

**NASA
Technical
Paper
2482**

1985

Handling Qualities of a
Wide-Body Transport Airplane
Utilizing Pitch Active Control
Systems (PACS) for Relaxed
Static Stability Application

William D. Grantham, Lee H. Person, Jr.,
and Philip W. Brown

*Langley Research Center
Hampton, Virginia*

Lawrence E. Becker and George E. Hunt

*Sperry Corporation
Hampton, Virginia*


J. J. Rising, W. J. Davis,
C. S. Willey, W. A. Weaver,
and R. Cokeley

*Lockheed-California Company
Burbank/Palmdale, California*



National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1. Report No. NASA TP-2482	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Handling Qualities of a Wide-Body Transport Airplane Utilizing Pitch Active Control Systems (PACS) for Relaxed Static Stability Application		5. Report Date December 1985	
		6. Performing Organization Code 505-34-03-03	
7. Author(s) William D. Grantham, Lee H. Person, Jr., Philip W. Brown, Lawrence E. Becker, George E. Hunt, J. J. Rising, W. J. Davis, C. S. Willey, W. A. Weaver, and R. Cokeley		8. Performing Organization Report No. L-15928	
		10. Work Unit No.	
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665-5225		11. Contract or Grant No.	
		13. Type of Report and Period Covered Technical Paper	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001		14. Sponsoring Agency Code	
		15. Supplementary Notes William D. Grantham, Lee H. Person, Jr., and Philip W. Brown: Langley Research Center, Hampton, Va. Lawrence E. Becker and George E. Hunt: Sperry Corporation, Hampton, Va. J. J. Rising, W. J. Davis, C. S. Willey, W. A. Weaver, and R. Cokeley: Lockheed-California Company, Burbank/Palmdale, Calif.	
16. Abstract Piloted simulation studies have been conducted to evaluate the effectiveness of two pitch active control systems (PACS) on the flying qualities of a wide-body transport airplane when operated at negative static margins. These two pitch active control systems consisted of a simple "near-term" PACS and a more complex "advanced" PACS. Eight different flight conditions, representing the entire flight envelope, were evaluated with emphasis on the cruise flight conditions. These studies were made utilizing the Langley Visual/Motion Simulator (VMS) which has six degrees of freedom. The simulation tests indicated that (1) the flying qualities of the baseline aircraft (PACS off) for the cruise and other high-speed flight conditions were unacceptable at center-of-gravity positions aft of the neutral static stability point; (2) within the linear static stability flight envelope, the near-term PACS provided acceptable flying qualities for static stability margins to -3 percent; and (3) with the advanced PACS operative, the flying qualities were demonstrated to be good (satisfactory to very acceptable) for static stability margins to -20 percent.			
17. Key Words (Suggested by Authors(s)) Transport airplanes Flying qualities Active control systems Ground-based simulation Flight tests Negative static margin		18. Distribution Statement  Subject Category 08	
19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 107	22. Price

SUMMARY

Transport aircraft fuel consumption can be significantly reduced by relaxing the longitudinal static stability and, consequently, the trim drag. However, the flying qualities of an aircraft with relaxed static stability can be significantly degraded. The flying qualities can be restored by using a highly reliable pitch active control system (PACS) to provide longitudinal stability augmentation.

Ground-based simulator studies were conducted to evaluate the effectiveness of two pitch active control systems on the flying qualities of a wide-body transport airplane when operated at negative static margins. These two pitch active control systems consisted of a simple "near-term" PACS and a more complex "advanced" PACS. Flying qualities were evaluated at eight different flight conditions, representing the entire flight envelope, with emphasis on the cruise flight conditions.

The piloted-flight simulation tests indicated that (1) the flying qualities of the baseline aircraft (PACS off) for the cruise and other high-speed flight conditions were unacceptable at center-of-gravity positions aft of the neutral point (neutral static stability); (2) the near-term PACS provided acceptable flying qualities for static stability margins to -5 percent; and (3) the flying qualities with the advanced PACS operative were demonstrated to be good (satisfactory to very acceptable) for static stability margins to -20 percent.

The near-term PACS was also flight tested on a derivative L-1011 airplane at negative static margins up to 3 percent for a typical cruise flight condition. In general, the pilots rated the flying qualities to be better during the flight tests than during the ground-based simulation tests. However, subsequent simulation tests indicated that the major reason for the pilot-rating differences was that the pilots tended to maneuver the airplane less aggressively during the flight tests. Hence, it is extremely important to impress the test pilots with the necessity of using the same techniques/procedures/tasks for simulator tests as for flight tests whenever possible. The results of this study also indicated that the addition of "artificial" cues to simulate important cues that are missing in ground-based simulators may enhance the validity of the results. Specifically, buffet and stick-shaker models were "substituted" for continuous acceleration cues in the present study, thereby improving the agreement of pilot ratings between the simulator tests and the flight tests.

INTRODUCTION

Jet-aircraft fuel cost has increased from 12 cents per gallon in 1972 to \$1 or more in 1984; thus, the fuel portion of aircraft direct operating cost has increased substantially. The result has been a heavy emphasis on the development of next generation transport aircraft with significantly improved aerodynamic performance. Conventional high-speed subsonic transports with inherent static stability are designed with large stabilizer surfaces and a forward center-of-gravity range, both of which penalize performance. Application of the concept of relaxed static stability (RSS) provides a technological advance which will alleviate these performance penalties. By applying the RSS concept and utilizing an active control stability

augmentation system, an airplane can be designed with (1) reduced aerodynamic trim drag because of a farther aft center-of-gravity balance and/or (2) reduced aerodynamic parasite drag and lower structural weight because of a smaller horizontal tail surface. Also, the RSS concept will have an even larger payoff for new commercial transport designs having high-aspect-ratio wings and a supercritical airfoil that result in substantially increased levels of trim drag at "conventional" static margins.

The state of the art in flight-control-system technologies has progressed to the point where it is believed that the RSS concept can be incorporated in the next generation of commercial transports. However, current flying qualities criteria and airworthiness requirements may be too restrictive to allow full realization of the benefits of relaxed static stability. Consequently, there is a need to develop criteria to insure satisfactory handling qualities and guarantee safety of flight for these advanced transport designs. Therefore, the application of RSS has been studied in a joint effort by NASA and the Lockheed-California Company to determine ways of improving the energy efficiency in transport aircraft designs. Piloted simulator investigations were conducted with the six-degree-of-freedom ground-based Langley Visual/Motion Simulator (VMS) and a math model of a derivative Lockheed L-1011 wide-body jet transport. This study was conducted in two phases: the first phase evaluated a simple, near-term, stability augmentation system suitable for application to aircraft operating with "low" levels of negative static margin (up to 5 percent); and the second phase evaluated a more advanced, more complex system designed for application to future transport concepts requiring operation at "high" levels of negative static margin (10 percent or greater) to achieve optimum performance. Both systems are described in the appendix.

The aforementioned "near-term" PACS was also flight tested on a derivative L-1011 airplane at negative static margins up to 3 percent for a typical cruise flight condition. The "advanced" PACS has not been flight tested.

The primary objective of the investigation was to evaluate the effectiveness of these two pitch active control systems in improving the aircraft handling qualities when operated at negative static margins.

BACKGROUND

The NASA Aircraft Energy Efficiency (ACEE) program was initiated in 1976. In 1977, the Lockheed-California Company received an ACEE program contract for the development and flight evaluation of active control concepts for subsonic transport aircraft. The contract resulted in the development of an aileron active system (AACS) which provided wing load alleviation. The AACS allowed a 5.8-percent increase in wing span for the L-1011-500 aircraft (in-service date, 1980) that decreased fuel consumption by approximately 3 percent. Also, research studies were conducted under the contract to evaluate the benefits of a pitch active control system PACS. Piloted-flight simulations were conducted, at Lockheed, on a moving-base simulator with an L-1011 cab. These simulation tests showed that with static longitudinal stability relaxed to near neutral, and in heavy turbulence, a lagged pitch-rate damper provided flying qualities that were equivalent to those of the baseline aircraft with a positive static stability margin of 15 percent. Thus, these results provided a sufficient basis for proceeding to a flight evaluation of the PACS; these subsequent flight demonstration tests showed that for a nominal cruise flight condition, the PACS provided good flying qualities of the aircraft for

static stability margins to +1 percent. In addition, further analytic analyses of this "simple" PACS indicated that by increasing the PACS feedback-loop gains, satisfactory flying qualities characteristics might be possible at slightly negative static stability margins. Consequently, a "near-term" PACS follow-on flight test program was proposed.

The objective of the extended near-term PACS program was to demonstrate by flight that the NTPACS with increased feedback gains would provide flying qualities for static stability margins to -3 percent which were equivalent to those of the baseline aircraft with a positive static stability margin of 15 percent. The major tasks for this "extended near-term" PACS program were:

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

The flying qualities analysis and piloted-flight simulation tests were limited to evaluation of two cruise flight conditions and one landing condition. Aircraft preparation included analysis required for determining operating restrictions, safety reviews, and aircraft modifications. The flight tests were limited to evaluation of a series of static stability margins for one cruise flight condition.

In May 1980, when the ACEE program was restructured to concentrate on the development of future PACS technologies such as the aforementioned "near-term" PACS, the development of an "advanced" PACS was also planned. The ADVPACS was to provide good flying qualities to a negative static stability margin of 10 percent and for high-Mach/high-acceleration flight conditions. However, flight tests of the advanced system were to be limited to flight at a negative static stability margin of 3 percent because of the L-1011 flight-test aircraft structural and center-of-gravity management limitations.

In the fall of 1981, Lockheed decided to phase out production of the L-1011 airplane; consequently, the scope of the program was reduced. The near-term PACS development was to be continued as previously planned (through flight testing), but the advanced PACS development was to be continued only through the piloted simulation phase. The advanced PACS program consisted of control law development, flying qualities analysis, piloted-flight simulation testing on a moving-base simulator, and architectural development of a PACS that could be used for a future test program.

This paper discusses the results of the flying-qualities-analyses phase of the program conducted at the Lockheed-California Company and the results of the "extended near-term" PACS and the "advanced" PACS piloted-flight simulation phases of the program conducted at the NASA Langley Research Center. Also, a brief discussion is presented wherein the flight simulation test results with the "near-term" PACS operative are compared with the corresponding airplane flight test results.

SYMBOLS

Measurements and calculations were made in U.S. Customary Units, and all calculations are based on the aircraft body axes.

A,B,C,D,E	coefficients of advanced PACS gain-schedule equation
$C_{m,cg}$	pitching-moment coefficient about a particular aircraft center of gravity
\bar{c}	mean aerodynamic chord
F_C	column force
F^*	multiplier factor on pitch-rate damper gain
g	acceleration due to gravity ($1g = 32.17 \text{ ft/sec}^2$)
K	gain
K_3	combined pitch-attitude/velocity gain
K_{FF}	feedforward gain
K_{n_z}	normal-acceleration gain
K_q	pitch-rate damper gain
K_S	column feel spring gradient, lbf/in.
K_X	calculated gain for advanced PACS
M	Mach number
M_d	dive Mach number
M_{MO}	maximum operational Mach number
m_C	column mass
n_L	load factor limit
n_z	normal acceleration
n_α	steady-state normal-acceleration change per unit change in angle of attack for an incremental horizontal-tail deflection at constant airspeed, g units/rad
N_0	stick-free neutral point
q	pitch rate
\bar{q}	dynamic pressure
s	Laplace transform operator

t	time, turbulence
V	airspeed
V _{MO}	aircraft maximum operating speed
V _S	stall speed
W	aircraft weight
w _g	vertical turbulence gust value
w _{g,peak}	peak vertical turbulence gust value
α	angle of attack
Δ	increment
δ	ratio of atmospheric pressure at altitude to pressure at sea level
δ_c	total column deflection, in.
$\delta_{c,MTC}$	column deflection due to Mach trim compensation
$\delta_{c,p}$	column deflection due to pilot force input
$\delta_{c,PACS}$	column deflection (software only) due to pitch active control system, in.
$\delta_{c,str}$	column deflection due to cable stretch, in.
$\delta_{c,trim}$	column deflection due to pilot trim beeper input
δ_{col}	software stick position, in.
δ_e	elevator surface deflection, deg
δ_f	flap deflection, deg
δ_{HT}	horizontal-tail deflection, deg
δ_{HT}^*	modified horizontal-tail feedback signal for secondary gain scheduling (function of α , ϕ , and M)
$\delta_{H,com}$	commanded stabilizer deflection, deg
ζ	damping ratio
θ	pitch attitude, deg
θ_f	filtered pitch-attitude feedback signal
τ_1	numerator time constant of lag-lead transfer function
τ_2	denominator time constant of lag-lead transfer function

τ_c	force sensor filter time constant
τ_{lag}	pitch damper lag
ϕ	bank angle, deg
ω	frequency
ω_n	damped frequency
ω_d	undamped natural frequency

Subscripts:

cg	center of gravity
FRL	fuselage reference line
ph	phugoid mode
sp	short-period mode
trim	trimmed flight

Abbreviations:

AACS	aileron active control system
accel	acceleration
ADVPACS	advanced pitch active control system
ang	angle
c.g.	center of gravity
col	column
fwd	forward
ILS	instrument landing system
KEAS	knots of equivalent airspeed
max	maximum
min	minimum
MTC	Mach trim compensator
NTPACS	near-term pitch active control system
PACS	pitch active control system

pos	position
PR	pilot rating
RSS	relaxed static stability
SAS	stability augmentation system
stab	stabilizer
vert	vertical
VMS	Visual/Motion Simulator

DESCRIPTION OF SIMULATED AIRPLANE

The Lockheed L-1011 is a current-generation, subsonic, commercial transport aircraft (fig. 1). The aircraft is powered by three Rolls-Royce RB 211-22B high-bypass-ratio turbofan engines, and the stabilizer, which has a geared elevator, is the primary longitudinal control. Aircraft geometry and weight data are given in table I. A unique version of the L-1011 aircraft was used throughout the PACS/RSS program analyses, design, simulation, and flight tests. Features of this aircraft, a basic Lockheed L-1011-1 with an extended-span wing and an aileron active control system (AACS), are indicated in figure 2. These features were installed prior to the subject RSS studies for improved aerodynamic efficiency and maneuver load relief. For the RSS studies a downrigged elevator, a center-of-gravity management system, and the near-term PACS were added (see fig. 2).

The simulated L-1011 uses elevator, stabilizer, and active outboard ailerons for longitudinal control, inboard and outboard ailerons and spoilers for lateral control, and rudder for directional control (fig. 3).

Aircraft longitudinal control is achieved by the basic longitudinal control system and the active control stability augmentation system (SAS) that determine stabilizer, elevator, and active aileron deflections. The basic-longitudinal-control-system modeling includes servoactuator, cable stretch, and control surface position and rate limiting. The longitudinal active control SAS includes the "near-term" or the "advanced" pitch active control system (PACS) and the aileron active control system (AACS). In addition to column position commanded by the pilot, both PACS utilize pitch-angular-rate feedback and column-force feedforward to compute a contribution to "software" column position. (The advanced PACS also uses additional feedbacks, such as normal acceleration, pitch angle, etc.) The AACS also uses angular and angular-rate feedbacks to determine a symmetric (both outboard ailerons equally deflected in the same direction) outboard aileron position. The Mach trim compensator (MTC)--while actually a type of SAS--is included as a basic control since it is usually active and is, therefore, an integral part of column deflection. The "normal" high-speed MTC was designed to alleviate the nose-down (tuck under) maneuver that transports experience as Mach number approaches 0.8. This is due to the rearward shift of the aircraft center of pressure as Mach number increases. The low-speed MTC was specifically designed for column position contributions when Mach number is less than 0.295, flaps-down configuration. (This low-speed MTC was designed especially for the subject RSS simulation program and is not used on conventional L-1011 aircraft.) The low-speed MTC has a negligible effect at higher Mach numbers. Both MTC contributions add directly to the physical column

position. A detailed description of the basic longitudinal control system of this derivative L-1011 airplane is presented in the appendix.

Aircraft lateral control is achieved by the basic lateral control system, which determines aileron and spoiler deflections and includes servoactuator and position limiter modeling. Only the four outboard spoiler panels (per wing) are modeled for lateral control.

Aircraft directional control is achieved by the directional control system, which determines manual and SAS contributions to the rudder position. The directional SAS consists of a yaw damper that includes aileron input, servoactuator, and rate and position limiter modeling for improved turn coordination.

Although the subject simulation study utilized six-degree-of-freedom equations of motion (with nonlinear aerodynamic and thrust input data), the lateral-directional flight characteristics are not addressed in this paper since this was a "longitudinal" handling qualities study.

DESCRIPTION OF SIMULATION EQUIPMENT

The simulation study was made with the general-purpose cockpit of the Langley Visual/Motion Simulator (VMS), a ground-based motion simulator with six degrees of freedom. For this study, it had a transport-type cockpit equipped with conventional flight and engine-thrust controls and a flight-instrument display representative of the controls and panel found in current transport airplanes. (See fig. 4.) Instruments that indicate angle of attack, angle of sideslip, flap angle, horizontal stabilizer angle, and column force were also provided.

The control forces on the wheel, column, and rudder pedals were provided by a hydraulic system coupled with an analog computer. The system incorporated variable-feel characteristics of stiffness, damping, Coulomb friction, breakout forces, detents, and inertia. The longitudinal control loading system of the VMS is described in the appendix.

The airport-scene display used for approach and landing was an "out-the-window" virtual image system of the beam-splitter, reflective-mirror type. (See fig. 5.) A runway "model" was programmed that had a width of 200 ft, a total length of 11 500 ft, roughness characteristics, and a slope from the center of the edge representing a runway crown. Only a dry runway was considered in this study.

The average total motion delay of the VMS, including computational throughput, is less than 70 msec and is quite compatible with the rest of the system, including visual delays. The washout system used to present the motion-cue commands to the motion base is nonstandard. It was conceived and developed at the NASA Langley Research Center (ref. 1). The basis of the washout is the continuous adaptive change of parameters to (1) minimize a cost functional through continuous steepest descent method and (2) produce the motion cues in translational accelerations and rotational rates within the motion envelope of the synergistic base.

The only aural cues provided were engine noises and landing-gear extension and retraction noises.

TESTS AND PROCEDURES

This study evaluated the handling qualities by analysis of recorded aircraft-motion time histories, calculation of various flying qualities parameters, and pilot comments on the flying qualities of the simulated L-1011 transport aircraft and the effects of various stability and control augmentation systems on these characteristics.

The eight flight conditions indicated in table II and figure 6 were simulated during the present studies. These flight conditions represent the entire flight envelope of the L-1011 aircraft--from takeoff, to cruise, to landing. When evaluating the effects of the NTPACS, the three flight conditions designated conditions 10, 11, and 18 were flown; but, when evaluating the ADVPACS, all flight conditions were flown except condition 11. Five research test pilots participated in the flight simulation program, although all pilots did not evaluate either PACS concept at all of its designated flight conditions.

Evaluation Tasks During Cruise

Wind-up turns.-- Wind-up turns were performed to evaluate maneuvering force and stability characteristics by stabilizing at increasing load factors.

S-pattern turns.-- The aircraft was banked to a 4-min turn attitude and flown through a 90° heading change while descending 500 ft. Then, the bank angle was reversed, and the aircraft was turned back and rolled out on the initial heading while climbing 500 ft.

Trimmability.-- The workload to initially trim the aircraft and to recapture trim from a disturbed condition was used as another measure of performance. The trim recapture was evaluated by advancing power to upset the aircraft altitude and flying back to the initial altitude without retrimming.

Airline operational turns.-- Banked turns of 20° and 30° were performed while maintaining constant speed and using column force to control attitude and altitude. Turn entry and exit characteristics were also evaluated.

Pitch-attitude change.-- Attitude stability was evaluated by changing and holding a new pitch attitude with column force inputs.

Power effects.-- Power was advanced and retarded to restabilize the aircraft on a new pitch attitude while maintaining speed by applying column control force.

Emergency descent.-- Power was pulled back to idle, and the nose of the aircraft was pushed over to start the aircraft descent. The aircraft was maneuvered into a banked turn, after start of descent, to increase drag.

Short-period dynamic stability.-- The short-period characteristics were evaluated by using quick forward and aft control column inputs and releasing the column to upset the aircraft from 1g flight. Pitch attitude and load factor were observed while the aircraft returned to 1g trim.

Phugoid dynamic stability.-- The aircraft was displaced slightly from trim, and the phugoid damping and period were evaluated by observing excursions in rate of climb and pitch attitude.

Static stability.- Longitudinal static stability, sometimes referred to as speed stability, was evaluated by determining the variation of column force with deviation from trim speed.

Evaluation Tasks at Maximum Operating Speed

Tasks performed at maximum operational speeds included wind-up turns, operational turns, and trimmability. Descriptions of these tasks are the same as those described for the cruise flight conditions.

Evaluation Tasks During Landing

Wind-up turns.- Wind-up turns were conducted to evaluate maneuvering force characteristics by stabilizing at load factors up to 1.2g.

ILS approach.- The approach task was initialized 8 miles from the airport, at an altitude of 2000 ft, and with a 1000-ft lateral offset from the localizer beam. The task involved flying the airplane to the localizer, capturing the glide slope, and tracking the localizer and glide slope down to an altitude of 50 ft. A few flares and touchdowns were performed, but the pilots commented that this part of the task added nothing to the evaluation in this particular study. Most approaches were made utilizing "raw-data" displays; however, a few approaches were flown using the available flight director.

Evaluation Tasks While Holding

Airline operational turns (30° banked turns) were flown while maintaining speed and using column force to control attitude and altitude.

Evaluation Tasks at Takeoff

The takeoff condition was initialized with the aircraft climbing in the second-segment configuration. Controllability was evaluated during 30° banked turns through 30° heading changes.

RESULTS AND DISCUSSION

The results of this study are discussed in terms of the previously stated objectives. The two pitch active control systems (PACS) evaluated are discussed separately--first, the more simple (near-term) PACS and, second, the effects of the more complex (advanced) PACS on the aircraft handling qualities. Finally, with the near-term PACS operative in each test, a brief discussion is presented wherein the flight simulation test results are compared with the airplane flight test results. Since this was a "longitudinal" handling qualities study, the lateral-directional flight characteristics of the aircraft are not addressed in this paper. The lateral-directional characteristics simulated were judged by the pilots to be "well-enough-behaved" that they would not influence the pilots' ability to adequately evaluate the longitudinal characteristics.

Table III presents the Cooper-Harper pilot rating system used for the handling qualities evaluations. Unless specifically noted otherwise, the results are discussed in relation to the cruise flight conditions designated flight condition 10 in figure 6 and table II.

Near-Term PACS

A block diagram of the near-term PACS is presented in figure 7. This augmentation system consists of (1) a pitch damper loop with pitch rate fed back into the series servo to enhance the aircraft short-period characteristics and (2) a feed-forward loop with column position (column minus trim) fed back to enhance the aircraft maneuver stability. The nonlinear gains and time lag schedules of this system are indicated in figure 8. This PACS (fig. 7) is described in more detail in the appendix of this paper and in reference 2.

The three flight conditions evaluated during the near-term PACS simulation program were those designated as 10, 11, and 18. (See table II and fig. 6.) The flying qualities for flight condition 10, a nominal cruise condition, were evaluated more extensively than the other two flight conditions. The simulation tests were performed with static stability margins from +15 percent to -5 percent. (The previous near-term PACS study by Lockheed covered a range of center-of-gravity positions from $0.25\bar{c}$ to $0.39\bar{c}$, representing static stability margins from +15 percent to +1 percent, respectively, for the cruise flight condition.) The analyses and pilot evaluations included speed stability, maneuver stability, dynamic stability, and turbulence response. The results are compared with the flying qualities requirements/criteria of reference 3 (FAR Part 25) and reference 4 (MIL-F-8785C) to determine the adequacy of the near-term PACS capabilities.

