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Extended Flight Evaluation of a Near-Term Pitch Active Controls System

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FOREWORD

This program was conducted during the period of December 1982 through June 1983 for the NASA Langley Research Center. The NASA Program Monitor was D. W. Bartlett and the Lockheed Program Manager was W. A. Guinn. The principal Lockheed-California Company and NASA people responsible for successfully completing the program were:

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SUMMARY

Fuel savings can be achieved by moving the center of gravity (c.g.) of an aircraft aft which reduces the longitudinal static stability margin and consequently the trim drag. However, flying qualities of an aircraft with relaxed static stability can be significantly degraded. The flying qualities can be restored by using a pitch active control system (PACS). Consequently, a PACS was developed by Lockheed under a NASA Aircraft Energy Efficiency (ACEE) program contract.

A near-term PACS with pitch rate feedback and column-minus-trim feedforward command signals was developed, installed on a flight test aircraft (L-1011 S/N 1001), and flight demonstrated during the initial phase of this program (see Reference 1). The PACS was shown to provide good flying qualities for static stability margins to positive 1%.

This report documents the work accomplished during a follow-on program to perform flight tests at further aft c.g. locations with the near-term PACS. The follow-on program flight test results reported herein demonstrate that within the linear static stability flight envelope the near-term PACS with increased pitch rate feedback gains provides good flying qualities for static stability margins to negative 3%.

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LIST OF SYMBOLS

AACS	Aileron active control system
C_L	Lift coefficient
C_m	Pitching moment coefficient
c.g.	Aircraft center of gravity
C-T	Column-minus-trim feed-forward command signal
deg	degrees
F_C	Control column force ∿ lbs
FAR	Federal Air Regulations
FARM	Feedback Amplitude ratio margin
FC	Flight condition
ft	Feet
g	Load factor ∿ 32.2 ft/sec^2
g_{rms}	Load factor root-mean-square value
Hz	Cycles/sec
in.	Inches
j	Imaginary number ($\sqrt{-1}$)
K_{FF}	Column-minus-trim signal gain
K_G	Control column to stabilizer gearing ratio
$K_{\dot{\theta}}$	Pitch rate damper gain
K_1	PACS C-T gain switch factor
K_2	PACS $\dot{\theta}$ gain switch factor
K_3	PACS combined C-T and $\dot{\theta}$ gain switch factor
KCAS	Calibrated air speed - knots
KEAS	Equivalent air speed - knots
lbs	Pounds

LIST OF SYMBOLS

L-1011	Lockheed wide-body jet transport
M	Mach number
M_D	Maximum dive Mach number
mac	Mean aerodynamic chord
MTC	Mach trim compensation system
n_L	Aircraft limit load factor
ND	Aircraft nose-down
NU	Aircraft nose-up
$N_{Z_{c.g.}}$	c.g. Normal acceleration
$N_{Z_{rms}}$	Normal acceleration root-mean-square value
OEW	Operating empty weight
PACS	Pitch active control system
rms	Root-mean-square
s	Laplace transform parameter
sec	Second
S/N	Serial number
T	Designates turbulent flight points on Cooper-Harper rating charts
TED	Trailing edge down
TEU	Trailing edge up
TOW	Takeoff weight
V	Aircraft velocity
VAC	Alternating voltage
V_c	Aircraft velocity $\sim$ calibrated air speed
V_D	Maximum dive velocity
V_e	Aircraft velocity $\sim$ equivalent air speed

V_S	Aircraft stall speed ∿ KEAS
V_T	Aircraft trim speed
VMS	NASA Langley Research Center Visual motion simulator
W	Aircraft weight ∿ lbs
x_C	Control column displacement ∿ in.
x_S	Series servo displacement ∿ in.
$x_{S_{rms}}$	Series servo displacement ∿ root-mean-square
x_T	Stabilizer trim ∿ deg
ZFM	Zero fuel weight
α	Aircraft angle of attack
α_L	Local flow at angle of attack probe
δ	Ratio of ambient air pressure at flight altitude to pressure at sea level
δ_A	Outboard aileron deflection
δ_F	Wing flap deflection ∿ deg
δ_H	Horizontal stabilizer deflection ∿ deg
S_{H_c}	Command signal to series servo
ζ	Aircraft response damping coefficient
θ	Aircraft pitch attitude
$\dot{\theta}$	Aircraft pitch rate ∿ deg/sec
$\dot{\theta}_{rms}$	Aircraft pitch rate root-mean-square value
τ_{Lag}	Feedback signal time lag ∿ sec
ϕ	Aircraft roll angle
ω_d	Damped frequency of short-period or phugoid mode

ω_n Natural frequency of short-period or phugoid mode

% Percent

1. INTRODUCTION

1.1 Background

A near-term PACS was developed during the initial phase of this program and installed on a Lockheed L-1011 flight test aircraft (S/N 1001). Flight demonstration tests within the linear static stability flight envelope showed that the PACS provided good flying qualities of the aircraft for static stability margins to positive 1%.

Evaluation of the flight test results indicated that by increasing the PACS feedback loop gains, satisfactory flying quality characteristics would be possible at negative static margins. Load limit criteria, capability to control the aircraft in case of a PACS failure, and c.g. management constraints indicated that it was feasible to perform flight tests with static stability margins to negative 3%. Consequently, the near-term PACS follow-on flight test program was proposed.

1.2 Program Objective

The program objective was to demonstrate by flight test that the near-term PACS with increased feedback gains would provide flying qualities for static stability margins to negative 3% which were equivalent to those of the baseline aircraft with a positive 15% static stability margin.

1.3 Scope of the Program

The major program tasks for the near-term PACS extended flight test program were:

- Flying qualities analysis
- Piloted flight simulation test
- Aircraft preparation for flight test
- Flight test

The flying qualities analysis and piloted flight simulation test were limited to evaluation of two cruise conditions and one landing condition.

Aircraft preparation included analysis required for determining operating restrictions, safety reviews, and aircraft modifications.

The flight test was limited to evaluation of a series of static stability margins for one flight condition. The program was to consist of approximately 20 hours of flight time.

2. AIRCRAFT DESCRIPTION

A detailed description of the flight test aircraft is given in Reference 1. The aircraft is unique. It has a long fuselage like the L-1011-1 model, and extended wing tips and aileron active control system (AACS) like the short fuselage L-1011-500 model. It has a flying stabilizer with a geared elevator which was downrigged 5 degrees to provide the required nose-down authority for flight at the aft c.g. conditions. The elevator downrig was designed to provide a nose-down angular acceleration of at least -5.73 deg/sec^2 at the critical high angle-of-attack condition.

The baseline aircraft configuration is that with the AACS operating and the PACS off. The AACS has a significant impact on the static stability margin of the aircraft. When the AACS is off, the neutral point is at 45% mac. When the AACS is operating during a maneuver, the ailerons move symmetrically upward to provide wing load alleviation and cause a nose-up pitching moment. This results in a shift of the neutral point forward to 40% mac. Thus, the baseline aircraft for the PACS has a neutral point at 40% mac and in case of a PACS failure during flight the static stability margin can be increased by disengaging the AACS.

A water ballast system was installed on the aircraft to provide c.g. management. This system provided static stability margins from +15% (c.g. at 25% mac) to -3% (c.g. at 43% mac).

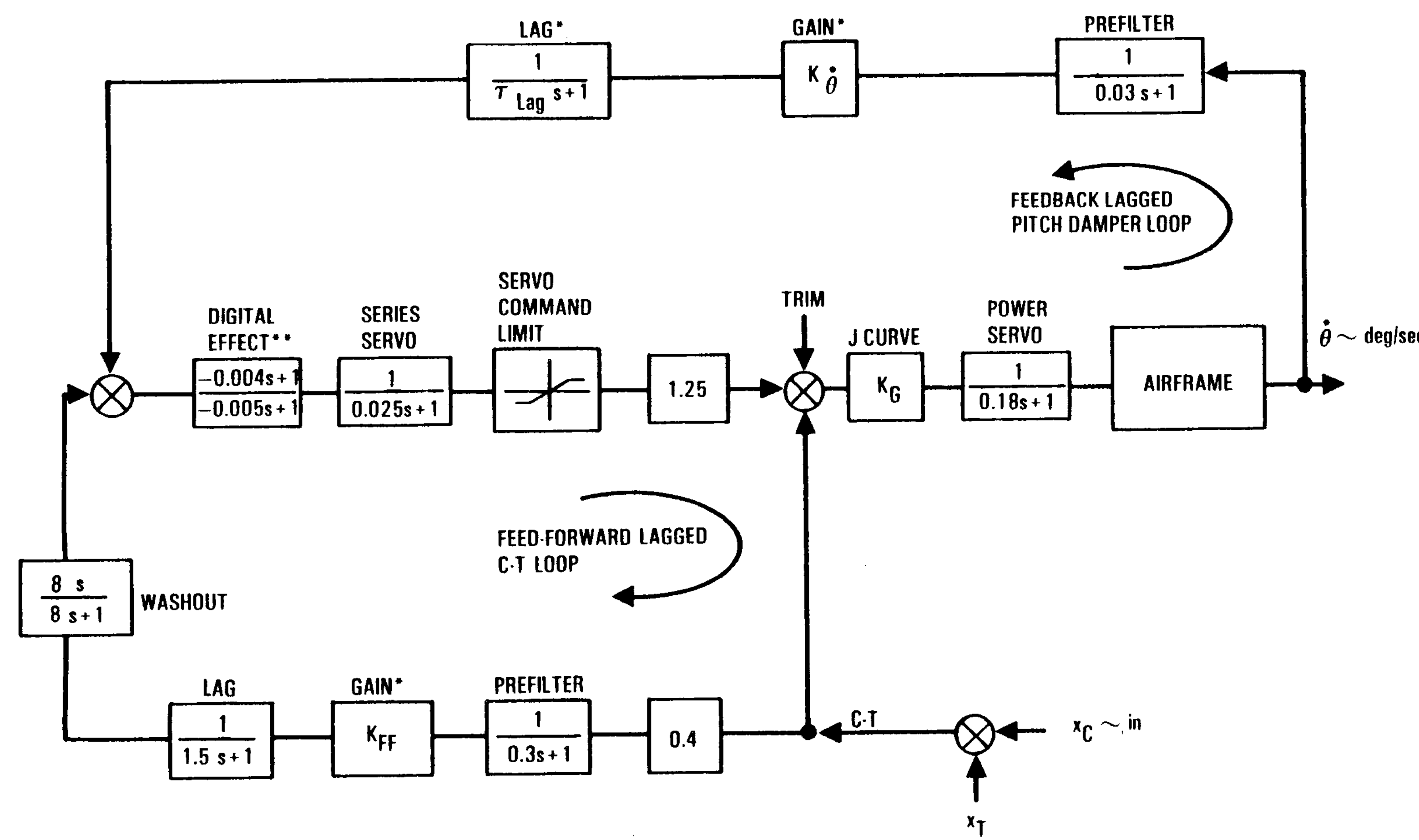
3. PACS DESCRIPTION

A detailed description of the PACS is given in Reference 1. Therefore, only a brief description of the PACS is given in this report.

The basic PACS analytical block diagram with the significant control system dynamics represented by Laplace domain transfer functions is given in Figure 1. The diagram shows two loops: a feedback lagged pitch damper loop and a feed-forward lagged column-minus-trim (C-T) loop. Provisions are made in the feed-forward loop for C-T signal washout during maneuvers. The PACS is considered to have four configurations for purposes of analyses and test evaluations. They are:

- PACS off (baseline aircraft)
- Pitch damper only
- Pitch damper with feed-forward
- Pitch damper with feed-forward washout

The pitch rate gain ($K_{\dot{\theta}}$), time lag (τ_{Lag}), and C-T feed-forward gain (K_{FF}) were scheduled as a function of calibrated airspeed (KCAS) as shown in Figure 2. The scheduling was necessary to assure that the PACS configured aircraft flying qualities for all flight conditions were equivalent to the baseline aircraft flying qualities with a 25% mac c.g. position. The 1.3 $K_{\dot{\theta}}$ through 2.0 $K_{\dot{\theta}}$ pitch rate gains were required to provide good flying qualities for c.g. positions between 39% and 45% mac.



NOTES: *THESE PARAMETERS ARE SCHEDULED WITH AIRSPEED
**ANALYTICAL APPROXIMATION FOR SAMPLE AND HOLD AND TRANSPORT DELAYS IN DIGITAL COMPUTER

Figure 1. - PACS analytical block diagram.

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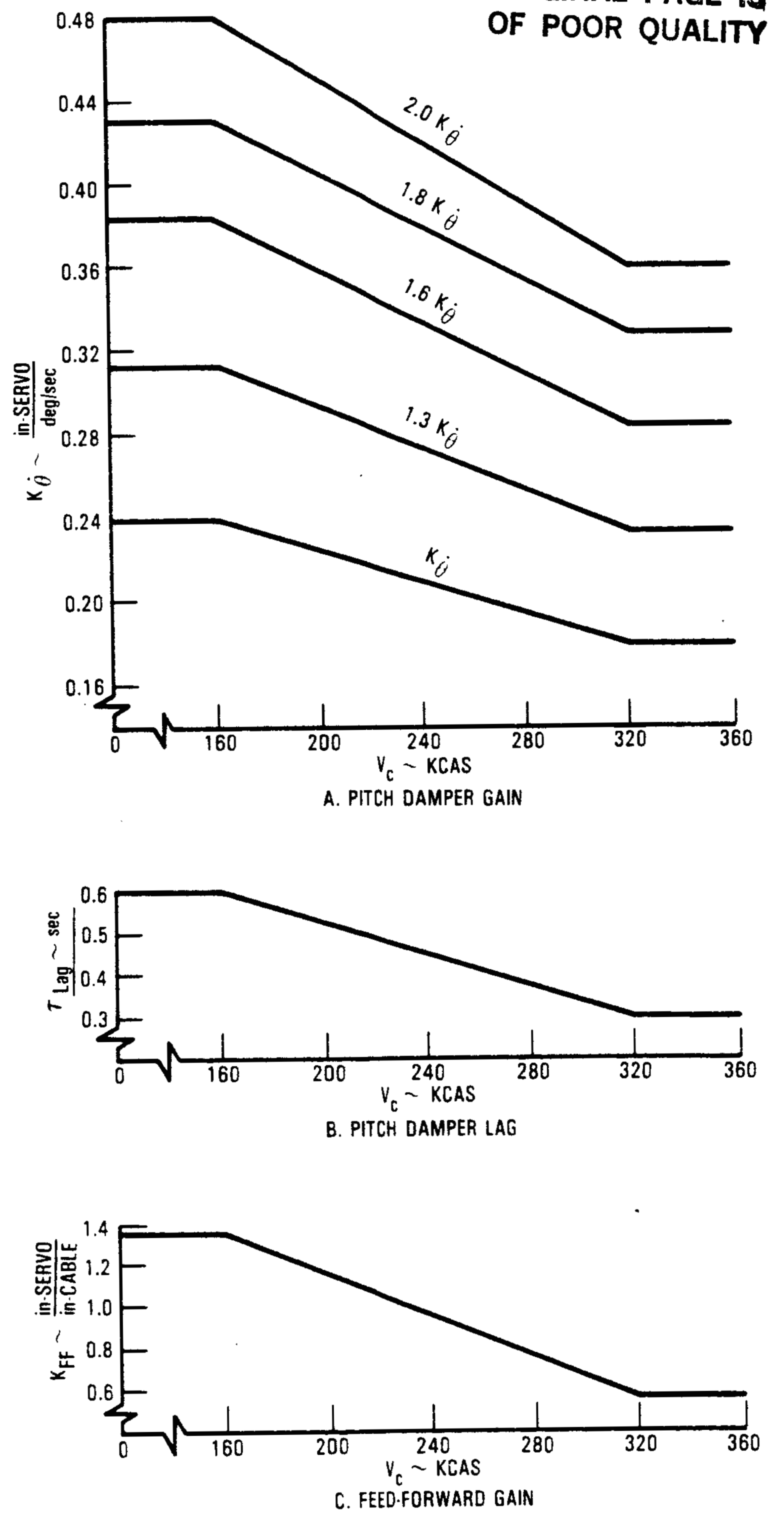

Figure 2. - PACS gain and time lag schedules.

4. FLYING QUALITIES ANALYSIS

Flight conditions selected for evaluation during the near-term PACS follow-on flight test program are listed in Table 1. Flight condition 10 was selected for flight testing to a negative 3% static stability margin. This margin represents the negative stability limits of the flight test aircraft. Flight conditions 11 and 18 were selected along with condition 10 for piloted flight simulation tests to broaden the data base. The simulation tests were to be performed with static stability margins to negative 5%.

Analyses were performed for the flight conditions listed in Table 1 to evaluate the near-term PACS flying qualities for flight at static stability margins to negative 5% since previous analyses were only for stability margins to positive 1%. The analyses included speed stability, maneuver stability, dynamic stability, and turbulence response. Results of the analyses were compared with MIL-F-8785C and FAR Part 25 flying qualities criteria to determine adequacy of the PACS capabilities.

4.1 Speed Stability

The speed stability analysis determined the column force (F_C), required to maintain the aircraft at a speed other than trim speed.

FAR Part 25 defines satisfactory column force characteristics as follows.

- A pull force shall be required to maintain speed below trim speed and a push force shall be required to maintain speed above trim speed.
- Column force shall vary monotonically with speed.
- The average column force gradient shall be at least -1 lb per 6 KEAS throughout the speed range.

TABLE 1. - FLIGHT CONDITIONS EVALUATED

Flight Condition	Weight (1000 lb)	c.g. (% mac)	Alt. (1000 ft)	V_e (KEAS)
10. Cruise ($W/\delta = 1.4 \times 10^6$ lb)	360	25-45	33	280 (M = 0.83)
11. Cruise ($W/\delta = 1.0 \times 10^6$ lb)	360	25-45	26	325 (M = 0.83)
18. Landing (δ_F = 33 deg)	330	25-45	2	135 (1.3 V_s)

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Flight condition 10 is selected for discussion in this report since it was the condition that was chosen for flight testing. The predicted flight condition 10 speed stability column force characteristics are shown in Figure 3 and satisfy the FAR Part 25 design criteria for c.g. positions of 25% and 45% mac. Since pitch rate is not generated when the aircraft is stabilized at the various speeds, the PACS off and PACS on with pitch damper only have the same column force characteristics as shown. Column forces were reduced significantly for the PACS operating configuration of pitch damper with feed-forward. Column forces for the PACS with pitch damper and feed-forward washout would be the same as with the PACS off except for lighter control column forces required to initiate the speed change.

4.2 Maneuver Stability

Maneuver stability analysis determined the column forces required to maintain the aircraft in steady wind-up turns or quasi-steady pushovers.

Maneuver column force criteria of MIL-F-8785C requires a steadily increasing push force to maintain load factors less than one and a steadily increasing pull force to maintain load factors greater than one. The upper and lower column force maneuver gradient criteria for cruise are:

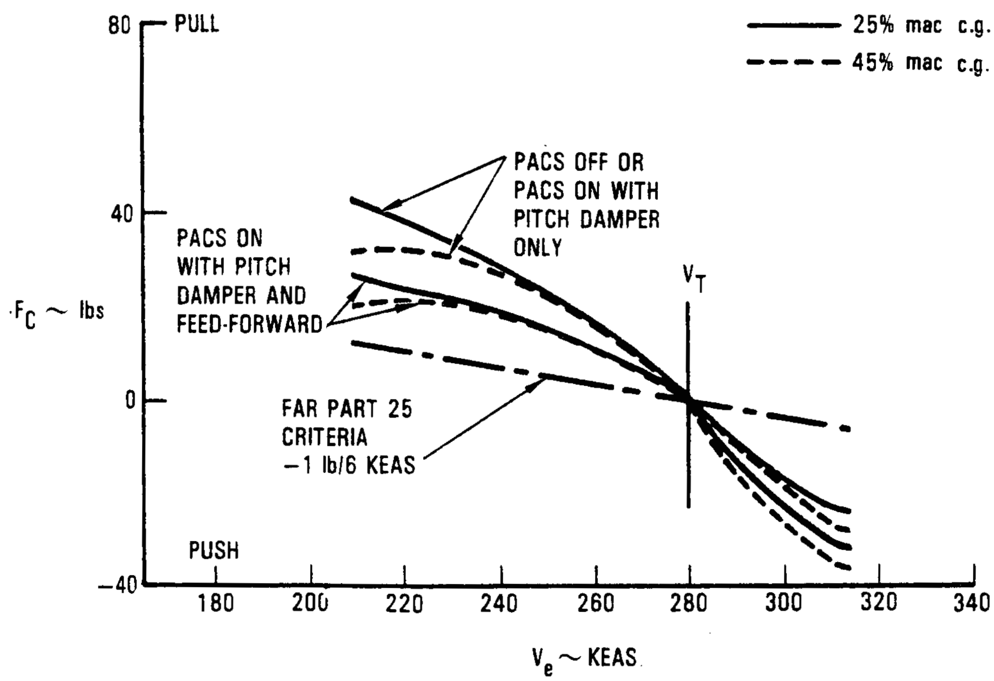

Figure 3. - Predicted speed stability column force characteristics, flight condition 10.

