4.5	4.5

Note that there are no values for $Z_{\dot{w}}$ and $M_{\dot{w}}$. These derivatives could not be determined directly with the parameter identification technique used by Calspan. $Z_{\dot{w}}$ was assumed to be zero, and $M_{\dot{w}}$ is effectively included in the derivatives above. For example, the M_q listed above is really the basic $M_q+U_oM_{\dot{w}}$ and M_w is the basic $M_w+M_wZ_{\dot{w}}$; i.e., M_q and M_w are considered "lumped" stability derivatives (6:211), as used in Section II.

The transfer functions for each of the configurations were obtained using equations [6], [7], [9], and [10] and are summarized below.

<u>LAHOS Configuration 1-1</u>

$$\Delta = [0.17,0.13][0.73,1.03]$$

$$N^{\theta}_{\delta_e} = 0.33685(0.0827)(0.7007)$$

$$N^{a_{z}p}_{\delta_e} = -1.066(0)(0.0266)[0.05,6.85]$$

$$N^{\theta}_{w_g} = -0.0037(0)[0.23,0.18]$$

<u>LAHOS Configuration 2-1</u>

$$\Delta = [0.15,0.17][0.57,2.30]$$

$$N^{\theta}_{\delta_e} = 0.33685(0.0848)(0.6950)$$

$$N^{a_{z}p}_{\delta_e} = -1.066(0)(0.0260)[-0.03,6.83]$$

$$N^{\theta}_{w_g} = -0.0089(0)(0.0817)(-1.359)$$

<u>LAHOS Configuration 3-1</u>

$$\Delta = [0.13,0.20][0.25,2.19]$$

$$N^{\theta}_{\delta_e} = 0.33685(0.0850)(0.6929)$$

$$N^{a_{z}p}_{\delta_e} = -1.066(0)(0.0260)[0.09,6.82]$$

$$N^{\theta}_{w_g} = -0.0014(0)(0.0389)(-15.1)$$

LAHOS Configuration 4-1

$$\Delta = [0.25,0.12](1.391)(2.841) = [0.25,0.12][1.06,2.0]$$

$$N^{\theta}_{\delta_e} = 0.33685(0.0848)(0.6946)$$

$$N^{a_{z}p}_{\delta_e} = -1.066(0)(0.0260)[-0.15,6.83]$$

$$N^{\theta}_{w_g} = -0.0170(0)[0.79,0.21]$$

LAHOS Configuration 5-1

$$\Delta = [0.15,0.18][0.53,3.89]$$

$$N^{\theta}_{\delta_e} \quad 0.33685(0.0859)(0.6813)$$

$$N^{a_{z}p}_{\delta_e} = -1.066(0)(0.0259)[-0.14,6.77]$$

$$N^{\theta}_{w_g} = -0.0159(0)(0.\text{[illegible]})(-2.8940)$$

LAHOS Configuration 6-1

$$\Delta = [0.15,0.16][0.65,1.94]$$

$$N^{\theta}_{\delta_e} = 0.33685(0.0853)(0.6870)$$

$$N^{a_{z}p}_{\delta_e} = -1.066(0)(0.0258)[-0.02,6.80]$$

$$N^{\theta}_{w_g} = -0.0085(0)(-0.0051)(-0.6528)$$

The flight control systems for the LAHOS configurations are shown in Table 27, and Table 28 shows the actual flight control system/aircraft dynamics combinations used. Configuration 6-1 was the original YF-17 configuration and 6-2 was the modified YF-17 configuration. These two configurations are described in the main body of the report.

Table 27

LAHOS Flight Control Systems

FIRST ORDER FILTERS

	A	B	C	1	2	3	4	5
K	2.5	3.0	5.0	1.0	10.0	4.0	2.0	1.0
τ_1	4.0	3.33	2.0	0.0	----	---	---	---
τ_2	10.0	10.0	10.0	0.0	10.0	4.0	2.0	1.0

SECOND AND FOURTH ORDER FILTERS

	6	7	8	9	10	11
K	256	144	81	36	16	65536
ζ_1	0.7	0.7	0.7	0.7	0.7	0.93
ω_{n_1}	16	12	9	6	4	16
ζ_2	---	---	---	---	---	0.38
ω_{n_2}	---	---	---	---	---	16

First order systems: $\dfrac{K(s+\tau_1)}{(s+\tau_2)}$

Second and fourth order systems: $\dfrac{K}{(s^2+2\zeta\omega_{n_1} s+\omega_{n_1}^2)(s^2+2\zeta\omega_{n_2} s+\omega_{n_2}^2)}$

Table 28

LAHOS Flight Control System and Aircraft Dynamics Combinations

Filter	Configuration 1	2	3	4	5
-A	X	X			
-B	X				
-C	X	X	X	X	
-1	X	X	X	X	X
-2	X	X	X		
-3	X	X	X	X	X
-4	X	X		X	X
-5					X
-6	X	X	X	X	X
-7		X	X	X	X
-8	X				
-9		X			
-10		X		X	
-11	X	X		X	X

HAVE PIO Configurations

In order to determine approximate stability derivatives for the HAVE PIO configurations, LAHOS 1-1 was used as a baseline configuration, and the feedback characteristics of the aircraft were used to estimate the new stability derivatives. The three stability derivatives which can be modified are Z_w, M_w, and M_q as

$$\begin{aligned} Z'_w &= Z_w - Z\delta_e K\alpha/U_o \\ M'_w &= M_w - M\delta_e K\alpha/U_o \\ M'_q &= M_q - M\delta_e K_q/U_o \end{aligned} \qquad [27]$$

The gains K_α and K_q are the feedback gains needed to get the desired stablity derivatives. Using the short period approximation, the stability derivatives in turn determine the short period damping ratio as

$$\omega_n^2 = Z'_w M'_q - M'_w U_o$$
$$2\zeta\omega_n = -M'_q - Z'_w \qquad [28]$$

Substituting LAHOS 1-1 values in [27] and then substituting the result into [28] gives:

small

$$\omega_n^2 = 1.04587 + 0.25264K_q + 0.34093K_\alpha + 0.00181K_\alpha K_q \qquad [29]$$
$$2\zeta\omega_n = 1.51 + 0.33685K_q + 1.1K_\alpha/205.0$$

[29] can then be solved for K_q and K_α for a given value of ζ and ω_n. K_q and K_α are then substituted back into [27] along with LAHOS 1-1 values to give

$$Z'_w = -0.75 - 1.1K_\alpha/205.0$$
$$M'_w = -0.0023213 - 0.33685K_\alpha/205.0 \qquad [30]$$
$$M'_q = -0.76 - 0.33685K_q$$

Equation [30] provides estimates of the stability derivatives required to give the desired values of ω_n and ζ. Note that K_α and K_q are meaningless except as a stepping stone to determine the new derivatives.

The above technique was tested using the remaining five LAHOS configurations. Using LAHOS 1-1 as a baseline configuration, the technique was able to estimate the stability derivatives for the remaining LAHOS configurations within five percent.

The technique was then applied to the desired short period characteristics of the HAVE PIO configurations. The dynamic characteristics of the HAVE PIO configurations are shown in Table 29. Note that HAVE PIO configuration 2-1 is very close to LAHOS configuration 2-1, and HAVE PIO configuration 5-1 is very close to LAHOS configuration 6-1 (YF-17).

Table 29

HAVE PIO Dynamic Characteristics

Parameter	2-1	3-1	4-1	5-1
ω_{sp}	2.41	4.22	3.04	1.70
ζ_{sp}	0.63	0.97	0.73	0.68
X_u	-0.041	-0.041	-0.041	-0.041
X_w	0.11	0.11	0.11	0.11
X_q	0.0	0.0	0.0	0.0
X_{δ_e}	0.0032	0.0032	0.0032	0.0032
Z_u	-0.26	-0.26	-0.26	-0.26
Z_w	-0.80642	-0.92116	-0.84168	-0.76979
Z_q	0.0	0.0	0.0	0.0
Z_{δ_e}	1.1	1.1	1.1	1.1
M_u	0.0	0.0	0.0	0.0
M_w	-0.01960	-0.05474	-0.03040	-0.00838
M_q	-2.26560	-7.27889	-3.59834	-1.54220
M_{δ_e}	0.33685	0.33685	0.33685	0.33685
Θ_0	4.5	4.5	4.5	4.5

The transfer functions for each of the configurations were obtained using equations [6], [7], [9], and [10] and are summarized below.

HAVE PIO Configuration 2-1

$$\Delta = [0.15, 0.17][0.63, 2.41]$$

$$N^{\theta}_{\delta_e} = 0.33685(0.0845)(0.6990)$$

$$N^{a_z p}_{\delta_e} = -1.063(0)(0.026)[-0.06, 6.86]$$

$$N^{\theta}_{w_g} \; -0.0111(0)(0.0108)(-1.019)$$

HAVE PIO Configuration 3-1

$$\Delta = [0.17, 0.16][0.97, 4.22]$$

$$N^{\theta}_{\delta_e} = 0.33685(0.08470(0.6987)$$

$$N^{a_z p}_{\delta_e} = -1.0626(0)(0.0262)[-0.44, 6.85]$$

$$N^{\theta}_{w_g} = -0.0355(0)(-0.6566)(-0.0048)$$

HAVE PIO Configuration 4-1

$$\Delta = [0.16, 0.16][0.73, 3.04]$$

$$N^{\theta}_{\delta_e} = 0.33685(0.0846)(0.6988)$$

$$N^{a_z p}_{\delta_e} = -1.0626(0)(0.0261)[-0.16, 6.86]$$

$$N^{\theta}_{w_g} = -0.0176(0)(0.0084)(-0.9395)$$

HAVE PIO Configuration 5-1

$$\Delta = [0.16, 0.15][0.68, 1.70]$$

$$N^{\theta}_{\delta_e} = 0.33685(0.0845)(0.6989)$$

$$N^{a_z p}_{\delta_e} = -1.0626(0)(0.0260)[-0.01, 6.86]$$

$$N^{\theta}_{w_g} = -0.0075(0)(-0.0422)(-0.3432)$$

APPENDIX B

PILOT COMMENT CARDS

This appendix contains the pilot comment cards for each configuration. The cards include all summarized comments, PIO and Cooper-Harper ratings, and information on the flight control system (FCS) used and the gearing selected. The FCS information is summarized in the same manner as the rest of the report:

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

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

INFLIGHT PILOT COMMENT CARD

FLT NO.= 3 RUN NO.= 4 ω_{nSP} = 2.4 DATE: 17MAY86
CONFIGURATION NO.= 2-B ζ_{SP} = 0.64 PILOT: A
GEARING = 0.170 FCS = 3.0(3.33)/(10.0) IP: PARRAG

PIO RATING = 3 C-H RATING = 7 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Light to medium forces
- PITCH SENSITIVITY: Medium pitch sensitivity

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Medium response rate
- FINAL RESPONSE: Medium response rate
- PREDICTABILITY: Less than satisfactory
- PILOT COMPENSATION: Reduced gain required
- PIO TENDENCY: Yes

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Adequate (± 500 feet) 50 % of time
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Medium
- AGGRESSIVENESS: Medium
- SPECIAL CONTROL: Reduced gain
- REASON APP. ABANDON: PIO

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: Light turbulence on final
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Poor pitch control in flare. Low amplitude, medium frequency PIO made touchdown accuracy difficult.
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO.= 17 RUN NO.= 1 ω_{nSP} = 2.4 DATE: 29MAY86
CONFIGURATION NO.= 2-B ζ_{SP} = 0.64 PILOT: B
GEARING = 0.170 FCS = 3.0(3.33)/(10.0) IP: HARPER

PIO RATING = 2 C-H RATING = 3 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium to heavy, no factor
- PITCH SENSITIVITY: Medium

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Fast
- FINAL RESPONSE: Fast
- PREDICTABILITY: Good
- PILOT COMPENSATION: Medium
- PIO TENDENCY: None

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: Medium gain
- SPECIAL CONTROL: Medium
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: Head wind at 10 kt gusting to 18 kt
- TURBULENCE: Light
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Undesirable jerky motion during flare, but no factor in achieving desired performance
- GOOD FEATURES: No PIO tendency noted, performs well except for flare.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 10 RUN NO.= 4 ω_{nSP} = 2.4 DATE: 22MAY86
CONFIGURATION NO.= 2-B ξ_{SP} = 0.64 PILOT: C
GEARING = 0.170 FCS = 3.0(3.33)/(10.0) IP: HARPER

PIO RATING = 2 C-H RATING = 3 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium
- PITCH SENSITIVITY: Medium pitch sensitivity

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Fast
- FINAL RESPONSE: Medium
- PREDICTABILITY: Satisfactory
- PILOT COMPENSATION: Medium compensation required to shape the inputs and lower gain.
- PIO TENDENCY: Slight

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired(± 5 kt)
- TOUCH DOWN POINT: Adequate (+ 500 feet) due to long flare
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: Very high
- SPECIAL CONTROL: Compensation required to lower gain during flare
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Small amplitude, high frequency oscillation tendency, did not affect task performance.
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO.= 15 RUN NO.= 4 ω_{nSP} = 2.4 DATE: 29MAY86
CONFIGURATION NO.= 2-B ξ_{SP} = 1.0 PILOT: C
GEARING = 0.170 FCS = 3.0(3.33)/(10.0) IP: HARPER

PIO RATING = 1 C-H RATING = 3 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium forces
- PITCH SENSITIVITY: High

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Fast
- FINAL RESPONSE: Fast
- PREDICTABILITY: Satisfactory
- PILOT COMPENSATION: Small control stick deflections in flare
- PIO TENDENCY: None

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet).
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: High gain
- SPECIAL CONTROL: None
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: None.
- GOOD FEATURES: Good flying qualities.

INFLIGHT PILOT COMMENT CARD

FLT NO.: 16	RUN NO.: 1	ω_{nSP} = 2.4	DATE: 29MAY86
CONFIGURATION NO.: 2-1		ζ_{SP} = 0.64	PILOT: A
GEARING = 0.170		FCS = 1	IP: EASTER

PIO RATING = 1 C-H RATING = 2 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium forces
- PITCH SENSITIVITY: Medium

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Medium to fast
- FINAL RESPONSE: Medium
- PREDICTABILITY: Excellent
- PILOT COMPENSATION: None
- PIO TENDENCY: None

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: Medium to high gain
- SPECIAL CONTROL: None
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS:

- GOOD FEATURES: Good flying qualities

INFLIGHT PILOT COMMENT CARD

FLT NO.: 6	RUN NO.: 3	ω_{nSP} = 2.4	DATE: 21MAY86
CONFIGURATION NO.: 2-1		ζ_{SP} = 0.64	PILOT: B
GEARING = 0.170		FCS = 1	IP: EASTER

PIO RATING = 1 C-H RATING = 2 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium forces
- PITCH SENSITIVITY: Medium pitch sensitivity

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Quick
- FINAL RESPONSE: Quick
- PREDICTABILITY: Good
- PILOT COMPENSATION: Not required
- PIO TENDENCY: None

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: Medium
- SPECIAL CONTROL: None
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: 70 degrees cross wind at 15 kt
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: None.