Speed stability.- The stability analysis determined the column force F_C required to maintain the aircraft at a speed other than trim speed. Reference 3 defines satisfactory column force characteristics as follows:

1. 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.
2. Column force shall vary monotonically with speed.
3. The average column-force gradient shall be at least -1 lbf/6 KEAS throughout the speed range.

Speed stability characteristics for flight condition 10 are presented in figure 9. For airspeeds of approximately ± 50 knots from trim, the reference 3 design criteria for speed stability are satisfied for center-of-gravity positions of $0.25\bar{c}$ and $0.45\bar{c}$. 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. Column forces were reduced significantly for the PACS configuration wherein the pitch damper and feedforward modes were operative. Column forces for the PACS with pitch damper and feedforward washout would be the same as with the PACS off, except for lighter control column force required to initiate the speed change.

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

Maneuver column force criteria of reference 4 require a steadily increasing push force to maintain load factors less than 1 and a steadily increasing pull force to maintain load factors greater than 1. The upper and lower column force maneuver gradient criteria for cruise are

- Upper boundary = $120/(n_T - 1)$, lbf/g units
- Lower boundary = $35/(n_T - 1)$, lbf/g units

(The load factor limit n_T for the commercial L-1011 aircraft is 2.5g.)

The calculated maneuver stability characteristics of flight condition 10 are shown in figures 10, 11, and 12 for 25 percent, 39 percent, and 45 percent center-of-gravity positions, respectively. Part (a) in each of these figures presents the maneuver characteristics for the PACS off and for the PACS on with pitch damper only; part (b) in each figure presents the maneuver characteristics for the PACS on with pitch damper and feedforward. (The pilots confirmed these "calculated" maneuver stability characteristics on the simulator.) The PACS-on configuration with pitch damper and feedforward washout is not shown in the figures because it is dependent upon the rate at which the maneuver was accomplished. However, the column forces for this configuration lie between those of the other two PACS-on configurations. Also, the configuration is equivalent to the PACS with only pitch-rate damper for sustained maneuvers and is like the PACS with both pitch damper and feed forward for rapid maneuvers.

The pitch-rate damper increases force gradients, and the feedforward reduces the gradient for each center-of-gravity position shown in figures 10, 11, and 12. Also, the "initial" force gradients (gradients for load factors up to approximately 1.6g) for the PACS-on configurations are shown to lie within the prescribed limits of reference 4. At a load factor of 1.6g, the column force gradients begin to reduce--they "flatten" for the 0.25c̄ center-of-gravity position and "reverse" for the 0.39c̄ and 0.45c̄ center-of-gravity positions. These reduced gradients represent the end of the region where the aerodynamic data vary linearly with angle of attack. 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 1.6g.

The maneuver stability analysis for flight condition 11 showed that for load factors less than approximately 2.2g the force gradients with PACS on were within the limits prescribed by reference 4.

The analysis showed that the column force gradients for flight condition 18 (landing), with the PACS on or off, increased as the center-of-gravity position was moved aft. Also, at the aft center-of-gravity positions, the column force gradients exceeded the maximum limits prescribed by reference 4. The gradient increase at the aft center-of-gravity positions was caused by the primary control system gearing and associated feel system which were not designed for flight with the center of gravity at the aft positions.

Dynamic stability.— The dynamic stability analyses were performed to evaluate longitudinal mode characteristics of the PACS configured aircraft. The aircraft was considered to be rigid. The aileron active control system (AACS) and the Mach trim compensator (MTC) were considered to be operating. The dynamic stability characteristics were determined by obtaining roots of the aircraft and control system linearized equations.

The short-period and phugoid frequency and damping characteristics for flight condition 10 are presented in figure 13. The baseline aircraft ($K^* = 0$) with a $0.25\bar{c}$ center-of-gravity position has a short-period damping ratio ζ near 0.7 and a frequency ω_n of 1.25 rad/sec, both meeting the Level 1 flying qualities criteria of reference 4 (fig. 13(a)). The damping ratio of the phugoid mode for the baseline aircraft was 0.076, which also meets the requirement of reference 4. (Ref. 4 requires that ζ_{PH} be at least 0.04. (See fig. 13(b).))

With the PACS on and the aircraft center of gravity located at $0.43\bar{c}$, it can be seen from figure 13(b) that $1.8K_Q$ is required before the phugoid mode is stabilized. Also, note from figure 13(a) that the short-period mode of this configuration (PACS on, c.g. = $0.43\bar{c}$, $1.8K_Q$) has ζ_{sp} of 0.512 and ω_n of 2.543, values which still satisfy the requirements of reference 4. Therefore, prior to the piloted simulation tests, it was expected that the pilots would prefer the $1.8K_Q$ PACS.

The near-term PACS was considered to have four configurations for purposes of analyses and simulation test evaluations. They were

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

In addition to the information provided in figure 13, which indicates the effect of various levels of K_Q on the eigenvalues as the center-of-gravity position is varied, figure 14 presents time histories of the pitch-attitude response following a pulse of the column for various levels of K_Q for a center-of-gravity position of $0.45\bar{c}$ and with no feedforward. Even the "basic" pitch-rate feedback gain ($F^* = 1.0$) makes the aircraft appear to have a stable response within the indicated time frame. (The pitch attitude is beginning to return toward its trim value.) It may also be seen from figure 15 that the feedforward portion of the PACS (K_{FF}) tends to quicken the pitch response to a column force input. Therefore, the full-time feedforward may be expected to be preferred by the pilots.

Simulated test results.— The piloted-flight simulation test results are presented in terms of Cooper-Harper ratings (table III) for two cruise flight conditions (conditions 10 and 11) and the landing flight condition (condition 18). (See table II.) The ratings are for calm-air atmospheric conditions except for points on the figures marked with the letter "t" that represent flight in moderate turbulence. The three flight conditions are discussed separately, with the PACS on and off, for the center-of-gravity range from $0.25\bar{c}$ to $0.45\bar{c}$. The baseline aircraft was configured with the aileron active control system (AACS) operating and the PACS off; that is, the AACS was always operative unless specifically indicated otherwise. It should be noted that the AACS may have a significant impact on the stability margin of the aircraft. As indicated in figure 16 for a typical cruise flight condition, when the AACS is off, the neutral point would be at a center-of-gravity position of approximately $0.45\bar{c}$; but when the AACS is on, the effective neutral point could be at a center-of-gravity position of approximately $0.40\bar{c}$. For example, when the AACS is operating during a "positive g" maneuver, the ailerons move symmetrically "upward" to provide wing-load alleviation and cause a nose-up pitching moment--this results in a forward shift of the neutral point to a center-of-gravity position of

approximately $0.40\bar{c}$. Thus, a positive increment in stability margin may be realized by disengaging the AACS.

Flight condition 10: Pilot ratings for the aircraft at cruise condition 10 with the PACS off are presented in figure 17 for the AACS on and off. The three pilots who evaluated this flight condition rated the handling qualities of the aircraft as being satisfactory whether the AACS was on or off, when the center of gravity was at $0.25\bar{c}$. Based upon the data shown in figure 17 (for example, see pilot 1), the baseline aircraft (AACS on) boundaries for satisfactory/unsatisfactory (Level 1/Level 2) and unsatisfactory/unacceptable (Level 2/Level 3) handling qualities ratings were approximately $0.37\bar{c}$ and $0.42\bar{c}$, respectively. (This center-of-gravity range represents a static margin range from approximately +3 percent to -2 percent.) Also note that the pilot ratings deteriorated very rapidly for center-of-gravity positions aft of the neutral point (c.g. $\approx 0.04\bar{c}$, with the AACS on). In figure 17, the AACS off configuration received acceptable pilot ratings for all center-of-gravity positions evaluated (c.g. = $0.25\bar{c}$ to $0.45\bar{c}$), an indication that the AACS had a destabilizing effect on the longitudinal characteristics. This destabilizing effect of the AACS is further illustrated in figure 18, which compares the incremental (from trim) pitch attitude response experienced, due to a pulse of the column, for AACS on and off for an aircraft with c.g. = $0.41\bar{c}$. It is shown that the pitch attitude tends to return to trim soon after the column is released ($t = 2.0$ sec) when the AACS is off; but, at least for the time frame presented and the center of gravity indicated (c.g. = $0.41\bar{c}$), the aircraft does not tend to return to its trim condition when the AACS is operative. (It should be noted that the neutral point is at c.g. = $0.40\bar{c}$ with the AACS operative for the cruise flight condition.) For comparison, figure 19 shows the effects of the AACS when the aircraft is quite stable (c.g. = $0.25\bar{c}$) and indicates that after a disturbance the aircraft returns to trim quite readily even when the AACS is operative.

Engagement of the PACS improved the pilot ratings significantly; compare figures 17 and 20. In figure 20, the PACS configurations tested for each center-of-gravity position and at various pitch-rate feedback gains are rated by four of the pilots. The rating at $0.25\bar{c}$ represents the baseline aircraft (PACS off, AACS on). The PACS configurations preferred by the pilots are shown for each specific center-of-gravity position.

The three pilots who flew the complete center-of-gravity range for flight condition 10 rated the handling qualities of the PACS-on aircraft the same as or better than the baseline aircraft (PACS off; AACS on; c.g. = $0.25\bar{c}$) at center-of-gravity positions as far aft as $0.41\bar{c}$. Pilot 1 and pilot 3 rated the PACS-on aircraft slightly worse than the baseline aircraft at center-of-gravity positions aft of $0.41\bar{c}$; however, their ratings remained in the satisfactory region. Pilot 2 found the aircraft more degraded with center-of-gravity positions aft of $0.41\bar{c}$ and rated the aircraft "acceptable, but unsatisfactory." Pilot 2 also provided ratings wherein he excluded the phugoid characteristics; and although these ratings are not indicated in figure 20, his ratings became "satisfactory" with the center of gravity at $0.43\bar{c}$. Pilot 4 only evaluated the PACS configuration with $2K_q$, full-time feedforward, and c.g. = $0.43\bar{c}$ at flight condition 10; he also found the PACS-on aircraft handling qualities to be "unsatisfactory, but acceptable." At c.g. = $0.39\bar{c}$, the pilot opinions for the preferred PACS configuration were divided between the pitch damper plus feedforward and the pitch damper with feedforward washout. At center-of-gravity positions aft of $0.39\bar{c}$, the pilots preferred the PACS configuration with pitch damper plus feedforward. The trend in the desired value of pitch-rate feedback gain was to increase F^* from 1.6 to 2.0 as the center of gravity was moved from $0.39\bar{c}$ to $0.45\bar{c}$.

The ratings by pilot 1 in moderate turbulence indicated the handling qualities to be unsatisfactory but acceptable. (See fig. 20.) The preferred PACS configurations were the same in turbulence as in calm air--neither an increased pitch-rate damping gain nor a different PACS operating configuration improved the pilot rating. The pitch-rate damping gains of $1.0K_q$, $1.3K_q$, and $1.6K_q$ appeared to be acceptable for the planned flight test program, which would be limited to a maximum aft center of gravity of $0.43\bar{c}$ and flight condition 10.

Flight condition 11: Figure 21 indicates that the pilot ratings for the PACS-off aircraft at flight condition 11 were similar to those of flight condition 10. (See fig. 6 and table II for differences in the two flight conditions.) The AACS-off pilot ratings at aft center-of-gravity positions were better than the AACS-on ratings; the AACS-on rating trend changed from satisfactory to unacceptable as the center of gravity was moved from $0.25\bar{c}$ to $0.43\bar{c}$. The data presented in figure 21 indicate that the baseline aircraft (PACS off; AACS on) boundaries for pilot ratings of satisfactory/unsatisfactory and unsatisfactory/unacceptable would be at center-of-gravity positions of $0.37\bar{c}$ and $0.43\bar{c}$, respectively.

The PACS-on pilot ratings for flight condition 11 (fig. 22) indicated similar results as those for flight condition 10 (fig. 20). In calm air, the ratings of all pilots showed satisfactory flying qualities at the $0.39\bar{c}$ and $0.41\bar{c}$ center-of-gravity positions. Whereas the ratings of pilots 2 and 4 indicated unsatisfactory flying qualities at $c.g. = 0.43\bar{c}$, the ratings of pilots 1 and 3 showed satisfactory flying qualities to a center-of-gravity position of $0.45\bar{c}$, for the preferred PACS configuration (pitch damper plus feedforward). The desired trend in pitch-rate feedback gain was the same for flight condition 11 as for flight condition 10; that is, F^* varied between 1.6 and 2.0 as the center of gravity was moved from $0.39\bar{c}$ to $0.45\bar{c}$.

Turbulence evaluations by pilots 1 and 3 showed that the flying qualities in moderate turbulence were degraded, relative to the flying qualities in calm air. (See fig. 22.) However, their ratings remained essentially constant over the center-of-gravity range, with pilot 1 rating the aircraft "unsatisfactory but acceptable" and pilot 3 rating the aircraft "marginally satisfactory" (PR = 3.5).

Randomly inserted PACS failures throughout the test evaluations of flight condition 11 at $c.g. = 0.43\bar{c}$ indicated that passive failures were benign. The pilots could easily detect when a failure occurred and were able to disengage the AACS to produce a positive increment in stability margin. These passive PACS failures therefore caused no appreciable handling and/or safety problems with the aircraft in the cruise flight condition. (The term "passive failure" as used here means that the PACS was simply disengaged, thereby causing the incremental deflection of the horizontal tail "due to the PACS" to become zero.)

Maximum-PACS-servo-authority hardover failures presented some difficulty in controlling the aircraft. The best recovery procedure was (1) to quickly deactivate the PACS, (2) to return the aircraft to $1g$ flight, and (3) to disengage the AACS. This procedure was adopted as the flight test procedure--should such a failure occur.

Flight condition 18: Pilot ratings of the baseline aircraft (PACS off; AACS on) for the approach and landing task (flight condition 18) are presented in figure 23. Three of the four pilots who flew the approach and landing task rated the baseline-aircraft handling qualities as satisfactory (Level 1) over the center-of-gravity range to $0.41\bar{c}$; but the ratings deteriorated to unsatisfactory (Level 2) at a center-of-gravity position of $0.43\bar{c}$.

Engagement of the PACS (fig. 24) only slightly improved the aircraft flying qualities for flight condition 18. This was not surprising, however, since the neutral point of the landing configuration is approximately $0.48\bar{c}$, compared with $0.40\bar{c}$ for the cruise configuration; it had been determined during the cruise simulation tests that the benefits of the PACS were most obvious for center-of-gravity positions aft of the aircraft's neutral point. The column-minus-trim feedforward gain (K_{FF}) of the PACS was increased for some of these tests, as indicated in figure 24, but did not improve the handling qualities. The desired pitch-rate feedback gain increased from $1.3K_q$ to $1.6K_q$ as the center of gravity was moved from $0.39\bar{c}$ to $0.43\bar{c}$.

It may be seen from figure 24 that the pilot ratings were only slightly worse when in moderate turbulence for flight condition 18.

Summary of near-term PACS simulation results.- The baseline aircraft (PACS off; AACS on) had unacceptable flying qualities for cruise flight conditions 10 and 11 at center-of-gravity positions aft of approximately $0.42\bar{c}$. The aircraft flying qualities were significantly better, however, 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 flying qualities of the baseline aircraft for the landing flight condition were acceptable throughout the center-of-gravity test range.

Engagement of the near-term PACS significantly improved the flying qualities for cruise flight conditions 10 and 11, but only slightly improved the flying qualities for the landing flight condition. With the PACS operative, the flying qualities were, in general, considered to be good over the center-of-gravity range tested and were close to meeting the design goals, which required the PACS configured aircraft flying qualities for the entire center-of-gravity range to be equivalent to or better than those of the baseline aircraft with a $0.25\bar{c}$ center-of-gravity position.

The preferred PACS operating configuration was determined to be the pitch-rate damper plus feed-forward configuration. The desired trend of pitch-rate feedback gain was from $1.0K_q$ at c.g. = $0.39\bar{c}$ to between $1.6K_q$ and $2.0K_q$ at c.g. = $0.45\bar{c}$. However, the majority of pilot ratings indicated that a gain of $1.6K_q$ was adequate at a center-of-gravity position of $0.43\bar{c}$.

Advanced PACS

The previously discussed near-term PACS was designed to provide satisfactory flying qualities at slightly negative static stability margins (up to 3 percent). However, the design objective of the advanced PACS program was to develop a PACS which would provide flying qualities, at negative static stability margins as high as 10 percent, that were at least equivalent to those of the baseline aircraft (PACS off; AACS on) with a center-of-gravity position of $0.25\bar{c}$. (The $0.25\bar{c}$ center-of-gravity position represents the existing L-1011 configuration which is considered to have satisfactory flying qualities.) Also, the advanced PACS was to compensate for high-Mach/high-g instabilities that degrade the flying qualities during "upset" recoveries and maneuvers.

A block diagram of the advanced PACS is presented in figure 25, and the PACS gain-schedule equation and equation coefficients are indicated in table IV.

This augmentation system input signals consist of four types--feedforward, feedback, primary gain scheduling, and secondary gain scheduling. (See table V.) This advanced PACS (fig. 25) is described in more detail in the appendix of this paper and in reference 5.

The flight conditions evaluated during the advanced PACS simulation program consisted of all conditions indicated in table II and figure 6, with the exception of flight condition 11. (Flight condition 11 was only evaluated during the near-term PACS simulation study.) The simulation tests were performed with static stability margins from +15 percent to -20 percent, representing center-of-gravity positions for the cruise flight conditions from 0.25c to 0.60c. (It should be noted that this advanced PACS was "optimized" for flight with a negative static margin of 10 percent (c.g. = 0.05c), but the piloted simulation tests were extended to a negative static margin of 20 percent (c.g. = 0.60c).) The analyses and pilot evaluations included speed stability, maneuver stability, dynamic stability, and turbulence response. The results are compared with the flying qualities requirements and criteria of references 3 and 4 to determine the adequacy of the advanced PACS capabilities. The analysis of the advanced PACS concentrated on high-altitude cruise flight (condition 7) because of the aircraft aerodynamic characteristics at this flight condition. (For flight condition 7, the angle of attack required for trim is within, or very near, the region of inherent pitch-up.)

As stated previously, the advanced PACS configured aircraft was designed to have the capability of operating over the full flight envelope with negative static stability margins up to 10 percent and to have flying qualities equivalent to or better than those of the baseline aircraft with the center-of-gravity at 0.25c. Other design objectives of this advanced PACS were as follows:

1. The short-period and phugoid modes frequency and damping characteristics should fall within the shaded s-plane areas indicated in figure 26.

2. The column force gradients should fall within the column-force load-factor boundaries indicated in figure 27 and should have nearly constant slope.

Speed stability.-- The speed stability characteristics for the holding and cruise conditions (flight condition 17 and 7, respectively) with the advanced PACS operative are presented in figure 28. Column force gradients for the holding flight condition comply with the design criteria of reference 3 in all respects, whereas the column force for the cruise flight condition does not vary monotonically with airspeed as is desired. However, the speed stability characteristics for all flight conditions evaluated with the advanced PACS were considered to be sufficient to continue the analyses with piloted-flight simulation tests.

Maneuver stability.-- The maneuver stability analysis determined the column forces required to maintain the airplane in steady wind-up turns. Satisfactory maneuver stability column forces, as required by reference 4, are a steadily increasing pull to maintain positive load factors and a steadily increasing push to maintain negative load factors. In addition, the upper and lower column force maneuver criteria boundaries for aircraft with wheel controllers are

- Upper boundary = $120/(n_L - 1)$, lbf/g units
- Lower boundary = $35/(n_L - 1)$, lbf/g units

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

The maneuver stability characteristics of the baseline aircraft in the takeoff configuration (fig. 29) indicate that the column forces were stable throughout the center-of-gravity range from 0.25c̄ to 0.50c̄. However, when compared to the reference 4 guidelines, the gradients were very steep for the more aft center-of-gravity positions. The nature of these column forces can be attributed to the low-speed aerodynamics and the "basic" control system of the L-1011 aircraft. Figure 30 presents the maneuver stability characteristics of the aircraft in the takeoff configuration with the advanced PACS operative. These data indicate that the advanced PACS reduces the spread of the column force gradients for the center-of-gravity range from 0.25c̄ to 0.50c̄ and that the gradients are within the boundaries of reference 4.

The maneuver stability characteristics of the baseline aircraft in the cruise configuration (fig. 31) indicate unsatisfactory column force characteristics for the complete center-of-gravity range. These unsatisfactory force characteristics can be attributed to the nonlinear high-speed pitching-moment characteristics and to the AACS. The maneuver stability characteristics of the aircraft in the cruise configuration with the advanced PACS operative are presented in figure 32; these data indicate that the advanced PACS completely removes the "dip" in the column force gradients presented in figure 31 for the PACS-off configuration. This was accomplished primarily by the pitch-up controller which is scheduled with Mach number and angle of attack. (See table V.) The maneuver stability characteristics presented in figure 32 indicate that the column force characteristics are satisfactory for all center-of-gravity positions, except at high load factors. Note that the "initial" (load factors up to approximately 1.4g) force gradients are essentially the same for the entire center-of-gravity range.

Dynamic stability.- The dynamic stability characteristics were obtained by calculating the eigenvalues of the small-disturbance equations of motion, and the flying qualities specifications of reference 4 were used as guidelines to evaluate the acceptability of these characteristics. Figure 33 presents the s-plane eigenvalues (cruise condition 7) for the baseline aircraft short-period and phugoid modes. As can be seen, the short-period characteristics do not meet the requirements of reference 4 when the center of gravity is aft of 0.25c̄. These data also indicate that the phugoid characteristics become unstable as the center of gravity is moved aft and violate the requirement for a minimum damping ratio of 0.04.

Figure 34 indicates that the dynamic stability characteristics of the aircraft in cruise condition 7, with the advanced PACS operative, comply with the specifications of reference 4. In fact, with the advanced PACS operative, the dynamic stability characteristics of all flight conditions satisfied the reference 4 requirements except for the holding flight condition (condition 17), which had a mild phugoid instability with the center of gravity at 0.25c̄. (This flight condition had an unstable phugoid with a time-to-double amplitude of 700 sec.)

Satisfactory flying qualities are defined in terms of stable responses to external disturbances and pilot control inputs. After experiencing a discrete vertical gust, the aircraft should quickly return to its trim equilibrium condition and any oscillations should be well damped. Also, the airplane should respond predictably to a column force step input, and the controls should give the pilot the capability of changing the pitch attitude precisely.

Figure 35 presents the discrete vertical gust model used in the analysis of cruise condition 7; this model was patterned after the gust model presented in reference 4. A gust amplitude of 54 ft/sec is considered a severe disturbance of heavy thunderstorm magnitude.

Figure 36 compares the responses to a -54 ft/sec vertical gust (updraft) of the baseline aircraft (PACS off) and the advanced PACS aircraft in flight condition 7. These time histories indicate that for this severe disturbance, the baseline aircraft with the center of gravity at $0.25\bar{c}$ will return to its initial trim condition. However, for center-of-gravity positions aft of $0.25\bar{c}$, the aircraft diverges from its trim condition and seeks a new equilibrium at high angle of attack. The disturbance is strong enough to drive the aircraft into the high-angle-of-attack, heavy-buffet region where the aircraft is quite stable. (See fig. 37 for the pitching-moment characteristics.) The response of the advanced PACS configured aircraft to the severe vertical gust had well-behaved, stable response characteristics and were determined to be essentially the same for all center-of-gravity positions from $0.25\bar{c}$ to $0.50\bar{c}$. (See fig. 36.)