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- Upper boundary = $120/(n_L-1)$ lb/g
- Lower boundary = $35/(n_L-1)$ lb/g

Where n_L is the load factor limit of the aircraft. The load limit for commercial L-1011 aircraft is 2.5 g.

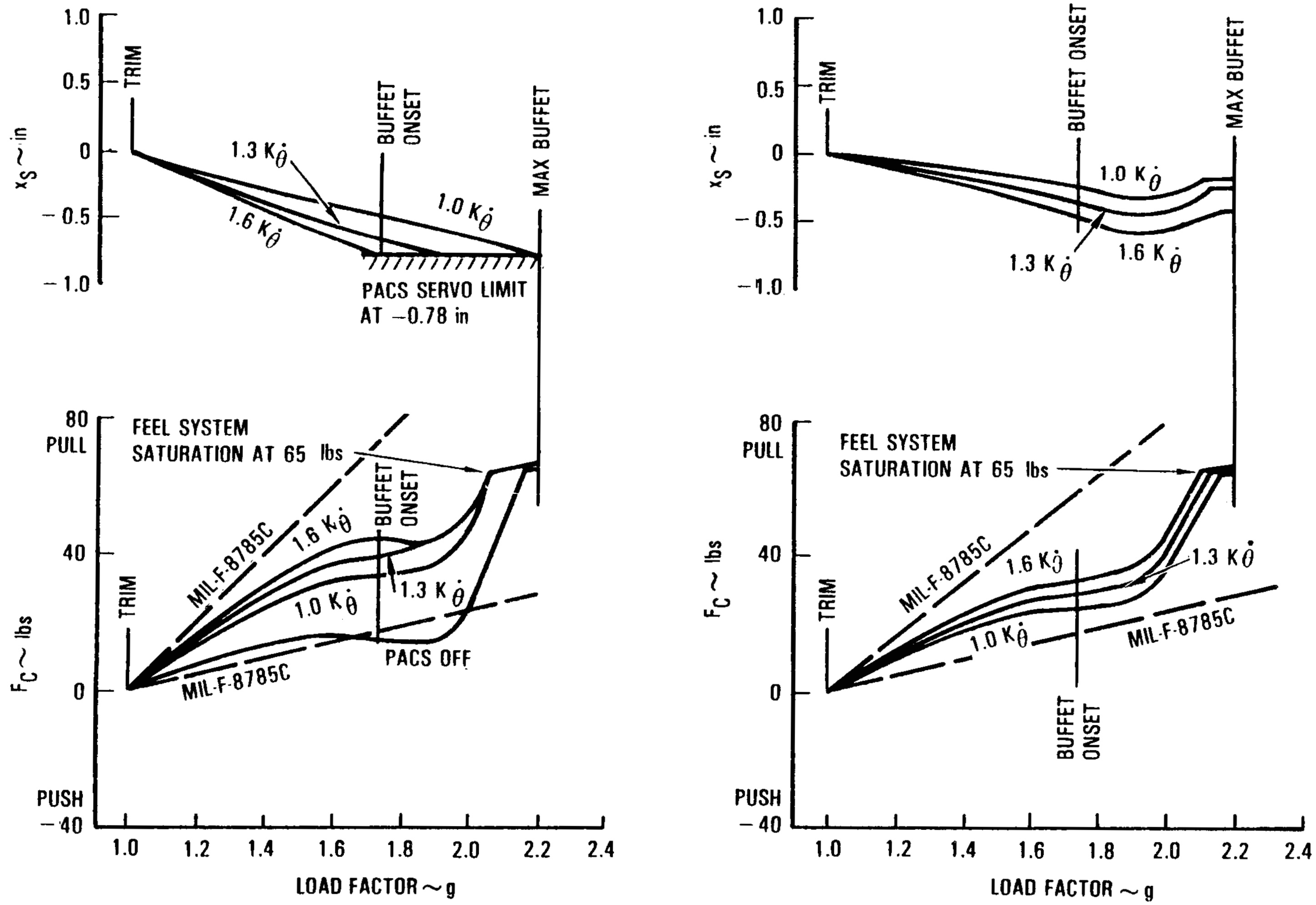
4.2.1 Flight condition 10.- The maneuver stability characteristics of flight condition 10 are shown in Figures 4 through 6 for 25%, 39%, and 45% c.g. positions respectively. Each plot in the figures gives the series servo displacement (x_S) and the column (F_C) as a function of the load factor (g). Plot A presents the maneuver characteristics for the PACS off and for the PACS on with pitch damper only. Plot B presents the maneuver characteristics for the PACS on with pitch damper and feed-forward.

The PACS operating configuration with pitch damper and feed-forward washout is not shown in the figures because it is dependent on the rate at which the maneuver was accomplished. However, the series servo displacements and column forces for this configuration lie between those of the other two PACS on configurations. Also, the configuration appears like the PACS with pitch rate damper only for sustained maneuvers, and like the PACS with pitch damper and feed-forward for quick maneuvers.

The pitch damper increases force gradients and the feed-forward reduces the gradient for each c.g. position as shown in Figures 4 through 6. Also, the initial force gradients for the PACS on configurations are shown to lie within the prescribed limits of MIL-F-8785C. At a load factor of 1.6 g, the column force gradients begin to reduce: they flatten for the 25% c.g. position and reverse for the 39% and 45% c.g. positions. The reduced gradients represent the end of the linear static stability region.

Since the objective of the near-term PACS extended flight test program was to evaluate the PACS at linear stability conditions, the load factor limit of the flight test aircraft was determined to be approximately 1.6 g. The lowest load factor at which the series servo displacement saturates is 1.72 g.

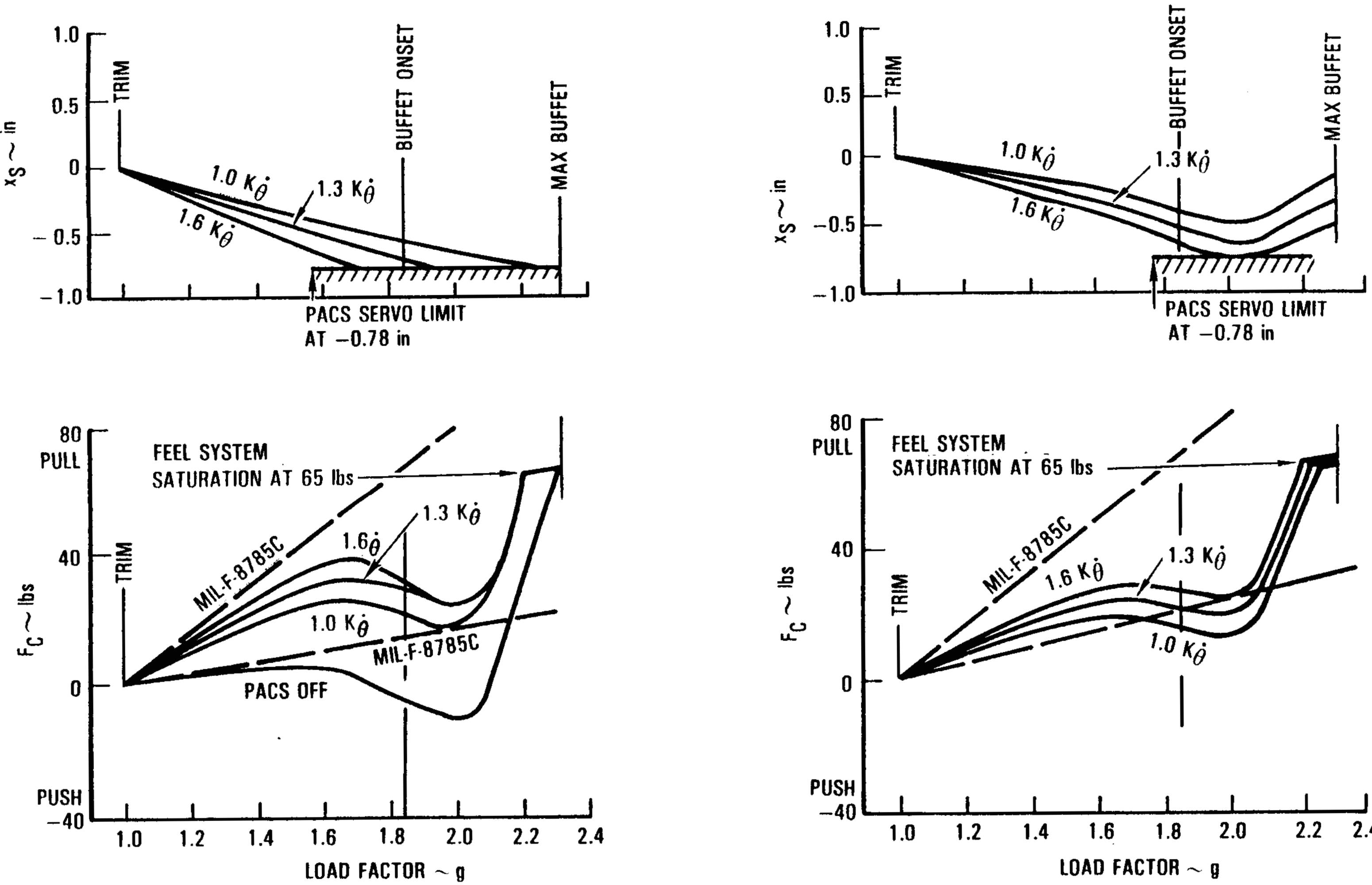
4.2.2 Flight condition 11.- The analysis for flight condition 11 showed that the initial force gradients with PACS on were within the limits prescribed by MIL-F-8785C. The linear stability region where the force gradients started to reduce was extended to a load factor of 2.2 g. The series servo output limits were reached at 2.1 g for the 45% mac c.g. position (negative 15% static stability margin) with the PACS-on pitch damper plus feed-forward configuration. The PACS-on configuration with pitch damper only had an output saturation at 1.8 g.



A. PACS ON WITH PITCH DAMPER ONLY

B. PACS ON WITH PITCH DAMPER AND FEED-FORWARD

Figure 4. - Predicted maneuver stability characteristics, flight condition 10, c.g. at 25% mac.



A. PACS ON WITH PITCH DAMPER ONLY

B. PACS ON WITH PITCH DAMPER AND FEED-FORWARD

Figure 5. - Predicted maneuver stability characteristics, flight condition 10, c.g. at 39% mac.

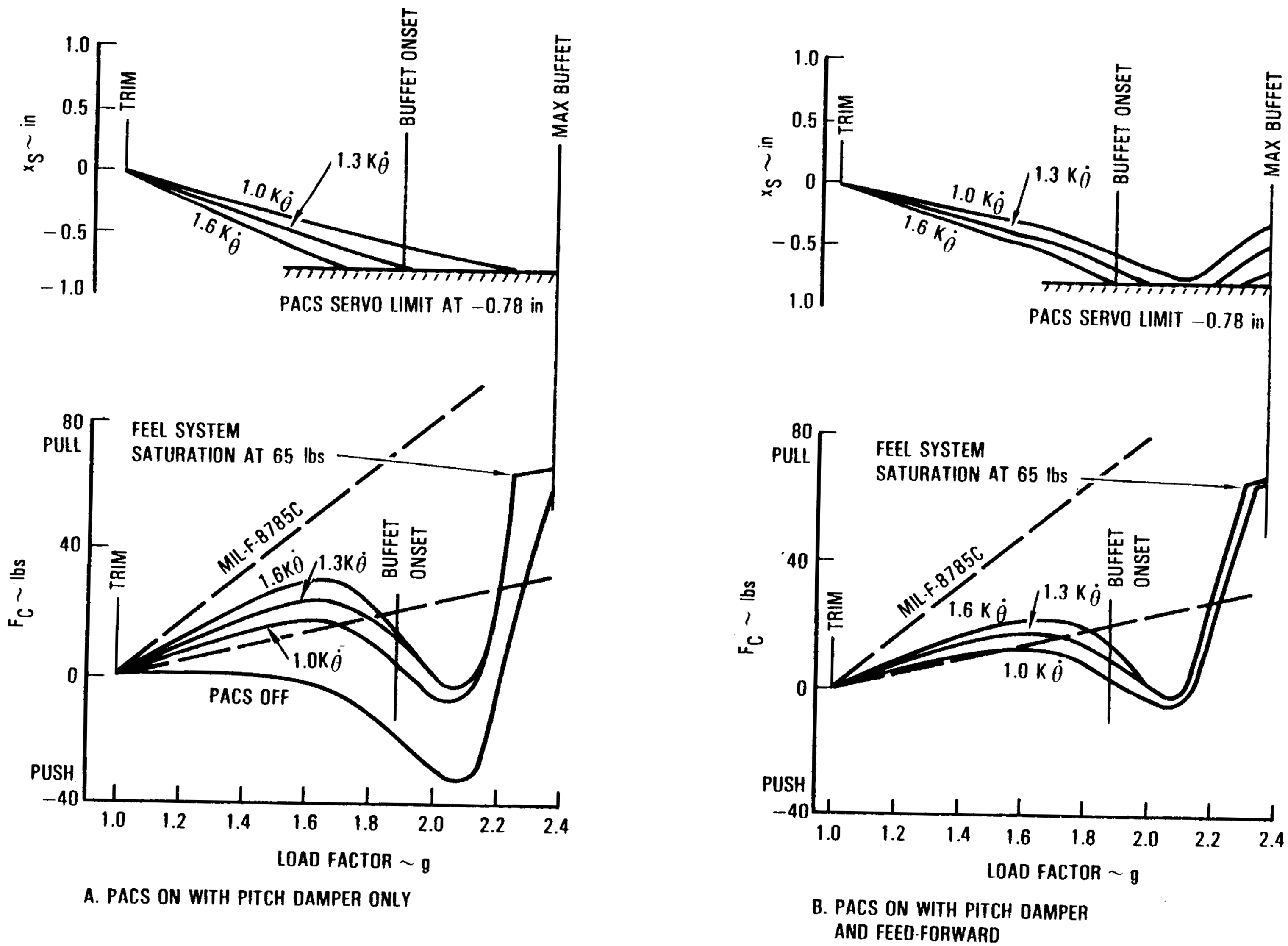


Figure 6. - Predicted maneuver stability characteristics, flight condition 10, c.g. at 45% mac.

4.2.3 Flight condition 18.- Analysis showed that the column force gradients for flight condition 18 with the PACS on or off increased as the c.g. position was moved aft. Also, at the aft c.g. positions the column force gradients exceeded the maximum limits prescribed by MIL-F-8785C. The gradient increase at the aft c.g. positions was caused by the primary control system gearing and associated feel system which were not designed for flight with the c.g. at the aft positions. The PACS series servo displacement reached saturation at relatively low load factors for the PACS pitch damper only configuration. The load factor at this saturation decreased as the pitch rate feedback gains were increased. For the PACS configuration with pitch damper plus feed-forward, the servo saturation occurred at a load factor well beyond that required for normal maneuvers because the feed-forward opposes the pitch rate damper command.

4.3 Dynamic Stability

The dynamic stability analyses were performed to evaluate the PACS configured aircraft longitudinal mode characteristics.

The aircraft was considered to be a point mass and have a rigid body. The AACS and Mach trim compensation system (MTC) were considered to be operating. The modes were determined by obtaining roots of the aircraft and control system linearized equations.

4.3.1 Flight condition 10.- The short-period and phugoid modes frequency and damping characteristics with AACS on for flight condition 10 are shown in Figure 7. The baseline aircraft ($K_{\dot{\theta}} = 0$) with a 25% mac c.g. position has a short-period damping ratio (ζ) near 0.5. With the PACS on this level of damping is achieved for the 45% mac c.g. by using a pitch rate feedback gain of 1.3 $K_{\dot{\theta}}$. A 1.6 $K_{\dot{\theta}}$ is shown to be required for stabilization of the phugoid mode and this was the recommended gain for the simulation program.

4.3.2 Flight condition 11.- For flight condition 11 with the PACS on and the c.g. at 45% mac, a pitch rate feedback gain of $K_{\dot{\theta}}$ provided a damping ratio equivalent to that of the baseline aircraft with the c.g. at 25% mac. However, a value of 1.6 $K_{\dot{\theta}}$ was required to stabilize the phugoid mode at the 45% mac c.g. position.

4.3.3 Flight condition 18.- The PACS gain requirements for flight condition 18 were the same as those of flight condition 11.

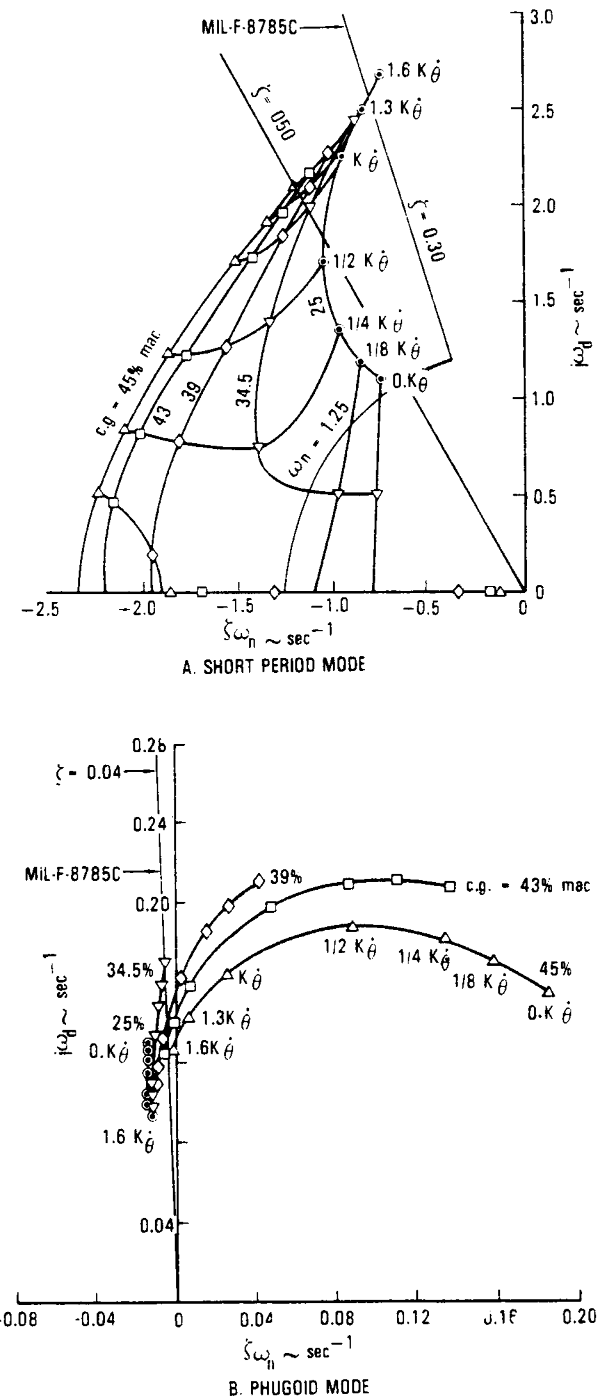


Figure 7. - Effect of pitch rate feedback gain on dynamic stability characteristics.