- GOOD FEATURES: Quick response. Corrections were quickly damped. Felt like normal flare except for quicker response.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 15	RUN NO.= 3	ω_{nSP} = 2.4	DATE: 29MAY86
CONFIGURATION NO.= 2-1		ζ_{SP} = 0.64	PILOT: C
GEARING = 0.170		FCS = 1	IP: HARPER

PIO RATING = 1 C-H RATING = 3 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium forces
- PITCH SENSITIVITY: Medium

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Medium
- FINAL RESPONSE: Medium
- PREDICTABILITY: Satisfactory
- PILOT COMPENSATION: None
- PIO TENDENCY: None

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: High gain
- SPECIAL CONTROL: A little lowered gain in flare
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: None.
- GOOD FEATURES: Good flying qualities.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 12	RUN NO.= 3	ω_{nSP} = 2.4	DATE: 27MAY86
CONFIGURATION NO.= 2-5		ζ_{SP} = 0.64	PILOT: A
GEARING = 0.250		FCS = 1.0/(1.0)	IP: HARPER

PIO RATING = 4 C-H RATING = 10 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium to heavy
- PITCH SENSITIVITY: Low to medium

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Sluggish
- FINAL RESPONSE: Slow to medium
- PREDICTABILITY: Unpredictable
- PILOT COMPENSATION: High gain shaping
- PIO TENDENCY: Low frequency PIO

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Adequate (± 500 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Dropped in
- AGGRESSIVENESS: High gain
- SPECIAL CONTROL: Lead compensation
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Low frequency, medium amplitude PIO in flare. High stick forces coupled with sluggish control led to quick out of phase PIO-not landable. Touchdowns occurred as PIO "bottomed out".
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO.= 17 RUN NO.= 3 ω_{nSP} = 2.4 DATE: 29MAY86
CONFIGURATION NO.= 2-5 ζ_{SP} = 0.64 PILOT: B
GEARING = 0.250 FCS = 1.0/(1.0) IP: HARPER

PIO RATING = 4 C-H RATING = 7 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium
- PITCH SENSITIVITY: Low

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Slow
- FINAL RESPONSE: Slow
- PREDICTABILITY: Poor
- PILOT COMPENSATION: High
- PIO TENDENCY: High

TASK PERFORMANCE :
- AIRSPEED CONTROL: Adequate(- 5 kt, + 10 kt)
- TOUCH DOWN POINT: Long
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Medium
- AGGRESSIVENESS: Medium gain
- SPECIAL CONTROL: High
- REASON APP. ABANDON: PIO

ADDITIONAL FACTORS :
- WIND: 210 / 10 G 18 kt
- TURBULENCE: Light
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Pilot out of phase. Low frequency wallowing motion. Very hard to control touch down point due to lag and overshoot. First approach divergent, next two were not divergent with considerable pilot compensation.
- GOOD FEATURES: Landed safely twice.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 11 RUN NO.= 3 ω_{nSP} = 2.4 DATE: 27MAY86
CONFIGURATION NO.= 2-5 ζ_{SP} = 0.64 PILOT: C
GEARING = 0.250 FCS = 1.0/(1.0) IP: EASTER

PIO RATING = 5 C-H RATING = 10 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium to heavy
- PITCH SENSITIVITY: Very low

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Very sluggish
- FINAL RESPONSE: Sluggish
- PREDICTABILITY: Very, very poor
- PILOT COMPENSATION: High
- PIO TENDENCY: High

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: No touch down
- RUNWAY ALIGNMENT: No touch down
- TOUCH DOWN SINK RATE: No touch down
- AGGRESSIVENESS: High
- SPECIAL CONTROL: Lowered gain to avoid oscillation
- REASON APP. ABANDON: Steady sustained oscillation on final. Divergent oscillation in flare

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Very slow frequency sustained oscillation on final approach, and divergent PIO in flare. Poor predictability and slow response in pitch.
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO.= 3 RUN NO.= 1 ω_{nSP} = 2.4 DATE: 17MAY86
CONFIGURATION NO.= 2-7 ζ_{SP} = 0.64 PILOT: A
GEARING = 0.170 FCS = 144/[0.7,12] IP: PARRAG

PIO RATING = 4 C-H RATING = 7 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Light forces
- PITCH SENSITIVITY: Sensitive in high gain

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Medium
- FINAL RESPONSE: Medium
- PREDICTABILITY: Satisfactory
- PILOT COMPENSATION: Satisfactory up to medium gain task
- PIO TENDENCY: Low

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: High gain
- SPECIAL CONTROL: Reduced gain during flare
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Using high gain in flare led to medium amplitude, high frequency PIO
- GOOD FEATURES: Good final approach handling

INFLIGHT PILOT COMMENT CARD

FLT NO.= 17 RUN NO.= 2 ω_{nSP} = 2.4 DATE: 29MAY86
CONFIGURATION NO.= 2-7 ζ_{SP} = 0.64 PILOT: B
GEARING = 0.170 FCS = 144/[0.7, 12] IP: HARPER

PIO RATING = 3 C-H RATING = 4 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium
- PITCH SENSITIVITY: Medium

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Slow
- FINAL RESPONSE: Medium
- PREDICTABILITY: Good
- PILOT COMPENSATION: Medium
- PIO TENDENCY: Low

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Medium
- AGGRESSIVENESS: Medium gain
- SPECIAL CONTROL: Medium
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: 210/10 G 18 kt
- TURBULENCE: Light
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Sluggish, low frequency pitch response with moderate lag. Not really PIO but small overshoots due to slow lagging response. Desired performance attainable, but deficiencies warrant improvement.
- GOOD FEATURES: Undesirable motion can be stopped in 1 to 2 cycles with moderate pilot compensation.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 10	RUN NO.= 2	ω_{nSP} = 2.4	DATE: 22MAY86
CONFIGURATION NO.= 2-7		ζ_{SP} = 0.64	PILOT: C
GEARING = 0.170		FCS = 144/[0.7, 12]	IP: HARPER

PIO RATING = 2 C-H RATING = 4 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium
- PITCH SENSITIVITY: Medium pitch sensitivity

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Medium
- FINAL RESPONSE: Medium
- PREDICTABILITY: Satisfactory
- PILOT COMPENSATION: Low compensation required
- PIO TENDENCY: Slight

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Less than adequate due to long flare
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: High
- SPECIAL CONTROL: Lower gain
- REASON APP ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Small amplitude, medium frequency oscillation in flare.
- GOOD FEATURES: Pilot could still control the aircraft effectively.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 8	RUN NO.= 1	ω_{nSP} = 2.4	DATE: 22MAY86
CONFIGURATION NO.= 2-8		ζ_{SP} = 0.64	PILOT: A
GEARING= 0.170		FCS = 81/[0.7, 9]	IP: HARPER

PIO RATING = 4 C-H RATING = 8 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium
- PITCH SENSITIVITY: High pitch sensitivity

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Medium
- FINAL RESPONSE: Medium
- PREDICTABILITY: Less than satisfactory
- PILOT COMPENSATION: Necessary to freeze stick inputs in flare to stop PIO.
- PIO TENDENCY: Moderate

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired(± 5 kt)
- TOUCH DOWN POINT: Less than adequate
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Medium
- AGGRESSIVENESS: Medium
- SPECIAL CONTROL: Stick freeze in flare to stop PIO
- REASON APP. ABANDON: PIO

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Low amplitude (± 2 degrees pitch), high frequency PIO in flare.
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO = 16	RUN NO.= 2	ω_{nSP} = 2.4	DATE: 29MAY86
CONFIGURATION NO.= 2-8		ζ_{SP} = 0.64	PILOT: A
GEARING = 0.170		FCS = 81/[0.7, 9]	IP: EASTER

PIO RATING = 4 C-H RATING = 10 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :

- FORCES: Medium to heavy forces
- PITCH SENSITIVITY: Low

PITCH ATTITUDE CONTROL :

- INITIAL RESPONSE: Sluggish
- FINAL RESPONSE: Sluggish
- PREDICTABILITY: Poor
- PILOT COMPENSATION: High compensation required
- PIO TENDENCY: Medium to high

TASK PERFORMANCE :

- AIRSPEED CONTROL: N/A
- TOUCH DOWN POINT: N/A
- RUNWAY ALIGNMENT: N/A
- TOUCH DOWN SINK RATE: N/A
- AGGRESSIVENESS: High gain
- SPECIAL CONTROL: High gain
- REASON APP. ABANDON: PIO

ADDITIONAL FACTORS :

- WIND: No factor
- TURBULENCE: PIO even in turbulence
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :

- MAJOR PROBLEMS: Aircraft motion lags control inputs. Any pitch inputs led to low frequency, medium amplitude PIO. PIO's up and away on downwind.
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO.= 5	RUN NO.= 1	ω_{nSP} = 2.4	DATE: 21MAY86
CONFIGURATION NO.= 2-8		ζ_{SP} = 0.64	PILOT: C
GEARING = 0.170		FCS = 81/[0.7, 9]	IP: EASTER

PIO RATING = 4 C-H RATING = 8 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :

- FORCES: Medium forces
- PITCH SENSITIVITY: Medium pitch sensitivity

PITCH ATTITUDE CONTROL :

- INITIAL RESPONSE: Medium response rate
- FINAL RESPONSE: Medium response rate
- PREDICTABILITY: Satisfactory
- PILOT COMPENSATION: Reduced gain required with PIO
- PIO TENDENCY: Medium

TASK PERFORMANCE :

- AIRSPEED CONTROL: Adequate (- 5 kt, + 10 kt)
- TOUCH DOWN POINT: No touch down
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: No touch down
- AGGRESSIVENESS: Very high
- SPECIAL CONTROL: Lower the gain
- REASON APP. ABANDON: PIO

ADDITIONAL FACTORS :

- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :

- MAJOR PROBLEMS: PIO tendency. Freezing stick often necessary to stop PIOs. Medium frequency, low amplitude motion, not divergent.
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO.= 7   RUN NO.= 4 ω_{nSP} = 4.1   DATE: 21MAY86
CONFIGURATION NO.= 3-D ζ_{SP} = 1.0   PILOT: A
GEARING = 0.500   FCS = 0.5(20.0)/(10.0)   IP: HARPER

PIO RATING = 1   C-H RATING = 2   CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Light to medium forces
- PITCH SENSITIVITY: Medium pitch sensitivity

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Quick
- FINAL RESPONSE: Quick
- PREDICTABILITY: Satisfactory
- PILOT COMPENSATION: Not required
- PIO TENDENCY: None

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: Low
- SPECIAL CONTROL: None
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: None.
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO.= 14   RUN NO.= 4 ω_{nSP} = 4.1   DATE: 27MAY86
CONFIGURATION NO.= 3-D ζ_{SP} = 1.0   PILOT: C
GEARING = 0.500   FCS = 0.5(20.0)/(10.0)   IP: EASTER

PIO RATING = 1   C-H RATING = 2   CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium
- PITCH SENSITIVITY: Medium to high

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Fast
- FINAL RESPONSE: Medium
- PREDICTABILITY: Satisfactory
- PILOT COMPENSATION: None
- PIO TENDENCY: None

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: High
- SPECIAL CONTROL: None
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS:
- GOOD FEATURES: Aircraft flew well both final and flare. Aircraft responds well to pilot

INFLIGHT PILOT COMMENT CARD

FLT NO.= 12	RUN NO.= 1	ω_{nSP} = 4.1	DATE: 27MAY86
CONFIGURATION NO.= 3-1		ζ_{SP} = 1.0	PILOT: A
GEARING = 0.421		FCS = 1	IP: HARPER

PIO RATING = 3 C-H RATING = 5 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :

- FORCES: Light to medium
- PITCH SENSITIVITY: Medium

PITCH ATTITUDE CONTROL :

- INITIAL RESPONSE: Medium
- FINAL RESPONSE: Medium
- PREDICTABILITY: Satisfactory except in flare
- PILOT COMPENSATION: Lower gain
- PIO TENDENCY: Light low frequency bobble in flare

TASK PERFORMANCE :

- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Adequate (± 500 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: High gain
- SPECIAL CONTROL: Reduced gain
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :

- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :

- MAJOR PROBLEMS: Low frequency, small amplitude bobble degraded spot landing.
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO.= 9	RUN NO.= 4	ω_{nSP} = 4.1	DATE: 22MAY86
CONFIGURATION NO.= 3-1		ζ_{SP} = 1.0	PILOT: B
GEARING = 0.421		FCS = 1	IP: EASTER

PIO RATING = 2 C-H RATING = 3 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :

- FORCES: Medium forces
- PITCH SENSITIVITY: Slightly high pitch sensitivity

PITCH ATTITUDE CONTROL :

- INITIAL RESPONSE: Quick response
- FINAL RESPONSE: Quick response
- PREDICTABILITY: Good
- PILOT COMPENSATION: Slight compensation required to set pitch attitude
- PIO TENDENCY: None

TASK PERFORMANCE :

- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: Medium
- SPECIAL CONTROL: Had to position nose of aircraft with small pitch corrections
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :

- WIND: 2 kt tail wind
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :

- MAJOR PROBLEMS: Pitch movement characterized by small jerky motions, did not affect task performance.
- GOOD FEATURES: No lag or delay was noted. The motion was fast with no residual overshoots.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 11 RUN NO.= 1 ω_{nSP} = 4.1 DATE: 27MAY86
CONFIGURATION NO. = 3-1 ξ_{SP} = 1.0 PILOT: C
GEARING = 0.421 FCS = 1 IP: EASTER

PIO RATING = 2 C-H RATING = 4 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium
- PITCH SENSITIVITY: Medium

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Medium
- FINAL RESPONSE: Medium
- PREDICTABILITY: Less than satisfactory due to overshoots
- PILOT COMPENSATION: Low to medium gain shaping
- PIO TENDENCY: Low

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Adequate (± 500 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Medium
- AGGRESSIVENESS: Medium gain
- SPECIAL CONTROL: Lower gain
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Medium frequency sustained oscillation.
- GOOD FEATURES: The amplitude of the oscillation was small and pilot could control the aircraft through the oscillation.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 16 RUN NO.= 3 ω_{nSP} = 4.1 DATE: 29MAY86
CONFIGURATION NO.= 3-3 ξ_{SP} = 1.0 PILOT: A
GEARING = 0.421 FCS = 4.0/(4.0) IP: EASTER

PIO RATING = 3 C-H RATING = 7 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium
- PITCH SENSITIVITY: Low to medium

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Slow to medium
- FINAL RESPONSE: Slow
- PREDICTABILITY: Poor
- PILOT COMPENSATION: Stairstep aircraft down to touchdown
- PIO TENDENCY: Low

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Dropped in
- AGGRESSIVENESS: High
- SPECIAL CONTROL: Stairstep flare to landing
- REASON APP. ABANDON: Handling qualities

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Dropped in flare.
  Low amplitude medium frequency bobble in flare.
  Time lag between input and aircraft response.
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO.= 9 RUN NO.= 1 ω_{nSP} = 4.1 DATE: 22MAY86
CONFIGURATION NO.= 3-3 ζ_{SP} = 1.0 PILOT: B
GEARING = 0.421 FCS = 4.0/(4.0) IP: EASTER

PIO RATING = 1 C-H RATING = 2 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium forces
- PITCH SENSITIVITY: Medium pitch sensitivity

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Quick
- FINAL RESPONSE: Quick
- PREDICTABILITY: Satisfactory
- PILOT COMPENSATION: Not required
- PIO TENDENCY: None

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: Medium
- SPECIAL CONTROL: None
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: 2 kt tail wind
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: None.
- GOOD FEATURES: Overall, no delay or lag was noted.
Pilot felt in phase with input.
Intentional inputs during flare did not induce PIO.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 15 RUN NO.= 1 ω_{nSP} = 4.1 DATE: 29MAY86
CONFIGURATION NO.= 3-3 ζ_{SP} = 1.0 PILOT: C
GEARING = 0.421 FCS = 4.0/(4.0) IP: HARPER

PIO RATING = 1 C-H RATING = 3 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium forces
- PITCH SENSITIVITY: Medium

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Medium
- FINAL RESPONSE: Medium
- PREDICTABILITY: Satisfactory
- PILOT COMPENSATION: None
- PIO TENDENCY: None

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Long due to high airspeed
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: High gain
- SPECIAL CONTROL: None
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS:
- GOOD FEATURES: Good flying qualities.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 7 RUN NO = 1 ω_{nSP} = 4.1 DATE: 21MAY86
CONFIGURATION NO.= 3-6 ξ_{SP} = 1.0 PILOT: A
GEARING = 0.421 FCS = $\cdot$256/[0.7, 16] IP: HARPER

PIO RATING = 2 C-H RATING = 5 CONFIDENCE RATING = B

FEEL SYSTEM CHARACTERISTICS :
- •FORCES: Medium to high forces
- •PITCH SENSITIVITY: Medium pitch sensitivity

PITCH ATTITUDE CONTROL :
- •INITIAL RESPONSE: Slow and sluggish
- •FINAL RESPONSE: Medium
- •PREDICTABILITY: Less than satisfactory
- •PILOT COMPENSATION: Gains reduced slightly
- •PIO TENDENCY: Slight

TASK PERFORMANCE :
- •AIRSPEED CONTROL: Desired (± 5 kt)
- •TOUCH DOWN POINT: Adequate (± 500 feet)
- •RUNWAY ALIGNMENT: Desired (± 5 feet)
- •TOUCH DOWN SINK RATE: Low
- •AGGRESSIVENESS: Medium
- •SPECIAL CONTROL: None
- •REASON APP. ABANDON: Handling qualities; high pitch force