Figure 38 presents the aircraft response to various column force step inputs for the high-altitude cruise flight condition (condition 7) with the center of gravity at $0.50\bar{c}$. These data indicate that the baseline aircraft diverges quickly from its trim condition for any constant force input until it reaches a region of increased stability at high angle of attack. However, the responses of the PACS configured aircraft to column force step inputs indicate that the advanced PACS works to reduce excessive excursions in angle of attack and load factor.

The dynamic stability characteristics, as well as the speed and maneuver stability characteristics, of the advanced PACS aircraft were determined using both linear and nonlinear aerodynamic and control system characteristics in various analytic tools. As a result, the dynamic stability characteristics were considered to be sufficient to warrant further studies involving piloted-flight simulation.

Simulated test results.- The piloted-flight simulation tests were performed to identify any pilot/control interface problems and evaluate the flying qualities of the advanced PACS. The specific flight conditions selected for these simulation tests are indicated in table II and figure 6. The results of the tests, discussed for each flight condition in the subsequent paragraphs, indicated that the advanced PACS fulfilled the functions for which it was designed. The pilot ratings indicated that the flying qualities of the advanced PACS configured aircraft with c.g. = $0.50\bar{c}$ were as good as the baseline aircraft with c.g. = $0.25\bar{c}$. Also, the benefits of the PACS were the most impressive at high-speed conditions where the handling qualities of the baseline aircraft quickly degraded to unacceptable levels (pilot ratings greater than 6.5) for center-of-gravity positions aft of approximately $0.42\bar{c}$. The data for the PACS configured aircraft indicated satisfactory handling qualities (pilot ratings equal to or less than 3.5) for a center-of-gravity position of $0.50\bar{c}$. In addition, very little degradation occurred when the center of gravity was moved from $0.50\bar{c}$ to $0.60\bar{c}$.

Flight condition 10 (nominal cruise): Flight condition 10 is an average cruise condition for commercial airline service ($W/\delta = 1.4 \times 10^6$ lbf). For the L-1011 airplane, the value of 1.4×10^6 lbf for the parameter W/δ , and Mach number of 0.83, represents a lift-coefficient value of 0.4. Since a constant lift-coefficient value is required to properly evaluate control characteristics, each test for flight condition 10 was initiated at the same value of W/δ and Mach number. The maneuver stability about trim is essentially linear at this flight condition, but a region of reduced maneuver stability can be reached at high load factors. (The aircraft remains in the region where the aerodynamic data are nearly linear functions of α for small maneuvers about this flight condition, but high-load-factor maneuvers can result in the penetration into the region where pitch-up occurs.)

Five pilots evaluated the flying qualities of the simulated L-1011 aircraft at flight condition 10; however, all center-of-gravity positions (which covered the range from 0.25c to 0.60c) were not evaluated by all pilots. Pilot ratings for the center-of-gravity positions tested by each pilot in calm air and in moderate turbulence are presented in figures 39 and 40, respectively. The baseline-aircraft pilot ratings for the calm-air and turbulence conditions indicate unacceptable flying qualities for center-of-gravity positions aft of approximately 0.40c. The wide scatter in the pilot ratings for c.g. = 0.39c is due to the sensitivity of the various pilots in judging the onset of unacceptable flying qualities. Engagement of the advanced PACS in calm air produced satisfactory flying qualities for center-of-gravity positions as far aft as approximately 0.55c and very acceptable (PR < 4) flying qualities for c.g. = 0.60c. The flying qualities in moderate turbulence were not as good as in calm air but were considered by the pilots to be very acceptable for center-of-gravity positions to 0.55c and acceptable at 0.60c. (See fig. 40.) Typical pilot comments regarding specific flying qualities characteristics for flight condition 10 at center-of-gravity positions from 0.25c to 0.60c (representing static margins from +15 percent to -20 percent) are presented in table VI.

Flight condition 15 (maximum-range cruise): The stability characteristics of the simulated L-1011 aircraft at this condition were essentially the same as at the intermediate W/δ (flight condition 10), except that the inherent pitch-up region is encountered at a lower load factor. Flight condition 15 was flown by only one pilot, and his evaluations of the flying qualities of the aircraft as the center of gravity was varied from 0.25c to 0.60c, with and without the advanced PACS engaged, in calm air and in moderate turbulence are presented in figures 41 and 42. These data indicate that the baseline aircraft flying qualities degrade rapidly for center-of-gravity positions aft of 0.40c. Engagement of the advanced PACS in calm air provided pilot ratings that were near the satisfactory/unsatisfactory boundary for the entire center-of-gravity range tested (fig. 41). In turbulence with the PACS operative, the pilot ratings were about the same over the center-of-gravity range but were not as good as for the calm-air conditions (fig. 42).

Flight condition 7 (high W/δ cruise): Flight condition 7 is the highest W/δ at which the simulated aircraft can operate with a 1.3g maneuver capability to buffet onset. (The 1.3g criterion is a typical transport aircraft operating restriction.) Flight condition 7 is near a region where the aerodynamic data are nonlinear functions of α which is due to wing aerodynamic flow separation. The nonlinear region begins approximately 0.1g from trim and is well into the unstable region of buffet onset, which is 0.3g.

Three pilots evaluated the flying qualities at flight condition 7, and their ratings in calm air and in moderate turbulence are presented in figures 43 and 44, respectively. This flight condition was the least stable of the three cruise conditions evaluated because of the closeness of the region of flow separation. This "reduced" stability is reflected by the rapid degradation of the baseline-aircraft flying qualities. Engagement of the advanced PACS in calm air provided satisfactory flying qualities to an aft center-of-gravity position of 0.50c (fig. 43). A comparison of the pilot ratings indicated in figures 43 and 44 shows that, with exception of pilot 4, the ratings in moderate turbulence are higher (degraded) than in calm air. The ratings of pilot 4 were satisfactory in both calm air and moderate turbulence to the 0.50c center-of-gravity position.

Pertinent parameters were recorded on strip charts during the pilot evaluation tests. Three strip-chart segments have been selected to illustrate differences in

pilot opinion between the baseline aircraft and the advanced PACS aircraft for flight condition 7. Figures 45, 46, and 47 compare the flight characteristics at center-of-gravity positions of 0.39c, 0.43c, and 0.50c, respectively.

The 0.39c center-of-gravity condition (fig. 45) was flown in moderate turbulence for only shallow banked turns. In each instance the airplane was first evaluated with the PACS disengaged; then the PACS was engaged, and the evaluation was repeated. The pilot workload, indicated by the control-force trace, was high; and the excursions in the normal acceleration at the aircraft center of gravity were approaching 0.5g with the PACS disengaged. With the PACS engaged, the normal-acceleration excursions and the control column input forces were significantly reduced.

Figure 46 presents the time histories obtained during the evaluation of the flying qualities at flight condition 7 with c.g. = 0.43c in calm air. With the PACS disengaged, the workload was similar to that when the center of gravity was at 0.39c and the aircraft was flown in moderate turbulence. (Again, only shallow banked turns were attempted.) With the PACS engaged, the pilot workload was dramatically reduced, and the pilot comfortably rolled into a 30° banked turn.

Figure 47 presents the evaluation time histories in calm air with c.g. = 0.50c. With the PACS disengaged, the aircraft was difficult to control, and large, rapid, cyclic, control column inputs were required to fly level. With the PACS engaged, however, the airplane could be comfortably rolled into a 30° banked turn.

Flight condition 16 (high speed): Flight condition 16 is near the knee of the simulated-aircraft maximum operational speed boundary (fig. 6). Because of the high dynamic pressure, the load factor to buffet onset is beyond the load factor limit (2.5g) of the L-1011 aircraft, and maneuvers about trim remain in the region where the aerodynamic data are linear with angle of attack.

The handling qualities of the aircraft at flight condition 16 was evaluated by three pilots in calm air and by one pilot in turbulence. The pilot ratings resulting from these evaluations are presented in figures 48 and 49. The PACS-on ratings indicated satisfactory flying qualities for the entire center-of-gravity range when in calm-air conditions (fig. 48) and near satisfactory flying qualities when in turbulent-air conditions (fig. 49).

Flight condition 17 (holding): Flight condition 17 is a typical intermediate-speed, flaps-up, holding pattern condition which is often encountered when approaching airports with heavy traffic. Maneuvers about this low-dynamic-pressure flight condition remain in the region of linear aerodynamic characteristics.

Only one pilot evaluated the handling qualities at flight condition 17, and the ratings in calm air and moderate turbulence at this flight condition are presented in figures 50 and 51, respectively. The baseline aircraft had reasonably good flying qualities (satisfactory to acceptable pilot ratings) in calm air to a center-of-gravity position of 0.50c; but the flying qualities became unacceptable at a center of gravity of approximately 0.55c. Engagement of the PACS resulted in satisfactory flying qualities over the entire center-of-gravity range in calm-air conditions (fig. 50). When flown in moderate turbulence and with the PACS engaged, the simulated airplane had unsatisfactory (but acceptable) flying qualities for flight condition 17--with the pilot ratings being between 4 and 5 over the entire center-of-gravity range (fig. 51).

Flight condition 18 (landing): Flight condition 18 represents a typical landing configuration at normal approach speeds and is characterized by linear aerodynamic characteristics. The handling characteristics at flight condition 18 were evaluated by three pilots in calm air and in moderate turbulence for the center-of-gravity range from 0.25 \bar{c} to 0.50 \bar{c} . The aft center-of-gravity position was limited to 0.50 \bar{c} by the nose-down authority of the trim system for this landing flight condition. The pilot ratings are presented in figures 52 and 53.

The baseline-aircraft flying qualities in calm air (fig. 52) were rated as being satisfactory for center-of-gravity positions forward of approximately 0.39 \bar{c} and acceptable, but unsatisfactory (PR < 4.5), for center-of-gravity positions aft of 0.39 \bar{c} . Engagement of the advanced PACS showed only slight improvements in the flying qualities. The pilot ratings for the baseline aircraft, when flown in moderate turbulence, were scattered throughout the unsatisfactory, but acceptable, rating band (fig. 53). Engagement of the advanced PACS reduced the scatter of the pilot ratings and indicated some improvement in the flying qualities--although they remained less than satisfactory. (Note that the flying qualities of the PACS-off configuration were evaluated as being acceptable for the center-of-gravity range tested--due to the rearward shift of the neutral point for the flaps-down configurations, that is, $N_0 \approx 0.48\bar{c}$.)

Flight condition 19 (takeoff): Flight condition 19 represents the takeoff configuration for the second-segment climb speed (1.2 V_S) and is in a region of essentially linear aerodynamic characteristics. Evaluations were made by one pilot at this flight condition, for calm air and moderate turbulence, over a center-of-gravity range from 0.25 \bar{c} to 0.50 \bar{c} . (See figs. 54 and 55.)

For the calm-air conditions, the baseline aircraft had satisfactory to acceptable flying qualities over the center-of-gravity range tested, and the engagement of the advanced PACS indicated an improvement in these flying qualities, particularly at the more aft center-of-gravity positions (fig. 54). Flight in turbulence degraded the flying qualities and resulted in the baseline aircraft being rated between 4 and 5 (fig. 55). Engagement of the PACS enhanced the flying qualities only slightly.

Summary of advanced PACS simulation results.-- Figure 56 presents the spread in the pilot ratings of the baseline and the PACS configured aircraft for the cruise and high-speed flight conditions (7, 10, 15, and 16). These pilot-rating "spreads" include both calm-air and turbulent-air flight conditions. These data indicate that the flying qualities of the baseline simulated aircraft in these four flight conditions became unacceptable (pilot rating greater than 6.5) for center-of-gravity positions aft of approximately 0.40 \bar{c} . Figure 56 also indicates that the advanced PACS improved the flying qualities of the aircraft significantly for the center-of-gravity positions aft of approximately 0.35 \bar{c} in that the pilot ratings varied between 2 and 4 (very satisfactory to quite acceptable). The holding flight condition 17 was not included in figure 56, but the pilot-rating trend was similar.

The advanced PACS did not provide a significant benefit for the landing and takeoff flight conditions (18 and 19) although some improvement in the flying qualities in turbulent flight was experienced.

Comparison of Simulator and Flight Test Results

A near-term PACS was developed by the Lockheed-California Company in 1979 and was installed on a Lockheed L-1011 flight test aircraft (ref. 2). Flight demonstration tests, within the region of essentially linear aerodynamic characteristics, showed that the PACS provided good flying qualities of the aircraft for static stability margins to +1 percent. The objective of the present near-term PACS program was to demonstrate, by flight tests, that this PACS with increased feedback gains would provide flying qualities, for static stability margins to -3 percent, which were equivalent to those of the baseline aircraft with a +15-percent static stability margin.

As stated previously, the flying qualities analyses and piloted-flight simulation tests for the near-term PACS configured aircraft were limited to evaluation of two cruise conditions (flight conditions 10 and 11) and one landing condition (flight condition 18). The flight tests, however, were limited to the evaluation of a series of static stability margins for one flight condition (cruise condition 10). Therefore, the subsequent discussion of the comparison of the ground-based simulation and the flight test results pertain to the effects of the AACS and the near-term PACS on the aircraft flying qualities for flight condition 10.

Two major differences were identified between the ground-based simulator and flight test results. First, the baseline flight test aircraft was rated by the pilots as having better flying qualities than those demonstrated during the simulation tests; and second, higher pitch-rate damping feedback gains were desired during flight tests than during simulation tests.

The better flying qualities of the baseline flight test airplane at the aft center-of-gravity positions are indicated by comparing the two charts presented in figure 57(a). The two charts presented in figure 57(b) indicated that there was no difference in the flying qualities with the AACS off. The explanation for the difference in the pilot ratings with the AACS engaged was that in the flight tests the aircraft was gently maneuvered around trim and in shallow banked turns; whereas during the simulation the aircraft was maneuvered more aggressively. Subsequent simulator tests (utilizing piloting techniques similar to the flight tests) verified this hypothesis. (See fig. 58.)

A comparison of the simulator and flight test results also indicated that higher pitch-rate damping feedback gains were desired during flight tests (fig. 59). Further investigation indicated a possible reason for this difference was due to the lack of realistic load factor (g) cues in the motion-base simulator. In the test aircraft the g -cues were much more apparent to the pilots, and since increasing the pitch-rate damping gains tended to reduce the g -oscillations, they preferred the higher damping gains. The aforementioned additional simulation tests also included incorporation of high-speed buffet and stick-shaker models which were used in conjunction with the available motion cues. The simulation was thus more realistic, and the differences in the preferred pitch-rate damping gains between the simulation and flight tests were considerably reduced (see fig. 60).

CONCLUDING REMARKS

A six-degree-of-freedom, ground-based simulator study has been conducted to evaluate the effectiveness of two pitch active control systems (PACS) in improving

the handling qualities of a wide-body transport airplane when operated at negative static margins. The flight characteristics were evaluated at eight different flight conditions representing the entire flight envelope, with emphasis on the cruise flight conditions. The two pitch active control systems evaluated consisted of a simple "near-term" PACS and a more complex "advanced" PACS. (The near-term PACS was also flight tested, and those flight test results are compared with the ground-based simulator results.) Five research test pilots participated in the flight simulation program although all pilots did not evaluate either PACS concept at all flight conditions. This paper summarizes the results of the study which support the following major conclusions.

Near-Term PACS

The baseline aircraft (pitch active control system (PACS) off; aileron active control system (AACCS) on) had unacceptable flying qualities for the cruise flight conditions evaluated at center-of-gravity positions aft of the neutral point (neutral static stability). However, the flying qualities were significantly better with the AACCS off because the AACCS has a destabilizing effect for maneuvering flight. The baseline-aircraft flying qualities for the landing flight condition were acceptable throughout the center-of-gravity test range.

Engagement of the near-term PACS improved the flying qualities for the cruise flight conditions significantly but only slightly improved the already acceptable flying qualities for the landing flight condition. With the PACS operative, the flying qualities were, in general, considered to be good over the center-of-gravity test range and were close to meeting the design goals.

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 feedforward washout. It was determined during the analysis portion of the study that the PACS must have pitch-rate gains, column-minus-trim (feedforward) gains, and time lag gains that are functions of the aircraft calibrated airspeed. The column-minus-trim gains and time lag 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 was changed from neutral to -5 percent.

Advanced PACS

The piloted-flight simulation results indicated that the addition of the advanced PACS to the L-1011 longitudinal control system provided flying qualities to a 20-percent negative static stability margin which were similar to the best baseline-aircraft flying qualities (15-percent positive static margin) for the cruise flight conditions. The PACS sensor inputs required for flight in the linear stability region were normal acceleration, pitch rate, and pitch attitude; while additional sensor inputs of angle of attack, bank angle, and Mach number were required for nonlinear stability flight conditions.

The advanced PACS did not provide a significant benefit for the takeoff and landing flight conditions although some improvement in the flying qualities for turbulent flight was experienced.

Comparison of Simulator and Flight Test Results

Two major differences were identified between the ground-based simulator and flight test results as follows: (1) the baseline flight test aircraft (PACS off; AACS on) was rated by the pilots as having better flying qualities than those demonstrated during the simulation tests; and (2) with the PACS and AACS engaged, higher pitch-rate damping feedback gains were desired during the flight tests than during the simulation. There were essentially no differences, between the flight test and simulator results, in the pilot opinion of the flying qualities of the aircraft when both the PACS and AACS were inoperative. (The aircraft was only flown at positive static margins when the AACS was inoperative.)

The explanation for the difference in the pilot ratings with the AACS engaged was that in the flight tests the aircraft was gently maneuvered around trim and in shallow banked turns, whereas during the simulation the aircraft was maneuvered more aggressively. Also, indications were that the preference for higher pitch-rate damping during the flight tests was due to the lack of realistic load factor cues in the motion-base simulator.

The results of the present study indicate (1) the extreme importance of impressing upon the test pilots the necessity to use the same techniques/procedures/tasks for simulator tests as for flight tests and (2) that the substitution of piloting cues may be used in ground-based simulators to enhance the validity of the simulation results. For example, buffet and stick-shaker models were used in the present simulation study, in conjunction with the available motion cues, to compensate for the lack of continuous acceleration cues. That is, a better agreement of pilot ratings between the flight tests and the simulator tests was achieved.

NASA Langley Research Center
Hampton, VA 23665-5225
August 5, 1985

APPENDIX

DESCRIPTION OF AUGMENTATION SYSTEMS

Detailed descriptions of the longitudinal control systems evaluated during the subject handling qualities simulation studies are given in references 2, 5, and 6. However, for convenience, a brief description of these various control systems is presented in the following sections.

Basic Control System

The basic longitudinal control system is comprised of both a high-speed and a low-speed Mach trim compensator, a control loading system (feel spring system), and a nonlinear column/stabilizer gearing. (See fig. 61.)

Both Mach trim compensator models compute an incremental column deflection that automatically changes the physical position of the column in the cockpit. (A distinction is made between "physical" and "software" column positions since the stability and control augmentation system inputs do not change the physical column position; whereas they do contribute to a fictitious "software" column position that determines control surface deflection.) The high-speed MTC utilizes a first-order lag with a 10-sec time constant to represent the Mach sensor. The column deflection data are a look-up function of the filtered Mach number. The low-speed MTC utilizes a first-order lag with a 20-sec time constant to represent a stabilizer filter signal that is used with the Mach sensor signal and flap setting to compute the column offset gain. (The column trim servo offset gain is a scheduled function of flap setting and the Mach sensor signal.) As indicated in figure 61, if the PACS is off or if the system switch is off, the compensation due to the low-speed MTC will be zero. When the low-speed MTC is operative, the high- and low-speed MTC signals are summed and sent through a first-order lag that models the stick servoactuator. This signal is in turn added to the trim button integrator output as shown in figure 61. It should be noted that the low-speed MTC was designed specifically for the subject RSS simulation program and is not used on conventional in-service L-1011 aircraft.

The feel spring system is composed of the control loading system with stick gradient feedback and summed integrator and MTC inputs. (See fig. 61.) The control-loading-system block diagram is presented in figure 62. The system is implemented on the Langley VMS by means of a McFadden analog computer. Force break-out, static friction, viscous friction, and velocity and position limits are set by potentiometers. The static and viscous frictional forces, stick force, bob weight, hinge moment, external aerodynamic force, and computed spring gradient (multiplied by total stick displacement) are summed and divided by column mass to determine stick acceleration. (See fig. 62.)

The column/stabilizer gearing determines δ_{HT} and δ_e based upon software stick position (δ_{col}), as shown in figure 61. The stick position integrator and MTC deflection sum ($\delta_{C,MTC}$) is added to the PACS output ($\delta_{C,PACS}$), cable stretch ($\delta_{C,STR}$), and hardware biased stick position ($\delta_{C,P} + 1.2$) to determine software stick position (δ_{col}). The trim button moves the stabilizer and the stick at the same time, thus compounding the trim button action. That is, the commanded stabilizer deflection ($\delta_{H,COM}$) is determined from a look-up function of nonlinear

gearing ratios (termed J-curve data, fig. 63). This gearing is also dependent upon the stabilizer position commanded from the trim button, as can be seen from the different curves generated with the stabilizer trimmed at various deflections. The stabilizer servoactuator is modeled by a first-order lag, with a time constant of 0.17 sec. (See fig. 61.) The elevator deflection is a look-up function dependent upon stabilizer position. (See fig. 64.)

Near-Term PACS

A near-term PACS was developed by the Lockheed-California Company in 1979 and evaluated, by Lockheed, on their Rye Canyon Simulator Facility. Subsequent flight demonstration tests showed that the PACS provided good flying qualities of the aircraft for relaxed static margins to +1 percent, verifying the simulation results. Further analysis of those flight test results, and additional analytic studies, indicated that by increasing the PACS feedback loop gains, satisfactory flying quality characteristics may be possible at negative static margins. Therefore, the earlier Lockheed near-term PACS study was extended, at the Langley Research Center, to evaluate the augmentation system (with modified system gains) at neutral to slightly statically unstable flight conditions.

The basic PACS analytical block diagram, with the significant control system dynamics represented by Laplace domain transfer functions, is presented in figure 7. The diagram shows two loops: a feedback lagged pitch damper loop, a feedforward lagged column-minus-trim loop. Provisions are also made in the feedforward loop for the column-minus-trim 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 feedforward
- Pitch damper with feedforward washout

The pitch-rate gain K_q , time lag τ_{lag} , and feedforward gain K_{FF} were scheduled as a function of calibrated airspeed, as shown in figure 8. The scheduling was necessary to assure that the flying qualities of the PACS configured airplane, for all flight conditions, were equivalent to the baseline-aircraft flying qualities with a 0.25 \bar{c} center of gravity. Increased pitch-rate gains ($1.3 < F^* < 2.0$), scheduled as a function of airspeed, were required to provide improved flying qualities for center-of-gravity positions between 0.39 \bar{c} and 0.45 \bar{c} .

Advanced PACS

The advanced PACS block diagram is shown in figure 25, and this system is divided into three parts for discussion as follows:

- Control column and actuator system--control column, column trim, series servos, J-curve, and stabilizer trim.

- Feedback loops--pitch rate, normal acceleration, and pitch attitude.
- Feed-forward loop--column force.

Control column and actuator system.-- Control column displacement, column trim, and resulting stabilizer deflection are discussed in the basic-longitudinal-control-system section.

The column trim consists of the parallel trim (which relieves the force on the control column) and the series trim (which places the control column at the desired location). The parallel trim and series trim are set simultaneously by an electrical "beeper" trim switch located on the control column.