4.4 Turbulence Response

The aircraft was considered to be a point mass with a rigid body. The Laplace transformed linearized longitudinal equations of motion and the von Karman form of the turbulence model were used for the analysis. The analysis was simplified by eliminating the linear gust gradient terms except for the vertical gust time rate of change that defined the effect on the angular acceleration of the aircraft. The rms response for each variable e.g. Nz_{rms}, g_{rms}, and $x_{s_{rms}}$ was computed by taking the square root of the frequency integral of a function. The function was obtained by multiplying the square of the absolute value of the transfer function for the specific variable by the power spectral density of the gust.

The load factor (Nz_{rms}), pitch rate ($\dot{\theta}_{rms}$), and series servo displacement ($x_{s_{rms}}$) rms values for a turbulence intensity of 1 ft/sec in both the horizontal and vertical directions are shown in Figure 8 for flight condition 10 with the PACS off and on. The PACS on results were calculated for a pitch rate feedback gain of 1.6 $K_{\dot{\theta}}$. The load factor and pitch rate response of the baseline aircraft (PACS off) are shown to increase as the c.g. is moved aft from 25% to 35% mac. This is the expected trend since the static stability margin is decreasing. As the c.g. is moved aft of 35% mac the load factor and pitch rate response are shown by the analysis to decrease in magnitude as indicated by the dashed lines. This can be explained by the effects of static stability characteristics and by the effects of AACS. In the aft c.g. range, the static margin is small so there is little pitch rate response to gust. Besides reducing load factor response, the AACS also reduces pitch response since the ailerons are far enough forward of the c.g. to accomplish this. Engagement of the PACS shows a significant reduction in the load factor and pitch rate response and these responses along with the servo displacement response remain relatively constant over the c.g. range. This is a desirable characteristic.

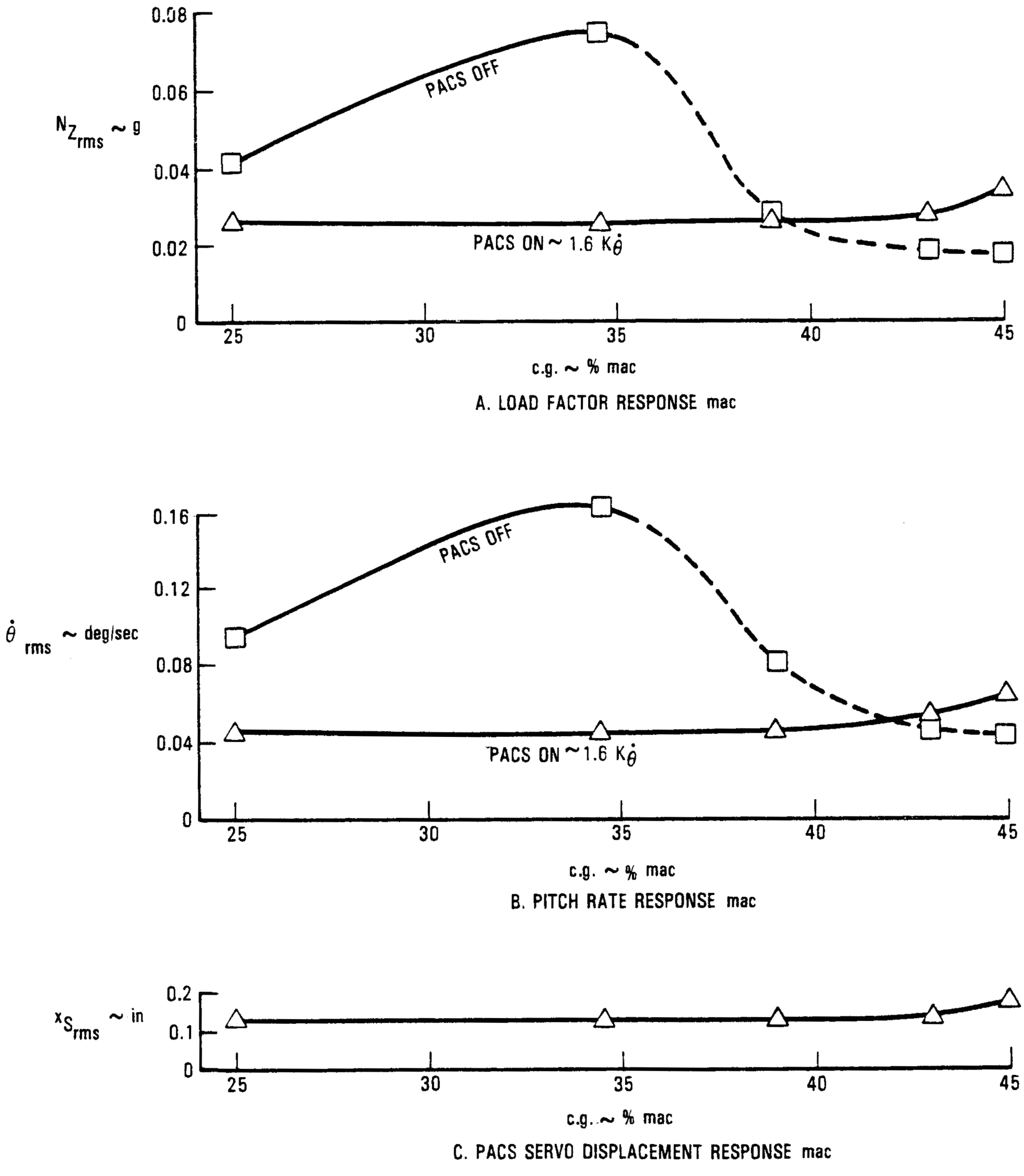


Figure 8. - Predicted aircraft response to an atmospheric turbulence level of 1 ft/sec, flight condition 10.

5. PILOTED FLIGHT SIMULATION TEST

The piloted flight simulation test was performed to confirm the analytically determined optimum PACS operating configurations and pitch rate feedback gains to be evaluated during the flight test program, and to assure that a PACS failure would not jeopardize the flight test aircraft. The simulation test flight time was 44 hours and was conducted by two Lockheed and two NASA pilots.

5.1 Simulation Model

The simulation mathematical model represented the flight test airplane, L-1011 S/N 1001. Engine characteristics were represented by the installed thrust of three Rolls Royce RB.211-22B turbofan engines. Control functions were represented by a complete dynamic model of the longitudinal system and a simplified model of the lateral-directional system. A complete description of the control functions is given in Reference 2.

5.2 PACS Configuration

The four PACS configurations defined in Section 3 were tested. The pitch rate feedback gains evaluated ($K_{\dot{\theta}}$, 1.3 $K_{\dot{\theta}}$, 1.6 $K_{\dot{\theta}}$) are given in Figure 2. The C-T feed-forward gain (K_{FF}) was increased to 1.3 K_{FF} and 1.6 K_{FF} for some of the flight condition 18 tests.

5.3 Flight Simulator

The NASA-Langley visual motion simulator (VMS) was used for the piloted-flight simulation test. The VMS is a general purpose simulator consisting of a two-man cockpit mounted on a six degree of freedom synergistic base. A collimated visual display provides 60 degree out-the-window color displays which were activated during the landing test simulation. A programmable hydraulic control loading system is provided for column, wheel, and rudder. The instruments and displays are typical of those for transport aircraft.

5.4 Flight Conditions

The piloted flight simulation test conditions are listed in Table 1. These conditions were tested at c.g. positions from 25% to 45% mac for the four PACS configurations (Section 3) with pitch rate feedback gains from $K_{\dot{\theta}}$ to 2.0 $K_{\dot{\theta}}$ (Figure 2).

Flight conditions 10 and 18 had been tested during the previous phase of the near-term PACS development program on the Lockheed Rye Canyon Laboratory simulator for c.g. positions from 25% to 39% mac with a pitch rate feedback gain of $K_{\dot{\theta}}$. Flight condition 11 was added for the NASA VMS test to provide PACS evaluation in an expanded linear stability region. Flight conditions 10 and 11 are shown on the speed-altitude limit envelope of Figure 9.

5.5 Evaluation Tasks

Most of the simulation tests were conducted for calm air conditions because of flight simulation time constraints and pilot agreements that differences between PACS configurations could be better evaluated without turbulence simulation.

The number of PACS configurations to be evaluated were reduced by using the following procedure.

- Pilot rating trends were used for increasing pitch rate feedback gains as the c.g. position was moved aft.
- Each new pilot started evaluation of a flight condition with the PACS configuration that was preferred by previous pilots.
- At the beginning of the second cruise condition evaluated by a pilot, he was provided with the preferred PACS configuration that he had selected for the first cruise flight condition. If the PACS configuration was found to be satisfactory further optimization was not attempted.

Piloting tasks used to determine the preferred PACS configurations included wind-up turns, speed changes, control pulses and releases, shallow-banked turns, S pattern turns, small pitch changes, power advances and retardations, emergency descents and large pitch changes.

To ensure the safety of the flight tests two types of PACS failures, the most probable and the worst, were investigated for the most adverse flight condition. The first was an undetected PACS failure and the second was a maximum servo authority hardover. Both, the undetected failures and hardovers were randomly inserted during evaluation of the Flight condition 11 test when the c.g. was at the 43% mac position.

5.6 Simulation Test Results

This section presents the piloted-flight-simulation test results in terms of pilot Cooper-Harper ratings for the two cruise conditions and the landing condition, (see Table 1). The ratings are for calm air atmospheric conditions except for the symbols on the pilot rating charts that are marked with a T which represents flight in moderate turbulence.

Test results of each flight condition are separately discussed. Initially, Coooper Harper ratings of the baseline aircraft (PACS off) are presented for the c.g. range from 25% to 45% mac. The ratings of the aircraft with the PACS on are then presented for the c.g. range from 39% to 45% mac.

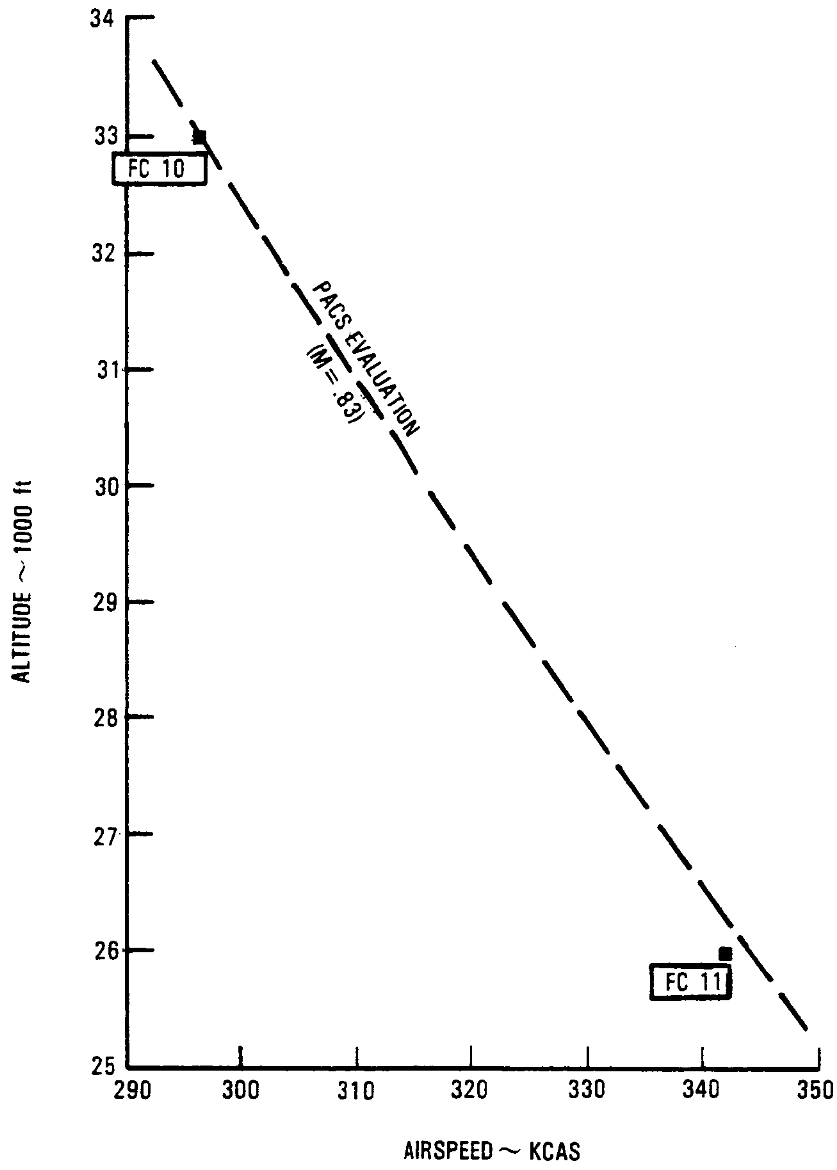


Figure 9. - Piloted flight simulation test cruise conditions on speed-altitude envelope.

5.6.1 Flight condition 10.- Pilot Cooper-Harper ratings for the aircraft at cruise condition 10 are given in Figure 10 for the AACS on and off. The three pilots who evaluated this flight condition rated the aircraft satisfactory for the 25% mac c.g. position and unacceptable for the 43% mac c.g. position. Based on the data shown, the baseline aircraft (AACS on) boundaries for satisfactory/unsatisfactory and unsatisfactory/unacceptable ratings are approximately 37% and 42% mac respectively. It should be noted that the pilot ratings deteriorate very rapidly once the c.g. is aft of the neutral point.

Engagement of the PACS improved the pilot Cooper-Harper ratings significantly as shown in Figure 11. The PACS configurations tested for each c.g. position are designated at the bottom of each rating chart. The different symbols represent the different pitch rate feedback gains. The shaded symbols designate the preferred PACS configuration chosen by the pilot for the specific c.g. position. The rating at 25% mac represents the baseline aircraft (PACS off, 0 $K_{\dot{\theta}}$). Symbols marked with a T represent flight in moderate turbulence.

The three pilots who completed their evaluation at this flight condition rated the PACS on aircraft the same as or better than the baseline aircraft (PACS off, c.g. = 25% mac) at c.g. positions up to 41% mac. Pilots 1 and 3 rated the aircraft slightly worse than the baseline aircraft at c.g. positions aft of 41% mac, however their ratings remained in the satisfactory range. Pilot 2 found the aircraft more degraded with c.g. positions aft of 41% mac and rated the aircraft unsatisfactory. Pilot 2 also provided ratings which excluded the phugoid. When the phugoid was excluded, his ratings remained satisfactory with the c.g. at 43% mac. Pilot 4 only evaluated a gain of 2.0 $K_{\dot{\theta}}$ with a c.g. position of 43% mac at this flight condition. He also found the PACS on aircraft unsatisfactory. At a c.g. of 39% mac pilot opinions for the preferred PACS operating configuration were divided between the pitch damper plus feed-forward and pitch damper with feed-forward washout. At farther aft c.g. positions the pilots preferred the PACS operating configuration with pitch damper plus feed-forward. The desired pitch rate feed back gain value trend was from $K_{\dot{\theta}}$ to between 1.6 and 2.0 $K_{\dot{\theta}}$ as the c.g. was moved from 39% to 45% mac.

Pilot 1 ratings in moderate turbulence indicated the flying qualities to be unsatisfactory. The preferred PACS configurations in turbulence were the same as in calm air. Neither an increased pitch rate damping gain nor a different PACS operating configuration would improve the rating. The pitch rate damping gains of $K_{\dot{\theta}}$, 1.3 $K_{\dot{\theta}}$ and 1.6 $K_{\dot{\theta}}$ appeared to be satisfactory for the flight test program which would be limited to a maximum aft c.g. of 43% mac and flight condition 10.

5.6.2 Flight condition 11.- Figure 12 shows pilot ratings for the aircraft at flight condition 11 are similar to those of flight condition 10. The AACS-off ratings at aft c.g. positions are better than the AACS-on ratings and the AACS-on rating trend is from satisfactory to unacceptable as the c.g. is moved from 25% to 43% mac. From the data shown the baseline aircraft

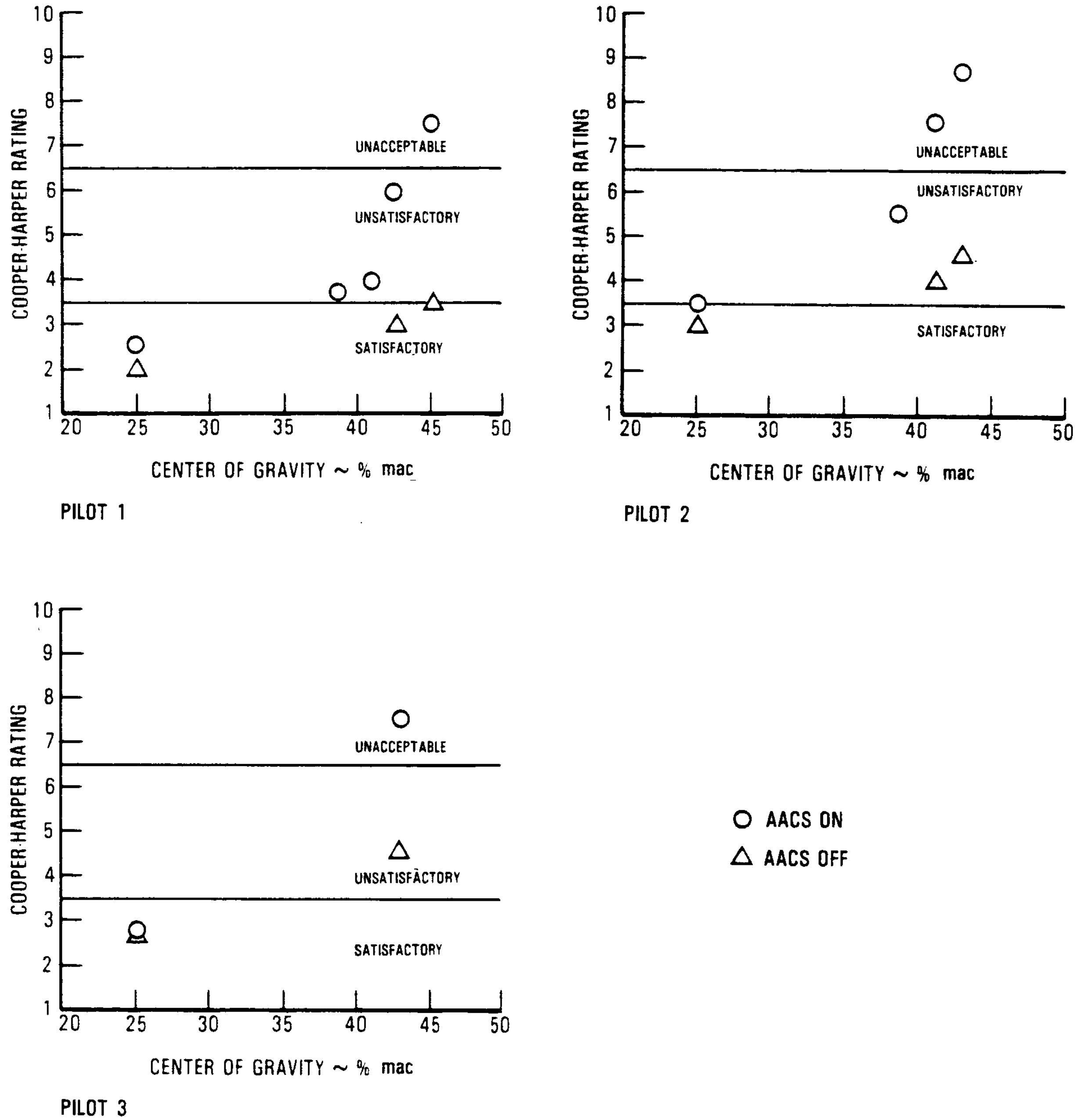


Figure 10. - Simulation test pilot Cooper-Harper ratings for flight condition 10, PACS off.