ADDITIONAL FACTORS :
- •WIND: 50 degrees cross wind at 15 kt
- •TURBULENCE: No factor
- •LAT-DIR PERFORMANCE: Light roll ratchet noticed in offset correction

SUMMARIZE EVALUATION :
- •MAJOR PROBLEMS: High stick forces. Confidence rating B due to cross wind and heavy fuel weight.
- •GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO.= 14 RUN NO.= 1 ω_{nSP} = 4.1 DATE: 28MAY86
CONFIGURATION NO.= 3-6 ξ_{SP} = 1.0 PILOT: C
GEARING = 0.421 FCS = 256/[0.7, 16] IP: EASTER

PIO RATING = 2 C-H RATING = 4 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- •FORCES: Medium
- •PITCH SENSITIVITY: Medium to high

PITCH ATTITUDE CONTROL :
- •INITIAL RESPONSE: Fast
- •FINAL RESPONSE: Medium
- •PREDICTABILITY: A little bobble tendency in flare
- •PILOT COMPENSATION: Low gain shaping
- •PIO TENDENCY: Low. A little bobble tendency in flare

TASK PERFORMANCE :
- •AIRSPEED CONTROL: Desired (± 5 kt)
- •TOUCH DOWN POINT: Long due to flare
- •RUNWAY ALIGNMENT: Desired (± 5 feet)
- •TOUCH DOWN SINK RATE: Smooth
- •AGGRESSIVENESS: Medium gain
- •SPECIAL CONTROL: Lower gain to avoid undesired motion
- •REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- •WIND: No factor (tail wind at 4 kt)
- •TURBULENCE: No factor
- •LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- •MAJOR PROBLEMS: Aircraft showed undesirable bobbling motion under high gain, so pilot was required to lower the gain.
- •GOOD FEATURES: Good aircraft until flare

INFLIGHT PILOT COMMENT CARD

FLT NO.= 8 RUN NO.= 3 ω_{nSP} = 4.1 DATE: 22MAY86
CONFIGURATION NO.= 3-8 ζ_{SP} = 1.0 PILOT: A
GEARING= 0.421 FCS = 81/(0.7, 9) IP: HARPER

PIO RATING = 4 C-H RATING = 8 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :

- FORCES: Light to medium
- PITCH SENSITIVITY: Medium pitch sensitivity

PITCH ATTITUDE CONTROL :

- INITIAL RESPONSE: Medium
- FINAL RESPONSE: Medium
- PREDICTABILITY: Less than satisfactory
- PILOT COMPENSATION: Reduced gain required
- PIO TENDENCY: Moderate

TASK PERFORMANCE :

- AIRSPEED CONTROL: Desired(± 5 kt)
- TOUCH DOWN POINT: Less than adequate
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: High
- AGGRESSIVENESS: Medium
- SPECIAL CONTROL: Reduced gain in flare
- REASON APP. ABANDON: PIO

ADDITIONAL FACTORS :

- WIND: No factor
- TURBULENCE: Slight turbulence induced oscillations
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :

- MAJOR PROBLEMS: Sustained medium amplitude, medium frequency PIO during light control (lightly damped).
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO.= 13 RUN NO.= 3 ω_{nSP} = 4.1 DATE: 27MAY86
CONFIGURATION NO.= 3-8 ζ_{SP} = 1.0 PILOT: B
GEARING = 0.421 FCS = 81/(0.7, 9) IP: EASTER

PIO RATING = 3 C-H RATING = 5 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :

- FORCES: Medium
- PITCH SENSITIVITY: Medium

PITCH ATTITUDE CONTROL :

- INITIAL RESPONSE: Fast
- FINAL RESPONSE: Medium
- PREDICTABILITY: Fair
- PILOT COMPENSATION: Freeze stick to stop movement
- PIO TENDENCY: Medium

TASK PERFORMANCE :

- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Long
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: Medium gain
- SPECIAL CONTROL: None
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :

- WIND: No factor
- TURBULENCE: Light
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :

- MAJOR PROBLEMS: More of an undesireable motion then PIO. High frequency, low amplitude bobbling during small corrections in flare. This made touchdown point accuracy more difficult. No delays or lag noted. Motions were too jerky for landing.
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO.= 5	RUN NO.= 3	ω_{nSP} = 4.1	DATE: 21MAY86
CONFIGURATION NO.= 3-8		ζ_{SP} = 1.0	PILOT: C
GEARING = 0.421		FCS = 81/[0.7, 9]	IP: EASTER

PIO RATING = 4 C-H RATING = 8 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium forces
- PITCH SENSITIVITY: Medium pitch sensitivity

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Medium response rate
- FINAL RESPONSE: Medium response rate
- PREDICTABILITY: Satisfactory
- PILOT COMPENSATION: Reduced gain required
- PIO TENDENCY: Medium

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: No touch down
- RUNWAY ALIGNMENT: No touch down
- TOUCH DOWN SINK RATE: No touch down
- AGGRESSIVENESS: Very high
- SPECIAL CONTROL: Lower gain
- REASON APP. ABANDON: PIO

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Sustained, high frequency, medium amplitude PIO in flare.
- GOOD FEATURES: Good control harmony and coordination

INFLIGHT PILOT COMMENT CARD

FLT NO.= 9	RUN NO.= 2	ω_{nSP} = 4.1	DATE: 22MAY86
CONFIGURATION NO.= 3-12		ζ_{SP} = 1.0	PILOT: B
GEARING = 0.421		FCS = 4/[0.7, 2]	IP: EASTER

PIO RATING = 4 C-H RATING = 7 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium forces
- PITCH SENSITIVITY: Medium pitch sensitivity

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Sluggish response
- FINAL RESPONSE: Sluggish response
- PREDICTABILITY: Poor
- PILOT COMPENSATION: Lead compensation required
- PIO TENDENCY: High

TASK PERFORMANCE :
- AIRSPEED CONTROL: Less than adequate
- TOUCH DOWN POINT: Less than adequate
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Medium
- AGGRESSIVENESS: Medium to high
- SPECIAL CONTROL: Let go of stick to stop PIO
- REASON APP. ABANDON: PIO

ADDITIONAL FACTORS :
- WIND: 2 kt tail wind
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Low frequency PIO. Pilot was out of phase during round-out to flare, ± 5 degrees pitch, did not seem divergent. Aircraft response was sluggish and lagging.
- GOOD FEATURES: This low frequency PIO probably could be controlled with practice.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 15	RUN NO.= 2	ω_{nSP} = 4.1	DATE: 29MAY86
CONFIGURATION NO.= 3-12		ξ_{SP} = 1.0	PILOT: C
GEARING = 0.421		FCS = 4/[0.7, 2]	IP: HARPER

PIO RATING = 5 | C-H RATING = 9 | CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS:
- FORCES: Medium forces
- PITCH SENSITIVITY: Low

PITCH ATTITUDE CONTROL:
- INITIAL RESPONSE: Sluggish
- FINAL RESPONSE: Sluggish
- PREDICTABILITY: Poor
- PILOT COMPENSATION: High degree of compensation
- PIO TENDENCY: High

TASK PERFORMANCE:
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: No touch down
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: No touch down
- AGGRESSIVENESS: High gain
- SPECIAL CONTROL: N/A
- REASON APP. ABANDON: Divergent low frequency PIO

ADDITIONAL FACTORS:
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION:
- MAJOR PROBLEMS: Slow response and time lag caused a low frequency divergent PIO
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO.= 7	RUN NO.= 2	ω_{nSP} = 4.1	DATE: 21MAY86
CONFIGURATION NO.= 3-13		ξ_{SP} = 1.0	PILOT: A
GEARING = 0.421		FCS = 9/[0.7, 3]	IP: HARPER

PIO RATING = 4 | C-H RATING = 10 | CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS:
- FORCES: Light forces
- PITCH SENSITIVITY: Medium to high pitch sensitivity

PITCH ATTITUDE CONTROL:
- INITIAL RESPONSE: Slow and sluggish
- FINAL RESPONSE: Medium
- PREDICTABILITY: Less than satisfactory
- PILOT COMPENSATION: Had to freeze stick to eliminate PIO
- PIO TENDENCY: High

TASK PERFORMANCE:
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: No touch down
- RUNWAY ALIGNMENT: No touch down
- TOUCH DOWN SINK RATE: No touch down
- AGGRESSIVENESS: Slightly aggressive
- SPECIAL CONTROL: Freeze stick in flare
- REASON APP. ABANDON: PIO

ADDITIONAL FACTORS:
- WIND: 60 degrees cross wind at 10 gusting to 18 kt
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION:
- MAJOR PROBLEMS: Medium frequency, medium amplitude (± 5 degrees pitch) sustained PIO in flare.
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO.= 14 RUN NO.= 3 ω_{nSP} = 4.1 DATE: 27MAY86
CONFIGURATION NO.= 3-13 ζ_{SP} = 1.0 PILOT: C
GEARING = 0.421 FCS = 9/[0.7, 3] IP: EASTER

PIO RATING = 5 C-H RATING = 10 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium to heavy
- PITCH SENSITIVITY: Low

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Sluggish
- FINAL RESPONSE: Sluggish
- PREDICTABILITY: Poor
- PILOT COMPENSATION: High, to input a lower stick gain
- PIO TENDENCY: High

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: No touch down
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: No touch down
- AGGRESSIVENESS: High
- SPECIAL CONTROL: Lowered gain in flare
- REASON APP. ABANDON: Divergent PIO on flare

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Aircraft entered divergent low frequency PIO during flare.
- GOOD FEATURES: Aircraft flew well on final.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 7 RUN NO.= 3 ω_{nSP} = 3.0 DATE: 21MAY86
CONFIGURATION NO.= 4-1 ζ_{SP} = 0.74 PILOT: A
GEARING = 0.200 FCS = 1 IP: HARPER

PIO RATING = 1 C-H RATING = 3 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Light to medium forces
- PITCH SENSITIVITY: Medium pitch sensitivity

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Quick
- FINAL RESPONSE: Quick
- PREDICTABILITY: Desired
- PILOT COMPENSATION: Not required
- PIO TENDENCY: None

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Long due to gusty wind
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: Medium
- SPECIAL CONTROL: None
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: 50 degrees cross wind at 6 gusting to 14 kt
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: None.
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO.= 17 RUN NO= 4 ω_{nSP} = 3.0 DATE: 29MAY86
CONFIGURATION NO.= 4-1 ζ_{SP} = 0.74 PILOT: B
GEARING = 0.200 FCS = 1 IP: HARPER

PIO RATING = 1 C-H RATING = 2 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS:
- FORCES: Medium
- PITCH SENSITIVITY: Medium

PITCH ATTITUDE CONTROL:
- INITIAL RESPONSE: Medium
- FINAL RESPONSE: Medium
- PREDICTABILITY: Good
- PILOT COMPENSATION: Low
- PIO TENDENCY: None

TASK PERFORMANCE:
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: Medium gain
- SPECIAL CONTROL: None
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS:
- WIND: 210 / 10 G 18
- TURBULENCE: Moderate
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION:
- MAJOR PROBLEMS: None
- GOOD FEATURES: Felt like normal aircraft. No problems noted.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 4 RUN NO.= 1 ω_{nSP} = 3.0 DATE: 17MAY86
CONFIGURATION NO.= 4-1 ζ_{SP} = 0.74 PILOT: C
GEARING = 0.200 FCS = 1 IP: EASTER

PIO RATING = 1 C-H RATING = 3 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS:
- FORCES: Light forces
- PITCH SENSITIVITY: Medium

PITCH ATTITUDE CONTROL:
- INITIAL RESPONSE: Medium
- FINAL RESPONSE: Medium
- PREDICTABILITY: Satisfactory
- PILOT COMPENSATION: A little reduced gain required
- PIO TENDENCY: None

TASK PERFORMANCE:
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Adequate (± 500 feet) 50 % of time
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Medium
- AGGRESSIVENESS: High
- SPECIAL CONTROL: Reduced gain
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS:
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION:
- MAJOR PROBLEMS: Aircraft tended to float. Adequate performance due to long flare, not a function of aircraft response.
- GOOD FEATURES: Good control harmony and coordination.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 16 RUN NO.= 4 ω_{nSP} = 3.0 DATE: 29MAY86
CONFIGURATION NO.= 4-2 ξ_{SP} = 0.74 PILOT: A
GEARING = 0.200 FCS = 10.0/(10.0) IP: EASTER

PIO RATING = 1 C-H RATING = 3 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS:
- FORCES: Medium
- PITCH SENSITIVITY: Medium

PITCH ATTITUDE CONTROL:
- INITIAL RESPONSE: Medium
- FINAL RESPONSE: Medium
- PREDICTABILITY: Good
- PILOT COMPENSATION: Low
- PIO TENDENCY: None

TASK PERFORMANCE:
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: Medium gain
- SPECIAL CONTROL: None
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS:
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION:
- MAJOR PROBLEMS:
- GOOD FEATURES: Flies like normal aircraft

INFLIGHT PILOT COMMENT CARD

FLT NO.= 9 RUN NO.= 3 ω_{nSP} = 3.0 DATE: 22MAY86
CONFIGURATION NO.= 4-2 ξ_{SP} = 0.74 PILOT: B
GEARING = 0.200 FCS = 10.0/(10.0) IP EASTER

PIO RATING = 1 C-H RATING = 3 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS:
- FORCES: Medium forces
- PITCH SENSITIVITY: Medium pitch sensitivity

PITCH ATTITUDE CONTROL:
- INITIAL RESPONSE: Quick response
- FINAL RESPONSE: Quick response
- PREDICTABILITY: Good
- PILOT COMPENSATION: Not required
- PIO TENDENCY: None

TASK PERFORMANCE:
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: Low to medium
- SPECIAL CONTROL: Not required
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS:
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION:
- MAJOR PROBLEMS: None.
- GOOD FEATURES: Initial response was fast with no lag or delay. No overshoots were observed. Small corrections during flare did not induce PIO or undesireable motion.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 14 RUN NO.= 2 ω_{nSP} = 3.0 DATE: 28MAY86
CONFIGURATION NO.= 4-2 ζ_{SP} = 0.74 PILOT: C
GEARING = 0.200 FCS = 10.0/(10.0) IP: EASTER

PIO RATING = 2 C-H RATING = 4 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- •FORCES: Medium
- •PITCH SENSITIVITY: Low to medium

PITCH ATTITUDE CONTROL :
- •INITIAL RESPONSE: Sluggish
- •FINAL RESPONSE: Medium
- •PREDICTABILITY: A little bobble tendency at initial response during flare
- •PILOT COMPENSATION: Low gain
- •PIO TENDENCY: A little undesired bobble in flare

TASK PERFORMANCE :
- •AIRSPEED CONTROL: Desired (± 5 kt)
- •TOUCH DOWN POINT: Desired (± 250 feet)
- •RUNWAY ALIGNMENT: Desired (± 5 feet)
- •TOUCH DOWN SINK RATE: Medium
- •AGGRESSIVENESS: Medium gain
- •SPECIAL CONTROL: Lower gain input required
- •REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- •WIND: No factor
- •TURBULENCE: No factor
- •LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- •MAJOR PROBLEMS: Undesirable, medium frequency bobble motion during flare. Aircraft initial response tended to be slow.
- •GOOD FEATURES

INFLIGHT PILOT COMMENT CARD

FLT NO.= 3 RUN NO.= 3 ω_{nSP} = 1.7 DATE: 17MAY86
CONFIGURATION NO.= 5-1 ζ_{SP} = 0.68 PILOT: A
GEARING = 0.100 FCS = 1 IP: PARRAG

PIO RATING = 1 C-H RATING = 2 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- •FORCES: Light forces
- •PITCH SENSITIVITY: Low to medium pitch sensitivity

PITCH ATTITUDE CONTROL :
- •INITIAL RESPONSE: Medium response rate
- •FINAL RESPONSE: Medium response rate
- •PREDICTABILITY: Satisfactory
- •PILOT COMPENSATION: Not required
- •PIO TENDENCY: None

TASK PERFORMANCE :
- •AIRSPEED CONTROL: Desired (± 5 kt)
- •TOUCH DOWN POINT: Desired (± 250 feet)
- •RUNWAY ALIGNMENT: Desired (± 5 feet)
- •TOUCH DOWN SINK RATE: Low
- •AGGRESSIVENESS: Medium
- •SPECIAL CONTROL: None
- •REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- •WIND: No factor
- •TURBULENCE: No factor
- •LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- •MAJOR PROBLEMS: None
- •GOOD FEATURES: No PIO tendency

INFLIGHT PILOT COMMENT CARD

FLT NO.= 10 RUN NO.= 1 ω_{nSP} = 1.7 DATE: 22MAY86
CONFIGURATION NO.= 5-1 ξ_{SP} = 0.68 PILOT: C
GEARING = 0.100 FCS = 1 IP HARPER

PIO RATING = 1 C-H RATING = 5 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium to heavy forces
- PITCH SENSITIVITY: Medium pitch sensitivity

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Medium
- FINAL RESPONSE: Medium
- PREDICTABILITY: Satisfactory
- PILOT COMPENSATION: Not required
- PIO TENDENCY: None

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Longer than adequate
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: High
- SPECIAL CONTROL: Small conpensation required to avoid float
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Desired performance not attainable due to float tendency in flare. No undesirable motions or PIOs were noted.
- GOOD FEATURES

INFLIGHT PILOT COMMENT CARD

FLT NO.= 8 RUN NO.= 2 ω_{nSP} = 1.7 DATE: 22MAY86
CONFIGURATION NO.= 5-9 ξ_{SP} = 0.68 PILOT: A
GEARING= 0.100 FCS = 36/(0.7, 6) IP: HARPER

PIO RATING = 4 C-H RATING = 7 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium
- PITCH SENSITIVITY: High pitch sensitivity

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Medium to fast
- FINAL RESPONSE: Medium to fast
- PREDICTABILITY: Less than satisfactory
- PILOT COMPENSATION: Reduced gain required
- PIO TENDENCY: Yes. With high gain input.