The input to the series servos is an electrical signal from the summed feed-forward and feedback loops. The transfer function in each servo block represents the servo lag characteristics. The output of the series servos are position-summed so that the control authority of each servo is 1.5° at the cruise trim setting of -1° . (This provides a maximum position-summed output of 3° at the cruise trim setting.) The series servos were position-summed so that failure of one servo would not provide a stabilizer hardover--which would result in loads greater than the aircraft limit loads.

Feedback loops.-- The q and n_z feedback signals are used for control of the short-period mode. These signals are filtered through the first-order, low-pass filters indicated in figure 25, where the filter time constants are both equal to 0.03 sec. The filtered signals are subject to gains of K_q and K_{n_z} , and the gain scheduling parameters \bar{q} and δ_{HT}^* are provided to set the desired gain values. A normalizing constant is used in each feedback loop so that the gain (from the gain schedules) through the J-curve for δ_{HT} of -10° is equal to 1.0.

The pitch-attitude (θ) feedback signal is used to control the phugoid mode. This signal is processed through a pitch synchronizer, a lag-lead circuit, and a gain amplifier. The pitch synchronizer suppresses the attitude hold during maneuvers and sets a new attitude reference at the synchronizer output when a control column force is applied. (See fig. 65.) The lag-lead circuit eliminates the need for a velocity gain sensor that would be required for phugoid-mode control.

Feedforward loop.-- The feedforward loop is used to provide the desired control column feed-forward gradients. The feel spring (part of the basic control system) converts the column displacement to pounds, and the force converts F_C to an electric voltage. A flaps-up/flaps-down bias signal switches the time constant of the feedforward, low-pass filter, which is related to the reference baseline aircraft short-period mode. This provides the frequency variant part of the feedforward transfer function, and the feedforward signal is then passed through the gain amplifier (K_{FF}) and summed with the feedback signals to provide the series servo input signal.

The feedback and feedforward gain values are changed by augmenting the gain-scheduling δ_{HT} value by a required increment to provide δ_{HT} value. (See figure 66.) The modified value (δ_{HT}^*) changes the feedback gains to provide the increased control command for the horizontal stabilizer and changes the feedforward gains to provide the "desired" column-force gradients. If the feedforward gains were not provided, the column-force gradients would be incorrect and severe column-force reversals might be experienced.

Active Ailerons Control System (AACS)

A detailed description of the AACS is given in reference 6; therefore, only a functional description is presented in this paper.

Reductions in wing design loads are achieved by automatically moving the outboard ailerons symmetrically in response to accelerations sensed at the wing tips and in the fuselage. In a positive-g maneuver (pullup or banked turn) or long-turn updraft, the ailerons deflect upward (downward for negative maneuvers and down-drafts), thus moving the wing center of pressure inboard and reducing the wing bending stresses. This active controls application is designated "maneuver load control." Also, when in the presence of atmospheric turbulence, motion in the first wing bending mode (in the frequency range of 1 to 2 hertz) is sensed by accelerometers at the wing tips. The ailerons are moved symmetrically so that the resulting air pressures oppose the wing-tip velocities and thus further reduce the stresses produced by the turbulence. This function is designated "elastic mode suppression."

In addition to moving the ailerons symmetrically, the system moves the horizontal stabilizer automatically to compensate for the airplane pitching moment produced when the airplane encounters a gust. This function is designated "gust alleviation."

REFERENCES

1. Martin, D. J., Jr.: A Digital Program for Motion Washout on Langley's Six-Degree-of-Freedom Motion Simulator. NASA CR-145219, 1977.
2. Guinn, Wiley A.: Development and Flight Evaluation of an Augmented Stability Active Controls Concept. NASA CR-165951, 1982.
3. Airworthiness Standards: Transport Category Airplanes. FAR Pt. 25, FAA, June 1974.
4. Military Specification - Flying Qualities of Piloted Airplanes. MIL-F-8785C, Nov. 5, 1980. (Supersedes MIL-F-8785B, Aug. 7, 1969.)
5. Guinn, Wiley A.; Rising, Jerry J.; and Davis, Walt J.: Development of an Advanced Pitch Active Control System for a Wide Body Jet Aircraft. NASA CR-172277, 1984.
6. Johnston, J. F.; et al.: Accelerated Development and Flight Evaluation of Active Controls Concepts for Subsonic Transport Aircraft - Volume I: Load Alleviation/Extended Span Development and Flight Tests. NASA CR-159097, 1979.

TABLE I.- AIRCRAFT GEOMETRY AND WEIGHT

Wing:
 Reference area, ft² 3456
 Reference mean aerodynamic chord, ft² 24.46
 Span, ft 164.33
 Aspect ratio 7.817
 Leading-edge sweep, deg 35

Horizontal tail:
 Area, ft² 1282
 Span, ft 71.58
 Aspect ratio 4.0
 Leading-edge sweep, deg 35

Vertical tail:
 Area, ft² 550
 Span, ft 29.67
 Aspect ratio 1.6
 Leading-edge sweep, deg 35

Weight:
 Maximum ramp, lbf 424 000
 Maximum takeoff, lbf 422 000
 Maximum landing, lbf 358 000
 Zero fuel, lbf 312 460
 Operating empty, lbf 261 000

TABLE II.- PILOTED-FLIGHT SIMULATION TEST CONDITIONS

Flight condition	Mode	Weight, lbf	Center of gravity, percent \bar{c} (a)	Altitude, ft	Airspeed, KEAS
7	Cruise ($W/\delta = 1.9 \times 10^6$)	408 000	25 to 60	37 000	254 ($M = 0.83$)
10	Cruise ($W/\delta = 1.4 \times 10^6$)	360 000	25 to 60	33 000	280 ($M = 0.83$)
11	Cruise ($W/\delta = 1.0 \times 10^6$)	360 000	25 to 60	26 000	325 ($M = 0.83$)
15	Cruise ($W/\delta = 1.6 \times 10^6$)	360 000	25 to 60	36 000	260 ($M = 0.83$)
16	M_{mo}/V_{mo} ($W/\delta = 0.9 \times 10^6$)	350 000	25 to 60	25 000	357
17	Holding	335 000	25 to 60	10 000	250
18	Landing ($\delta_f = 33^\circ$)	330 000	25 to 60	2 000	135 ($1.3V_S$)
19	Takeoff ($\delta_f = 26^\circ$)	380 000	25 to 60	2 000	137 ($1.2V_S$)

^aNear-term PACS center-of-gravity range from 25 to 45.

TABLE III.- PILOT RATING SYSTEM

PR

	<p>ACCEPTABLE</p> <p>May have deficiencies which warrant improvement, but adequate for mission.</p> <p>Pilot compensation, if required to achieve acceptable performance, is feasible.</p>	<p>SATISFACTORY</p> <p>Meets all requirements and expectations; good enough without improvement.</p> <p>Clearly adequate for mission.</p>	<p>1 Excellent, highly desirable.</p> <p>2 Good, pleasant, well behaved.</p> <p>3 Fair. Some mildly unpleasant characteristics. Good enough for mission without improvement.</p> <p>4 Some minor but annoying deficiencies. Improvement is requested. Effect on performance is easily compensated by pilot.</p> <p>5 Moderately objectionable deficiencies. Improvement is needed. Reasonable performance requires considerable pilot compensation.</p> <p>6 Very objectionable deficiencies. Major improvements are needed. Requires best available pilot compensation to achieve acceptable performance.</p> <p>7 Major deficiencies which require improvement for acceptance. Controllable. Performance inadequate for mission, or pilot compensation required for minimum acceptable performance in mission is too high.</p> <p>8 Controllable with difficulty. Requires substantial pilot skill and attention to retain control and continue mission.</p> <p>9 Marginally controllable in mission. Requires maximum available pilot skill and attention to retain control.</p>
<p>CONTROLLABLE</p> <p>Capable of being controlled or managed in context of mission, with available pilot attention.</p>	<p>UNACCEPTABLE</p> <p>Deficiencies which require improvement. Inadequate performance for mission even with maximum feasible pilot compensation.</p>	<p>UNSATISFACTORY</p> <p>Reluctantly acceptable. Deficiencies which warrant improvement. Performance adequate for mission with feasible pilot compensation.</p>	<p>10 Uncontrollable in mission.</p>
<p>UNCONTROLLABLE</p> <p>Control will be lost during some portion of mission.</p>	<p>UNCONTROLLABLE</p>	<p>UNCONTROLLABLE</p>	<p>10 Uncontrollable in mission.</p>

TABLE IV.- ADVANCED PACS GAIN-SCHEDULE EQUATION AND EQUATION COEFFICIENTS

$$\left[K_x = A + B\bar{q} + C\bar{q}^2 + D\delta_{HT}^* + E\delta_{HT}^{*2} \right]$$

Coefficient	K_q , sec	K_{nz} , deg/g units	$1/\tau_2$, sec ⁻¹	$(\tau_2 - \tau_1) - 1$	$K_3(\tau_1/\tau_2)$	K_{FF} , in/lbf
Flaps up						
A	-1.4295	-1.7055×10^{-1}	2.2332×10^{-2}	-2.9433×10	-1.4028×10^{-1}	2.1328×10^{-2}
B	1.5023×10^{-3}	1.5640×10^{-4}	-2.8474×10^{-5}	2.9511×10^{-1}	1.5431×10^{-4}	2.0571×10^{-4}
C	0	0	0	-4.1698×10^{-4}	0	-4.0915×10^{-7}
D	-5.0386×10^{-1}	-7.8711×10^{-2}	0	4.2547	-4.2834×10^{-2}	2.6975×10^{-2}
E	-7.6620×10^{-2}	-1.0552×10^{-2}	0	0	-7.4588×10^{-3}	3.8428×10^{-3}
Flaps down						
A	-3.6149	-6.3224×10^{-1}	8.7222×10^{-2}	-1.5771	-1.0483	3.2829×10^{-1}
B	1.1658×10^{-2}	1.7281×10^{-3}	-4.7143×10^{-4}	1.8067×10^{-1}	4.0908×10^{-3}	2.4014×10^{-3}
C	0	0	0	-1.4232×10^{-3}	0	-3.5719×10^{-5}
D	-6.0629×10^{-1}	-1.2270×10^{-1}	0	3.4827×10^{-1}	-1.5770×10^{-1}	6.8201×10^{-2}
E	-3.9313×10^{-2}	-7.5674×10^{-3}	0	0	-9.7027×10^{-3}	4.0296×10^{-3}

TABLE V.- ADVANCED PACS CONTROLLER INPUT SIGNAL

Symbol	Signal	Type	Use
F_C	Column force	Feedforward	Column-force gradient
n_z q	Normal acceleration Pitch rate	Feedback	Short-period mode
θ	Pitch attitude	Feedback	Phugoid mode
\bar{q} δ_{HT}^*	Dynamic pressure Modified horizontal-tail deflection	Primary gain Scheduling	Compensation for flight-condition changes
α ϕ M	Angle of attack Bank angle Mach number	Secondary gain scheduling	Compensation for pitch- up and AACS outboard aileron operation

TABLE VI.- TYPICAL PILOT COMMENTS FOR CRUISE FLIGHT CONDITION 10 IN CALM AIR

C.g., % \bar{c}	PACS off	Advanced PACS on
25	<ul style="list-style-type: none"> ● Trimmability was good. ● Altitude hold was ± 20 ft in 20° banked turns. ● Stability about trim was good and column forces were acceptable. ● High column forces during large maneuvers made control difficult. ● Short-period mode was well damped. ● Pitch attitude response was crisp and there was no bobble around the new attitude 	<ul style="list-style-type: none"> ● PACS improved attitude control, but forces to maneuver around trim were heavier. ● Column forces were objectively high during large maneuvers. ● Short-period mode was more heavily damped.
34.5	<ul style="list-style-type: none"> ● Trimmability was degraded. ● Altitude hold was ± 40 ft in 20° banked turns. ● Force lightening was apparent at about 1.8g. ● Short-period mode damping was good. ● Phugoid mode was divergent. ● Airplane appeared looser, and precise control was more difficult. 	<ul style="list-style-type: none"> ● Altitude hold was ± 30 ft in 20° banked turns. ● Forces were higher, but the airplane was much easier to control since it appeared more stable.

TABLE VI.- Continued

c.g., % \bar{c}	PACS off	Advanced PACS on
39	<ul style="list-style-type: none"> ● Trimmability was difficult. ● Altitude hold was ± 50 ft in 20° banked turns. ● Significant force lightening was observed at high load factors. ● Forces were too light. ● Short-period mode was reasonably damped. ● Phugoid mode was rapidly divergent. ● Pitch attitude oscillations were observed. ● Considerable pilot attention was required. 	<ul style="list-style-type: none"> ● Trimmability was significantly improved. ● Forces were heavier, and maneuvering characteristics were improved. ● Attitude control was improved.
43	<ul style="list-style-type: none"> ● Controllability was marginal. ● Trimmability was very difficult. ● Altitude hold was ± 150 ft in 20° banked turns. ● $\pm 0.5g$ oscillations occurred during 20° banked turns. ● Large maneuvers were no longer considered possible. 	<ul style="list-style-type: none"> ● Trimmability was excellent. ● Forces and controllability in turns and high-g maneuvers were good.
50	<ul style="list-style-type: none"> ● Airplane was no longer considered flyable. 	<ul style="list-style-type: none"> ● Same comments as PACS on at $43\% \bar{c}$.
55	<ul style="list-style-type: none"> ● Not flyable 	<ul style="list-style-type: none"> ● Altitude control was slightly looser than at $50\% \bar{c}$.

TABLE VI.- Concluded

c.g., % \bar{c}	PACS off	Advanced PACS on
60	<ul style="list-style-type: none"> ● Not flyable 	<ul style="list-style-type: none"> ● Altitude control noticeably looser. ● Nose wandering occurred during S-turns. ● Aware of reduced forces at about 1.8g. ● Control sensitivity was increased because of reduced stability and lighter forces.

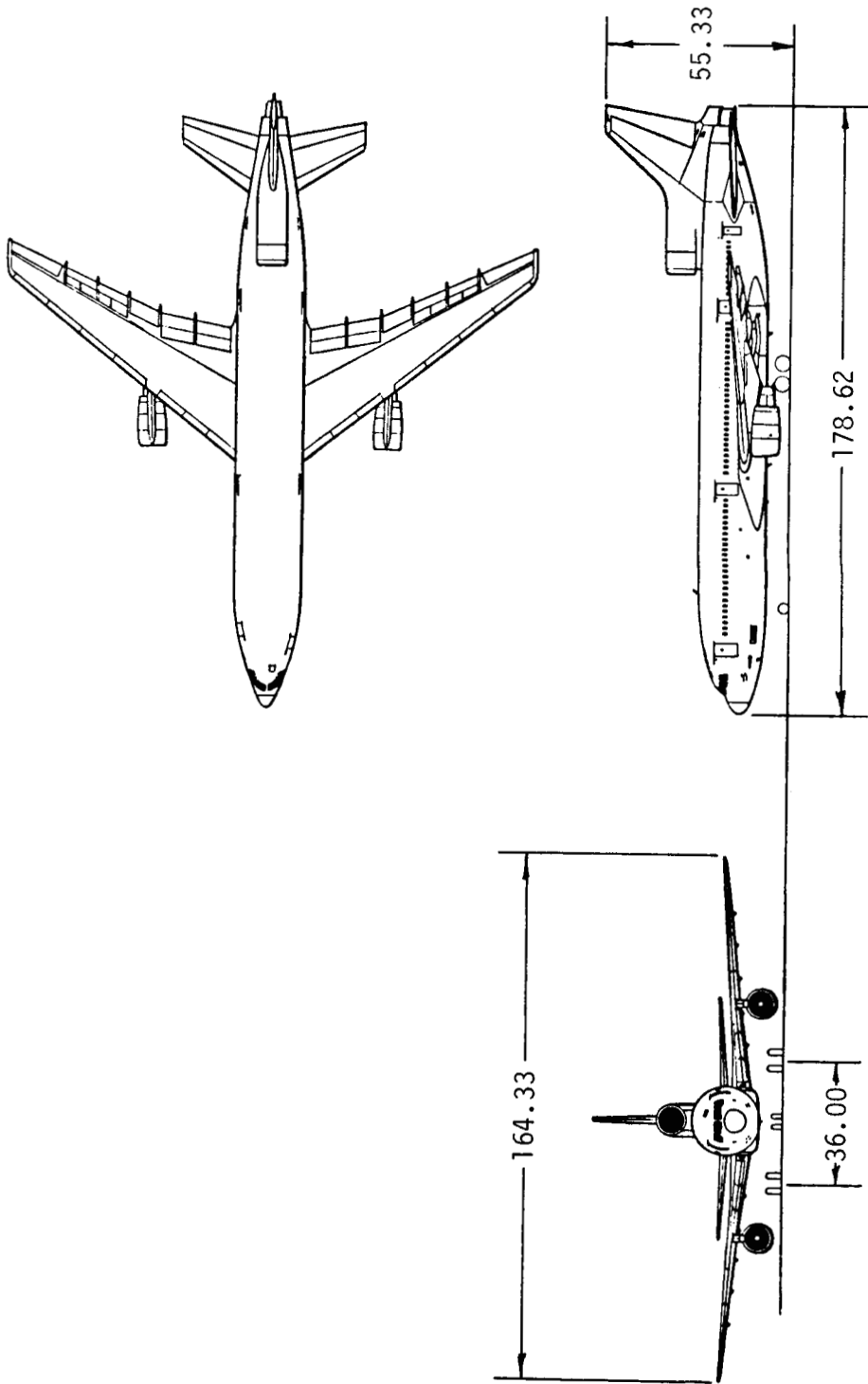


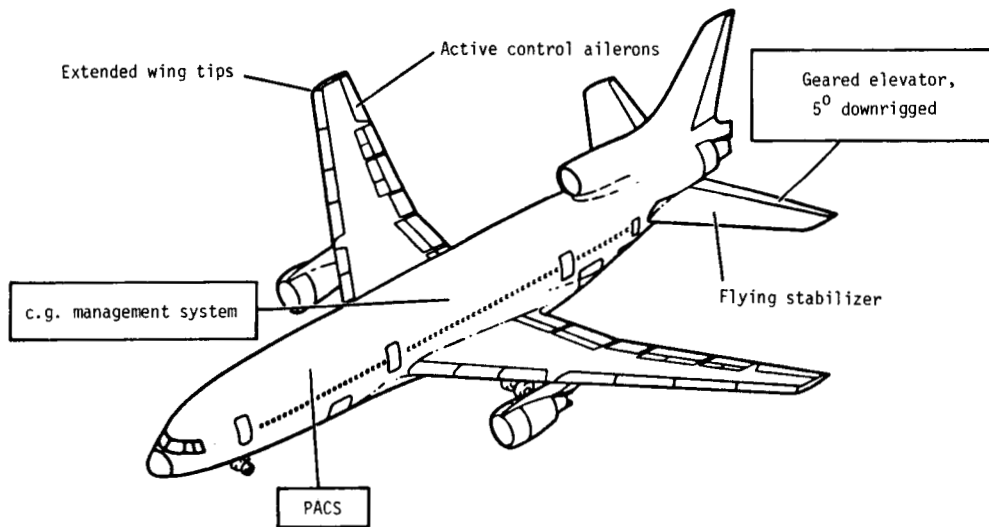
Figure 1.- Three-view sketch of simulated airplane. All dimensions indicated are in feet.

ORIGINAL PAGE
OF POOR QUALITY



(a) Flight test airplane.

L-83-11,999



(b) Modifications made for current program are shown in blocks.

Figure 2.- Photograph and features of simulated aircraft.

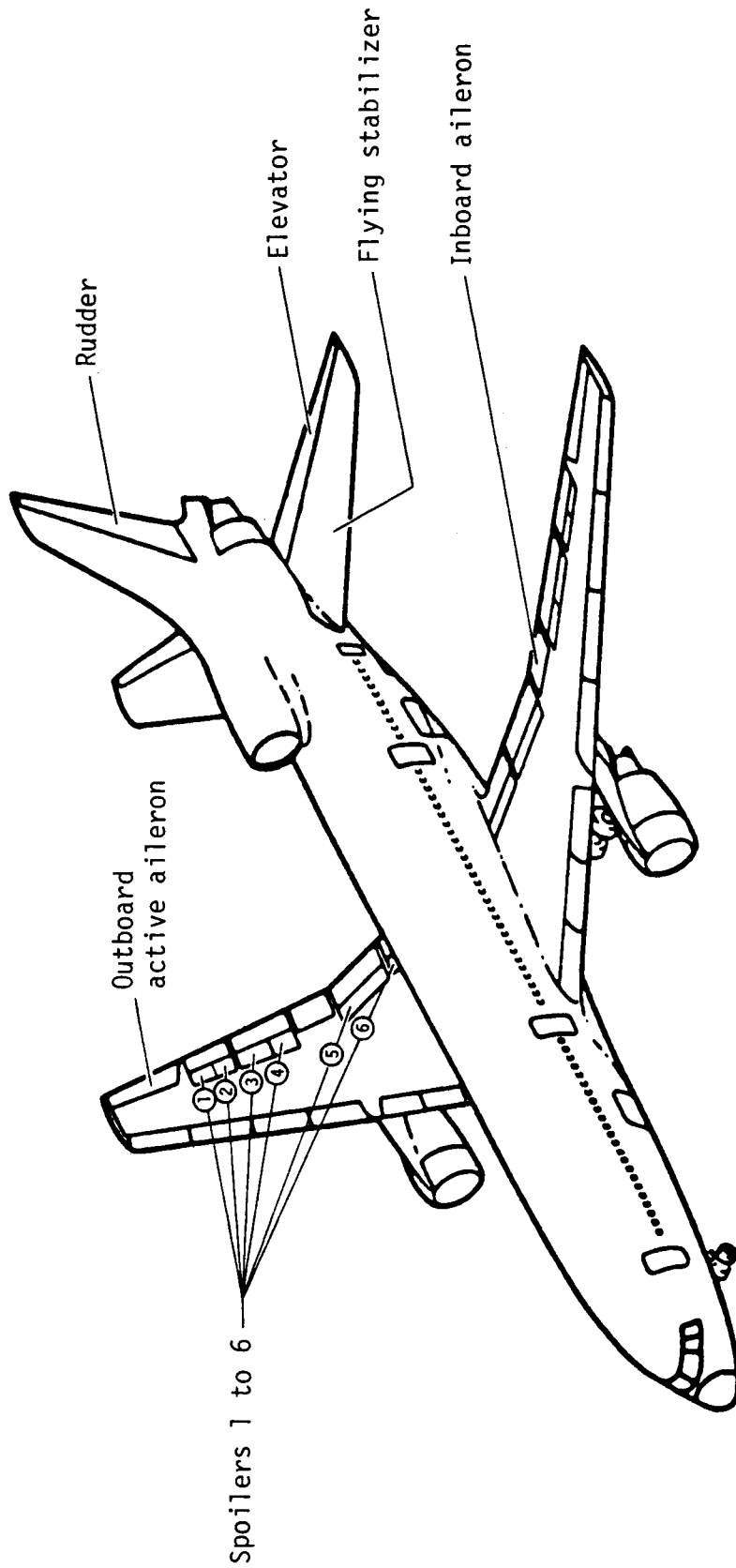
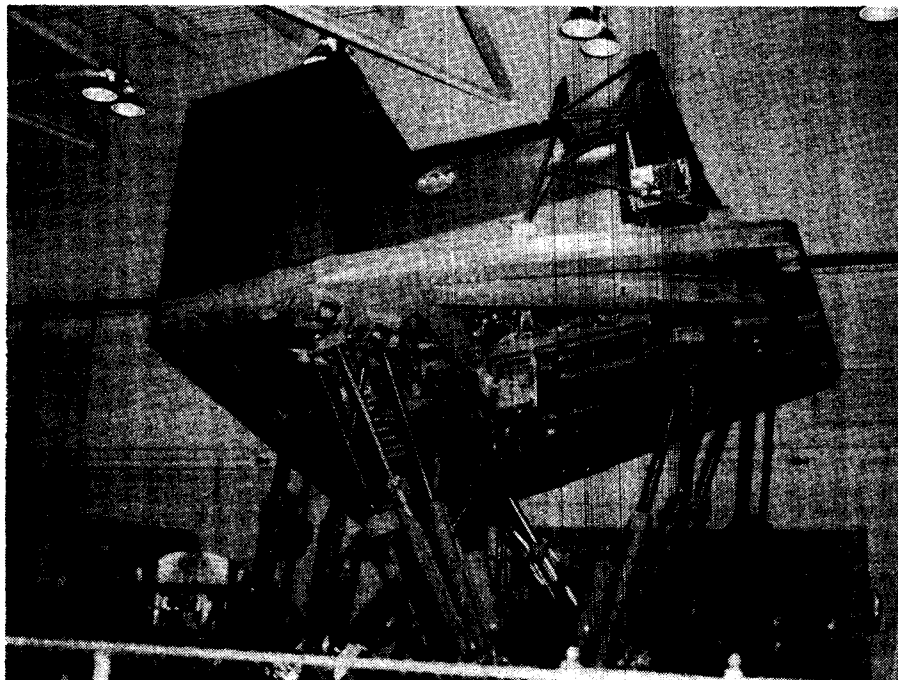
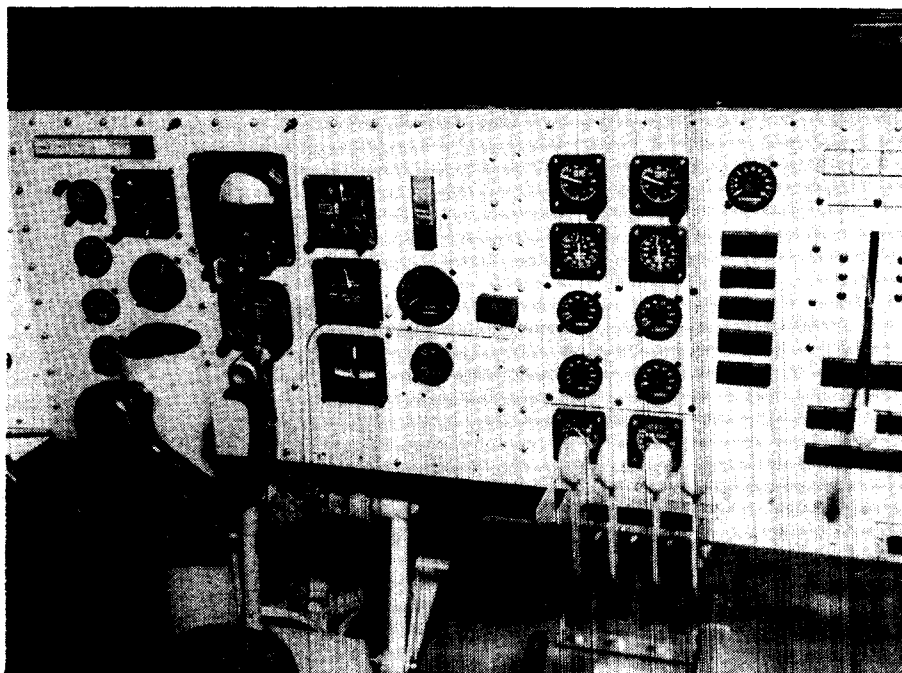


Figure 3.- Simulated L-1011 control surfaces.