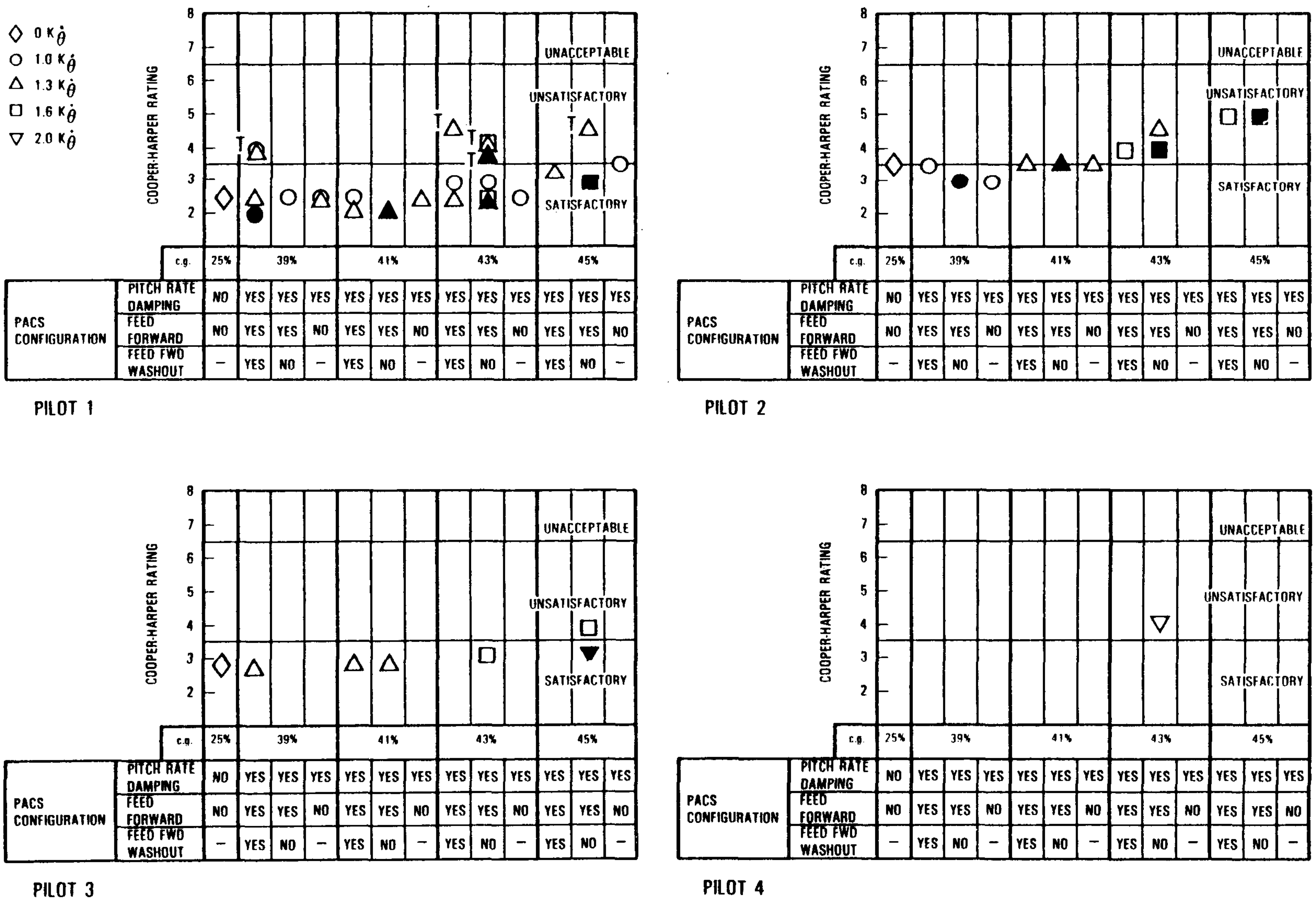


Figure 11. - Simulation test pilot Cooper-Harper ratings for flight condition 10, PACS on.

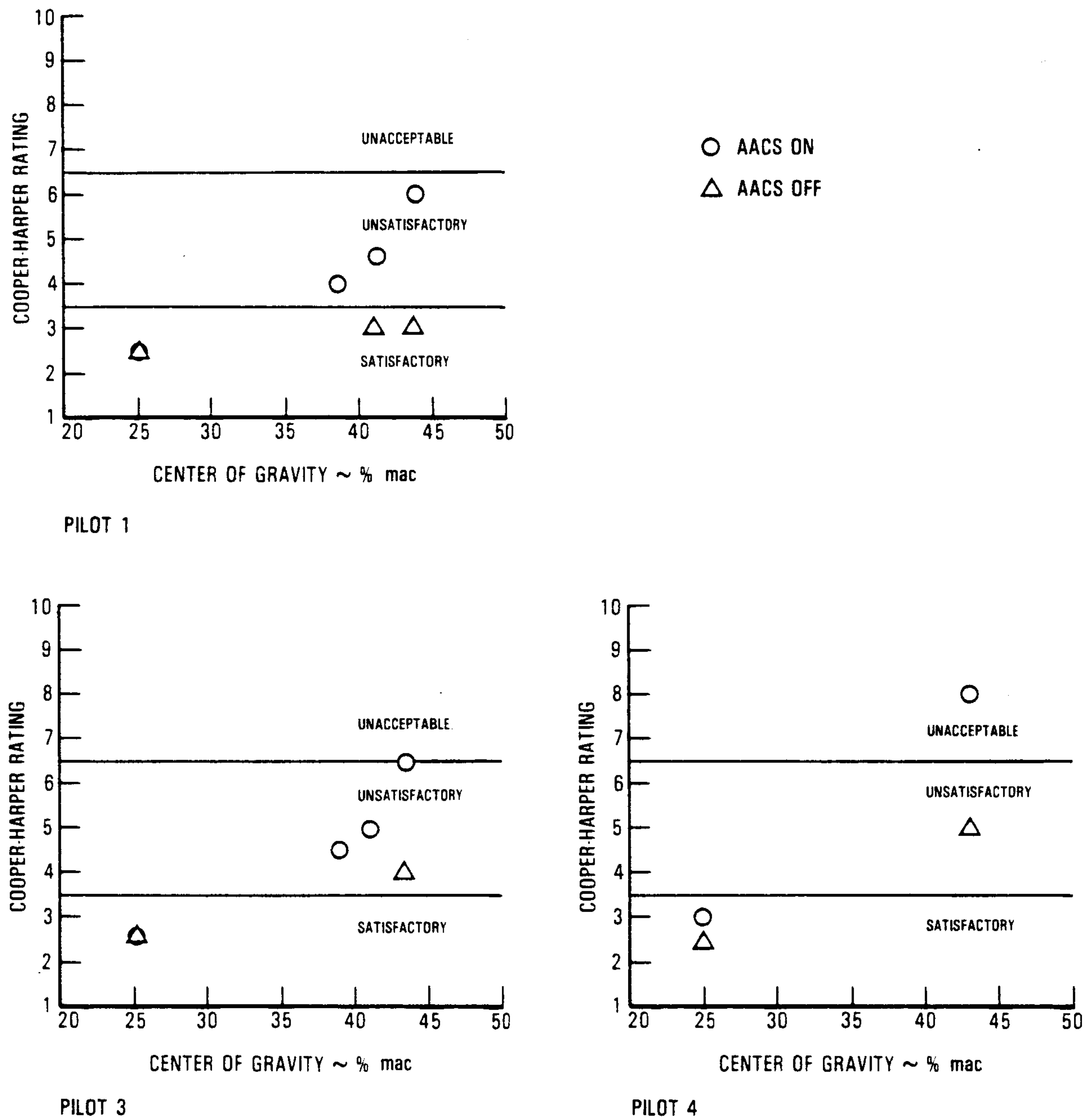


Figure 12. - Simulation test pilot Cooper-Harper ratings for flight condition 11, PACS off.

boundaries for satisfactory/unsatisfactory and unsatisfactory/unacceptable ratings are estimated to be 37% and 43% respectively.

Engagement of the PACS also showed similar results (Figure 13) to that of flight condition 10. The ratings of each pilot showed satisfactory flying qualities at the 39% and 41% mac c.g. positions. However, pilots 2 and 4 ratings at the 43% c.g. position showed unsatisfactory flying qualities, whereas Pilots 1 and 3 ratings showed satisfactory flying qualities to 45% for the preferred PACS configuration (pitch damper plus feed-forward). The desired pitch rate feedback gain trend was the same as it was for flight condition 10.

Turbulence evaluations by pilots 1 and 3 showed that flying qualities in moderate turbulence were degraded relative to the flying qualities in calm air. The pilot 1 ratings indicated the flying qualities were unsatisfactory while pilot 2 ratings showed satisfactory flying qualities. The pitch rate feedback trend was from $K_{\dot{\theta}}$ at 39% mac to 1.6 $K_{\dot{\theta}}$ at 43% mac. Their ratings remained essentially constant over the c.g. range with Pilot 1 rating the airplane unsatisfactory and Pilot 3 rating the airplane satisfactory.

Randomly inserted PACS failures throughout the Flight Condition 11 test with c.g. at 43% mac showed that passive failures were benign. The pilots were aware when a failure occurred and were able to disengage the AACS to produce a more stable aircraft.

Maximum PACS servo authority hardover failures presented some difficulty in controlling the aircraft. The best recovery procedure was found to be deactivation of the PACS quickly, recovering the aircraft to 1 g, and disengaging the AACS. This procedure was adopted as the flight test procedure should this failure occur.

5.6.3 Flight condition 18.- Pilot ratings for the baseline aircraft at flight condition 18 are given in Figure 14. All tests were performed with the PACS on. Pilots 1, 2, and 3 performed tests for moderate turbulence conditions. Three of the four pilots rated the baseline aircraft flying qualities to be satisfactory over the c.g. range to 41% mac. The pilot ratings at 43% indicated that the flying qualities were unsatisfactory.

Engagement of the PACS (Figure 15) slightly improved the aircraft flying qualities. The C-T feed-forward gain was increased for some of these tests as indicated in the figure but did not improve the flying qualities. The PACS with pitch damper plus feed-forward was the only configuration evaluated except for one test by Pilot 1 with the c.g. at 39% mac. The desired pitch rate feedback increased from 1.3 $K_{\dot{\theta}}$ to 1.6 $K_{\dot{\theta}}$ as the c.g. was moved from 39% to 43% mac.

The ratings decreased only a small amount for flight in moderate turbulence.

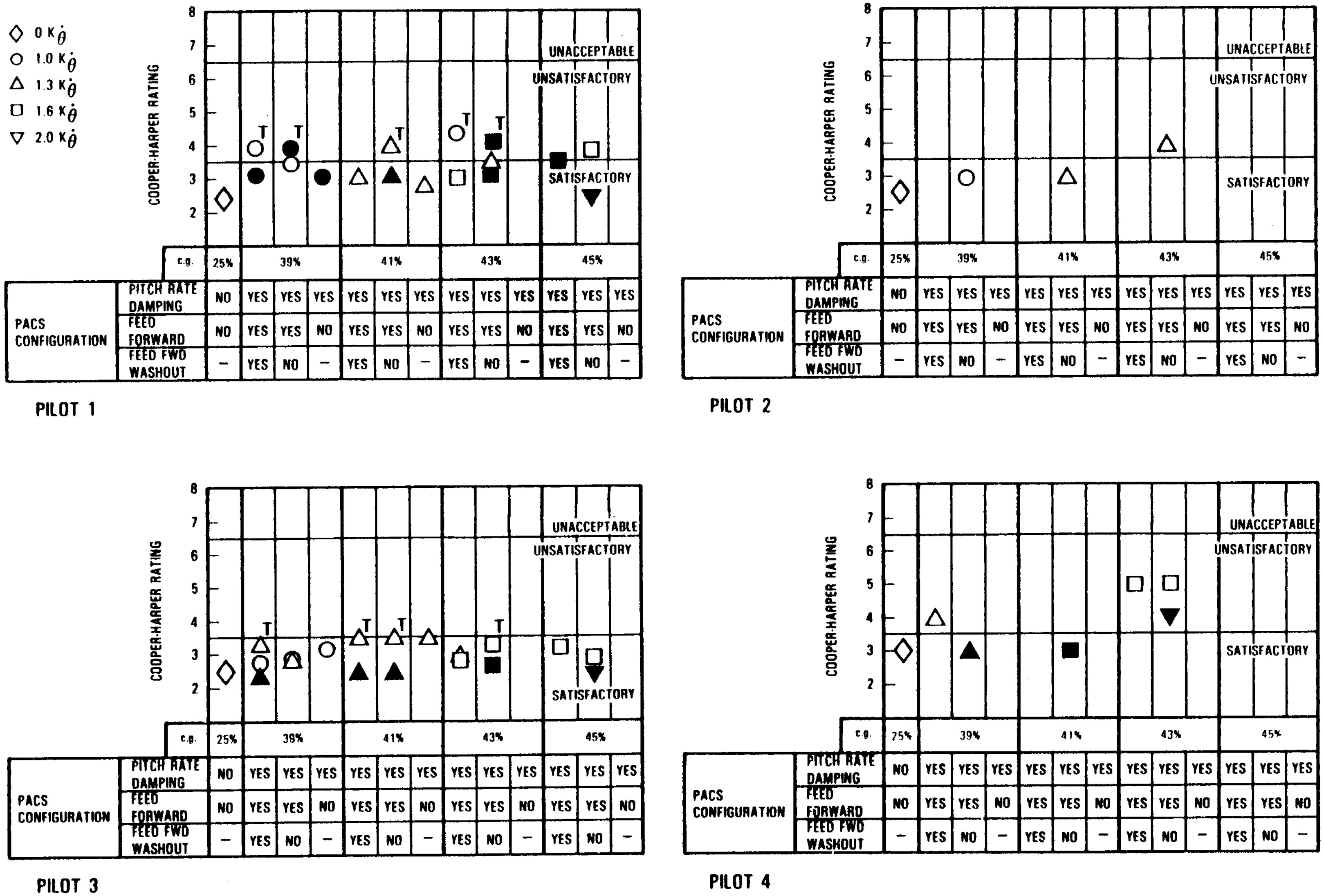


Figure 13. - Simulation test pilot Cooper-Harper ratings for flight condition 11, PACS on.

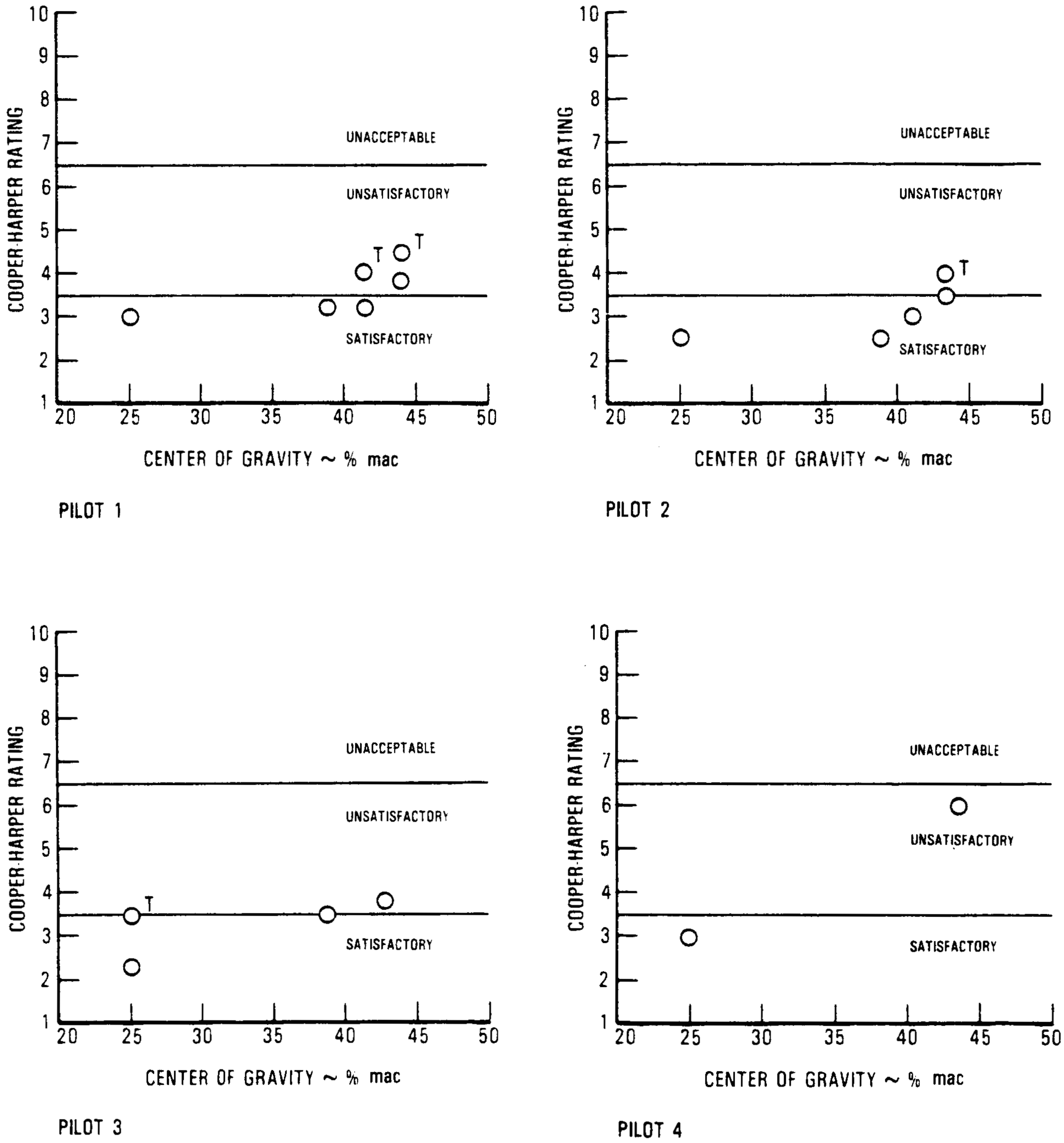


Figure 14. - Simulation test pilot Cooper-Harper ratings for flight condition 18, PACS off.

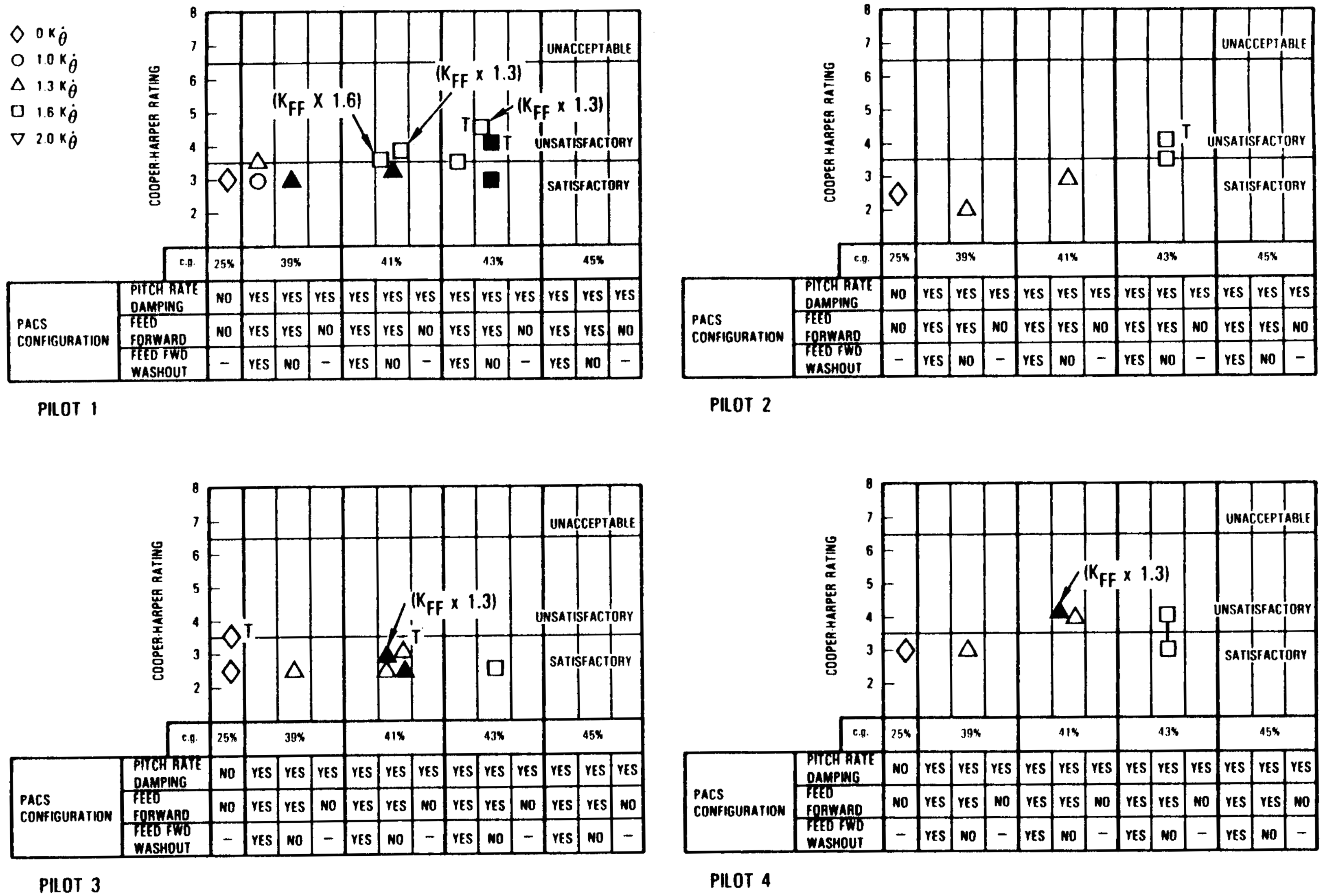


Figure 15. - Simulation test pilot Cooper-Harper ratings for flight condition 18, PACS on.