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired(± 5 kt)
- TOUCH DOWN POINT: Less than adequate
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Medium
- AGGRESSIVENESS: Medium
- SPECIAL CONTROL: Stick freeze in flare to stop PIO
- REASON APP. ABANDON: PIO

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: Slight turbulence induced oscillations
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Medium amplitude (± 5 degrees pitch), high frequency PIO with tight control.
- GOOD FEATURES: PIO quickly dies out with reduced inputs.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 13 RUN NO.= 4 ω_{nSP} = 1.7 DATE: 27MAY86
CONFIGURATION NO.= 5-9 ζ_{SP} = 0.68 PILOT: B
GEARING = 0.100 FCS = 36/(0.7, 6) IP: EASTER

PIO RATING = 5 C-H RATING = 8 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Heavier gradient than desired, didn't affect performance
- PITCH SENSITIVITY: Low

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Slow
- FINAL RESPONSE: Slow
- PREDICTABILITY: Poor
- PILOT COMPENSATION: High
- PIO TENDENCY: High

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Less than adequate
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: High
- SPECIAL CONTROL: Freeze stick to stop PIO
- REASON APP. ABANDON: PIO

ADDITIONAL FACTORS :
- WIND: No factor (head wind at 10 kt)
- TURBULENCE: Light
- LAT-DIR PERFORMANCE: Slow, some nose wonder.

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Sluggish response on final. During flare, got out of phase with inputs and response. Oscillations were low frequency and starting to become divergent. Very difficult to put on the ground. Lag was noticeable on final but was only a problem during flare.
- GOOD FEATURES: High stick forces were not a factor during flare.

INFLIGHT PILOT COMMENT CARD

FLT NO.= 5 RUN NO.= 2 ω_{nSP} = 1.7 DATE: 21MAY86
CONFIGURATION NO.= 5-9 ζ_{SP} = 0.68 PILOT: C
GEARING = 0.100 FCS = 36/(0.7, 6) IP: EASTER

PIO RATING = 4 C-H RATING = 7 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium forces
- PITCH SENSITIVITY: Medium pitch sensitivity

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Low response rate
- FINAL RESPONSE: Medium response rate
- PREDICTABILITY: Satisfactory
- PILOT COMPENSATION: Reduced gain required with PIO
- PIO TENDENCY: Medium

TASK PERFORMANCE :
- AIRSPEED CONTROL: Adequate (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: High sink rate
- AGGRESSIVENESS: High
- SPECIAL CONTROL: Lower gain to control PIO
- REASON APP. ABANDON: PIO (1 of 3 approaches)

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Low frequency PIO during flare. Had to freeze stick and let aircraft drop to hit touch down point, not desirable.
- GOOD FEATURES: Good control harmony and coordination

INFLIGHT PILOT COMMENT CARD

FLT NO = 3 RUN NO = 2	ω_{nSP} = 1.7	DATE: 17MAY86
CONFIGURATION NO = 5-10	ζ_{SP} = 0.68	PILOT: A
GEARING = 0.100	FCS = 16/[0.7,4]	IP: PARRAG

PIO RATING = 5   C-H RATING = 10   CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Light forces
- PITCH SENSITIVITY: Medium to high sensitivity

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Sluggish
- FINAL RESPONSE: Abrupt
- PREDICTABILITY: Poor
- PILOT COMPENSATION: Required pilot to lead inputs due to sluggishness
- PIO TENDENCY: High

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: No touch down
- RUNWAY ALIGNMENT: No touch down
- TOUCH DOWN SINK RATE: No touch down
- AGGRESSIVENESS: High
- SPECIAL CONTROL: No flare
- REASON APP. ABANDON: PIO

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Large amplitude (± 10 degrees pitch), low frequency PIO in flare. Apparent time delay in system response
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO = 10 RUN NO = 3	ω_{nSP} = 1.7	DATE: 22MAY86
CONFIGURATION NO = 5-10	ζ_{SP} = 0.68	PILOT: C
GEARING = 0.100	FCS = 16/[0.7, 4]	IP: HARPER

PIO RATING = 5   C-H RATING = 10   CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :
- FORCES: Medium
- PITCH SENSITIVITY: Low pitch sensitivity

PITCH ATTITUDE CONTROL :
- INITIAL RESPONSE: Sluggish
- FINAL RESPONSE: Slow
- PREDICTABILITY: Poor due to time lag
- PILOT COMPENSATION: Freeze stick to stop PIO
- PIO TENDENCY: High

TASK PERFORMANCE :
- AIRSPEED CONTROL: Desired(± 5 kt)
- TOUCH DOWN POINT: No touch down
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: No touch down
- AGGRESSIVENESS: High
- SPECIAL CONTROL: Reduced gain input required during flare
- REASON APP. ABANDON: Divergent PIO

ADDITIONAL FACTORS :
- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :
- MAJOR PROBLEMS: Low frequency divergent PIO. Pilot felt out of phase.
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO = 12 RUN NO = 2 ω_{nSP} = 1.7 DATE: 27MAY86
CONFIGURATION NO. = 5-11 ζ_{SP} = 0.68 PILOT: A
GEARING = 0.100 FCS = 65536/[0.93,16][0.38,16] IP: HARPER

PIO RATING = 2 C-H RATING = 7 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :

- FORCES: Heavy
- PITCH SENSITIVITY: Low

PITCH ATTITUDE CONTROL :

- INITIAL RESPONSE: Sluggish
- FINAL RESPONSE: Sluggish
- PREDICTABILITY: Satisfactory
- PILOT COMPENSATION: Lead input
- PIO TENDENCY: Low

TASK PERFORMANCE :

- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Medium
- AGGRESSIVENESS: High gain
- SPECIAL CONTROL: Lead input
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :

- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :

- MAJOR PROBLEMS: Heavy stick forces and low sensitivity. Caused pilot to get out of phase. Poor pilot rating due to heavy stick forces and low sensitivity combination.
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO = 6 RUN NO = 1 ω_{nSP} = 1.7 DATE: 21MAY86
CONFIGURATION NO. = 5-11 ζ_{SP} = 0.68 PILOT: B
GEARING = 0.100 FCS = 65536/[0.93,16][0.38,16] IP: EASTER

PIO RATING = 4 C-H RATING = 7 CONFIDENCE RATING = B

FEEL SYSTEM CHARACTERISTICS :

- FORCES: Medium forces
- PITCH SENSITIVITY: Medium pitch sensitivity

PITCH ATTITUDE CONTROL :

- INITIAL RESPONSE: Slow response rate
- FINAL RESPONSE: Medium response rate
- PREDICTABILITY: Poor because of delay
- PILOT COMPENSATION: Lead compensation required
- PIO TENDENCY: High

TASK PERFORMANCE :

- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Less than adequate
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Low
- AGGRESSIVENESS: Medium until flare, then high
- SPECIAL CONTROL: Cross wind raised gain, compensation required
- REASON APP. ABANDON: PIO

ADDITIONAL FACTORS :

- WIND: 30 degrees cross wind at 15 kt
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :

- MAJOR PROBLEMS: Precise control was difficult with delay. Tended to over control to compensate for delay. PIO did not seem to be divergent. Confidence rating B because first two approaches were disengaged too early to see very much.
- GOOD FEATURES:

INFLIGHT PILOT COMMENT CARD

FLT NO.= 11 RUN NO.= 2	ω_{nSP} = 1.7	DATE: 27MAY86
CONFIGURATION NO. = 5-11	ζ_{SP} = 0.68	PILOT: C
GEARING = 0.100	FCS = 65536/[0.93,16][0.38,16]	IP: EASTER

PIO RATING = 3 C-H RATING = 5 CONFIDENCE RATING = A

FEEL SYSTEM CHARACTERISTICS :

- FORCES: Medium to heavy
- PITCH SENSITIVITY: Low

PITCH ATTITUDE CONTROL :

- INITIAL RESPONSE: Sluggish
- FINAL RESPONSE: Sluggish
- PREDICTABILITY: Poor
- PILOT COMPENSATION: Medium to high compensation required
- PIO TENDENCY: Low

TASK PERFORMANCE :

- AIRSPEED CONTROL: Desired (± 5 kt)
- TOUCH DOWN POINT: Desired (± 250 feet)
- RUNWAY ALIGNMENT: Desired (± 5 feet)
- TOUCH DOWN SINK RATE: Dropped in
- AGGRESSIVENESS: Medium gain
- SPECIAL CONTROL: Slow input required
- REASON APP. ABANDON: N/A

ADDITIONAL FACTORS :

- WIND: No factor
- TURBULENCE: No factor
- LAT-DIR PERFORMANCE: No factor

SUMMARIZE EVALUATION :

- MAJOR PROBLEMS: Slow response in pitch during flare.
  Desired performance only attainable by dropping aircraft in.

- GOOD FEATURES: If pilot lowered his gain, PIO tended to be convergent and he could control the aircraft and land safely.