ORIGINAL PAGE IS
OF POOR QUALITY



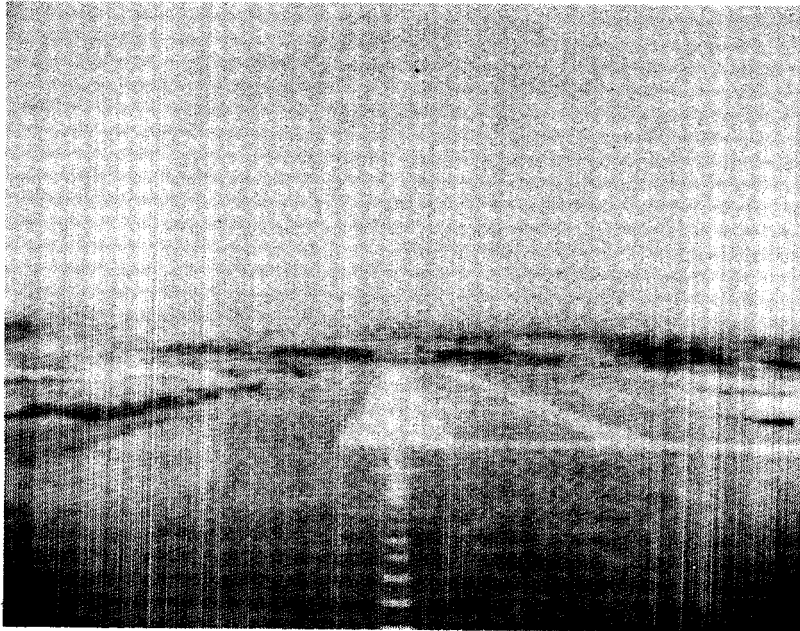
(a) Langley Visual/Motion Simulator. L-75-7570



(b) Instrument panel. L-78-7794

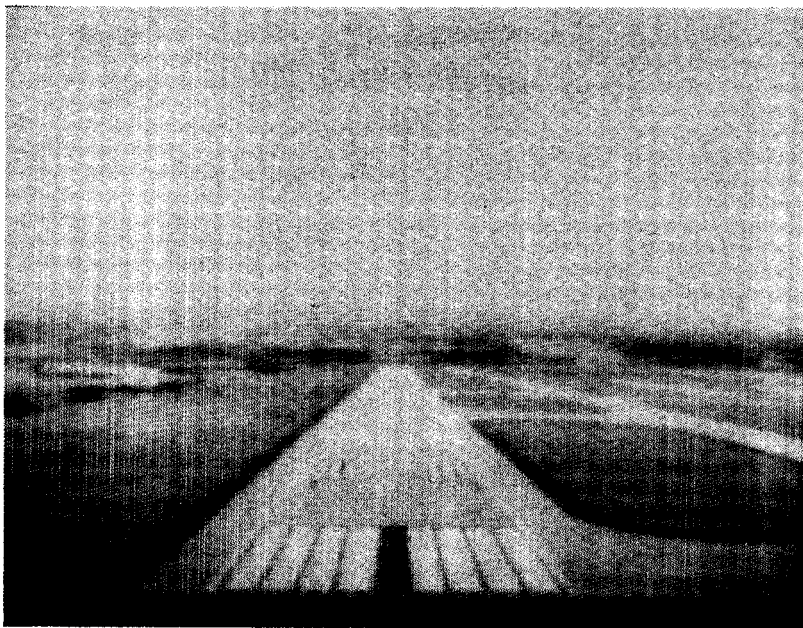
Figure 4.- Langley Visual/Motion Simulator and instrument panel display.

ORIGINAL PAGE IS
OF POOR QUALITY



(a) Approach scene.

L-79-5999



(b) Landing scene.

L-79-6000

Figure 5.- View of airport scene as seen by pilot.

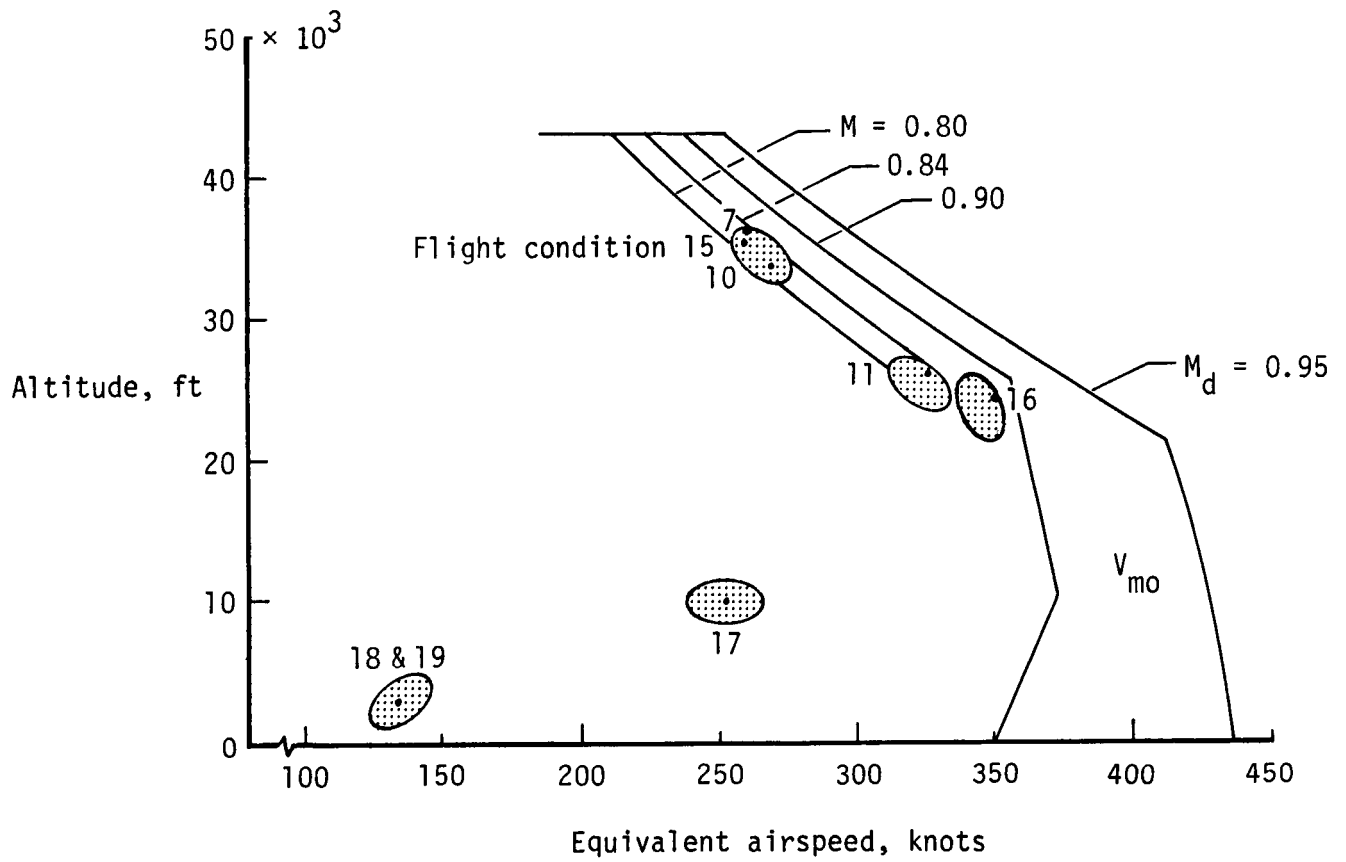


Figure 6.- Flight simulation test conditions.

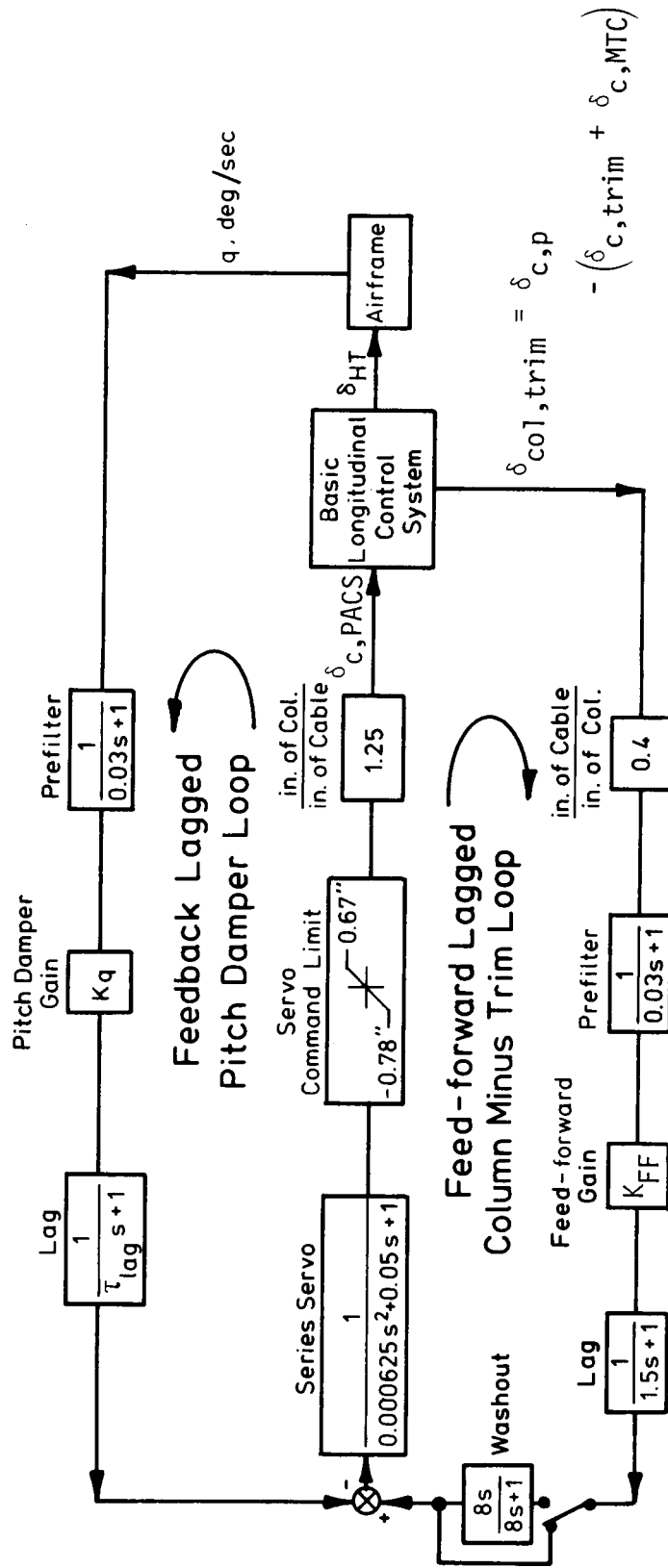
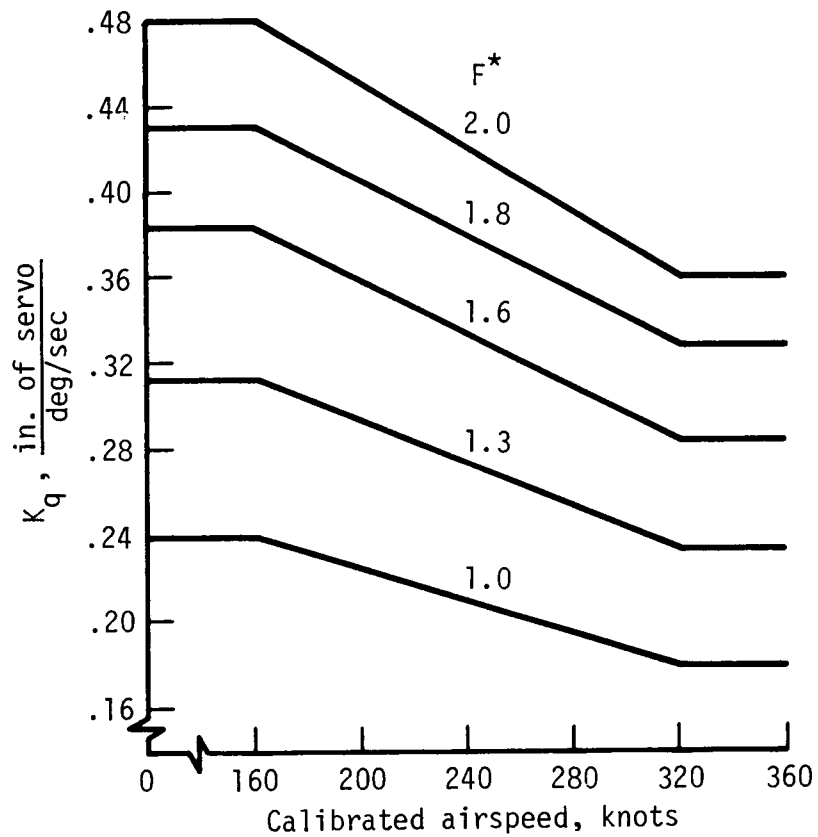
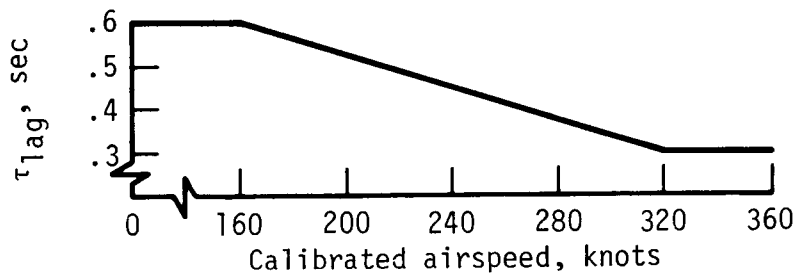


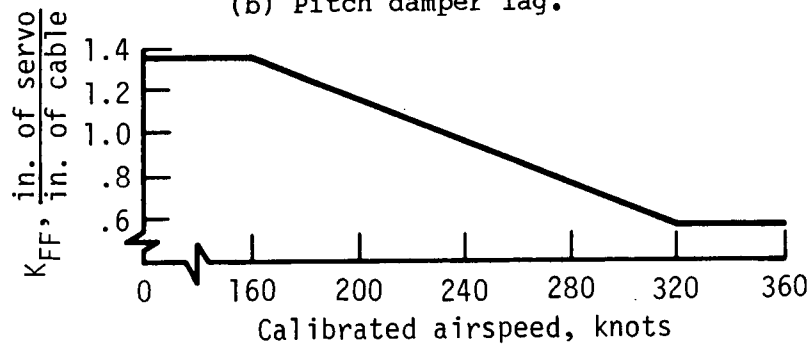
Figure 7.- Analytical block diagram of near-term PACS.



(a) Pitch damper gain.



(b) Pitch damper lag.



(c) Feedforward gain.

Figure 8.- Gain and time lag schedules of near-term PACS.

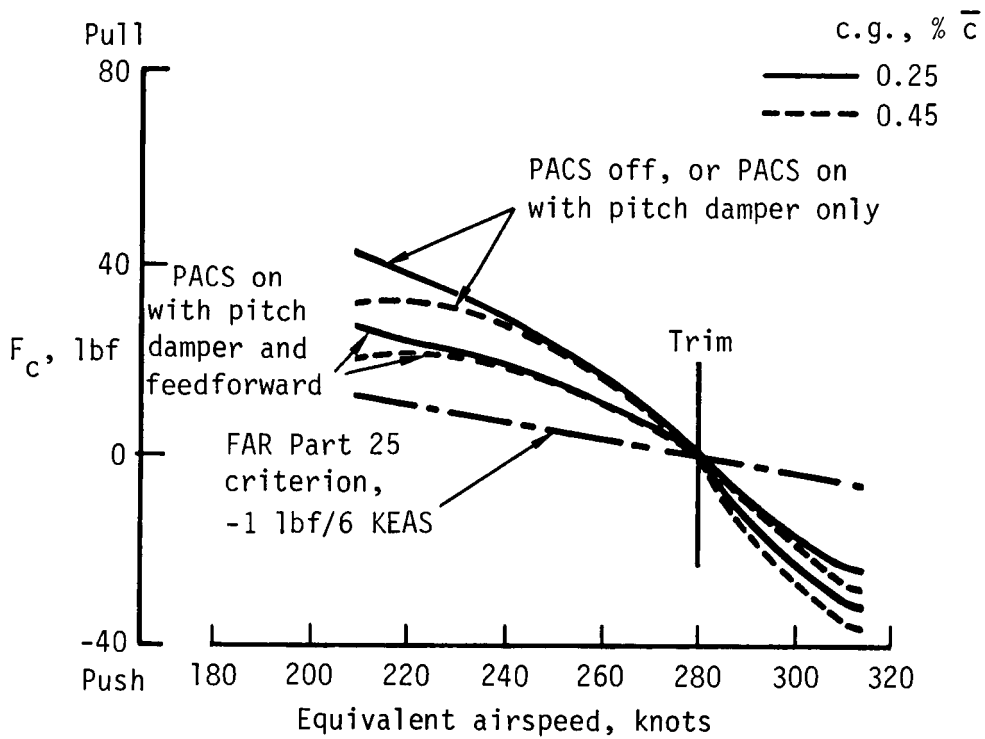
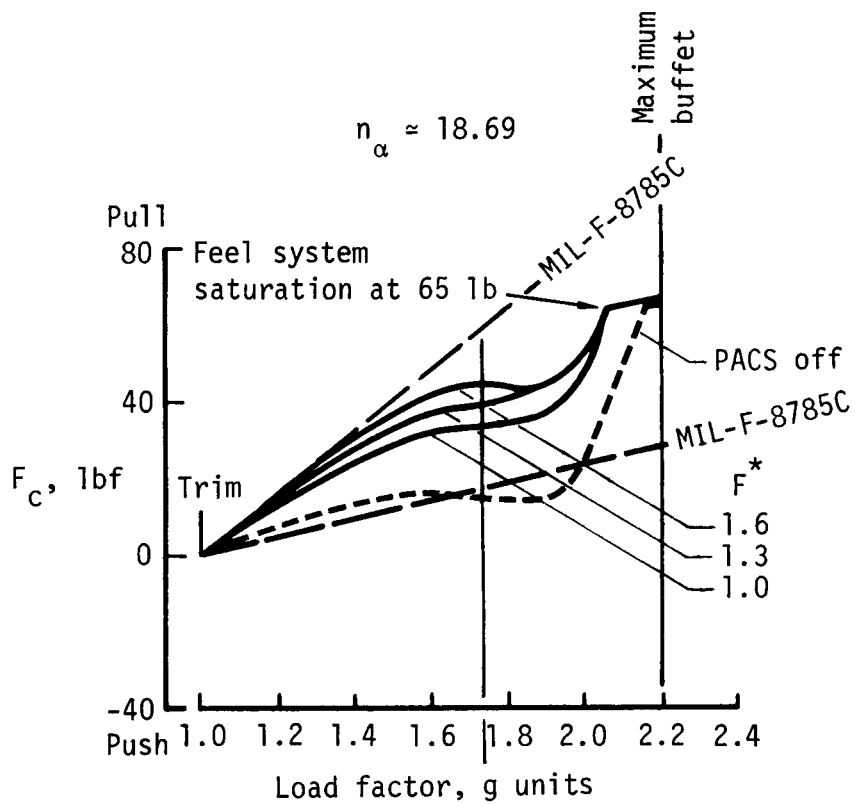
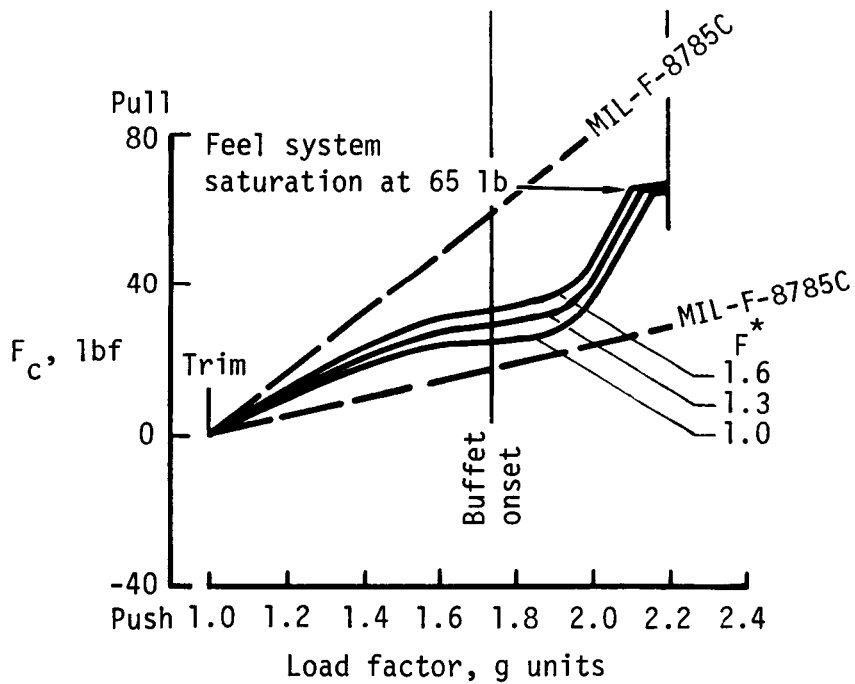


Figure 9.- Speed stability characteristics for flight condition 10.