5.7 Summary of Simulation Test Results

The baseline aircraft had unacceptable flying qualities for cruise flight conditions 10 and 11 at c.g. positions aft of 41% mac. However, the aircraft flying qualities were significantly better with the AACS off. Therefore, in case of a PACS failure during the flight test program, the AACS could be disengaged to enhance the aircraft flying qualities. The baseline aircraft flying qualities for the landing flight condition were acceptable throughout the c.g. test range.

Engagement of the PACS improved the flying qualities for cruise flight conditions 10 and 11 significantly but only slightly improved the landing flight condition 18. The flying qualities were considered good over the c.g. range and were close to meeting the design goals which required the PACS configured aircraft flying qualities for the entire c.g. range to be equivalent to those of the baseline aircraft with a 25% mac c.g. position.

The preferred PACS operating configuration was determined to be the pitch rate damper plus feed-forward configuration. The desired pitch rate feedback gain trend was from $K_{\dot{\theta}}$ at 39% mac to between 1.6 $K_{\dot{\theta}}$ and 2.0 $K_{\dot{\theta}}$ at 45% mac. However, the majority of pilot ratings indicated that a gain of 1.6 $K_{\dot{\theta}}$ was adequate at a 43% mac c.g. position and since this represented the aft c.g. limit of the flight test aircraft, the gain settings selected for the flight test aircraft PACS were $K_{\dot{\theta}}$, 1.3 $K_{\dot{\theta}}$, and 1.6 $K_{\dot{\theta}}$. The C-T feed-forward gain of K_{FF} was not changed from the value used during the initial flight test program.

6. FLIGHT TEST AIRCRAFT PREPARATION

6.1 Structural Loads

The previous program loads analysis developed the structural operating restrictions required to operate the flight test aircraft with the near-term PACS at an aft c.g. limit of 39% mac. These restrictions defined the structurally safe operating limits of the PACS aircraft based on predicted loads relative to structural capability. The loads analysis described here leads to the structural operating restrictions necessary to extend the aft c.g. limit to 43% mac and utilize pitch rate feedback gains to 2.0 $K_{\dot{\theta}}$.

The loads analysis criteria and methods remain the same as those described in the structural loads analysis section of Reference 1. The current loads analysis is divided into the following steps.

- Failure analysis
- Maneuver and dynamic gust loads analysis
- Structural operating restrictions

6.1.1 Failure analysis.- The previous program failure analysis determined the worst type of nonoscillatory failure to be an undetected hardover of the PACS series servo. Twenty-three time histories for this type of failure were performed. Variables were c.g., authority limit, and speed/altitude. From this analysis, a reduced allowable speed altitude (V_D/M_D) boundary was established for flight at a 43% mac c.g. position based on peak aircraft load factor and tail load. This boundary applies to the existing series servo authority limits of 0.68 degree aircraft nose-up and nose-down referenced to a trim setting of -1.0 degree, and the 2.0 second pilot recovery criterion of Reference 1. This V_D/M_D boundary of V_D = 325 KCAS and M_D = 0.86 was selected such that loads at 43% mac c.g. due to this type of failure do not exceed those established by the previous analysis at 39% mac and V_D/M_D boundary of V_D = 375 KCAS and M_D = 0.90. The reduced V_D/M_D boundary is shown as a part of Figure 16. The same probability of a hardover failure established for the previous analysis was utilized in assessing allowable airframe loads from an undetected hardover failure.

Distributed loads (panel loads) were computed for the seven most critical time history cases and compared with established aircraft strength capability to verify that undetected hardover failure loads do not exceed those of the previous analysis.

Oscillatory failure condition loads were judged not critical by a review of the initial program oscillatory failure analysis results.

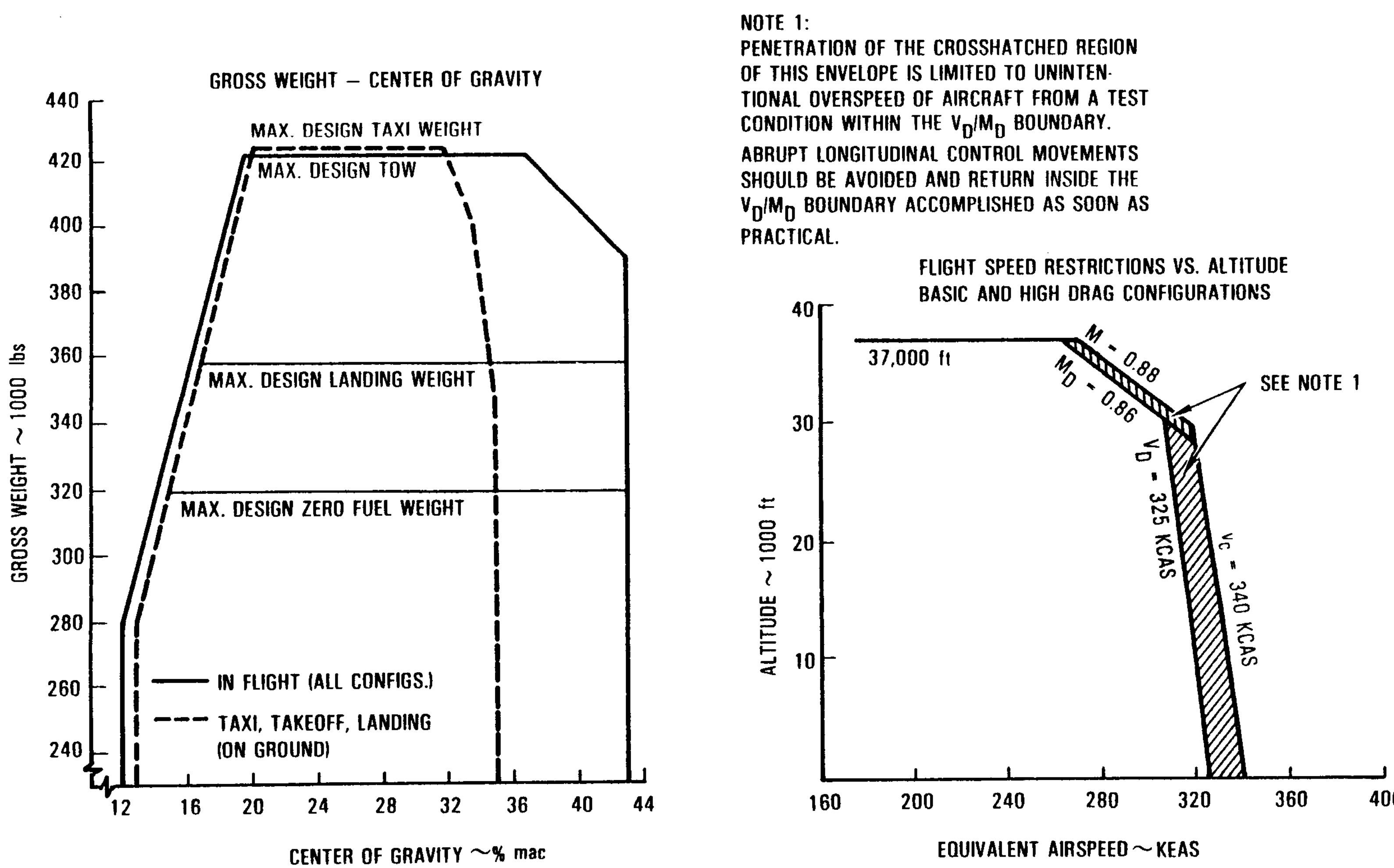


Figure 16. - Summary of L-1011 S/N 1001 operating restrictions for the near-term PACS flight test program.

6.1.2 Maneuver and dynamic gust loads analysis.- Distributed loads were computed for thirteen potentially critical steady maneuver conditions at the extended 43% mac aft c.g. boundary by using reduced maneuver load factors. These loads are within established aircraft strength capability. Thirty-eight transient maneuver time histories were generated at reduced load factors in order to investigate the effects of a more aft c.g. and increased PACS pitch rate feedback gain on peak tail loads. Additional transient maneuver distributed loads beyond those done for the previous program phase were judged unnecessary since these time histories yielded peak tail loads below those obtained in the previous analysis. The net result of the steady and transient maneuver analysis was a reduction in the AACS on allowable load factors from 2.2 to 2.0 for the basic and high-drag configurations and from 1.9 to 1.8 for the flaps-extended configuration. This was primarily a consequence of increased aft fuselage loads due to the additional fixed aft fuselage ballast required to reach 43% mac.

Dynamic gust condition loads were judged not critical on the basis of a review of the previous dynamic gust loads analysis results.

6.1.3 Structural operating restrictions.- The structural operating restrictions and requirements are the end product of the structural loads analysis task and reflect the structurally safe operating environment limits of the PACS flight test aircraft based on predicted loads relative to structural capability. Restrictions include aircraft load factor, speed/altitude, aircraft weight and c.g. limits (including ballast distribution), fuel loading and ground restrictions, and allowable turbulence and buffet limits. Requirements include loads monitoring. This material is specified through a revision to the existing L-1011 operating restrictions report and issuance of an Aircraft Structural Operating Limitations Memo

Figure 16 shows a composite summary of the more significant restrictions. Compared to previous restrictions, the AACS-on load factors are reduced from 2.2 to 2.0 for the basic and high-drag configurations, and from 1.9 to 1.8 for the flaps-extended configuration. The speed/altitude boundary is reduced to V_D = 325 KCAS and M_D = 0.86 from V_D = 375 KCAS and M_D = 0.90. The aft c.g. limit is extended from 39% to 43% mac. And, the maximum zero fuel weight is increased from 312,460 lb to 319,282 lb.

6.2 Stress

Stress activities for the near-term PACS extended flight test program included analysis and inspection of the ballast arrangement for the 43% mac c.g. configuration. The changes in the ballast arrangement for the 43% mac c.g. configuration relative to the 39% mac c.g. configuration were the addition of 3,750 lbs of fixed ballast. The allowable floor strength was exceeded when design flight and landing load factors were applied. The Structural Operating Restrictions described in Section 6.2 were set to reduce these load factors to a level within the strength capability of the floor structure. The capability of the 43% mac c.g. ballast installation in the aft passenger cabin to withstand emergency landing load factors was maintained. An inspection of the 43% mac c.g. ballast installation was made to insure drawing conformance.

6.3 Weight and c.g. Management

The flight test aircraft c.g. management system was revised to increase the aft c.g. limit from 39% to 43% mac. This was accomplished by increasing the fixed water ballast from 12,600 lbs to 14,000 lbs and the hard ballast from 19,250 lbs to 21,600 lbs. The revised ballast system is shown in Figure 17. The aircraft was weighed prior to the first flight to obtain gross weight and c.g. verification.

The c.g. position during flight was controlled from a weight engineers station by transferring movable water ballast and/or aircraft fuel. The c.g. position was maintained within a tolerance of ±0.5% mac for the c.g. range from 39% to 42% mac and within a tolerance of +0.0 to -0.3% mac for the 43% mac c.g. position. The c.g. management envelope is shown in Figure 18.

6.4 Flutter

Flutter analyses were performed to assure that flutter margins of the flight test aircraft met the flutter criteria for flight safety. The analyses examined aft c.g. aircraft configurations with c.g. positions of 39% and 43% mac.

6.4.1 Analysis methods.- Two analysis procedures were used to investigate flutter stability of the aircraft. One procedure was the classical method known as the velocity versus frequency and velocity versus damping solution. The other procedure was the phase versus gain method which assesses the phase and gain margins of the system at specific flight conditions and is known by the acronym FARM (feedback amplitude ratio margin). These methods of analysis are described in Reference 1.

6.4.2 Conditions analyzed.- The classical flutter analyses solved for the modal stability over the speed range of 20 to 600 KEAS at a constant Mach number of 0.88 with the PACS off and on. The FARM analyses investigated flight condition 10 for c.g. positions of 39% and 43% mac. The FARM analyses were performed for the PACS and AACS operating. The pitch rate feedback gains examined were $K_{\dot{\theta}}$ and 2.0 $K_{\dot{\theta}}$.

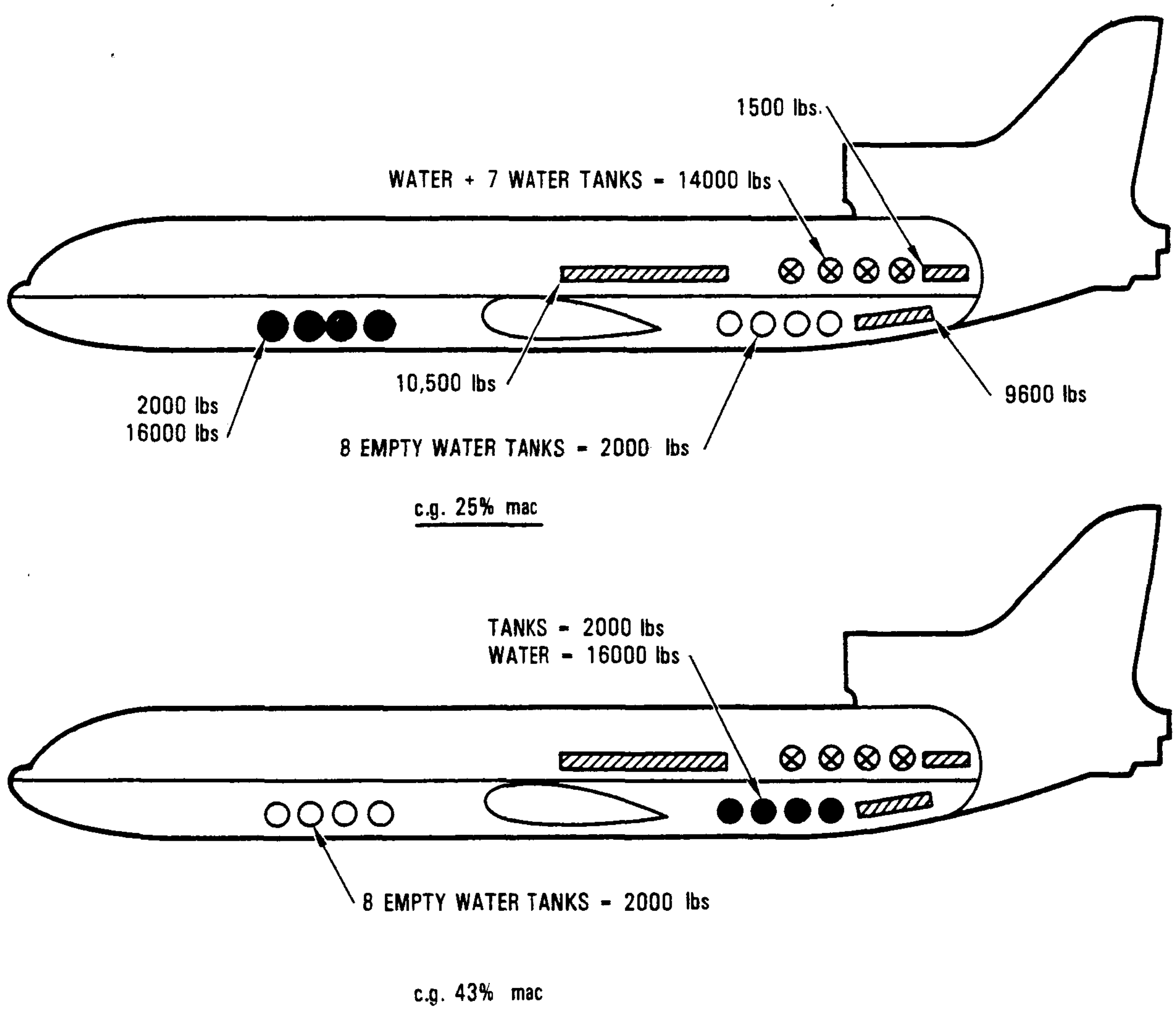


Figure 17. - c.g. management system of the flight test aircraft for the near-term PACS extended flight test program.

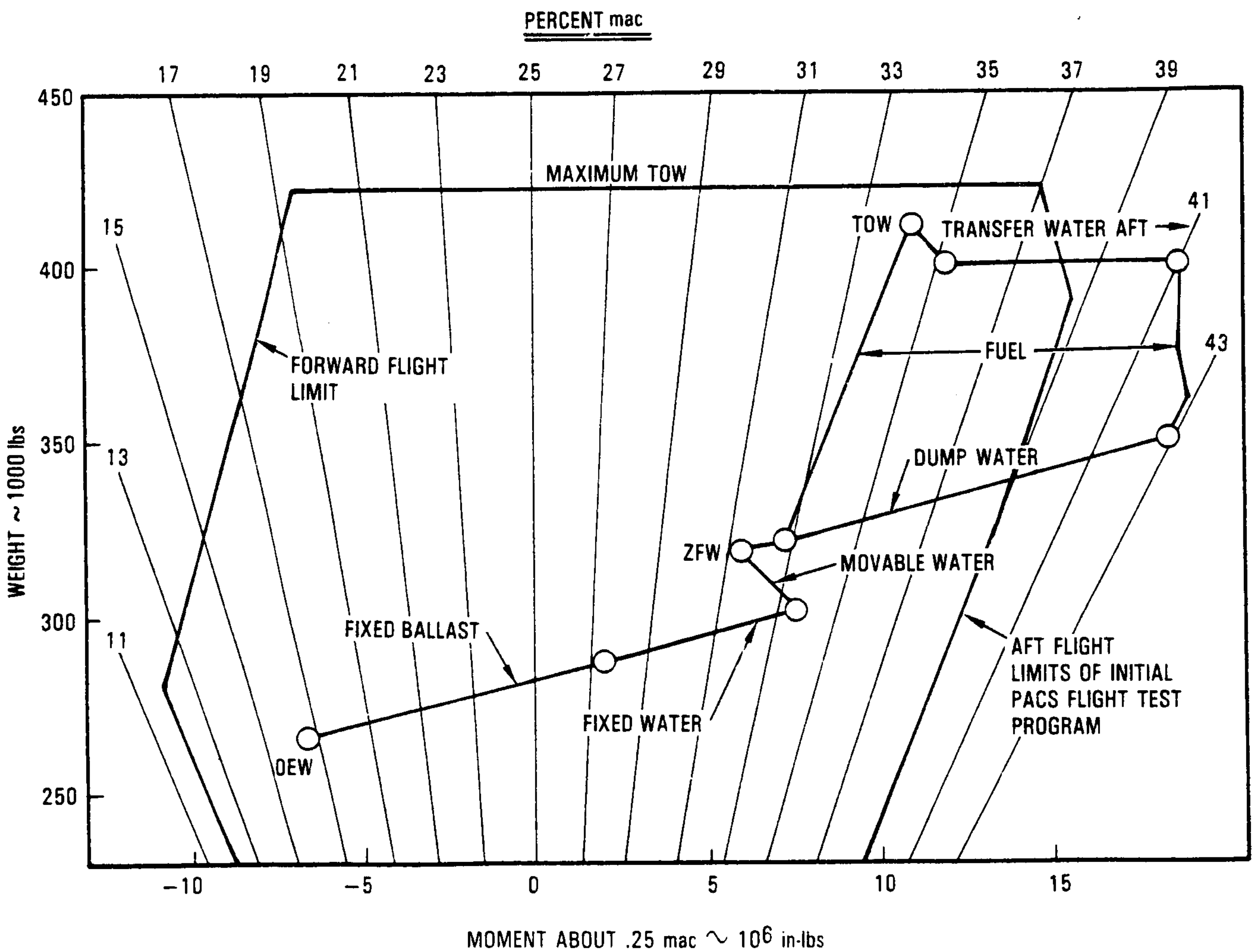


Figure 18. - c.g. management envelope.