APPENDIX C

SELECTED PARAMETER TIME HISTORIES

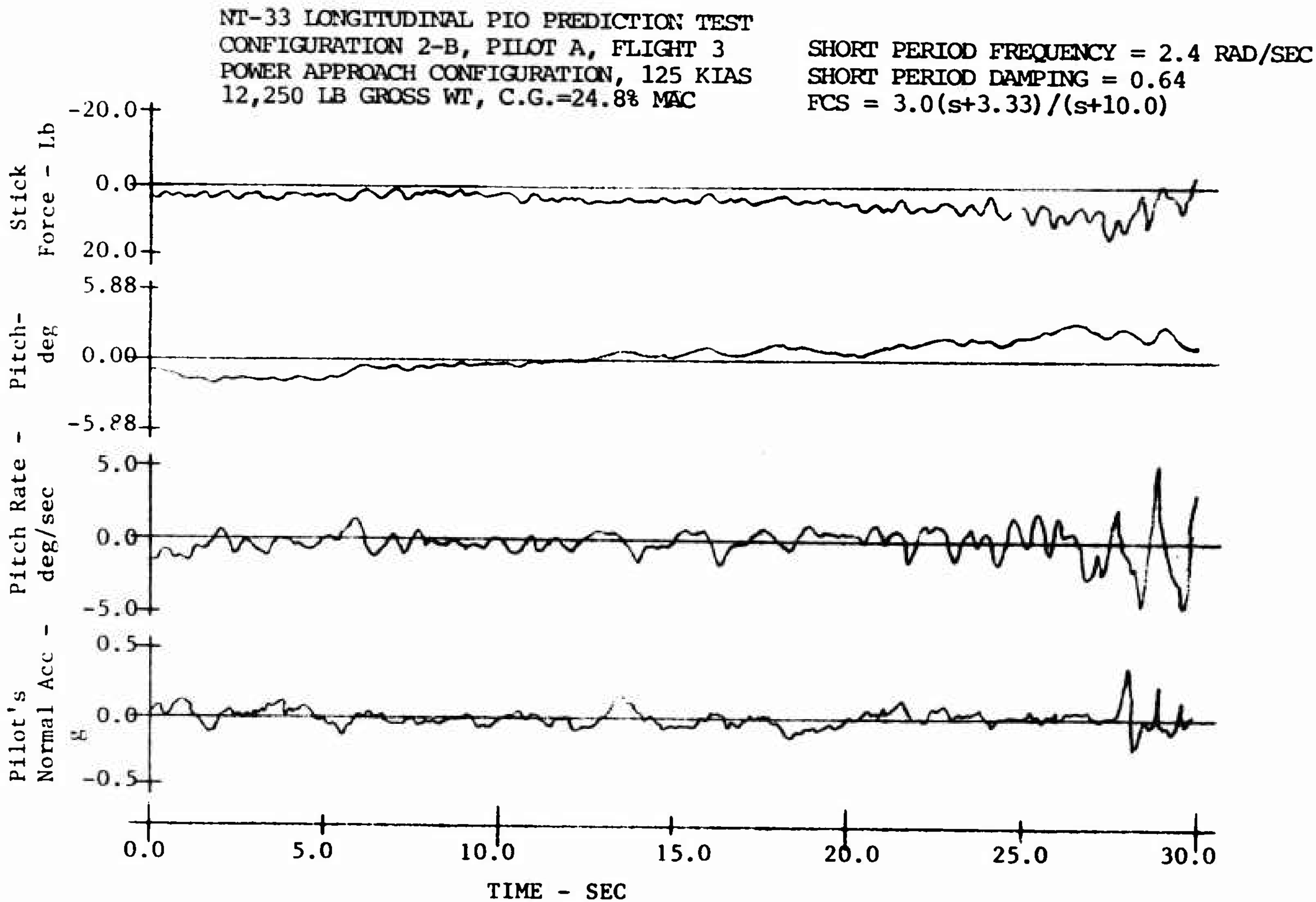


Figure 31. Selected Parameter Time Histories, Configuration 2-B

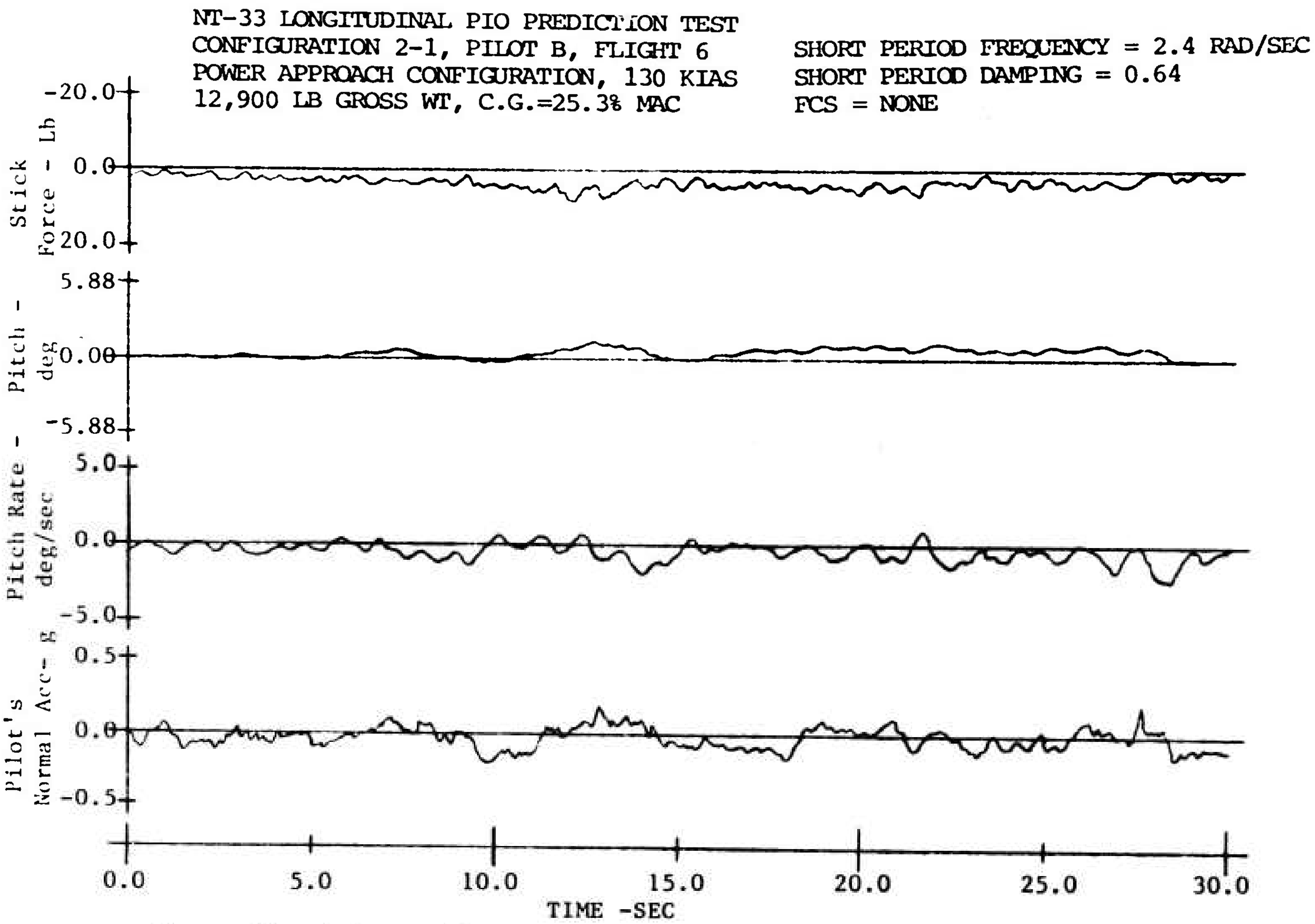


Figure 32. Selected Parameter Time Histories, Configuration 2-1

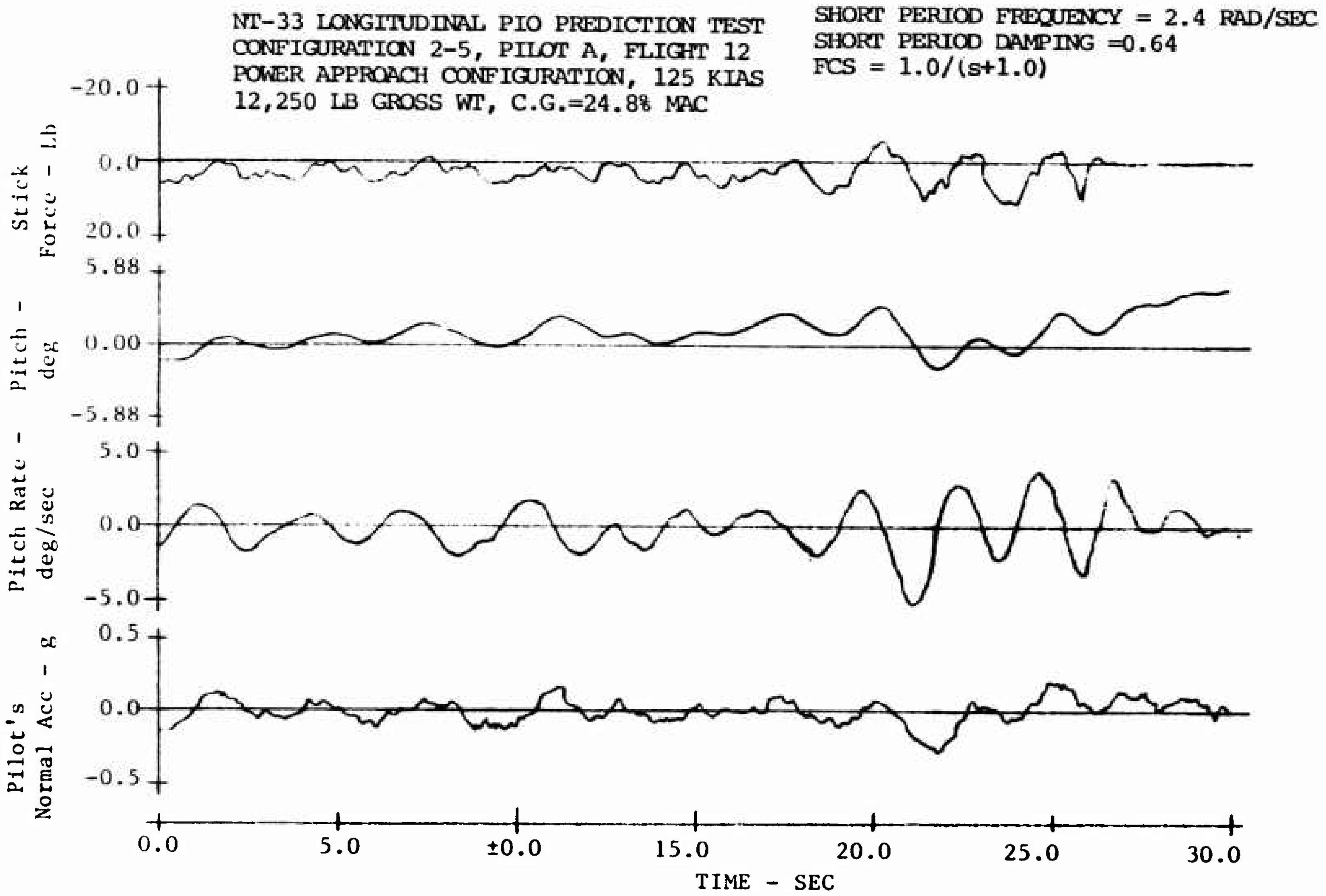


Figure 33. Selected Parameter Time Histories, Configuration 2-5

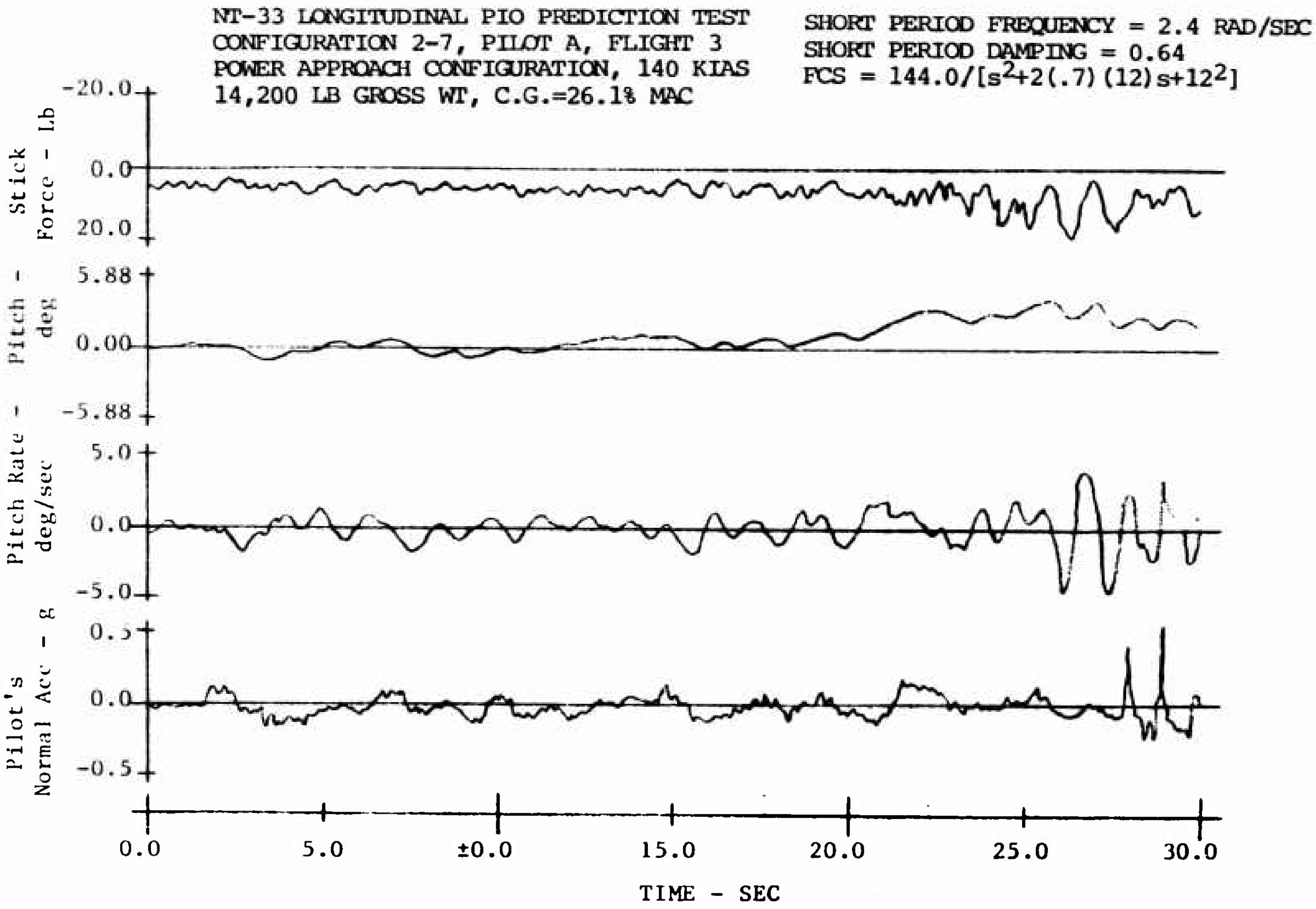


Figure 34. Selected Parameter Time Histories, Configuration 2-7

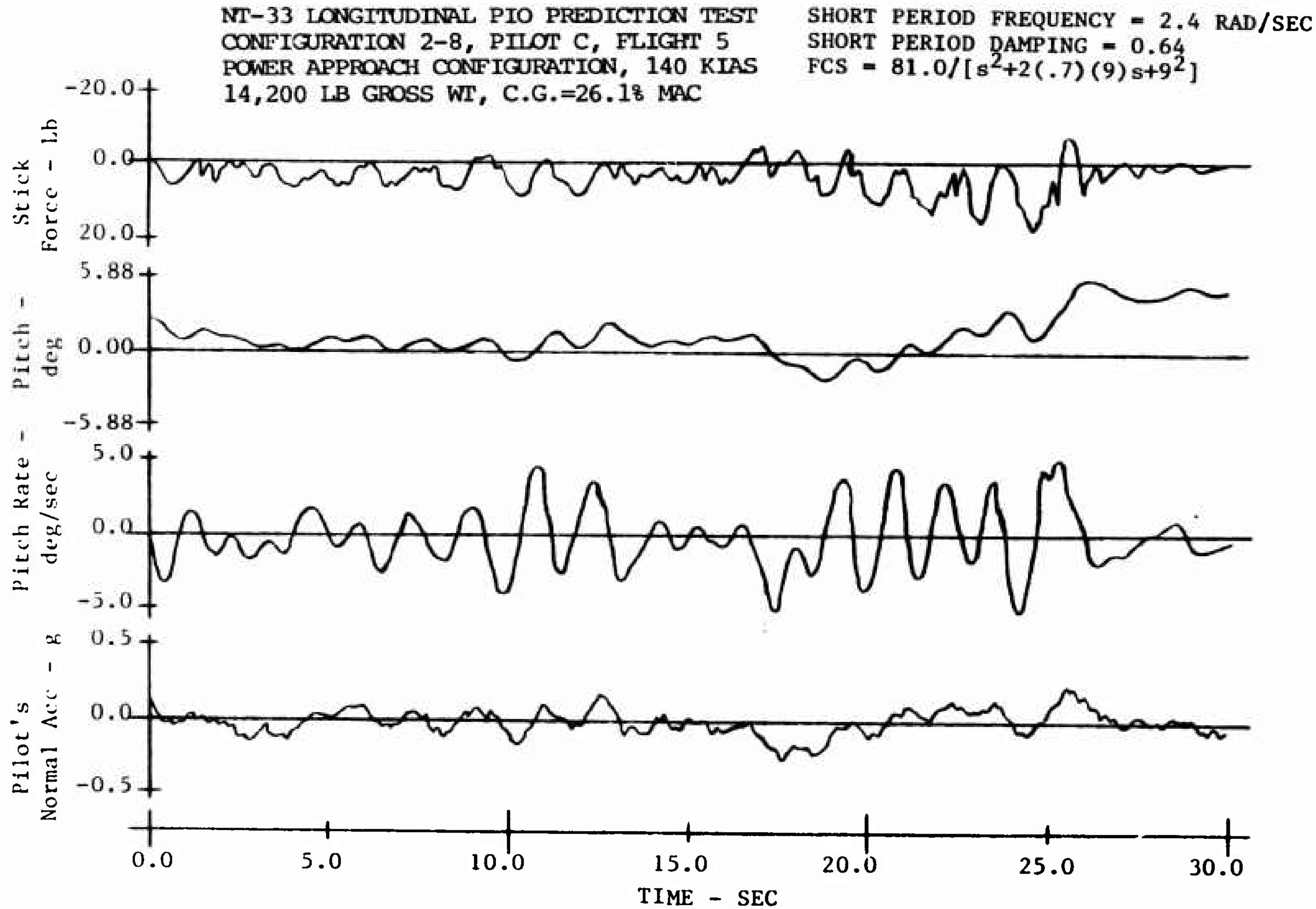


Figure 35. Selected Parameter Time Histories, Configuration 2-8

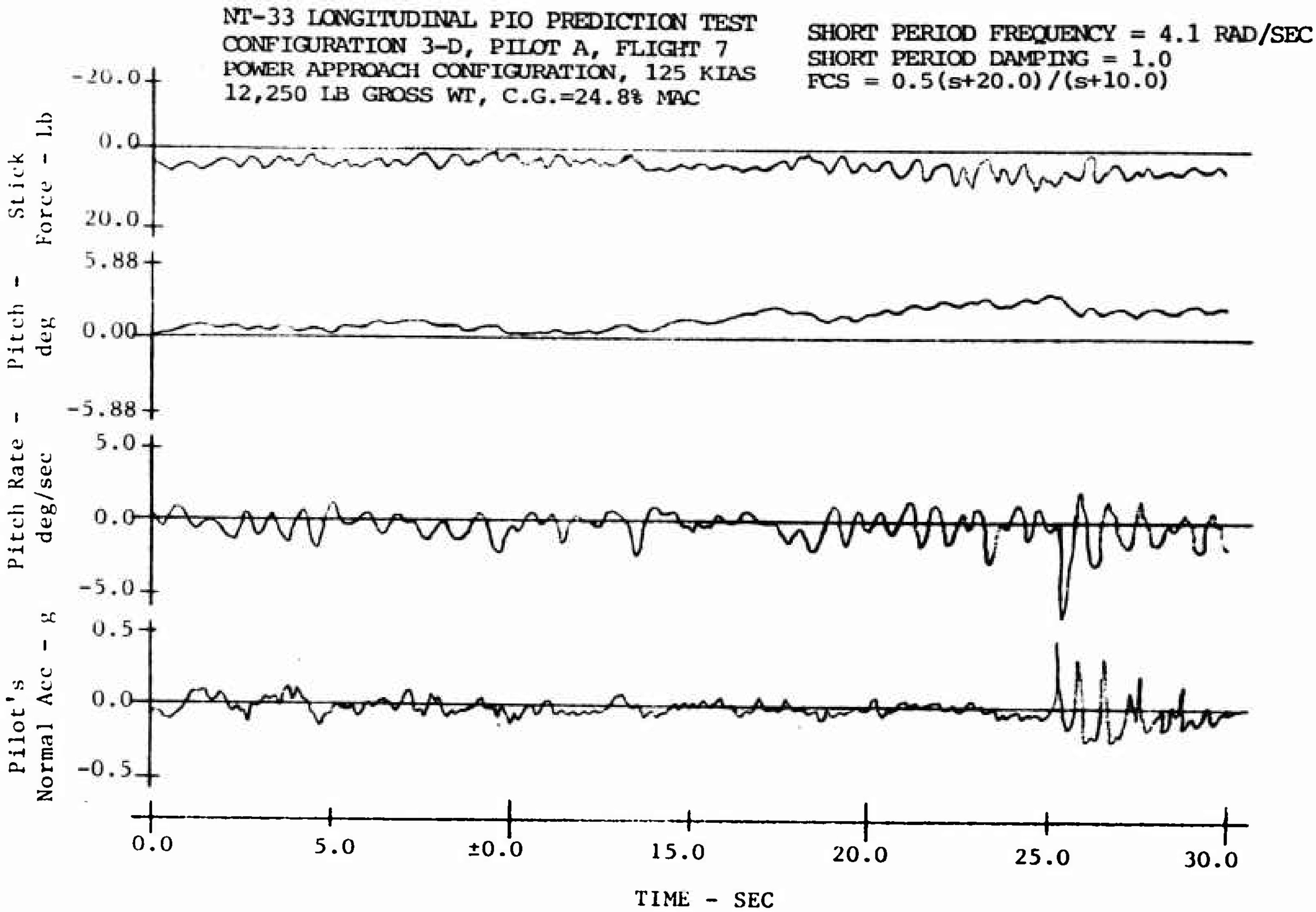


Figure 36. Selected Parameter Time Histories, Configuration 3-D

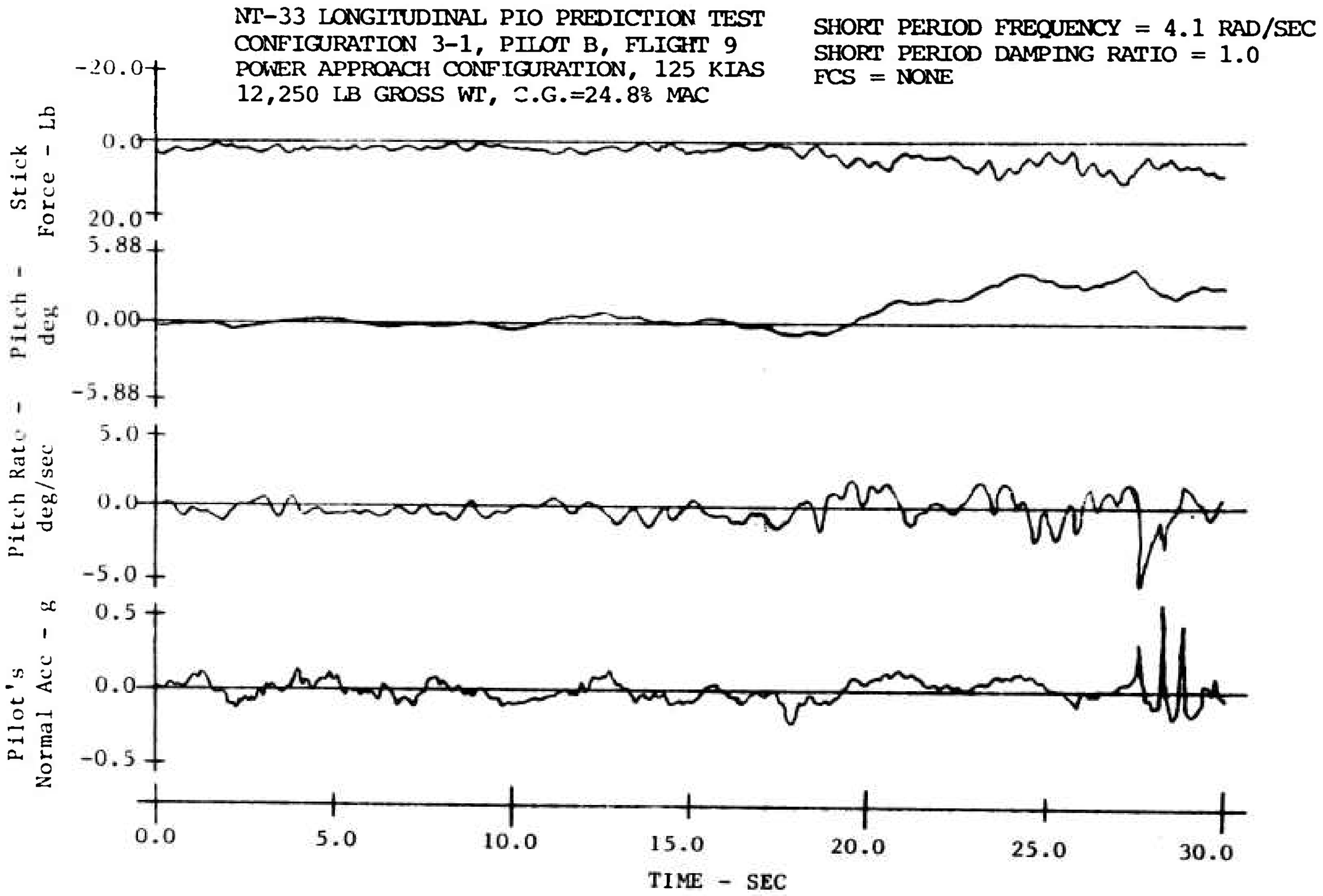


Figure 37. Selected Parameter Time Histories, Configuration 3-1

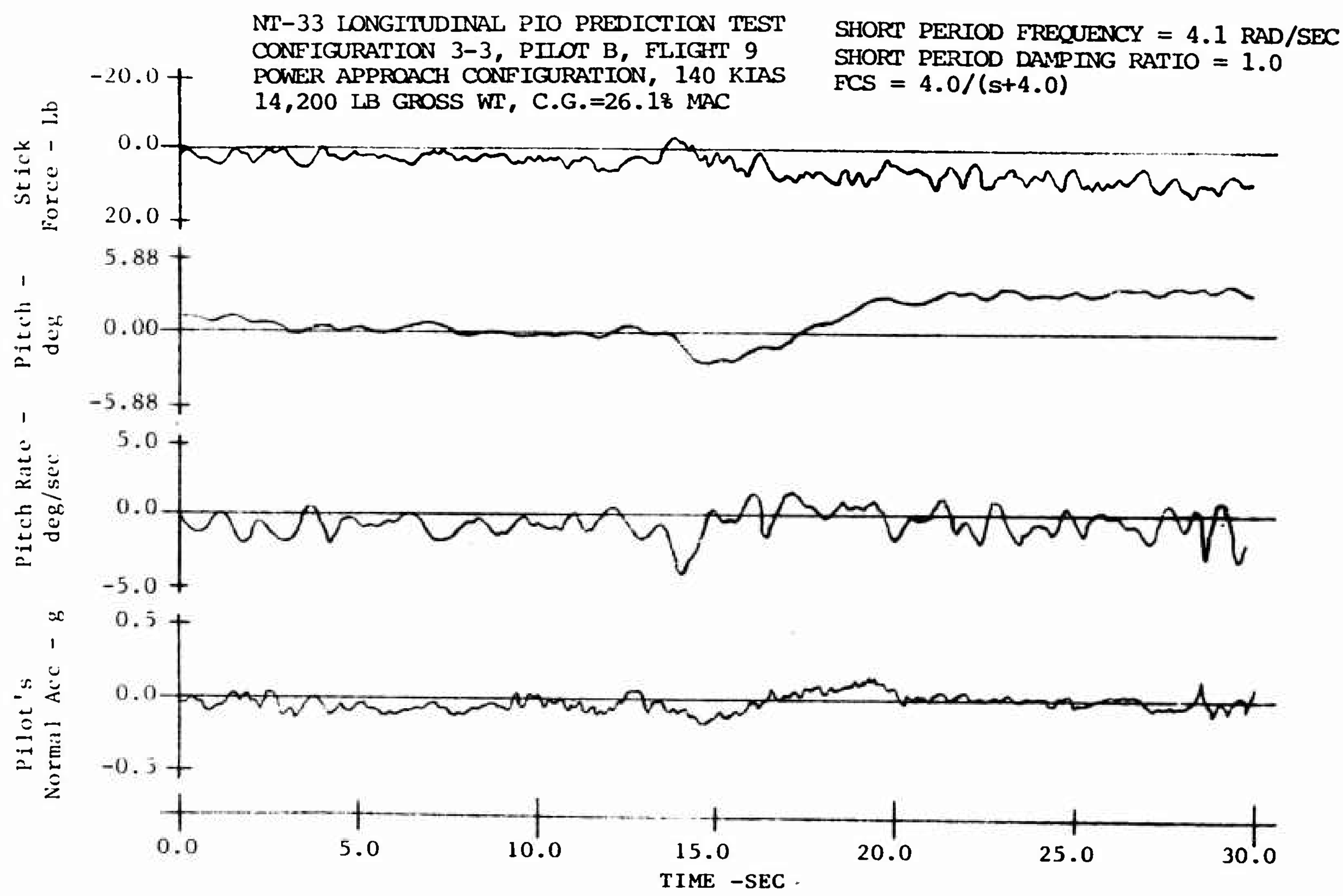


Figure 38. Selected Parameter Time Histories, Configuration 3-3

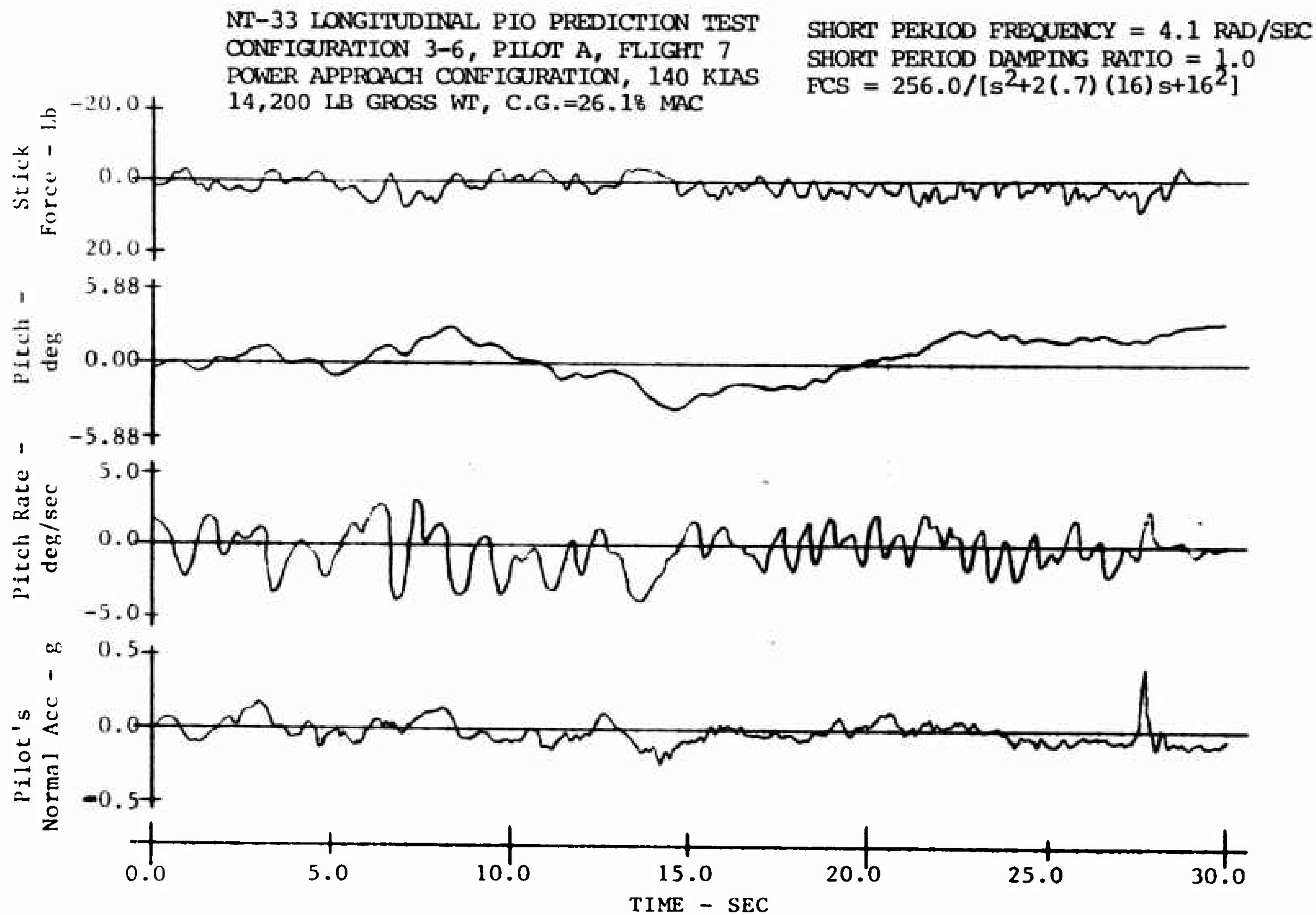


Figure 39. Selected Parameter Time Histories, Configuration 3-6