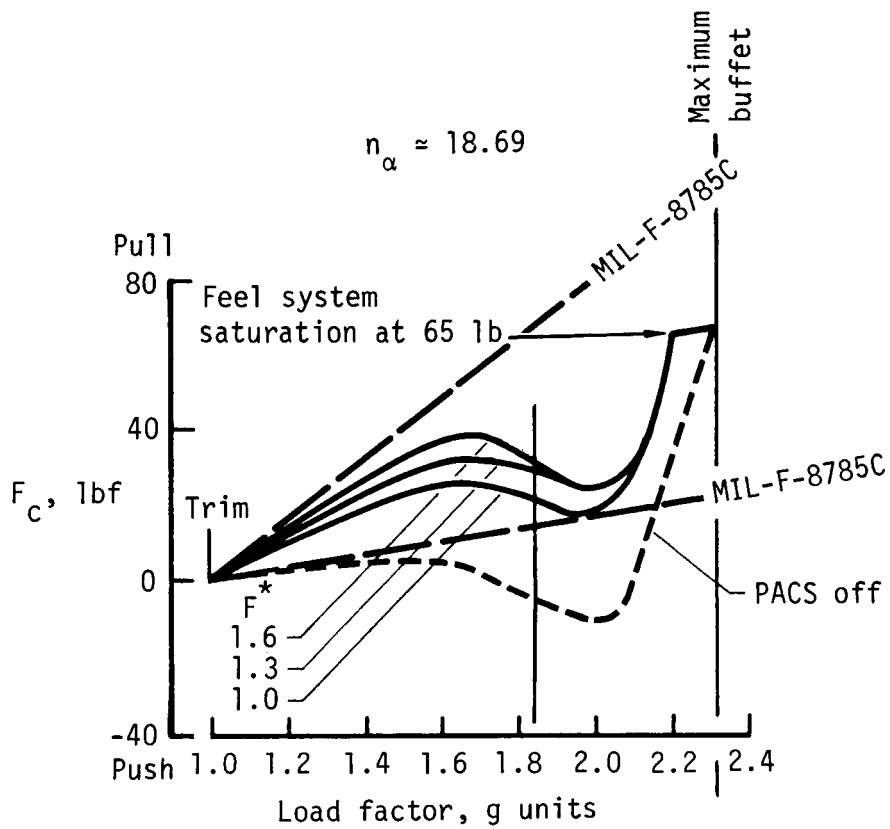


(a) PACS on with pitch damper only.

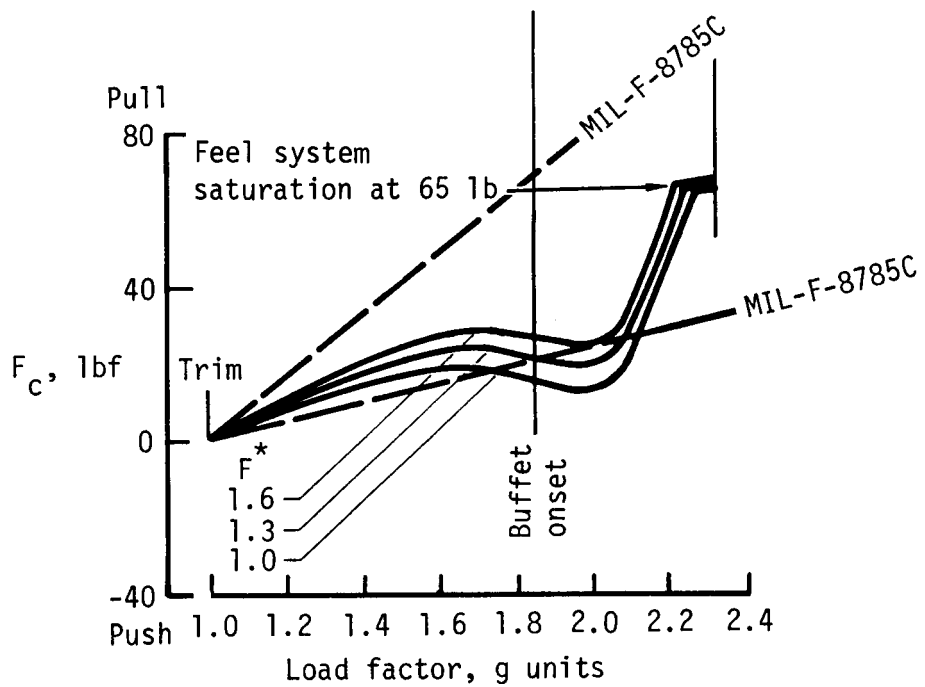


(b) PACS on with pitch damper and feed forward.

Figure 10.- Calculated maneuver stability characteristics for flight condition 10 and $c.g. = 0.25\bar{c}$.

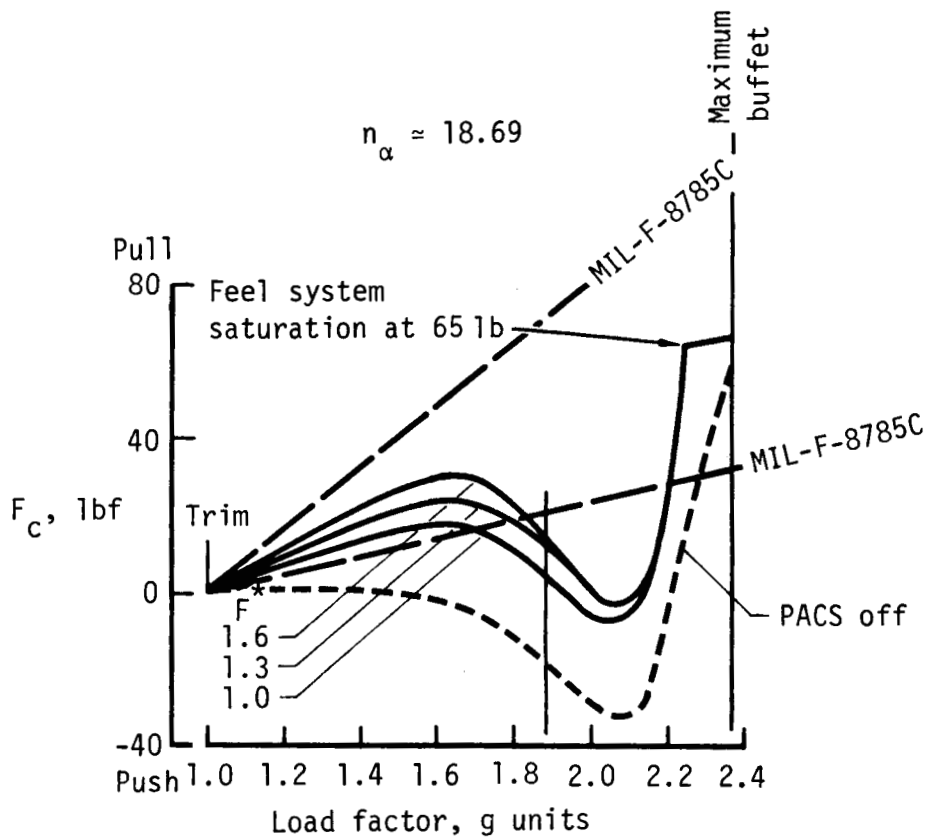


(a) PACS on with pitch damper only.

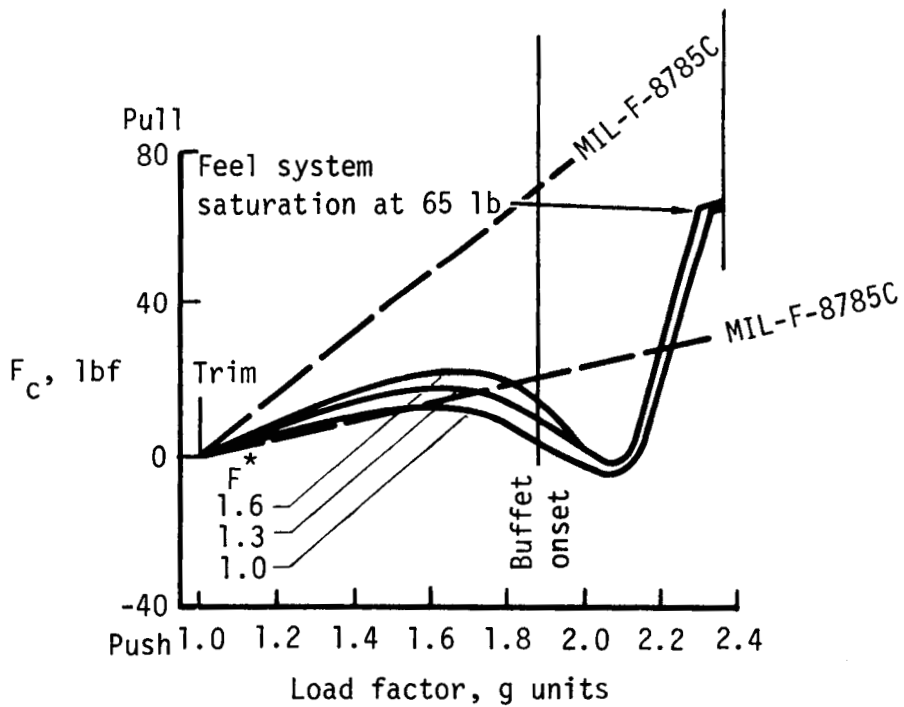


(b) PACS on with pitch damper and feedforward.

Figure 11.- Calculated maneuver stability characteristics for flight condition 10 and $c.g. = 0.39\bar{c}$.

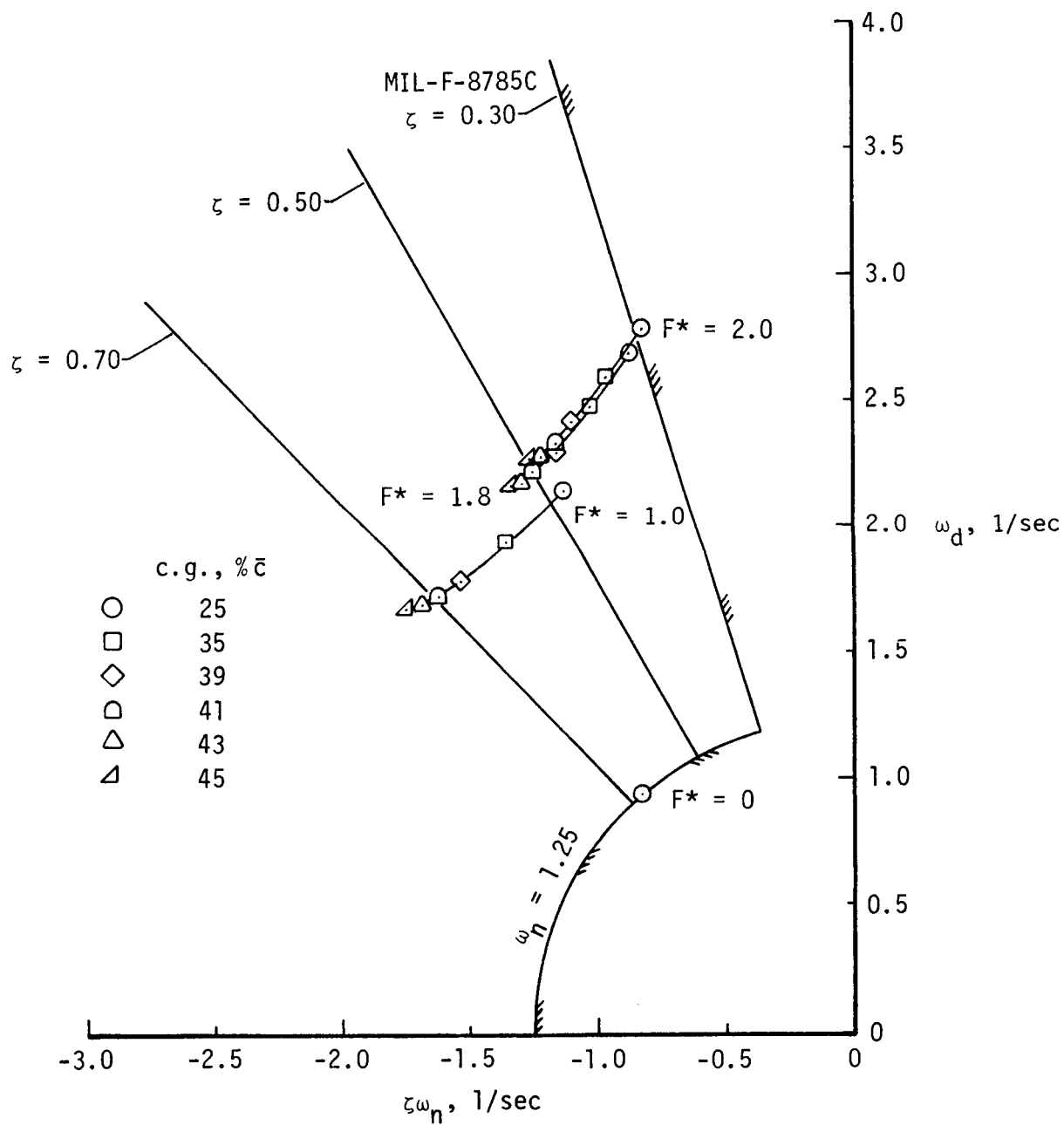


(a) PACS on with pitch damper only.



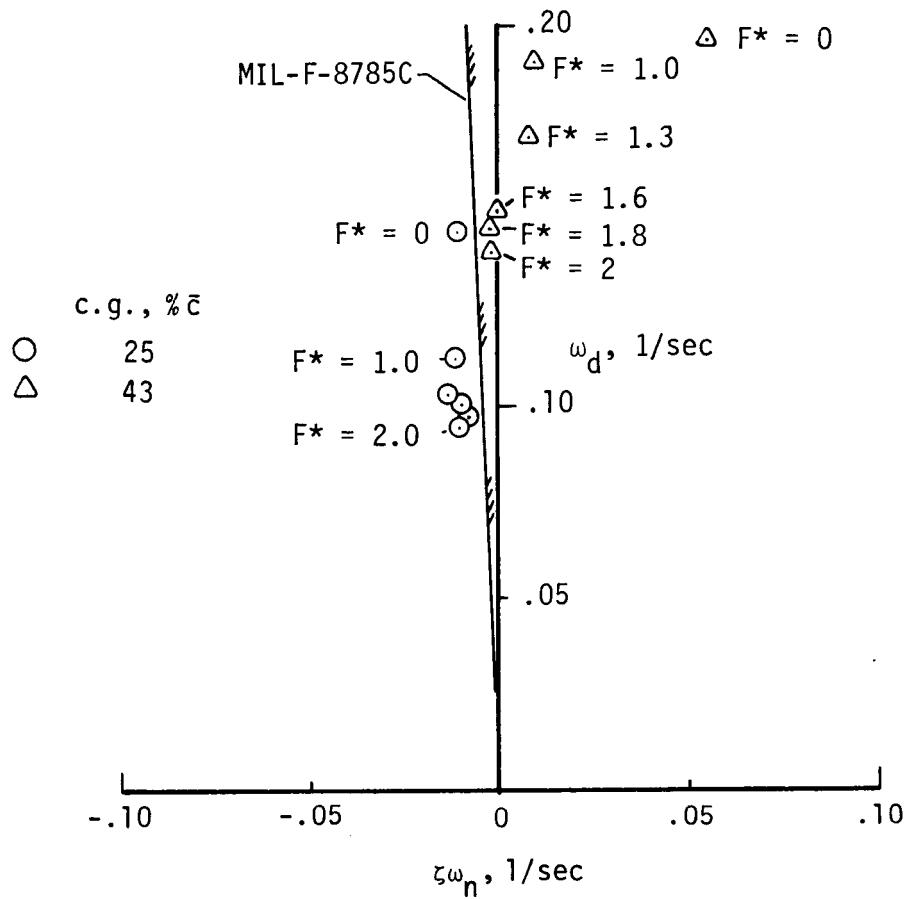
(b) PACS on with pitch damper and feedforward.

Figure 12.- Calculated maneuver stability characteristics for flight condition 10 and $c.g. = 0.45\bar{c}$.



(a) Short-period mode.

Figure 13.- Effect of pitch-rate feedback gain and center-of-gravity position on longitudinal dynamic stability characteristics of near-term PACS for flight condition 10.



(b) Phugoid mode.

Figure 13.- Concluded.

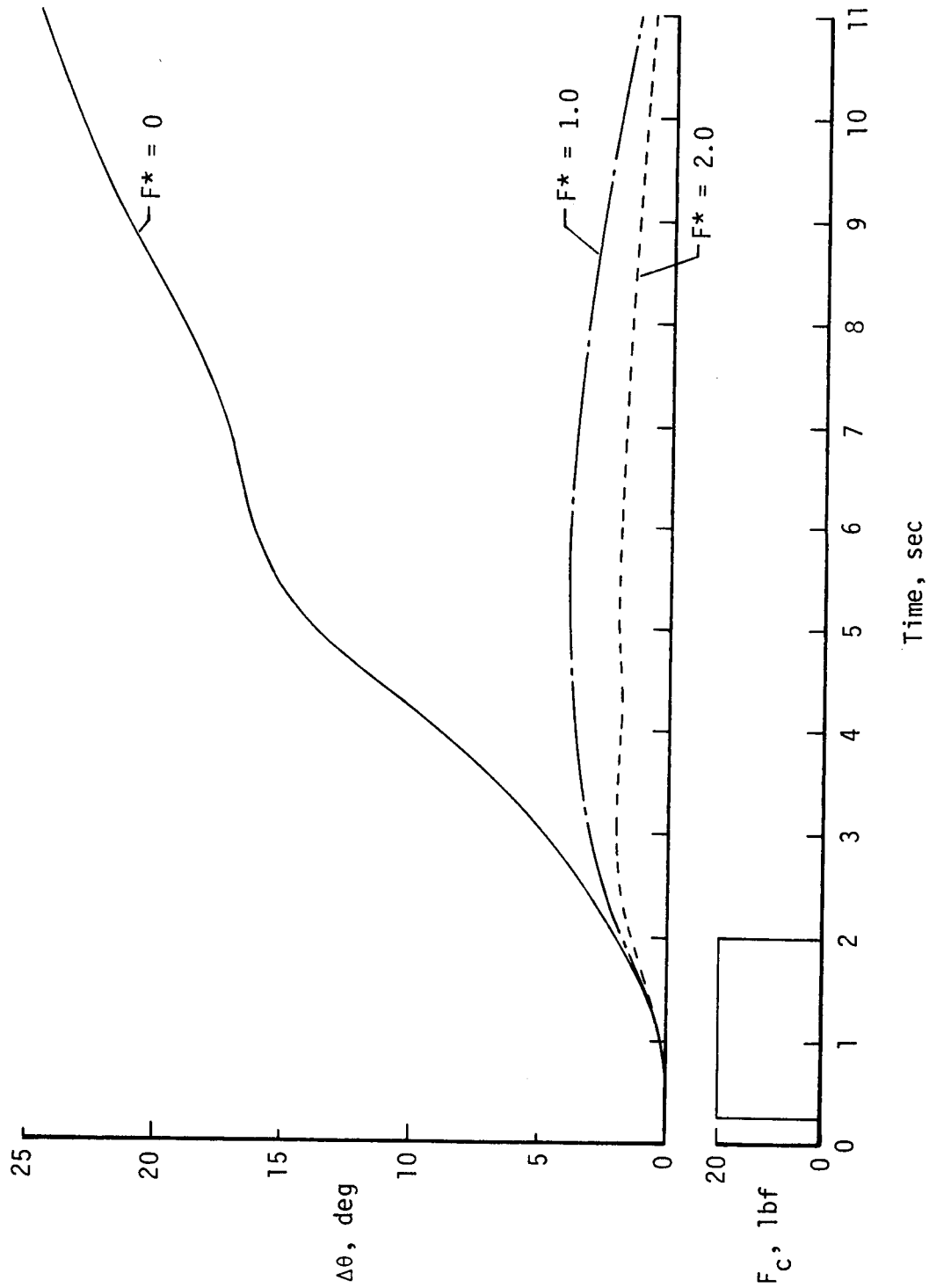


Figure 14.- Effect of pitch-rate feedback on pitch attitude response for a pulse-type column force input. Flight condition 10; near-term PACS; $K_{FF} = 0$; c.g. = 0.458; AACCS on.