6.4.3 Analysis results.- Results for the classical analyses at Mach 0.88 with PACS off and on showed the vehicle cleared to 1.2 V_D. Minimal differences existed between the PACS on and off results. The FARM analyses showed that the flutter margins were satisfied over the frequency range of 0.1 to 25.0 Hz for flight condition 10. There existed minimal differences in the results of the FARM analyses for the c.g. at 39% and 43% mac. The flight test aircraft was shown to be flutter free by analyses and was approved for flight testing.

6.5 Avionics

The avionics tasks consisted of three areas: flight test gain switch changes, validation of software changes and a study of the PACS system disable (kill) switch.

6.5.1 Flight test gain switch.- Software changes to the flight test module of the PACS computer were identified to give rise to new pitch rate feedback gains of 1.3 $K_{\dot{\theta}}$, 1.6 $K_{\dot{\theta}}$, 1.8 $K_{\dot{\theta}}$, and 2.0 $K_{\dot{\theta}}$. This was accomplished by changing the values of gains K_1, K_2, K_3 as shown in Figure 19A. The initial values for K_1, K_2 and K_3 are shown in Figure 19B. When these changes were flown on the flight test aircraft, it was discovered that the aircraft had different characteristics than the flight simulator. This difference resulted in new software changes being identified for the flight test module which in turn generated new pitch rate feedback gains of 1.3, 1.8, and 2.0. These gain changes are shown in Figure 19C

6.5.2 Software change validation.- The near-term PACS system was studied and an end to end check of the pitch axis scaling was made to determine the series servo response to column-minus-trim and/or body axis pitch rate signals. This was determined for all gains of both configurations (Figures 19B and 19C). A further validation was required of the software changes and that was verification of the modified PACS software program. This verification consisted of analyzing the software differences between the previous program and the present program to ensure that no errors were generated in the program areas that should not be changed and that the areas changed were changed correctly. This program verification was repeated for the four modifications to the flight test module software.

6.5.3 PACS kill switch.- A requirement to disengage the PACS system through deactivation of the autopilot disconnect switch on the Captain's and First Officer's control wheel was proposed and studied. Because there are PACS engagement/disengagement switches located on the Flight Control Electronics System Panel on the Captain's overhead panel that can perform this deactivation function; and because of the added complexity to the PACS and

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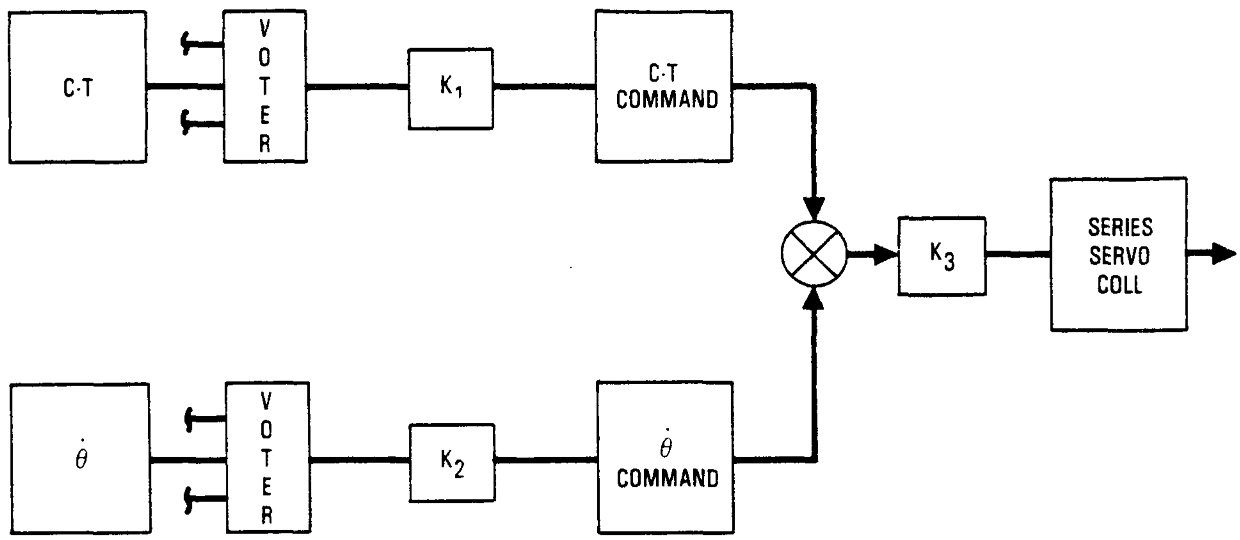

A. SCHEMATIC OF PACS GAIN SWITCH

FLIGHT TEST GAIN SWITCH	K_1	K_2	K_3	
	1.0	1.6	1.0	HIGH
	1.0	1.3	1.0	LOW
	1.0	1.8	1.0	NOMINAL

B. INITIAL GAIN SWITCH VALUES

FLIGHT TEST GAIN SWITCH	K_1	K_2	K_3	
	1.0	1.8	1.0	HIGH
	1.0	1.3	1.0	LOW
	1.0	2.0	1.0	NOMINAL

C. FINAL GAIN SWITCH VALUES

Figure 19. - Near-term PACS software gain changes for the extended flight test program.

concomitant reduction of system reliability with the addition of such a switch, the PACS kill switch was rejected. Instead, a safety procedure was developed for recovery in case of an undetected hardover.

6.6 Safety Review

A safety review was convened prior to the near-term PACS extended flight test program first flight. Those in attendance included members of the Flight Test Safety Board, the Operational Safety Board, the Safety Review Board, and the First Flight Review Committee. Also present were four representatives from the NASA Langley Research Center.

Items discussed included:

- Reactivation of the pitch series servo and PACS software, including software changes.
- Availability and use of a written PACS functional check procedure.
- Fixed and moveable/dumpable water ballast systems including water ballast transfer procedures.
- Aircraft structural operating limitations.
- Proposed instrumentation.
- PACS flight test plan including procedures for configuration changes and aft c.g. movement.
- Recovery procedures in the event of a PACS failure.

All board members, committee members, and NASA representatives were polled for their concurrence that the PACS flight test program would be conducted in the safest possible manner and that all required precautions had been taken. All persons so polled replied in the affirmative.

One open safety item required action prior to the PACS flight testing; the water ballast system dump capability at high-altitude, below-freezing conditions required demonstration. This item was subsequently demonstrated.

7. FLIGHT TEST

The flight test program was performed from the Palmdale, California U.S. Air Force facility by the same four pilots who conducted the piloted flight simulation test at NASA Langley Research Center. All tests were performed at flight condition 10 (see Table 1). The c.g. positions tested were 25%, 39%, 40%, 41%, 42%, and 43% mac. The four PACS configurations (Section 3) were evaluated. Feedback pitch rate gains evaluated were $K_{\dot{\theta}}$, 1.3 $K_{\dot{\theta}}$, 1.6 $K_{\dot{\theta}}$, 1.8 $K_{\dot{\theta}}$, and 2.0 $K_{\dot{\theta}}$ as shown in Figure 2.

A summary of the flight test program is given in Table 2. Testing was initiated with the c.g. position at 25% mac to provide the pilots a feel of the baseline aircraft flying qualities which served as a reference for flying qualities at other flight conditions. The c.g. position was then moved to 39% mac which was the most aft c.g. tested during the previous near-term PACS flight test program. Aft of 39% mac the c.g. was shifted aft in 1% mac increments to 43% mac.

Since the aft c.g. movements took place over several flights, a 39% mac c.g. position was evaluated at the beginning of each flight for pilot reference. Testing at each new aft c.g. position was always initiated with the AACS and PACS off. The AACS was engaged and the baseline airplane was evaluated after which the PACS was engaged and testing was initiated.

The flying quality evaluations included:

- Speed stability by using longitudinal control to stabilize at speeds away from trim.
- Maneuvering stability by conducting wind-up turns up to buffet nibble or 1.7 g.
- Dynamic stability of short-period and phugoid modes by using a small control column displacement and release.
- Typical transport aircraft operational turns of up to 30 degrees bank angle.
- Small pitch changes.
- Climbing and descending S-pattern turns.
- Trimmability.

The first series of tests at the relaxed static stability conditions showed that the pilots preferred higher pitch rate damping gains than those which were preferred during the simulation tests. Consequently, pitch rate gains of 1.8 $K_{\dot{\theta}}$, and 2.0 $K_{\dot{\theta}}$ were added for the test program as shown in Table 3.

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TABLE 2. - FLIGHT TEST PROGRAM SUMMARY

Test/Flight	Date	Flt Time	Pilots	c.g. in % mac
1761/1794	5-25-83	3 + 54	1, 2, 3	25
			1	39
1762/1795	5-27-83	3 + 36	1, 2, 3	39
			1, 2, 3	40
1763/1796	6-2-83	3 + 50	1, 2, 3	39
			1, 2, 3	41
			2	42
1764/1797	6-3-83	4 + 06	1, 2, 3	39
			1, 2, 3	42
			1, 2, 3	43
1765/1798	6-7-83	3 + 30	2, 4	25
			4	39
			4	42
			4	43
1766/1799	6-8-83	3 + 40	1, 2, 3	39
			1, 2, 3	42

TABLE 3. - PACS CONFIGURATIONS FLIGHT TESTED

PACS Configuration			Pilot				
			c.g. ∿ % mac				
Pitch Rate Damping Gain Factor	Feed-Forward	Feed-Forward Washout	39	40	41	42	43
1.0	Out	---					
1.3	Out	---		4			
1.6	Out	---			1,2,3	1,3	
1.8	OUt	---			2	1,2,3,4	
2.0	Out	---				4	1,2,3,4
1.0	In	In	1,3				
1.3	In	In	1,2,3,4	2,3			
1.6	In	In		1,2,3	1,2,3		
1.8	In	In				2,4	
2.0	In	In				1,3	1,2,3,4
1.0	In	Out	1,2,3				
1.3	In	Out	1,2,3,4	1,2,3			
1.6	In	Out		1,2,3	1,2,3	1,3	
1.8	In	Out			1,2,3	2,4	
2.0	In	Out				1,2,3,4	1,2,3,4

7.1 Speed Stability

Speed stability is a measure of static stability so long as power effects are small and the test is conducted in a speed range where Mach tuck has no influence. For the flight test aircraft power effects are small and the Mach tuck region is above Mach 0.86. However, the aircraft is equipped with a Mach Trim Compensation System (MTC) which provides artificial speed stability to give expected pilot control force versus speed characteristics by automatically retrimming the aircraft nose-up when speed increases and nose-down when speed decreases.

The MTC was operating during all PACS testing. Even though the MTC was operating, static stability can be assessed from the stabilizer requirements. The static neutral point being at 40% mac on the flight test aircraft is based upon the AACS operating. The AACS moves the outboard ailerons TEU as load factor increases thus moving the lift inboard and producing a destabilizing nose-up moment. During a speed stability test, the aircraft is essentially at 1 g and the AACS ailerons remain essentially faired. Since the AACS ailerons don't move, the aircraft appears 5% more statically stable (AACS effect) during a speed change than during a dynamic maneuver and the static neutral point in a speed stability test will be reached at a c.g. of 45% mac. Figure 20 depicts the difference between a speed change in C_L and a load factor change in C_L.

A time history has been selected from the flight test evaluations to show the speed stability at a 42% mac c.g. position (Figure 21). The aircraft is still statically stable at this c.g. as can be seen by the slight increase in up stabilizer at the slower speed.

7.2 Maneuvering Stability

Wind-up turns were conducted to evaluate maneuvering stability. The maneuver was terminated at the end of the linear stability region which was coincident with the onset of light airplane buffet. Figure 22 shows maneuvering force characteristics and stabilizer movement versus load factor for the three PACS operating configurations at a c.g. of 43% mac. The pitch rate damping gain factor is 2.0 $K_{\dot{\theta}}$. The fairings were calculated from the simulation math model. The pitch rate damping only and the pitch rate damping with feed forward fairings have been used to describe a shaded area on the force plot for pitch rate damping with feed-forward washed out. Maneuvering forces for this PACS mechanization can be anywhere within the shaded area depending upon how much feed-forward has been washed out. The test points tend to fall on the high side of the shaded region which indicates that the wind-up turn is a long-term maneuver and that most of the feed-forward has been washed out. Figure 22 also shows how the stabilizer remains essentially at the trim position throughout the maneuver which indicates that the airplane is operating at a relaxed stability center of gravity and that the forces are almost entirely the result of PACS operation.

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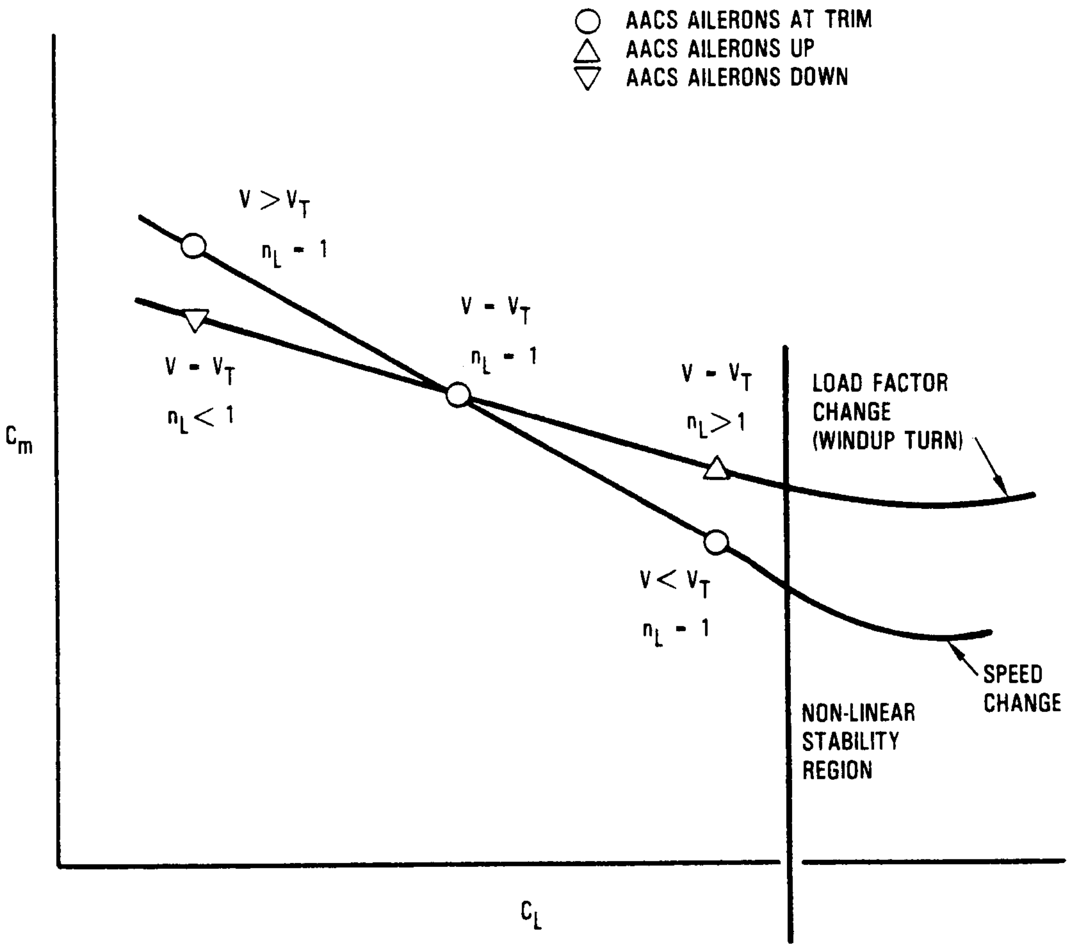

Figure 20. - Effect of the AACS on the aircraft pitching moment characteristics.

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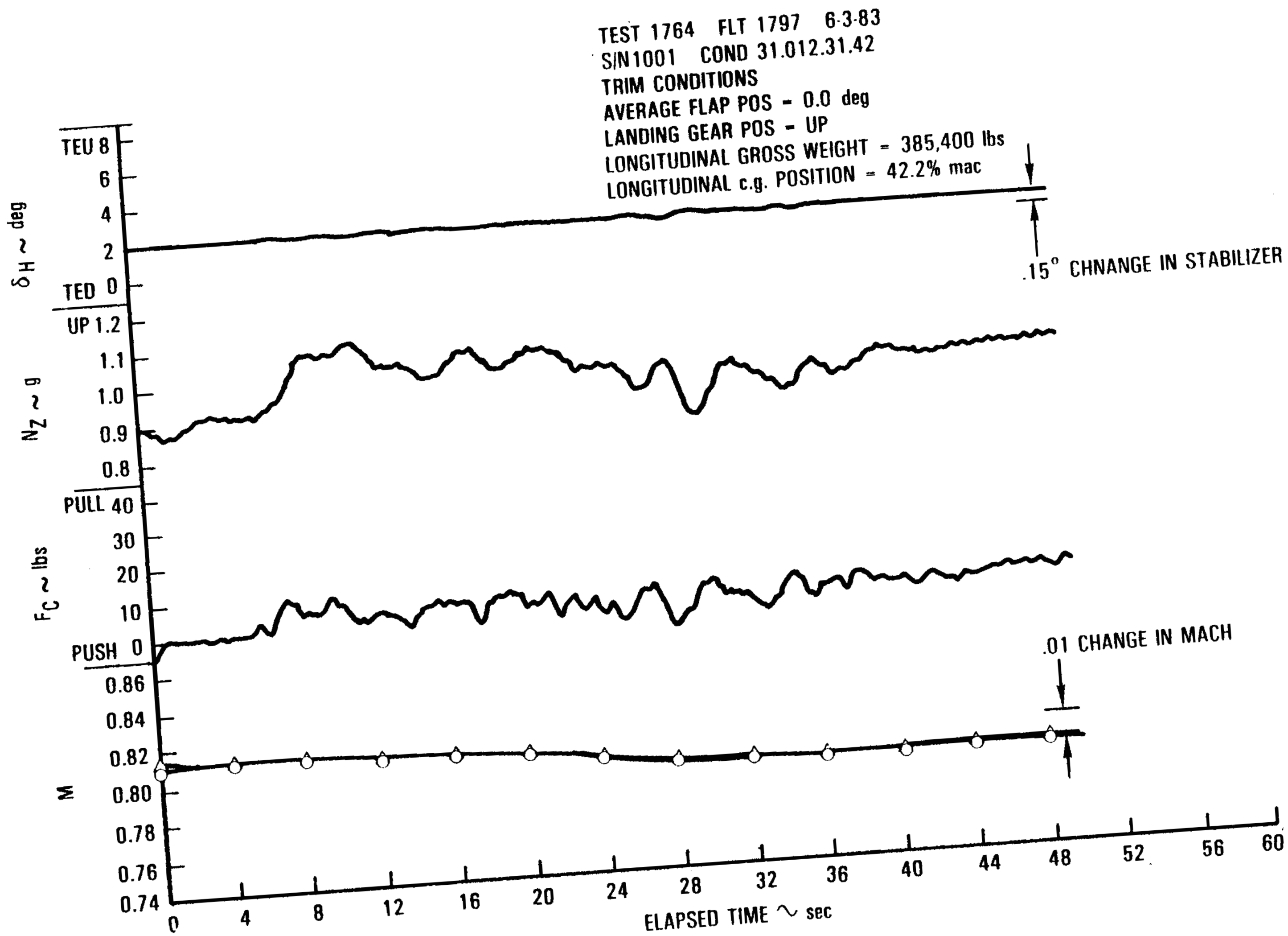


Figure 21. - Flight test speed stability, flight condition 10, c.g. at 42% mac, 2.0 $K_{\dot{\theta}}$.