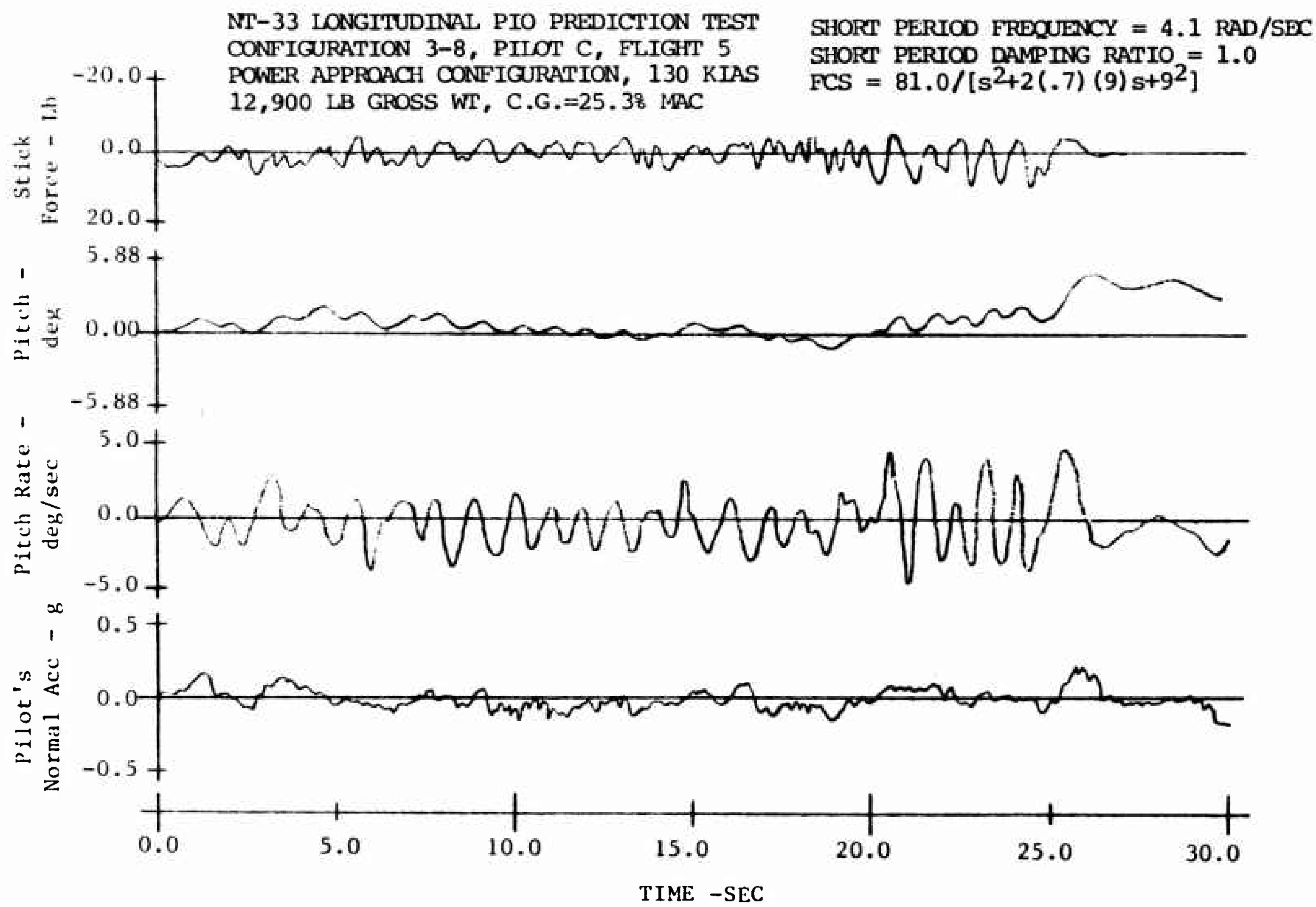


Figure 40. Selected Parameter Time Histories, Configuration 3-8

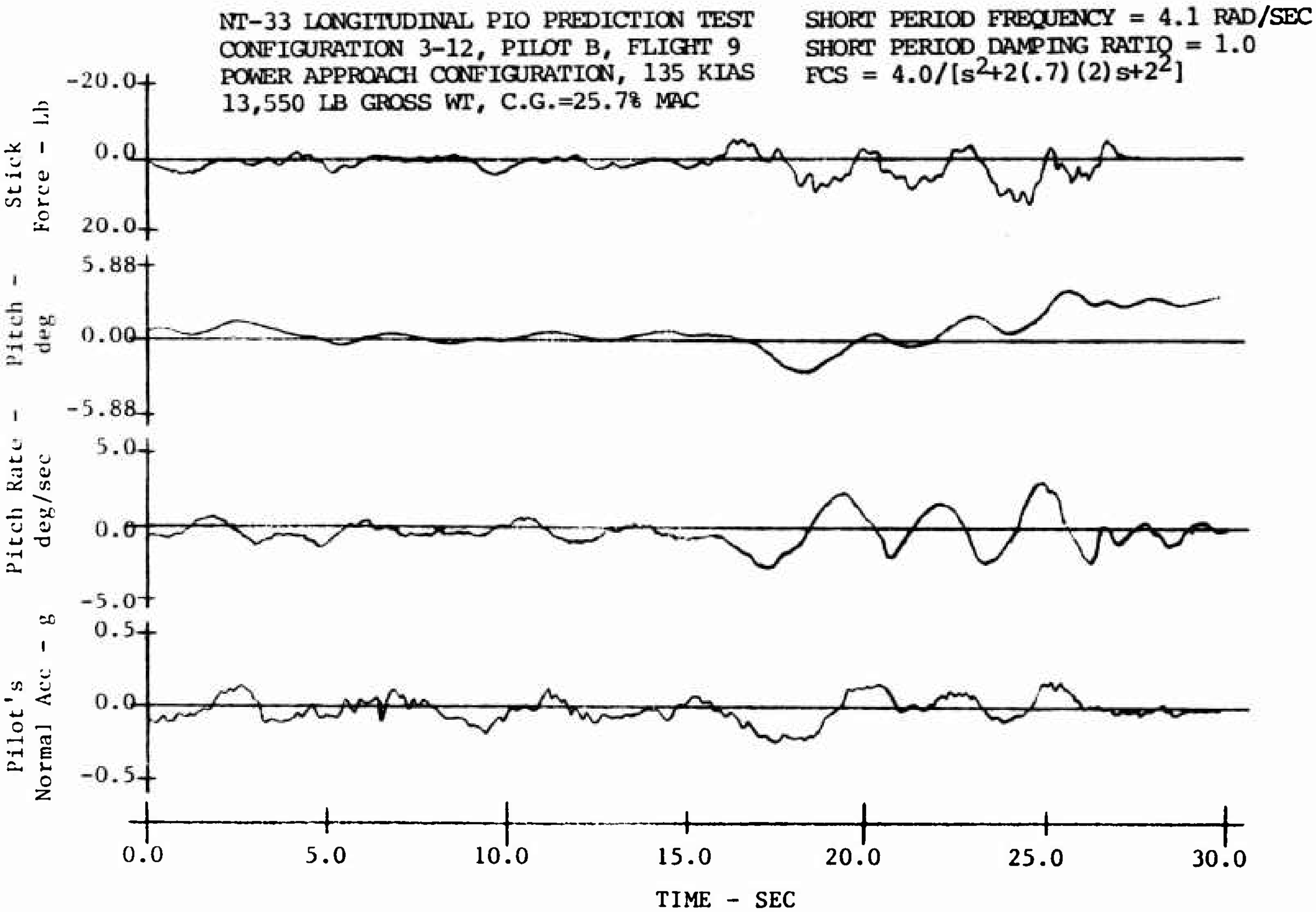


Figure 41. Selected Parameter Time Histories, Configuration 3-12

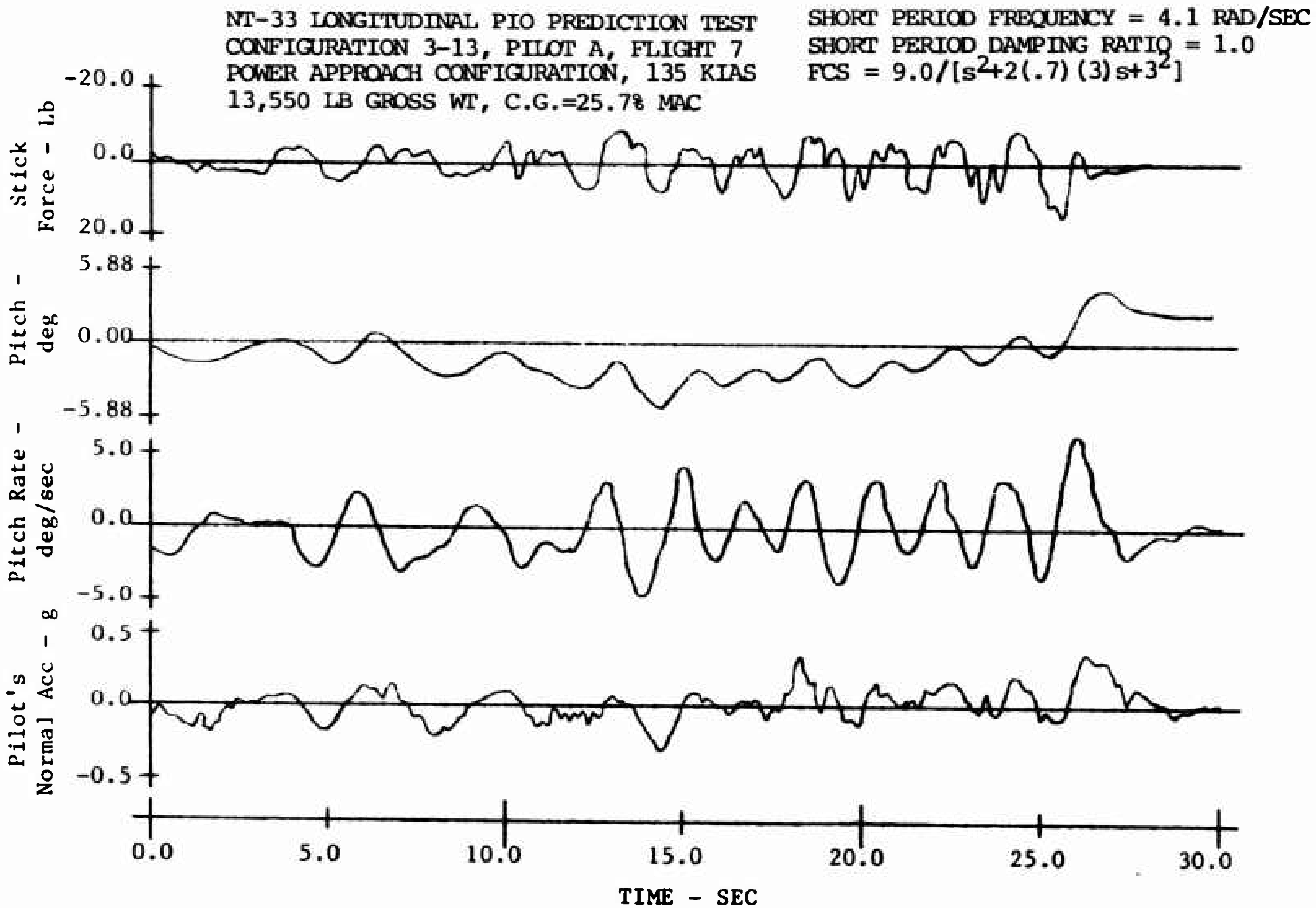


Figure 42. Selected Parameter Time Histories, Configuration 3-13

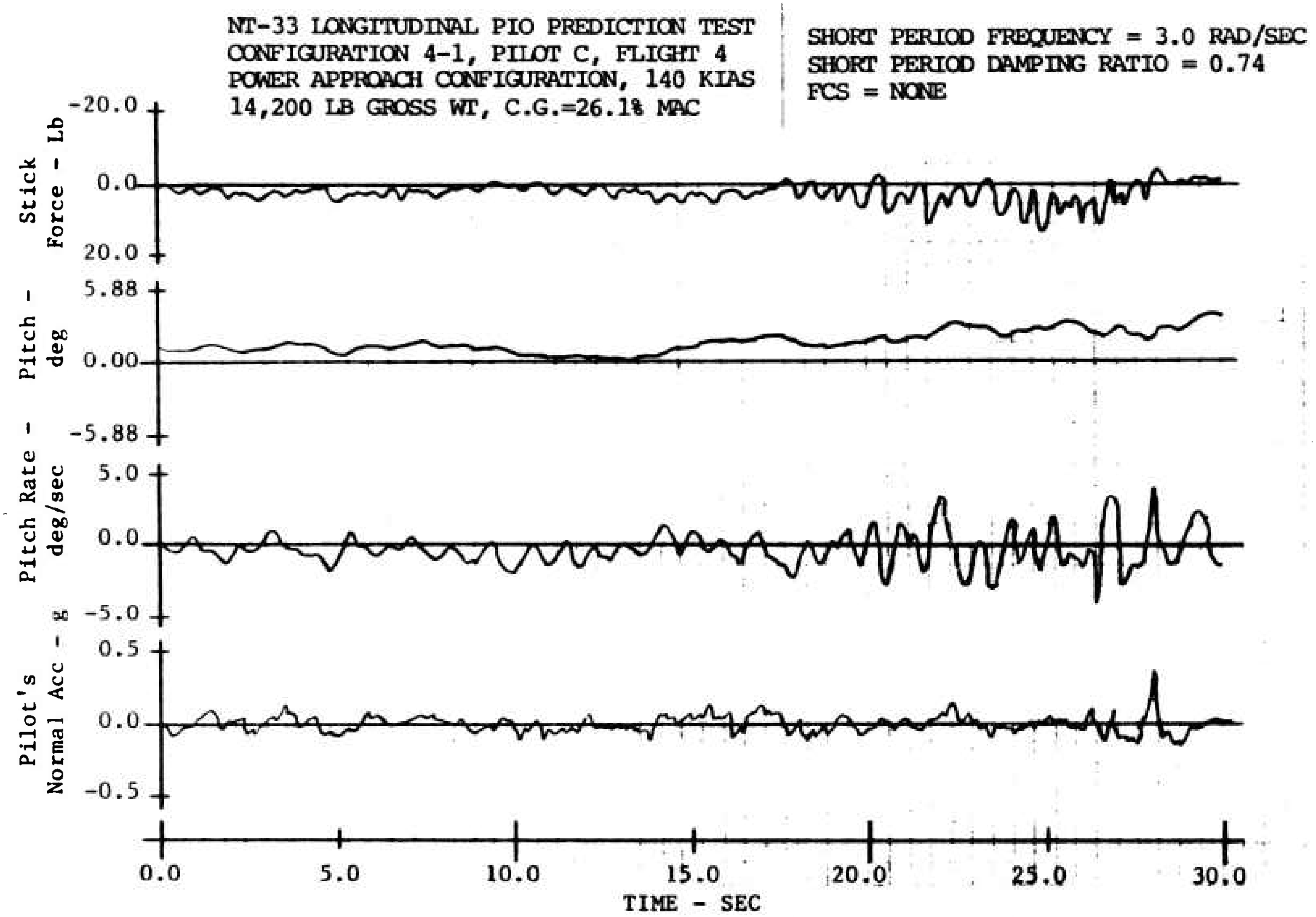


Figure 43. Selected Parameter Time Histories, Configuration 4-1

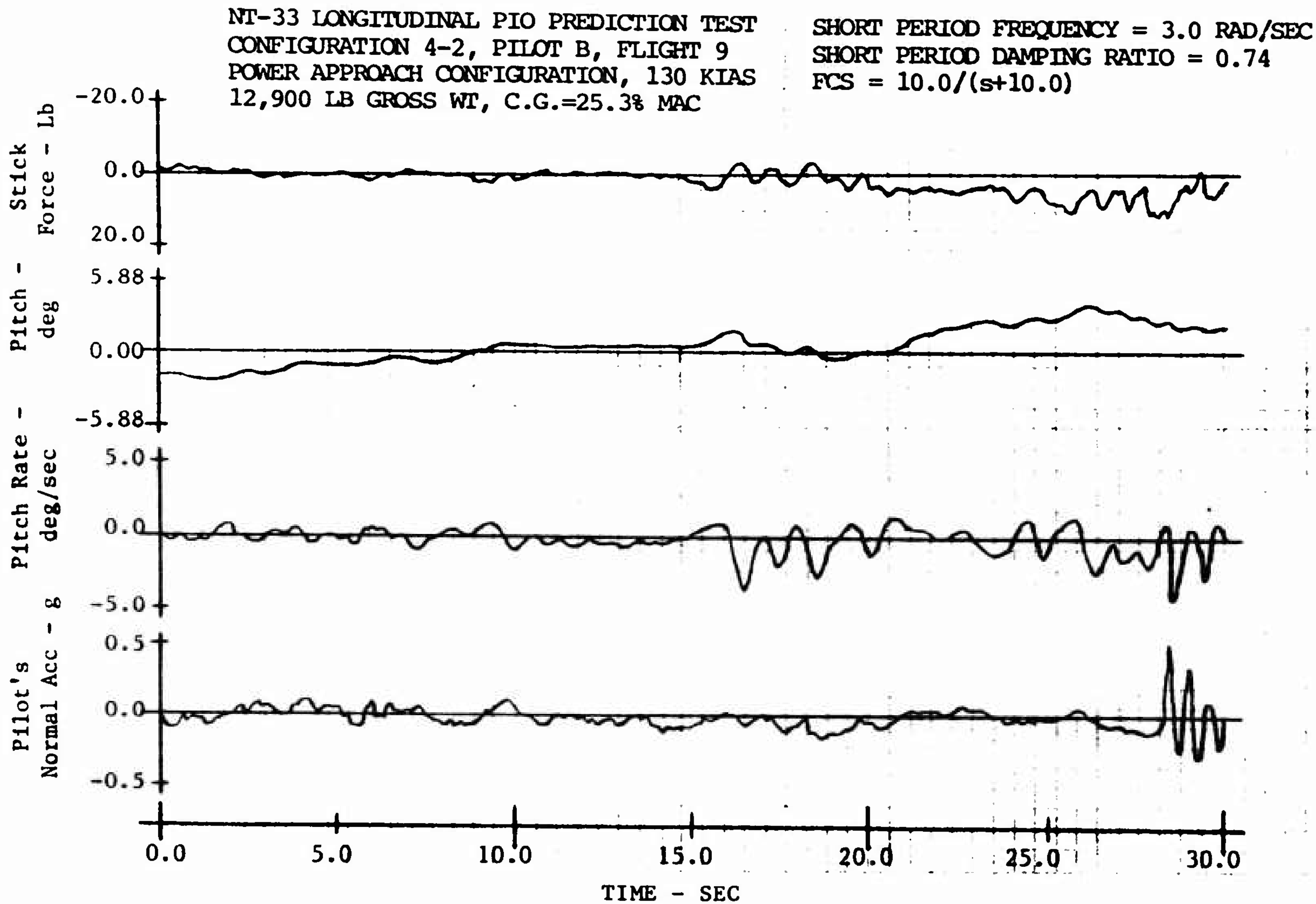


Figure 44. Selected Parameter Time Histories, Configuration 4-2

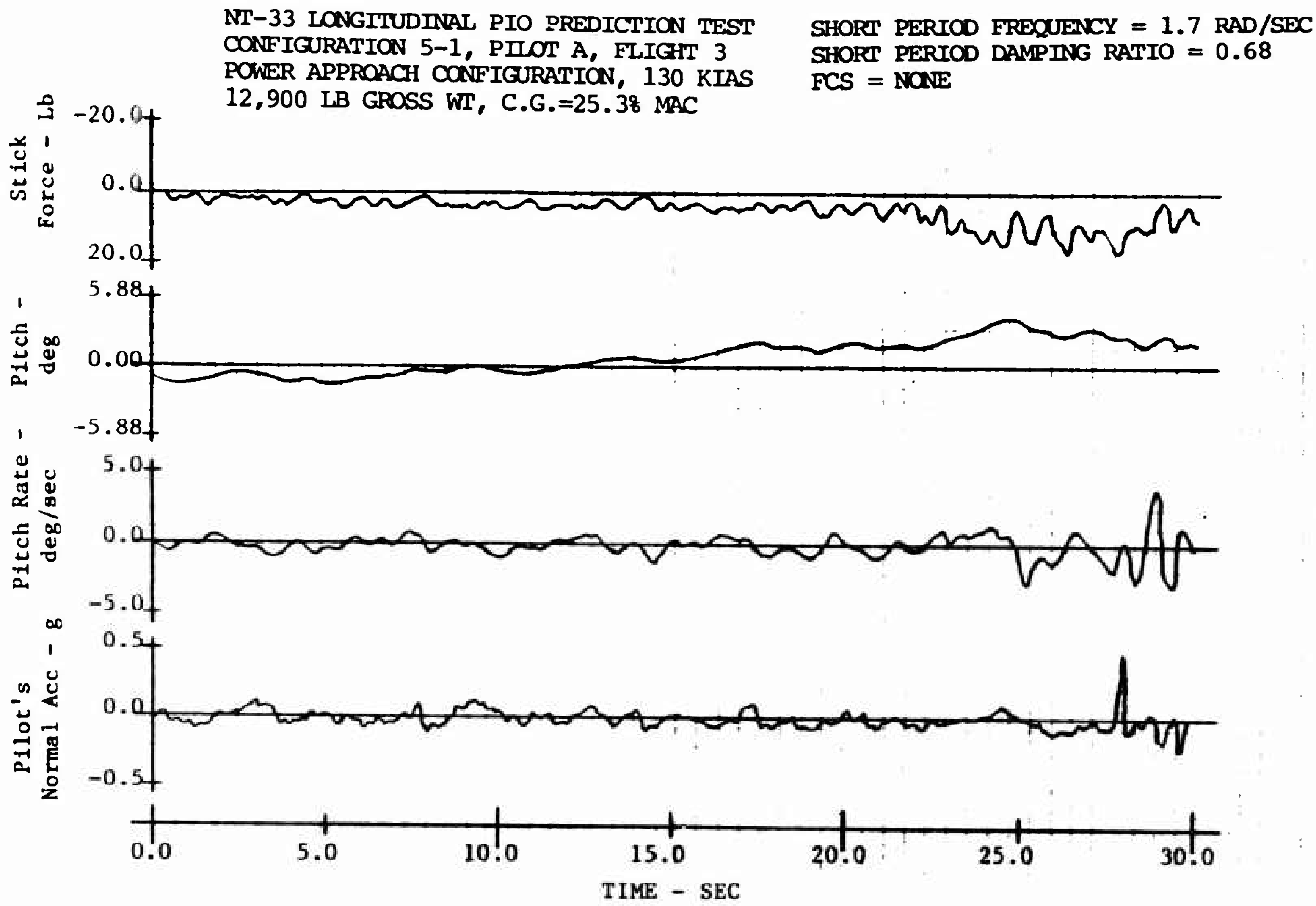


Figure 45. Selected Parameter Time Histories, Configuration 5-1

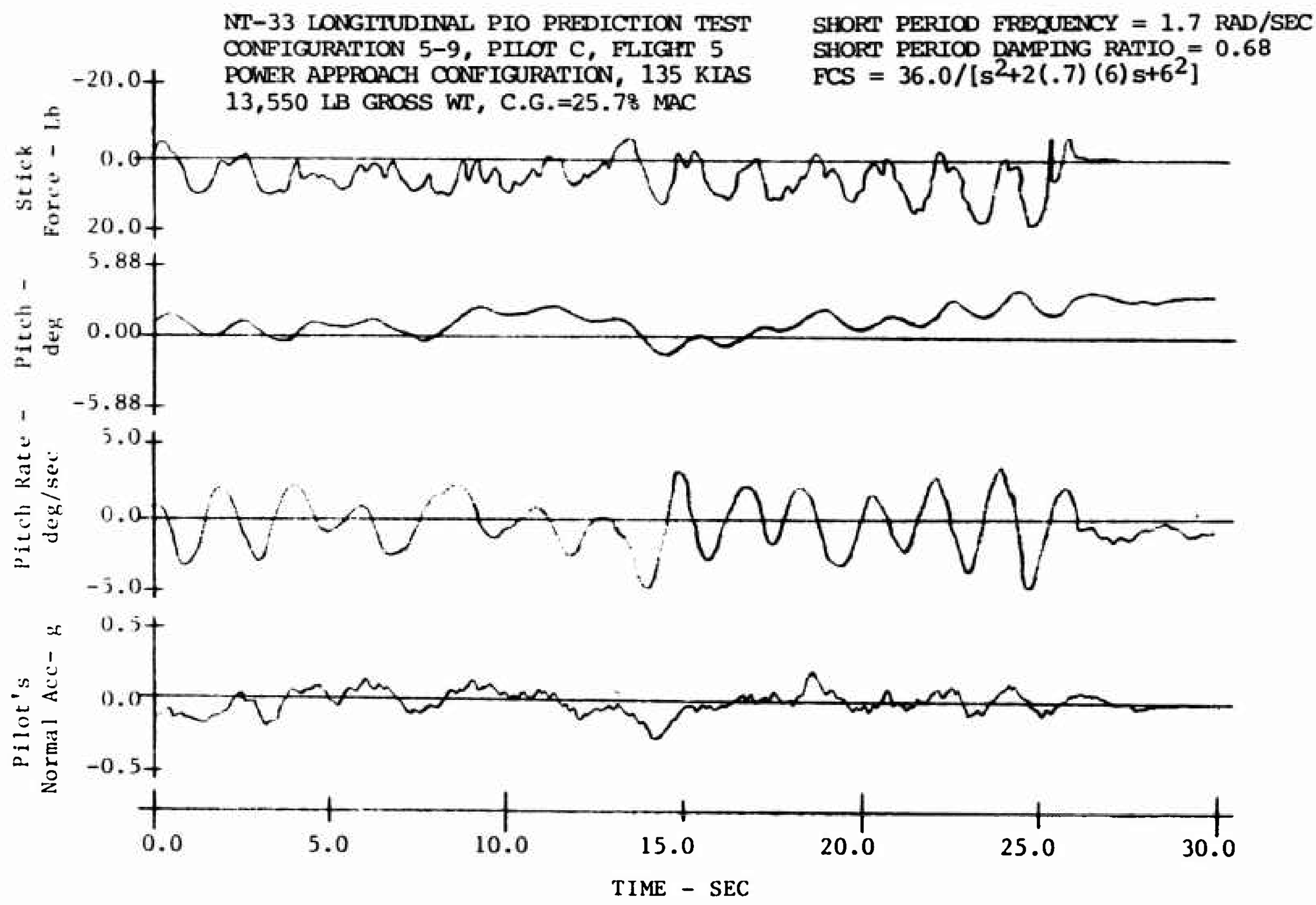


Figure 46. Selected Parameter Time Histories, Configuration 5-9

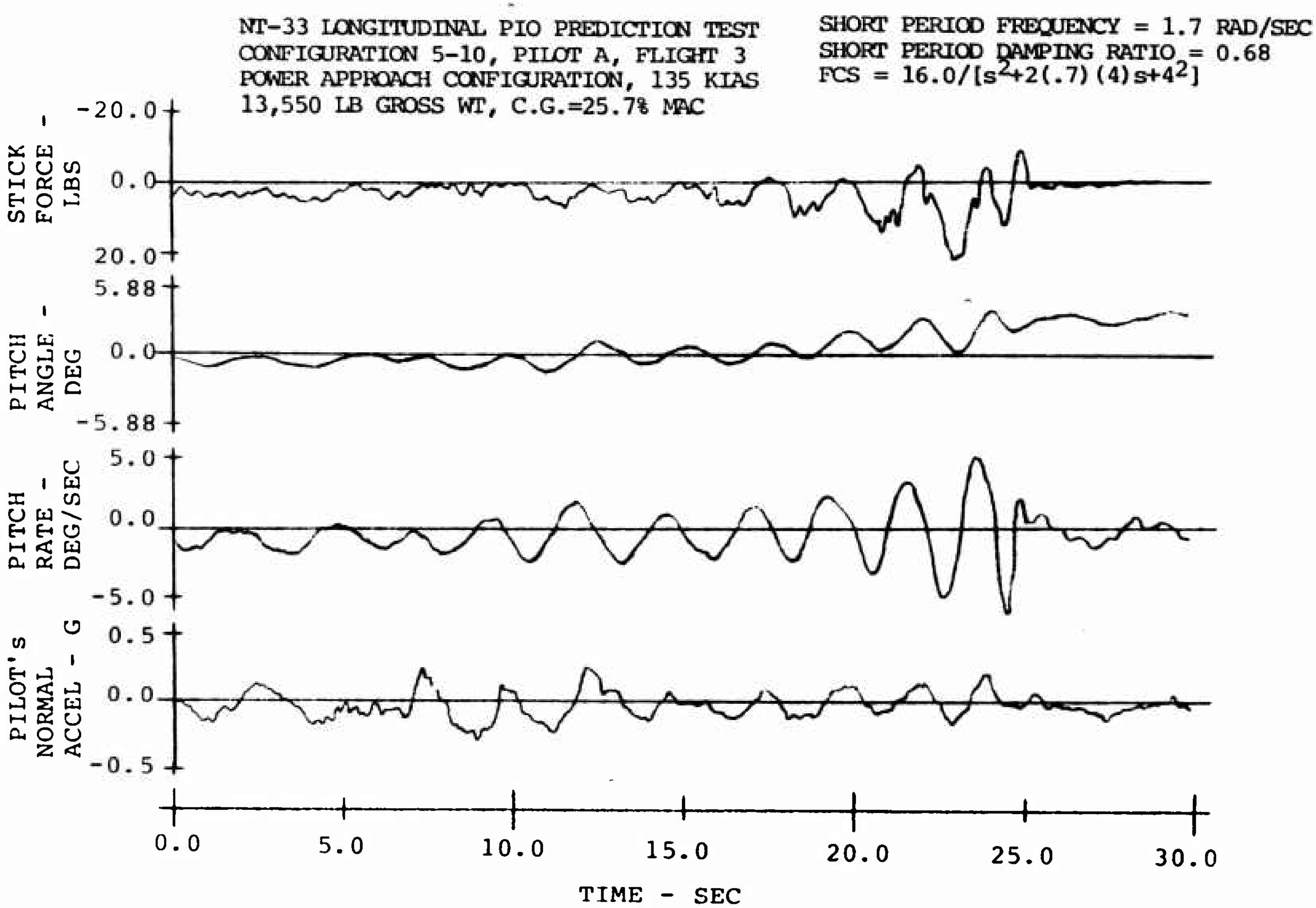


Figure 47. Selected Parameter Time Histories, Configuration 5-10

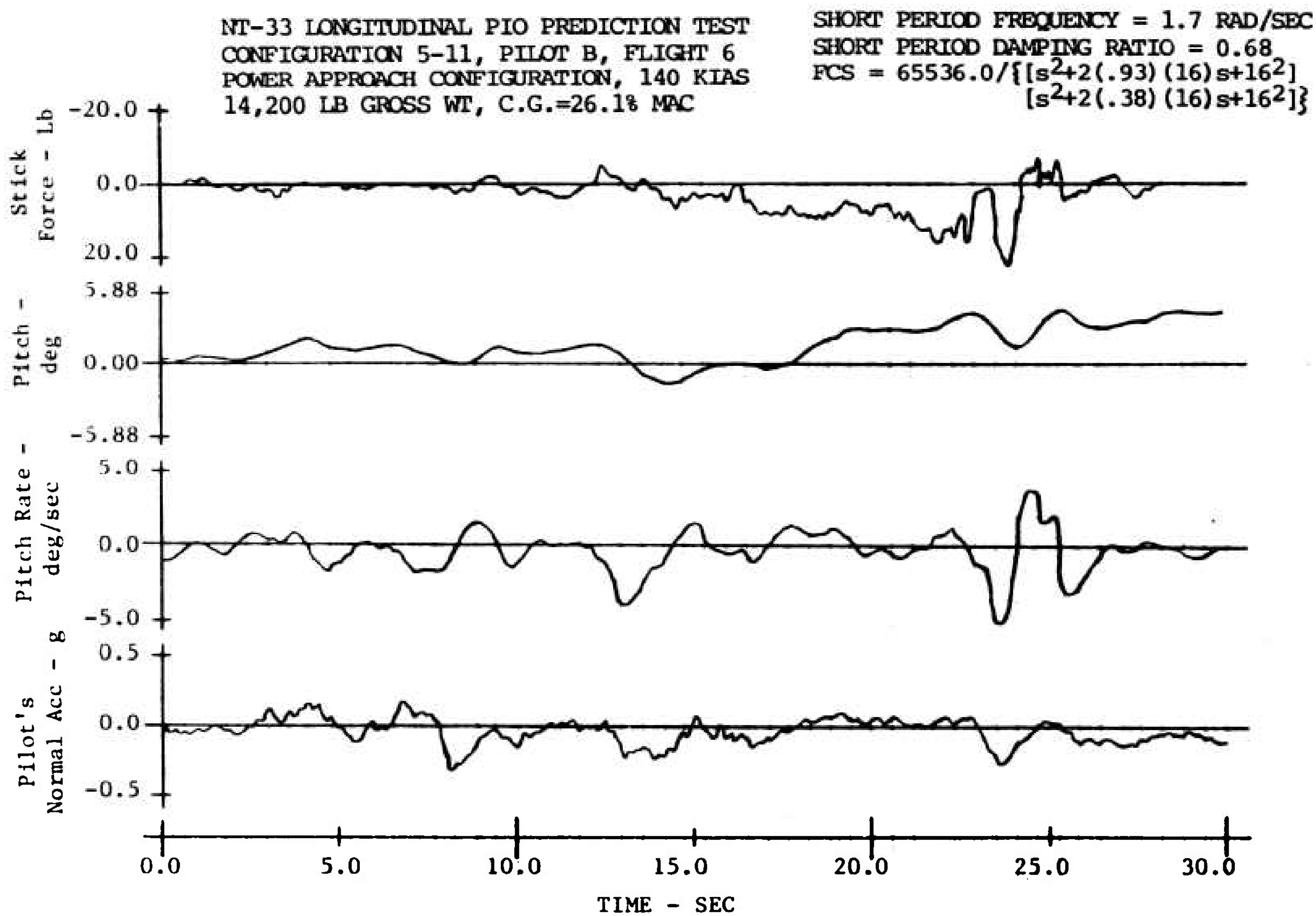


Figure 48. Selected Parameter Time Histories, Configuration 5-11

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VITA