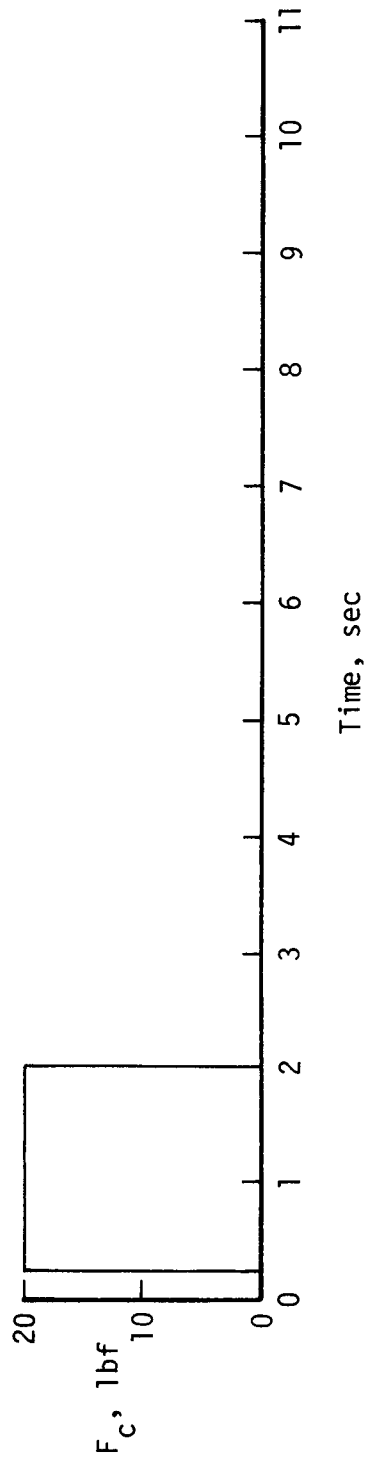
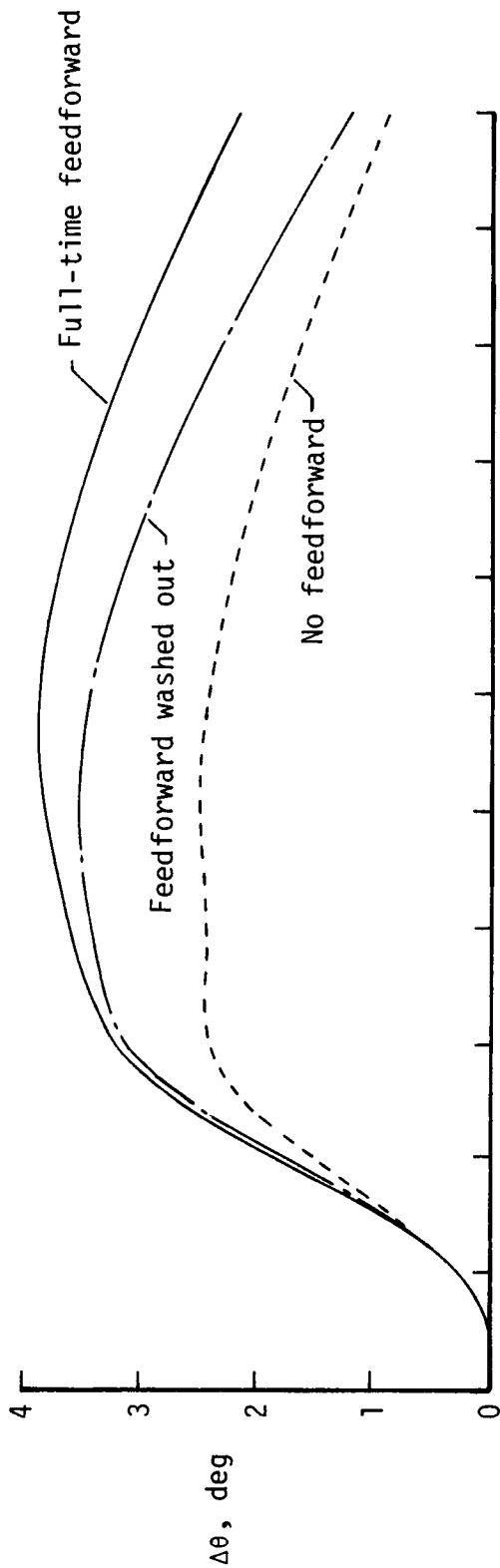


Figure 15.- Effect of column-minus-trim feed forward (K_{FF}) on pitch attitude response for a pulse-type column force input. Flight condition 10; near-term PACS; $K^* = 1.6$; c.g. = 0.456; AACCS on.

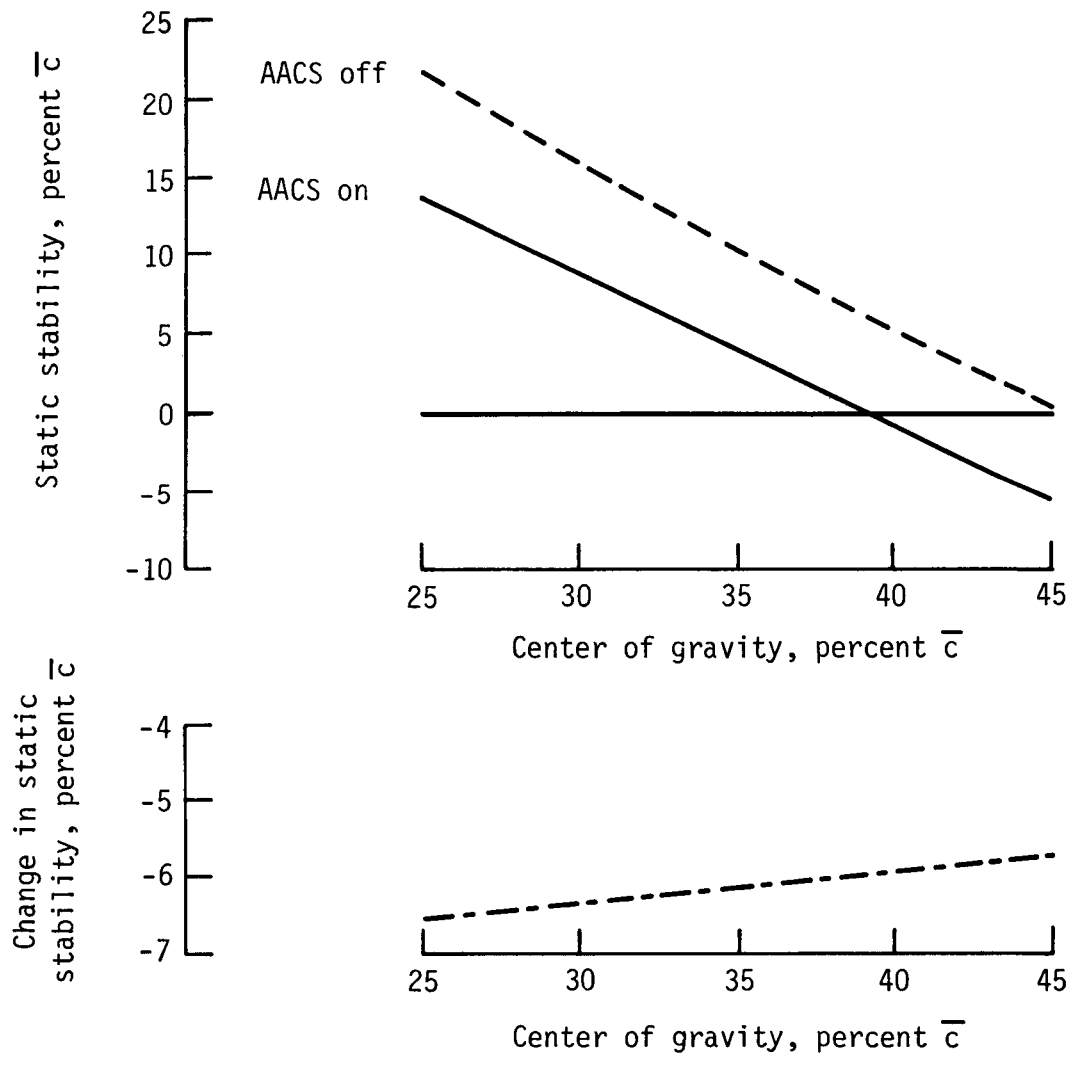


Figure 16.- Effect of aileron active control system (AACS) and center-of-gravity position on static stability for a typical cruise flight condition.

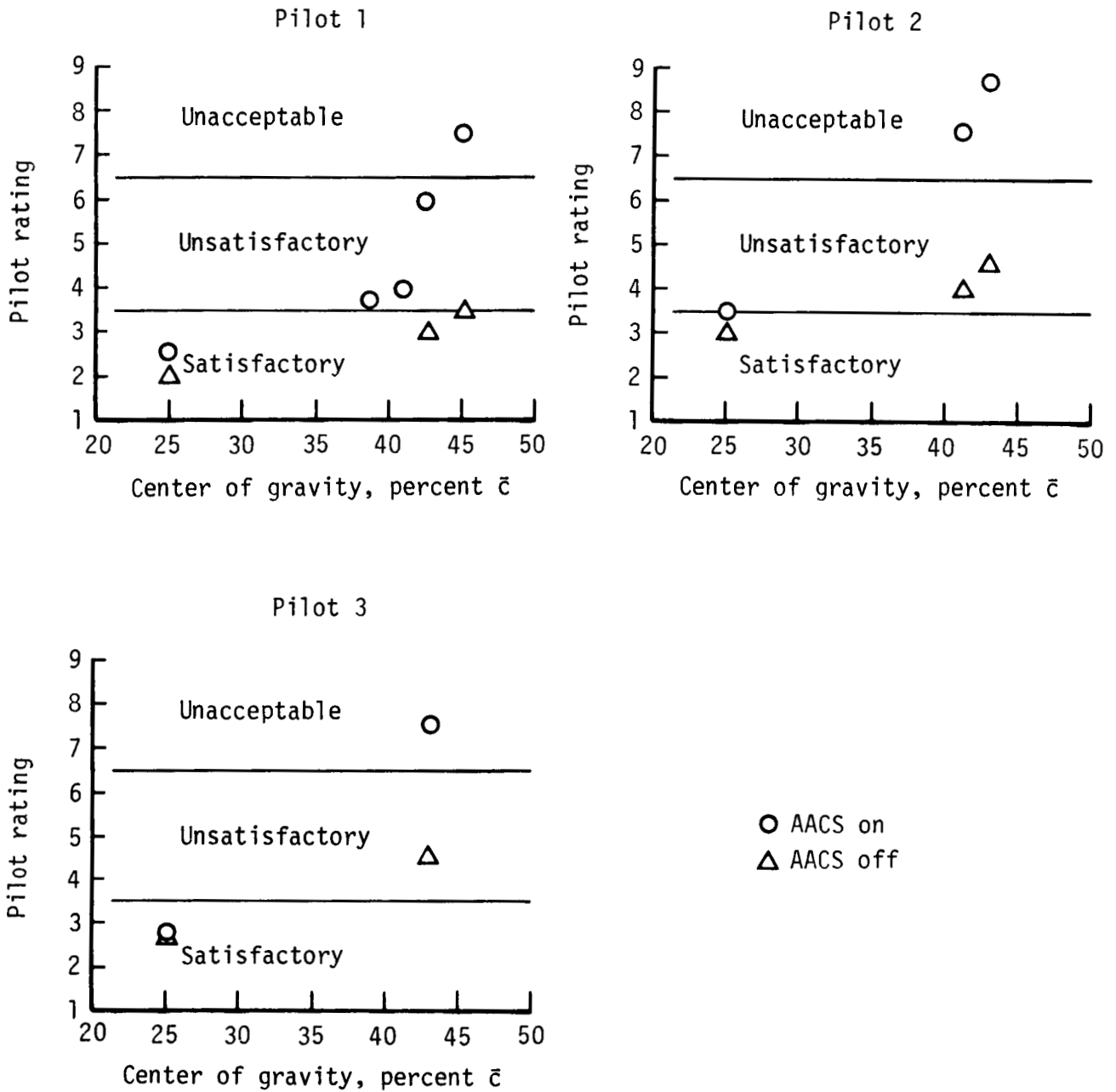


Figure 17.- Indication of the effects of AACs and center-of-gravity position on pilot rating for flight condition 10 with PACS off.

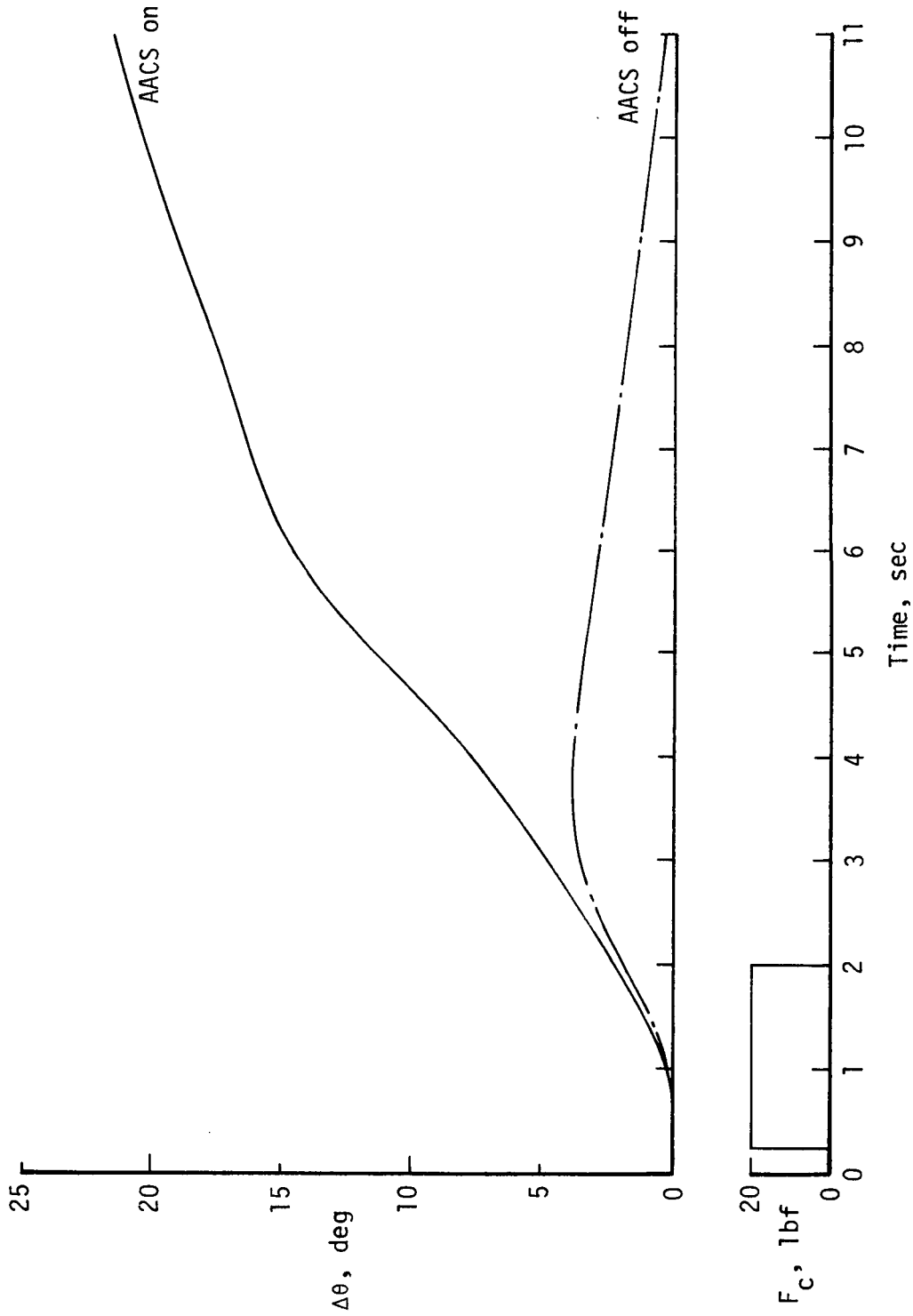


Figure 18.- Effect of AACCS on pitch attitude response for a pulse-type column force input with c.g. = 0.416. Flight condition 10; PACS off.

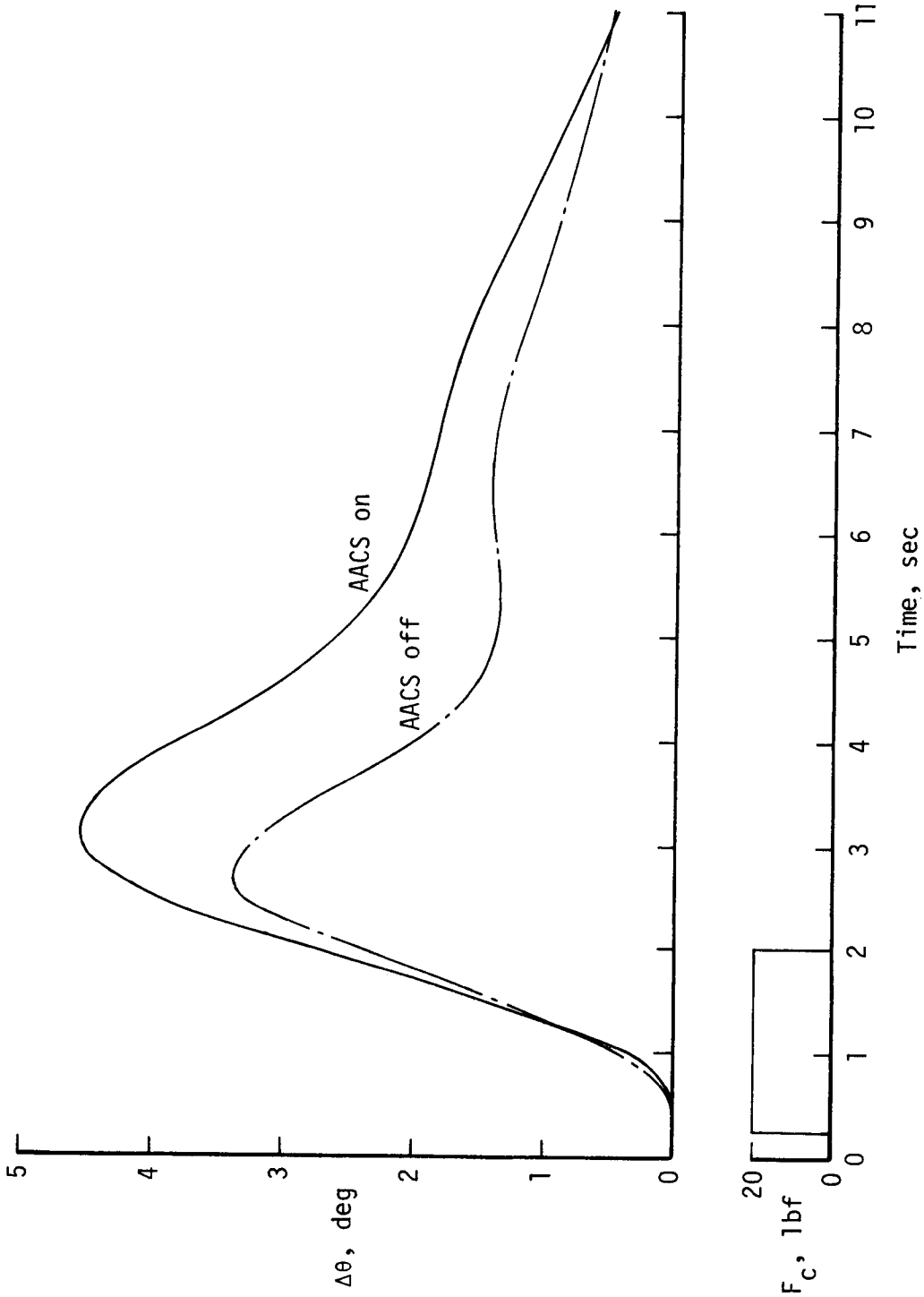


Figure 19.- Effect of AACCS on pitch attitude response for a pulse-type column force input with c.g. = 0.25 \bar{c} . Flight condition 10; PACS off.

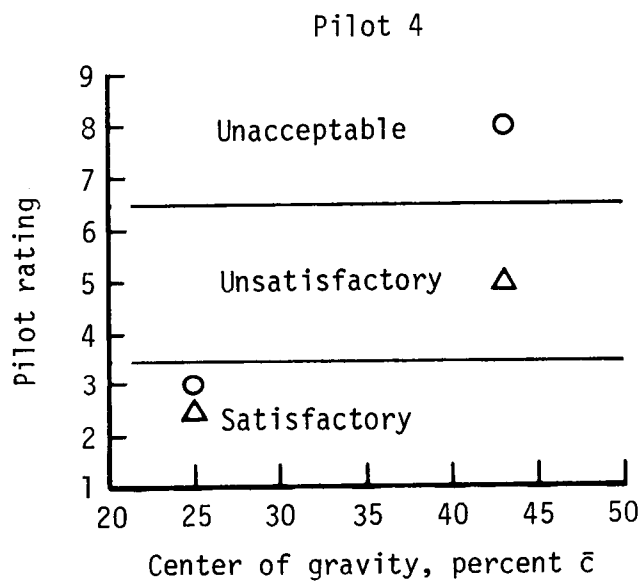
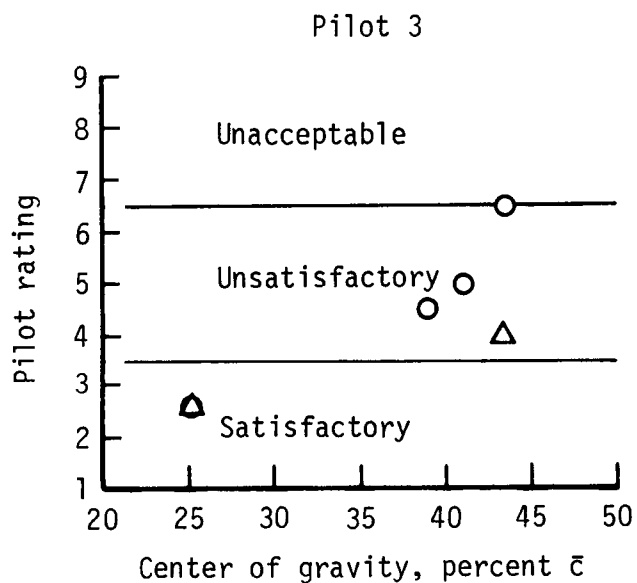
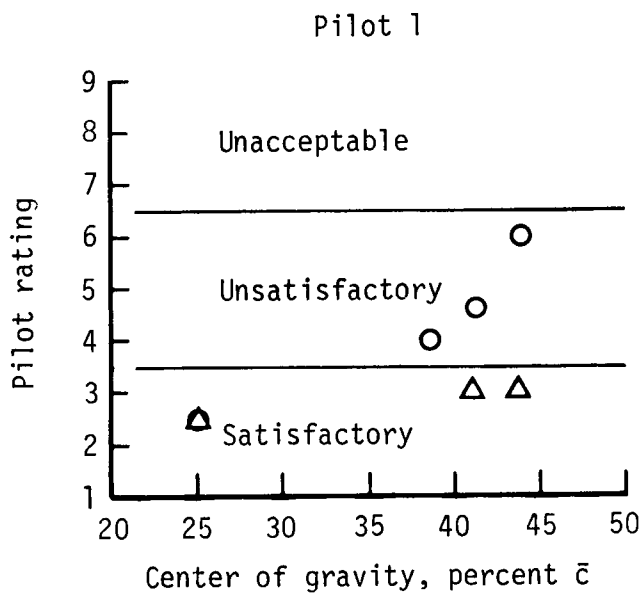
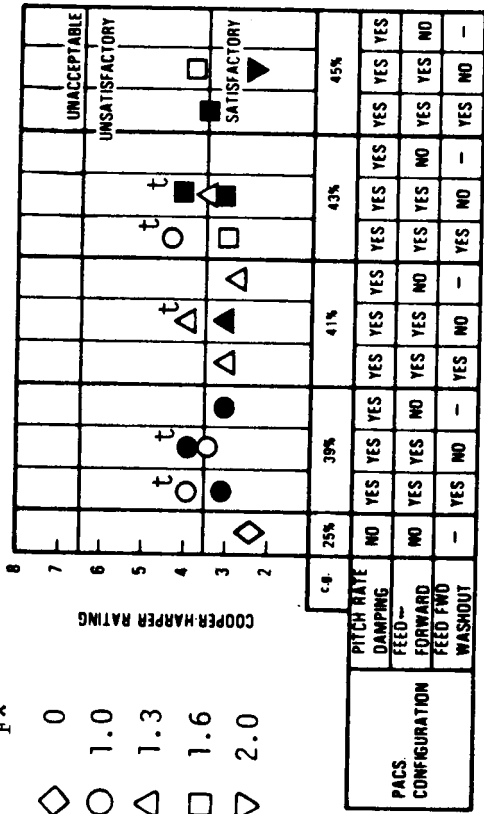


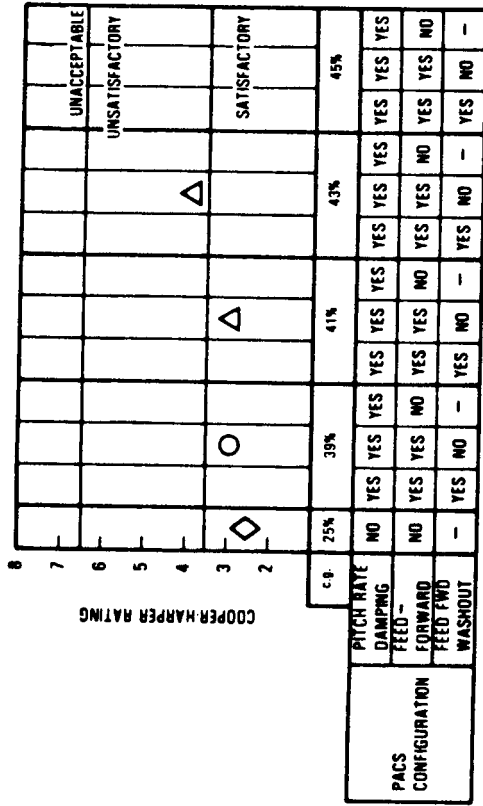
Figure 21.- Indication of the effects of AACS and center-of-gravity position on pilot rating for flight condition 11 with PACS off.