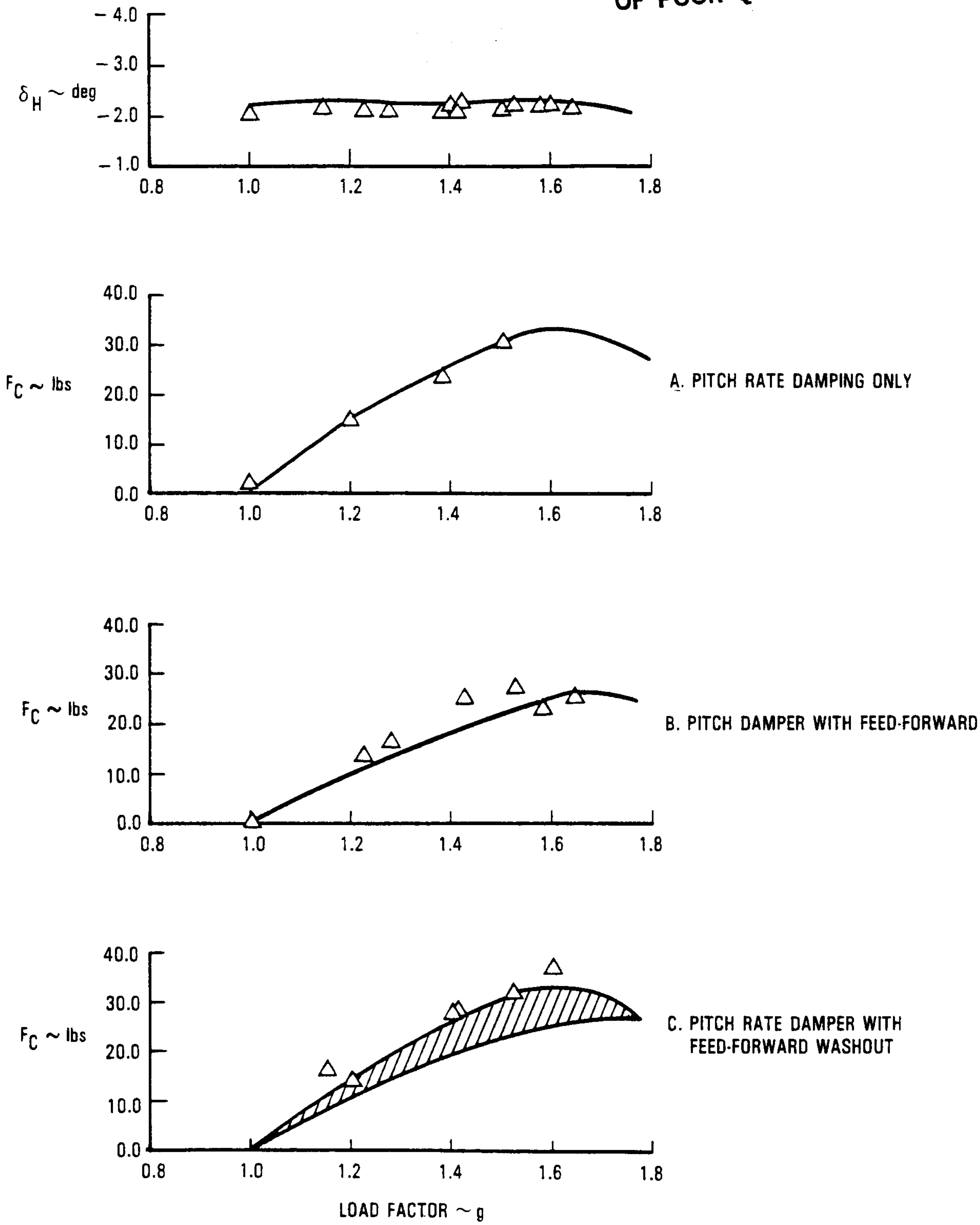


Figure 22. - Flight test maneuver stability, flight condition 10, c.g. at 43% mac, 2.0 $K_{\dot{\theta}}$.

The preferred PACS configurations were primarily selected because of flying qualities around trim, such as small pitch attitude changes and typical transport-type turns. Increased pitch rate damping gains improved handling qualities in these types of maneuvers but produced heavier forces than preferred in the wind-up turn maneuver. The pilots would have selected lower pitch rate damping gains if the wind-up turn was the primary task. A possible PACS mechanization change which would improve handling qualities around trim and reduce the forces in the wind-up turn maneuver would be to fade in an increased feed-forward gain above a certain load factor level.

7.3 Dynamic Stability

7.3.1 Short-Period Mode. The aircraft short-period dynamic stability effects are reflected in how precisely a maneuver can be accomplished. Several typical maneuvers have been selected to show the differences in precise control with the PACS on and off. Figure 23 shows controllability during small pitch attitude changes.

Figure 23A shows a 1 degree nose-down pitch attitude change with PACS off and Figure 23B shows a 1 degree nose-up pitch attitude change with PACS on. Both maneuvers were conducted with the c.g. at 43% mac. With PACS on, the pilot puts in a small control input, the aircraft responds and the pilot releases the column force as the aircraft achieves and maintaines the new pitch attitude. With PACS off, the pilot also puts in a small control input, the aircraft responds, but when the pilot releases the force, the pitch attitude continues to diverge. The pilot puts in a large opposite control input to stop the divergence and then alternates between push and pull inputs to stabilize at the new pitch attitude. In other words, the aircraft response to each control input has to be checked by an opposite control input such that the pilot must provide his own damping. Some of the pilots described the augemented aircraft control as a rate-command, attitude-hold system. Figure 24 particularly highlights this characteristic. Pitch attitude increases each time the pilot pulls the control column aft and the aircraft holds a new attitude after the control is released.

Turns with up to 30 degrees of bank were conducted to evaluate PACS operation during a representative airline maneuver. Figure 25 shows controllability with the PACS on and off during typical transport-type aircraft turns with the center of gravity at 43% mac. The PACS on configuration is the one preferred by most of the pilots at this c.g. Several aspects can be readily observed. With PACS off, the c.g. vertical g oscillations are more promounced. Control force inputs are more active and alternate between push and pull. The pilots in some instances quantified the task by estimating how close they felt that they could hold altitude. The time histories show much better altitude control with the PACS engaged.

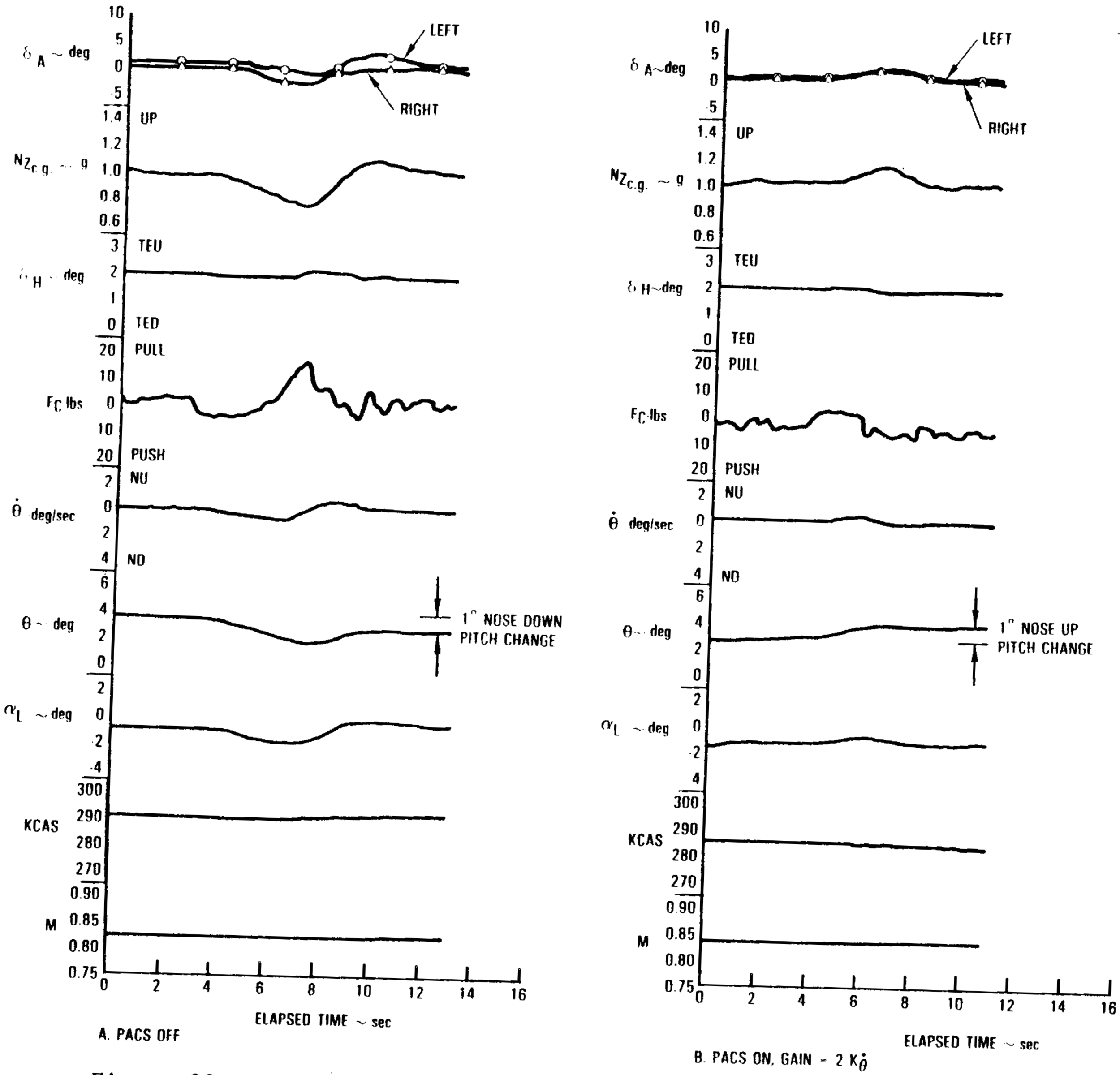
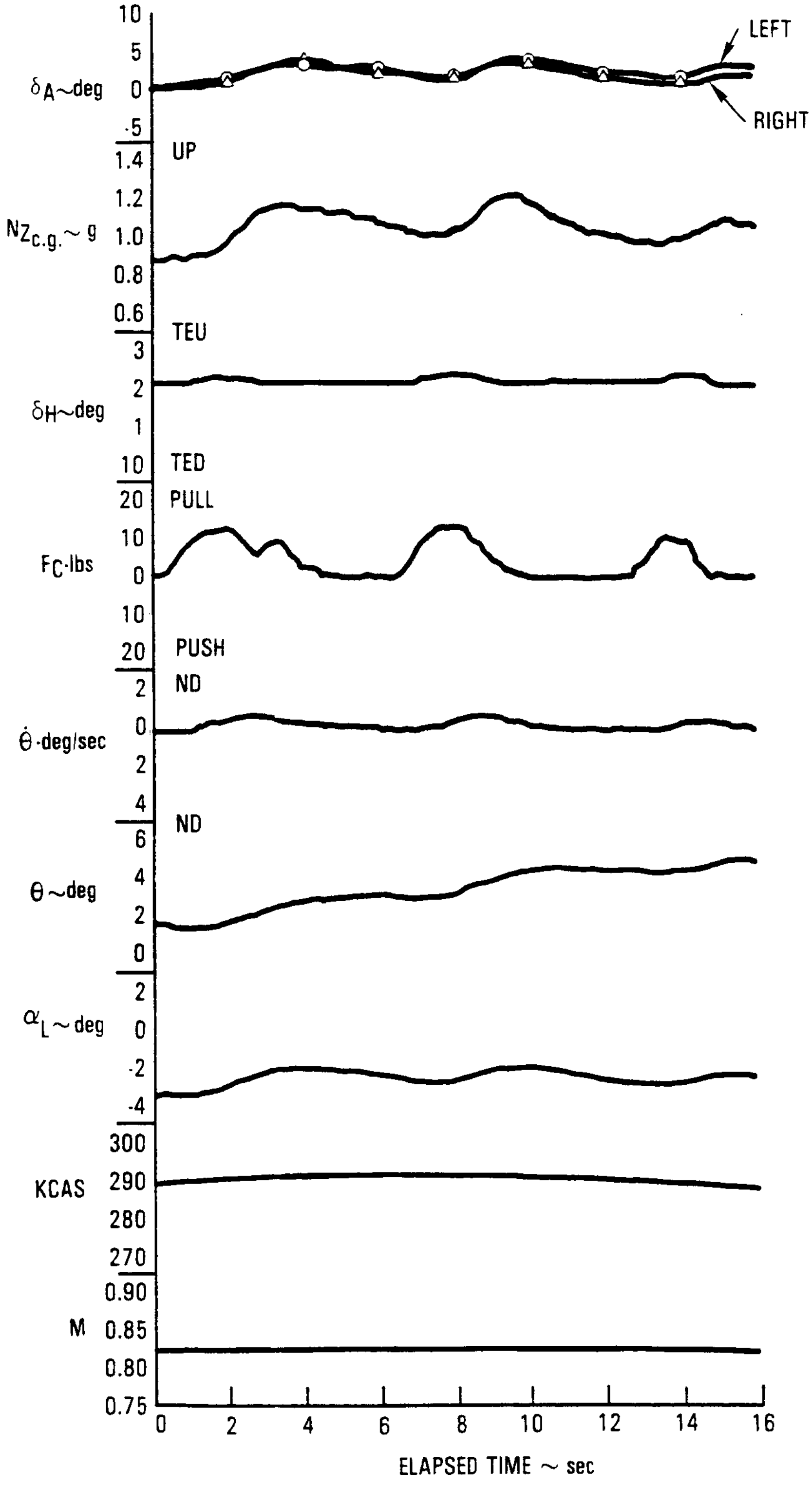
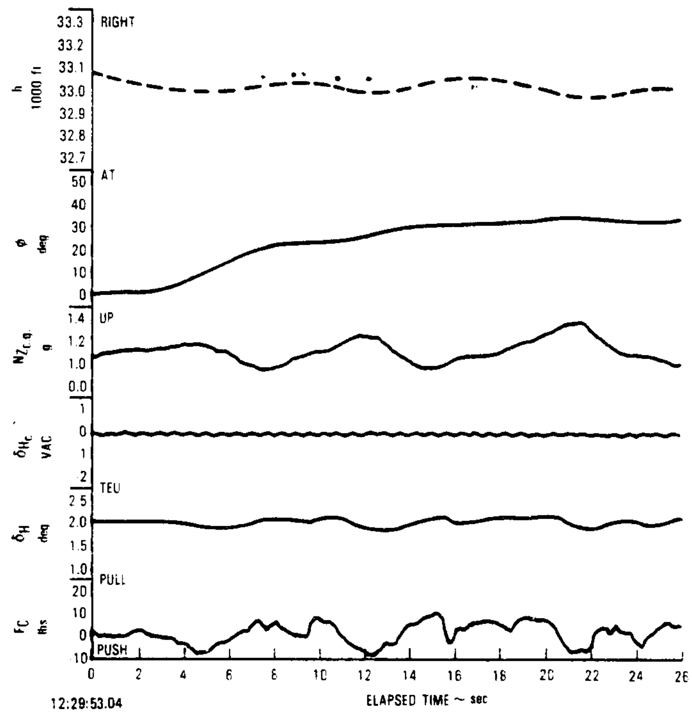


Figure 23. - Flight test dynamic response comparison for the PACS off and on, flight condition 10, c.g. at 43% mac

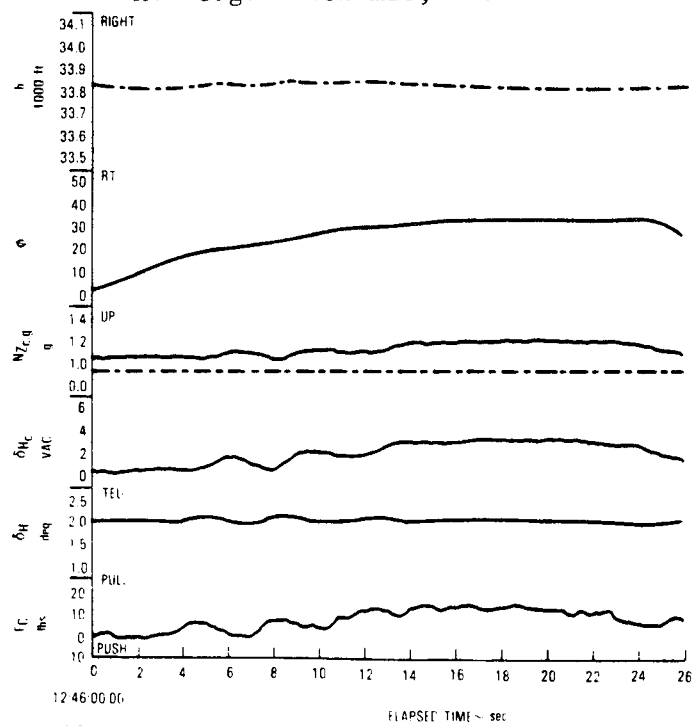


Note; c.g. = 41% mac, damper with feed-forward, Gain 1.8 $K_{\dot{\theta}}$

Figure 24. - Dynamic response, PACS on. Flight condition 10.



A. c.g. = 43% mac, PACS off



B. c.g. = 43% mac, PACS on, Pitch Rate Damping Only, Gain $K_{\dot{\theta}}$

Figure 25. - Turn time history, flight condition 10

7.3.2 Phugoid mode.- The flying qualities analysis to optimize the near-term PACS configurations for the extended flight test program showed that increased pitch rate damping gains were required to stabilize the phugoid mode. The puhgoid mode was excited by control column inputs and observed through several cycles during the flight test program. Three phugoid time histories are presented in Figure 26. Chart A shows that for the baseline aircraft with a 41% mac c.g. position, the phugoid mode response doesn't complete one cycle before the pilot recovers. The c.g. normal acceleration shows a linear divergence. Chart B shows that for the baseline aircraft with a 43% mac c.g. position the phugoid mode response again doesn't complete one cycle before the pilot recovers and this time the c.g. normal acceleration shows a second order divergence. Chart C shows that for the aircraft with PACS on and a 42% mac c.g. position, the phugoid mode is still slightly unstable but the rate of divergence is slow and can be easily controlled.

7.4 Turbulence Response

Light turbulence was intermittently encountered during most of the flights. Specific evaluations were not conducted to quantify the effects of turbulence with the PACS on and off. However, the pilots felt that the PACS improved the flying qualities in the light turbulence conditions.

7.5 Trimmability

A significant portion of the evaluation was spent looking at the airplane flying qualities near the trim point. One of the major deficiencies of the baseline aircraft at the relaxed static stability c.g. positions is the lack of good trimmability which necessitates full time pilot attention to maintain a flight condition. With the preferred PACS configurations operating, trimmability was better at the unstable static stability c.g. positions than for the baseline aircraft with the c.g. at 25% mac. The baseline aircraft at the unstable c.g. positions was considered untrimmable and if left unattended would diverge into an unstable phugoid mode. The pilots liked high pitch rate damping gains to improve trimmability. With the preferred PACS on, the airplane would maintain trim at the unstable c.g. positions without going into a phugoid oscillation.