Captain Eileen A. Bjorkman was born on [redacted] in Victoria, Texas. She graduated from high school in O'Fallon, Illinois, in 1974. She then attended the University of Washington, receiving the Bachelor of Science in Computer Science in June 1979. After graduation, she worked for the Northwest Medical Physics Center in Seattle, Washington, until she joined the Air Force in May 1980. After receiving a commission in the USAF from OTS in August 1980, she entered the AFIT undergraduate aeronautical engineering conversion program and received a Bachelor of Science in Aerospace Engineering in March 1982. She then worked for the 6585th Test Group, Holloman Air Force Base, New Mexico, as a flight test engineer until she entered the joint USAF/TPS program in July 1984.

Permanent address: [redacted]

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The purpose of this study was to determine if pilot induced oscillations (PIOs) can be predicted prior to flight using existing PIO prediction techniques. Two techniques to predict longitudinal PIO tendencies (Ralph Smith's theory and Roger Hoh's bandwidth method) were studied analytically using an existing PIO data base. Suggestions were made to both techniques to allow prediction of PIO rating. The two techniques were then applied to 18 aircraft/flight control system landing configurations. The 18 configurations were then flight tested using a flared landing task with the USAF/Calspan variable stability NT-33A. Smith's theory correctly predicted PIO tendencies and frequencies provided the configuration was not sensitive to the pilot model used. A suggested modification to Smith's theory correctly predicted PIO ratings within an average of 0.6 rating. A suggested modification to Hoh's bandwidth method predicted PIO ratings within an average of 0.5 rating.

The limited data base was too small to draw any definite conclusions. Recommendations for further study included collecting more PIO data and using existing data bases and simulator studies to better define the two techniques and to gain physical insights into PIO mechanization.