7.6 Pilot Ratings and Comments

Pilot Cooper-Harper ratings of the PACS configurations evaluated during the near-term PACS extended flight test program are presented in Fiugre 27. The shaded symbols in the figure designate the PACS operating configurations and pitch rate damper feedback gains that were preferred by the pilots. The pilot ratings and preferred PACS configurations were primarily determined from how the aircraft flew around the trim (i.e., small pitch changes, shallow banked turns, trimmability - maneuvers more typical to normal transport operation). Many wind-up turns were conducted to evaluate maneuvering stability;

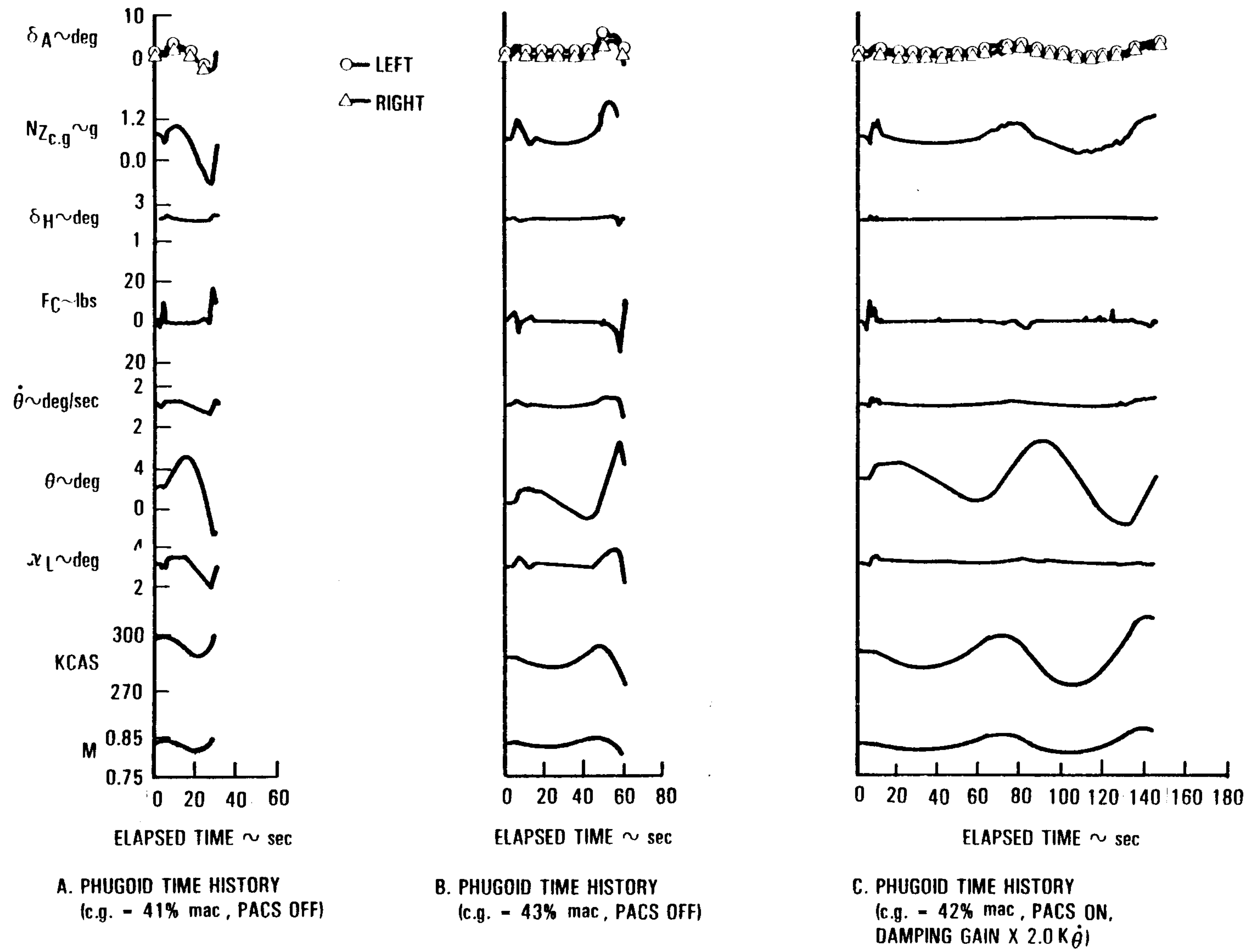


Figure 26. - Flight test phugoid mode time histories, flight condition 10.

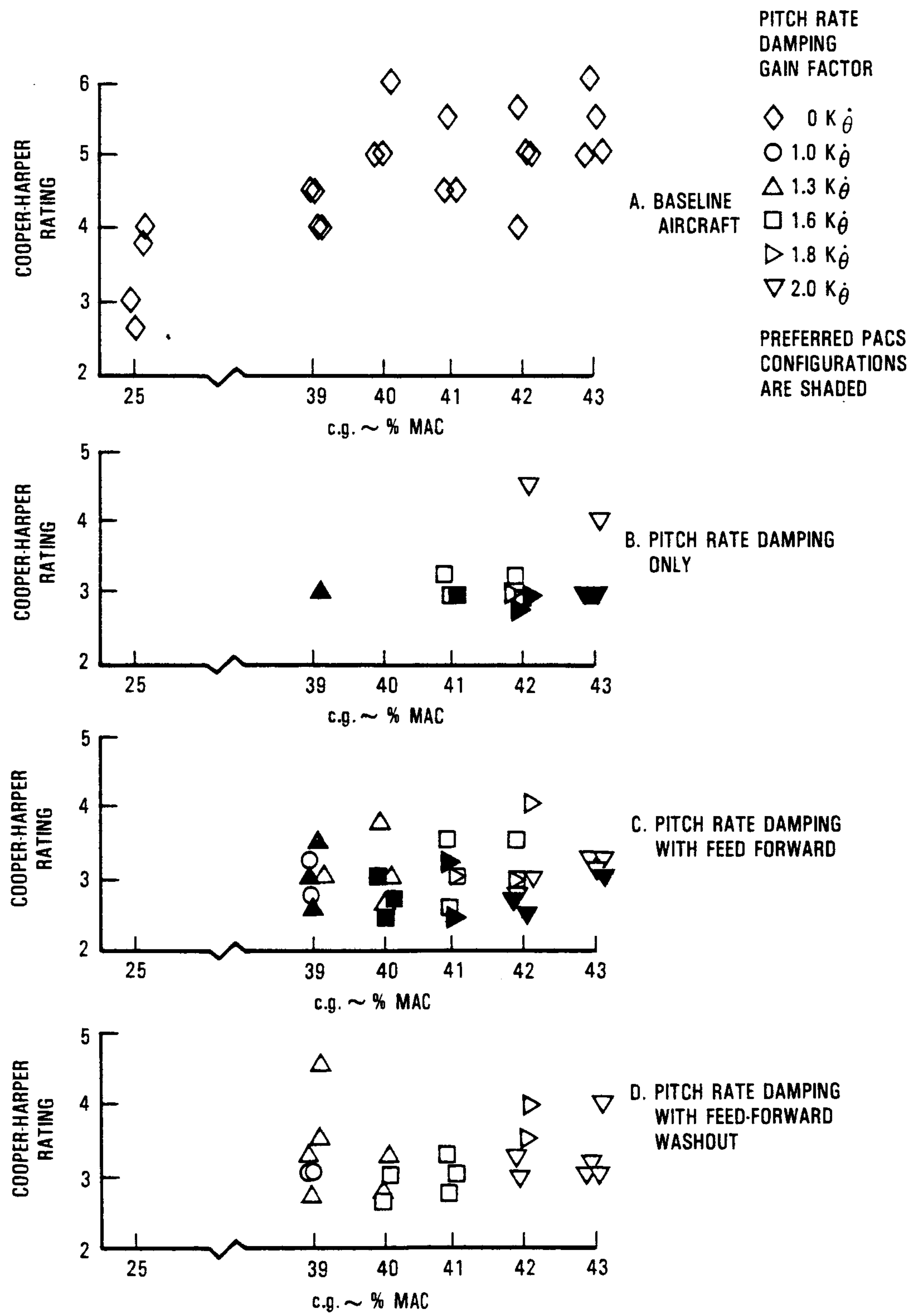


Figure 27. - Flight test Cooper-Harper ratings, flight condition 10.

however, the influence of the wind-up turn maneuver was not considered in the pilot rating.

Figure 27 shows that the preferred PACS operating configurations produce flying qualities for the 39% to 43% mac c.g. range as good as the baseline aircraft at 25% mac. The pilots generally favored the PACS operating configuration with pitch rate damping and feed-forward except for the most aft c.g. position tested (43% mac) where they selected the PACS configuration with pitch rate damper only. Observation of the shaded symbols will generally show a lesser pitch rate damping gain factor preferred for the PACS operating configuration with pitch rate damper only than when pitch rate damping was combined with feed-forward. It would be expected that the pitch rate damping with feed-forward could be the preferred configuration with the c.g. at 43% mac if the ability to test a pitch rate damping gain factor greater than 2.0 $K_{\dot{q}}$ had been available.

The aircraft with the PACS off was given only a minimal evaluation by each pilot, primarily to show that the aircraft was safely flyable in the event of a PACS failure. The brief evaluations did generate Cooper-Harper ratings for the PACS off airplane with AACS on and off. These ratings are presented along with similar ratings from the Langley VMS on Figure 28. General pilot statements and observations with PACS off at the aft centers of gravity were:

- AACS off improves the aircraft flying qualities.
- The aircraft can't really be trimmed and requires full time attention to keep it at the desired flight condition.
- The stability degradation for a 1% aft c.g. shift with AACS on is much more apparent when the 1% c.g. shift is from 42% to 43% mac.
- Push forces are required in shallow-banked turns.
- Pitch changes require a pilot to provide his own damping by checking the maneuver with an opposite control input to stop the pitch rate generated.

General statements with the PACS operating included:

- The aircraft controls like a flight vehicle with a rate-command and attitude-hold control system.
- Trimming is easier with PACS on at the aft c.g. positions than at a c.g. of 25% mac with the PACS off.
- There is a difference between the feed-forward and the feed-forward washed out configurations (the difference was hard for the pilots to quantify other than to say they just didn't like the way the washed-out feed-forward PACS configuration felt).

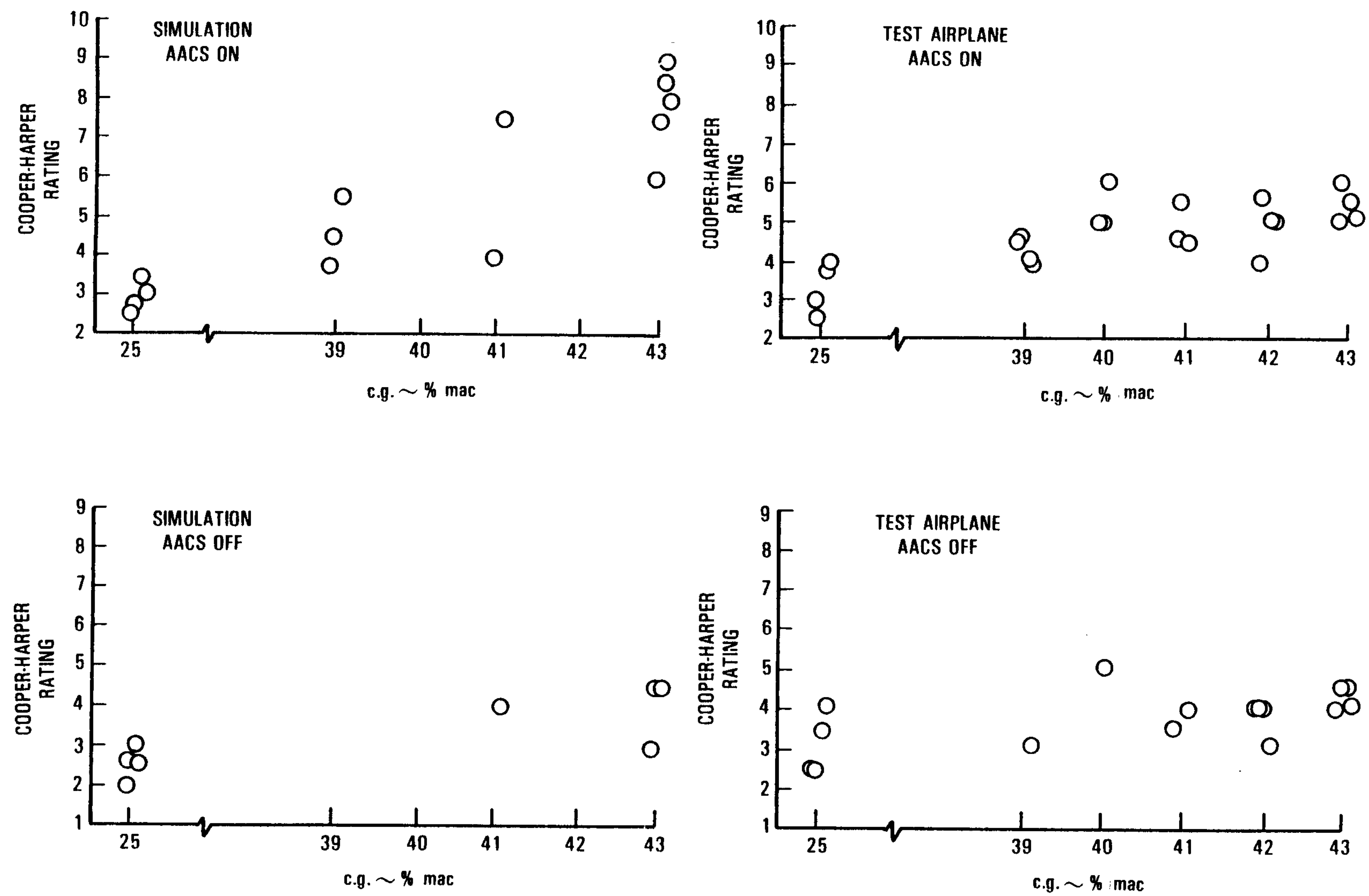


Figure 28. - Comparison of simulator and flight test aircraft Cooper-Harper ratings, PACS off.

- The preferred PACS configurations provide good airplane response around trim and good damping during pitch changes.
- PACS configurations with pitch rate damping gains which were lower than the optimum are loose around trim, harder to trim, and more difficult to precisely control.

8. COMPARISON OF SIMULATION AND FLIGHT TEST RESULTS

Two major differences were identified between the simulator test and flight test results: the baseline flight test aircraft was rated as having better flying qualities than those demonstrated during the VMS piloted flight simulation test, and higher pitch rate damping feedback gains were desired during flight test than during the simulation.

The better flying qualities of the baseline flight test aircraft at the aft c.g. positions are shown by comparing the two charts in the upper part of Figure 28. The charts in the lower part of the figure show that there is no difference in the flying qualities when the AACS is off. A possible explanation for the difference in ratings with the AACS on is that in the flight test the aircraft was gently maneuvered around trim and in shallow banked turns whereas during the simulation the aircraft was maneuvered more aggressively. At the aft c.g. positions the PACS off aircraft becomes quite sensitive with AACS on and the more aggressive maneuvering may have brought out some unpleasant handling qualities characteristics.

The higher pitch rate damping gains preferred for the flight test aircraft is illustrated in Figure 29. This difference may be due to the lack of realistic load factor (g) cues of the simulation. During the simulation the pilots focused most of their attention on pitch attitude and seldom observed the g oscillations. Since true g values were reduced and washed out, the simulation did not totally provide a real-life environment. In the test aircraft, the g cues were felt by the pilots and since increasing the pitch rate damping gain tended to reduce the g oscillations they preferred the higher damping gains.

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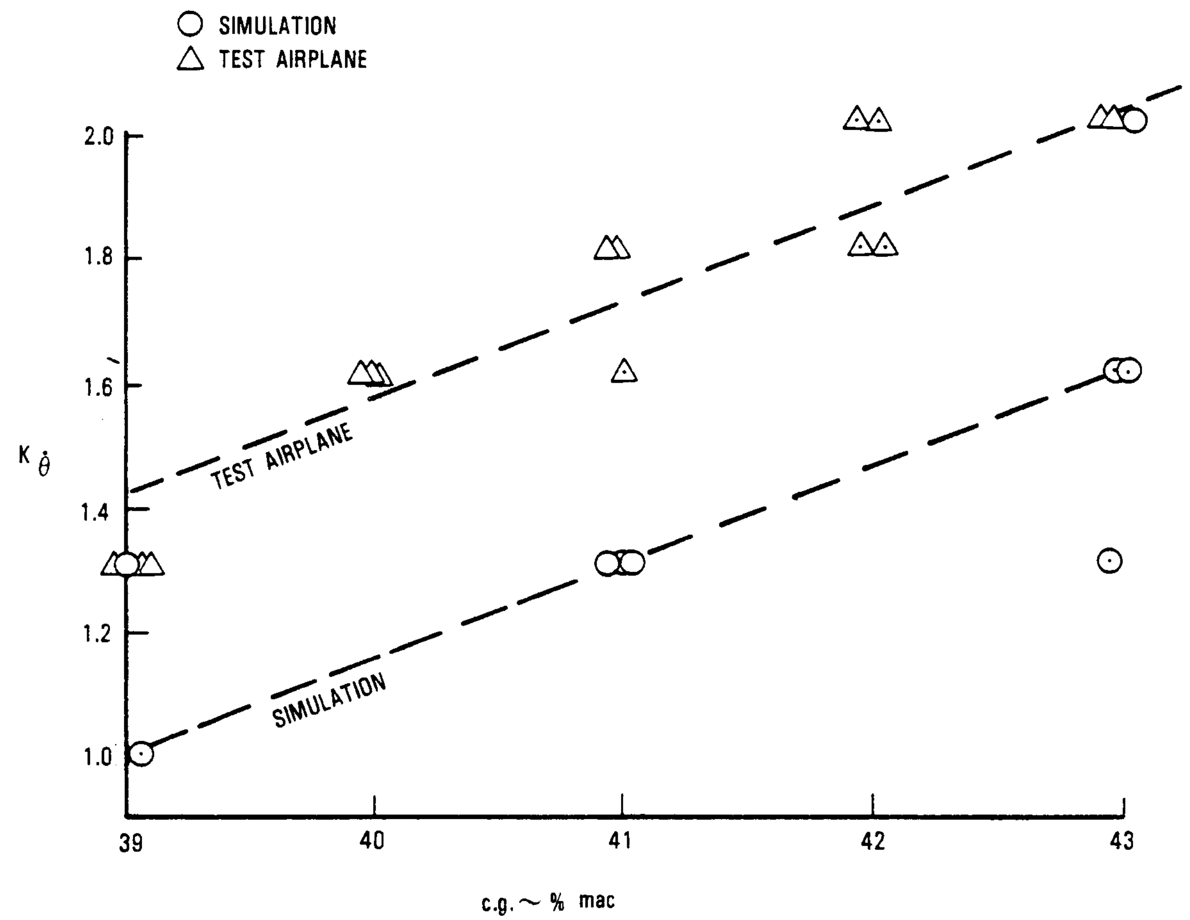

Figure 29. - Comparison of simulator and flight test aircraft pitch rate feedback gains.

CONCLUSIONS

Flight tests have demonstrated that a near-term PACS with pitch-rate feedback and column-minus-trim feed-forward signals provides good flying qualities within the linear static stability flight envelope for a large transport aircraft to negative 3% static stability margins.

A PACS operating configuration with pitch damper plus feed-forward was preferred to a configuration with pitch damper only or to a configuration of pitch damper with feed-forward washout. The PACS must have pitch rate gains, column-minus-trim gains, and time lag gains that are functions of the aircraft calibrated air speed. The column-minus-trim gains and time lag gains are independent of the static stability margin. However, the desired pitch rate feedback gain requirements were determined to double in value as the static stability margin is changed from neutral to a negative 3% value.

An additional improvement to the PACS would be to fade in the feed-forward at a certain load factor value which still needs to be determined. However, the technology for a PACS that utilizes analog sensors, a digital computer, and series servo to provide good flying qualities at relaxed static stability conditions has been demonstrated by flight test. The remaining task required for use of the PACS in commercial airline fleets is to establish that it has the reliability to comply with flight safety criteria.

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15. Supplementary Notes

Langley Technical Monitor: Dennis W. Bartlett

16. Abstract

Fuel savings can be achieved by moving the center of gravity of an aircraft aft which reduces the static stability margin and consequently the trim drag. However, flying qualities of an aircraft with relaxed static stability can be significantly degraded. The flying qualities can be restored by using a pitch active control system (PACS). This report documents the work accomplished during a follow-on program (see NASA CR-165951 for initial program report) to perform extended flight tests of a near-term PACS. The program included flying qualities analyses, piloted flight simulation tests, aircraft preparation and flight tests to demonstrate that the near-term PACS provided good flying qualities within the linear static stability envelope to a negative 3% static stability margin.

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