F*

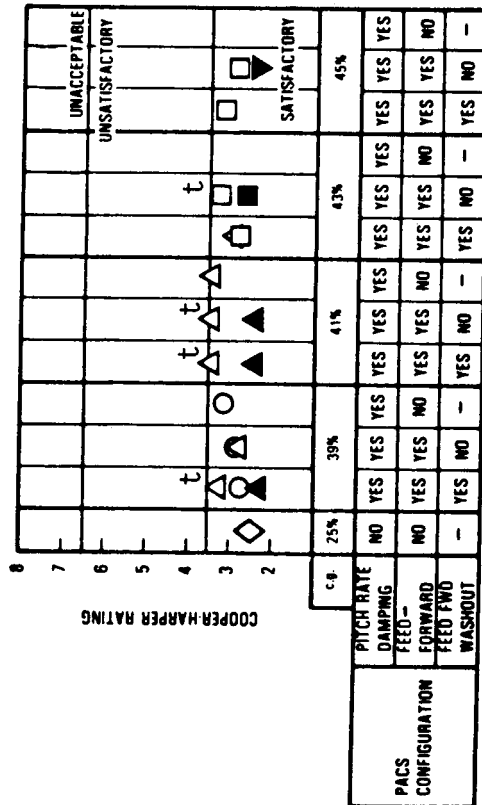
- ◇ 0
- 1.0
- △ 1.3
- 1.6
- ▽ 2.0



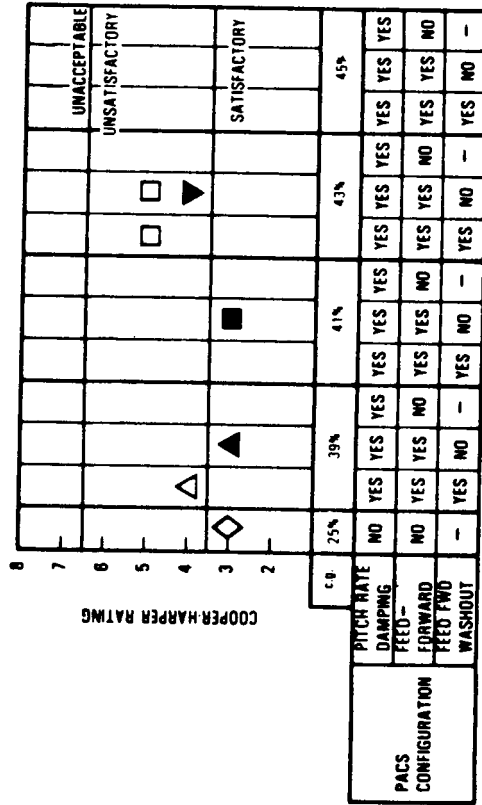
PILOT 1



PILOT 2



PILOT 3



PILOT 4

Figure 22.- Pilot ratings for flight condition 11 with PACS on and AACs on. Solid symbols denote PACS configuration preferred by pilots; t denotes turbulent atmosphere.

t Turbulent atmosphere
 ○ AACS on

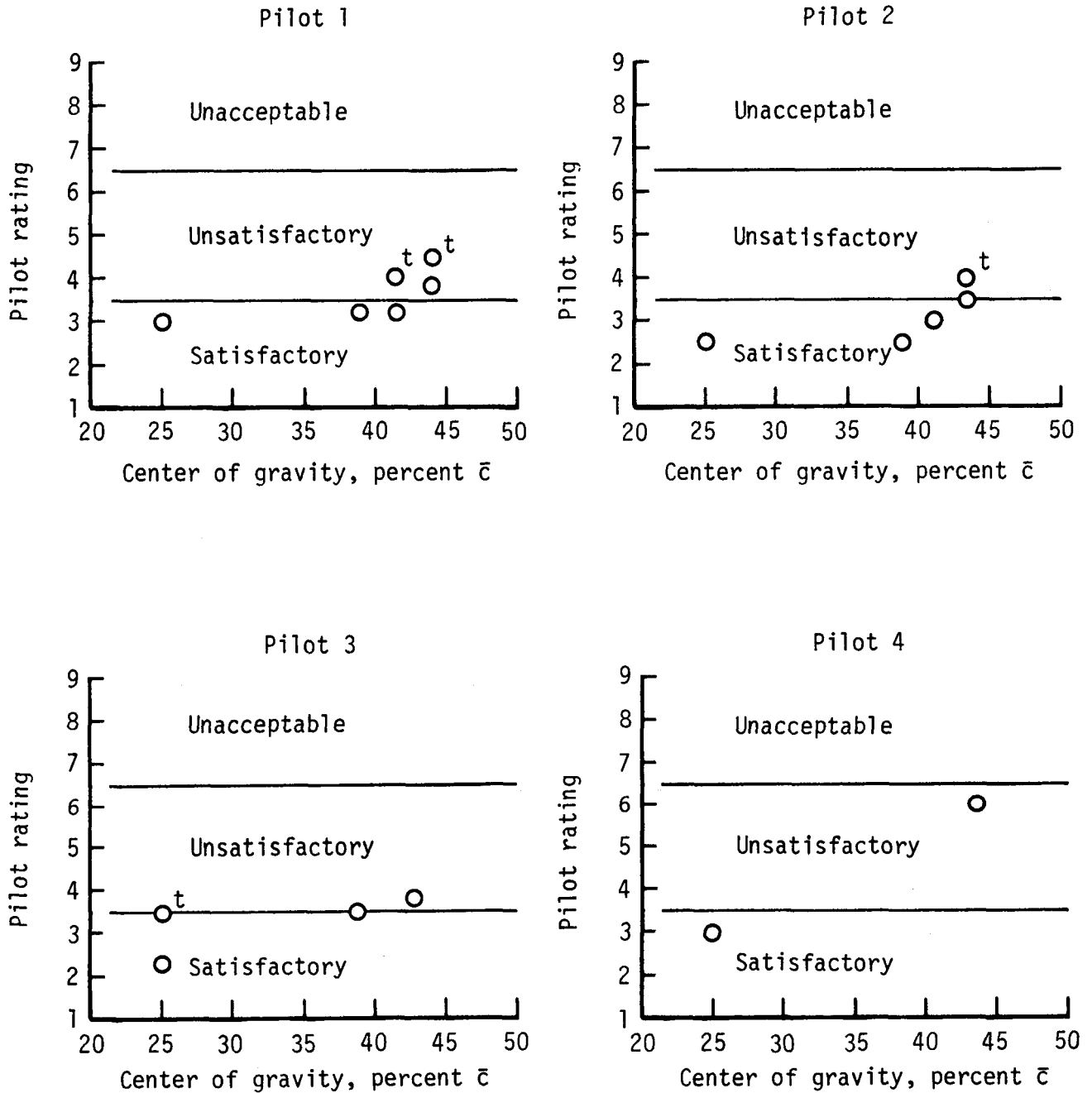
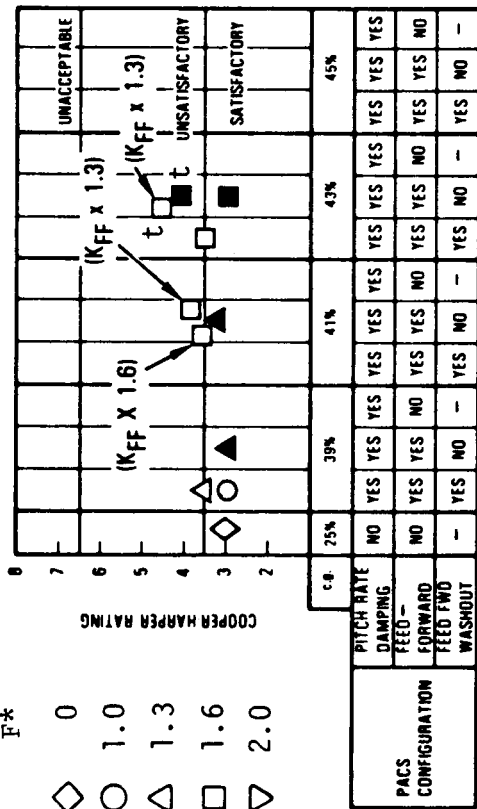


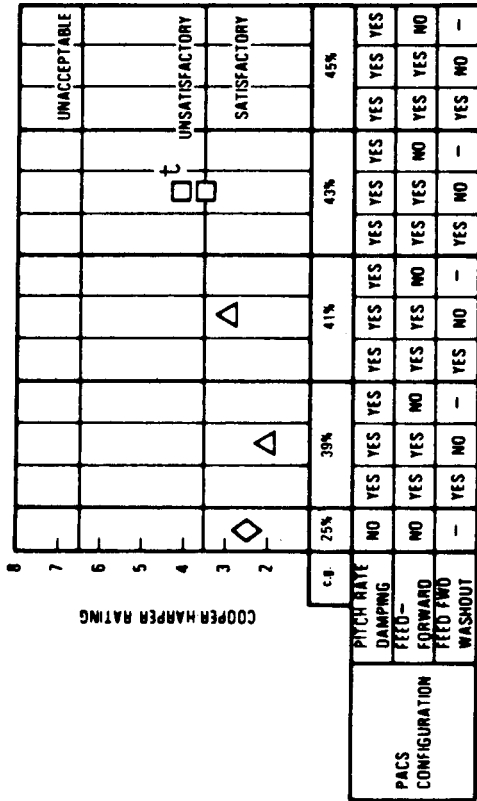
Figure 23.- Indication of the effects of center-of-gravity position on pilot rating for flight condition 18 with PACS off and AACS on.

F*

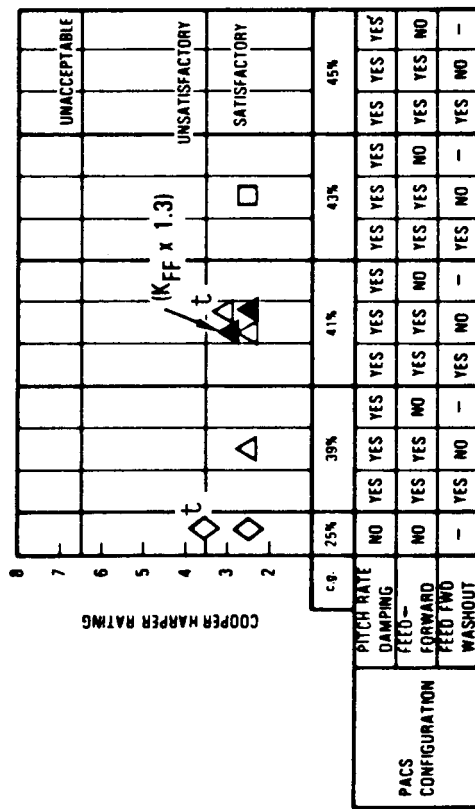
- ◇ 0
- 1.0
- △ 1.3
- 1.6
- ▽ 2.0



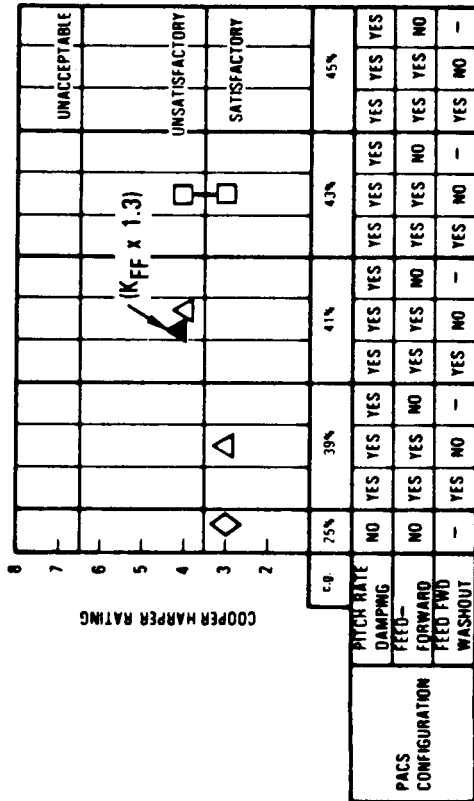
PILOT 1



PILOT 2



PILOT 3



PILOT 4

Figure 24.- Pilot ratings for flight condition 18 with PACS on and AACs on. Solid symbols denote PACS configuration preferred by pilots; t denotes turbulent atmosphere.

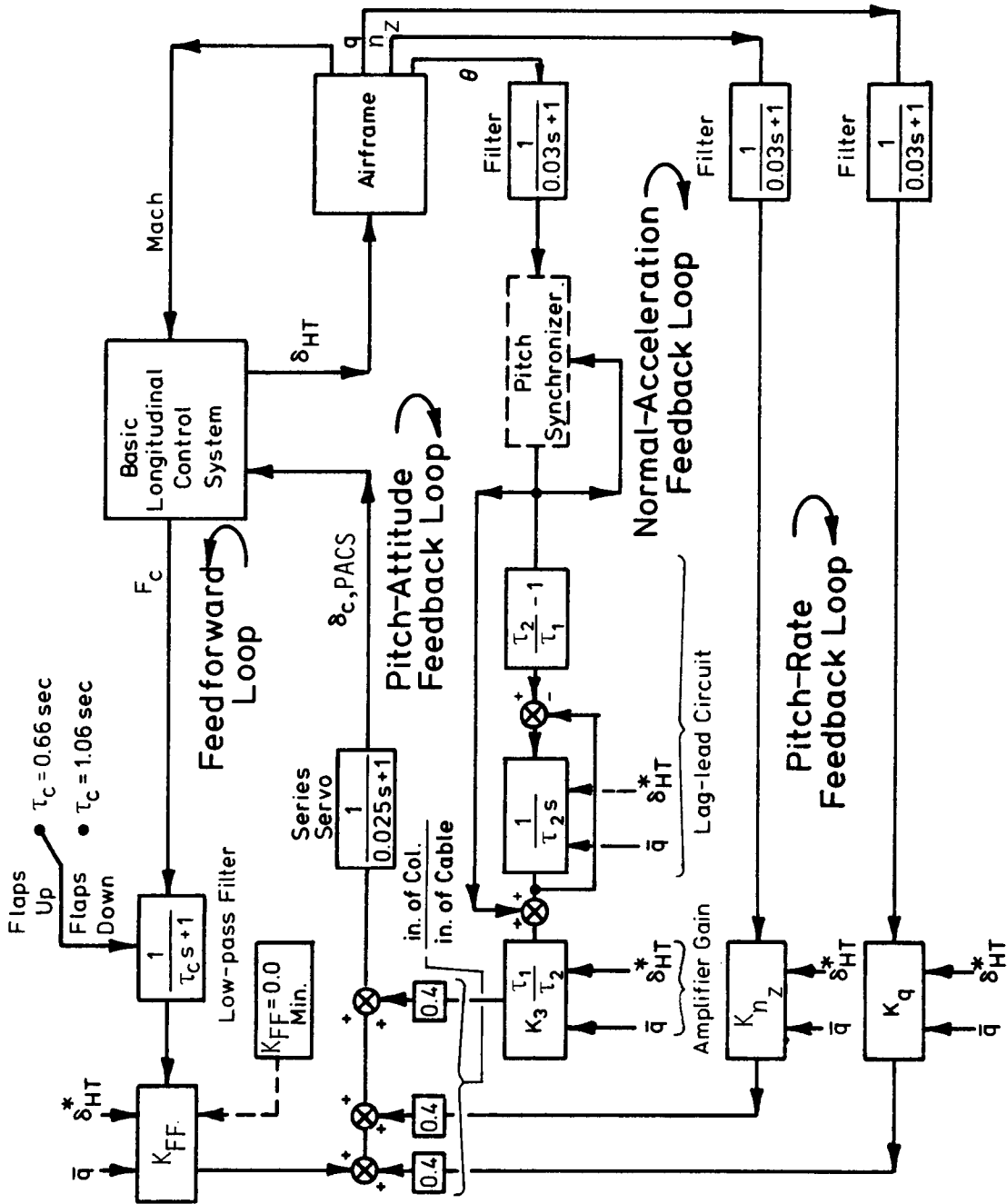
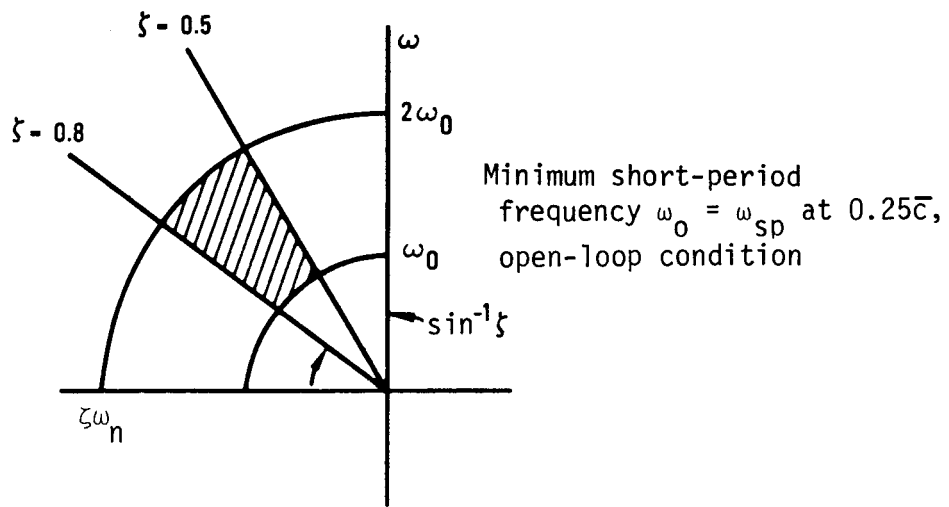
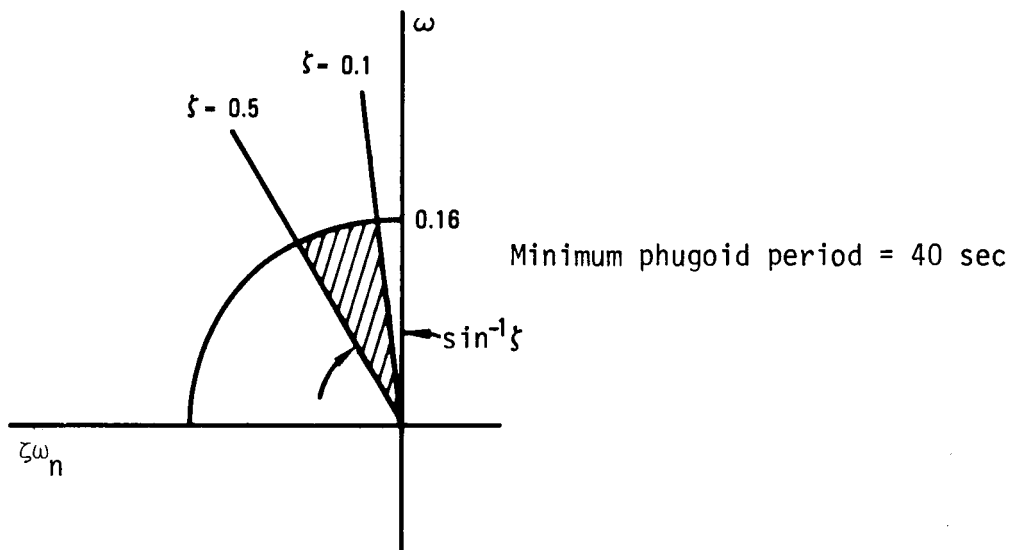


Figure 25.- Analytical block diagram of advanced PACS.

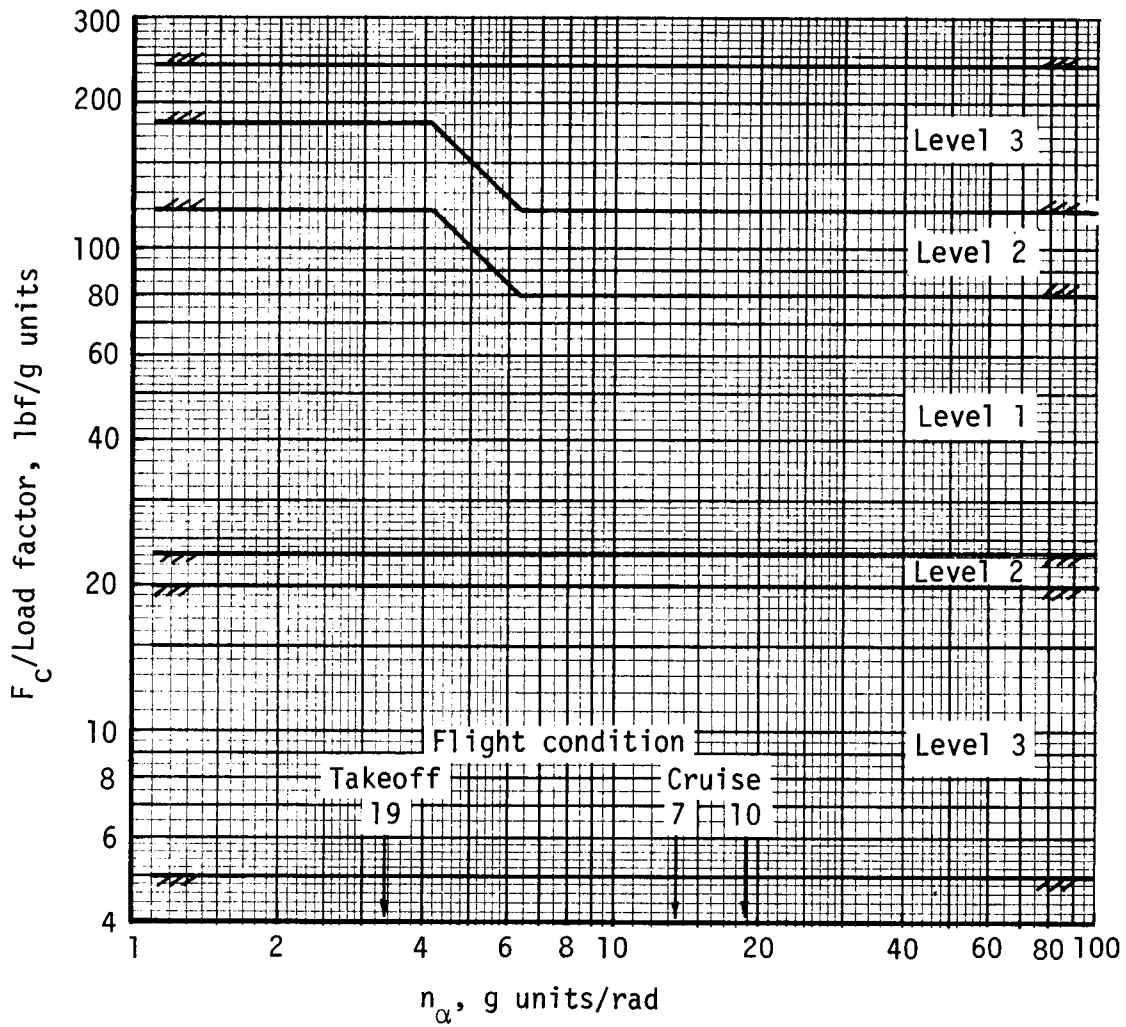


(a) Short-period mode.



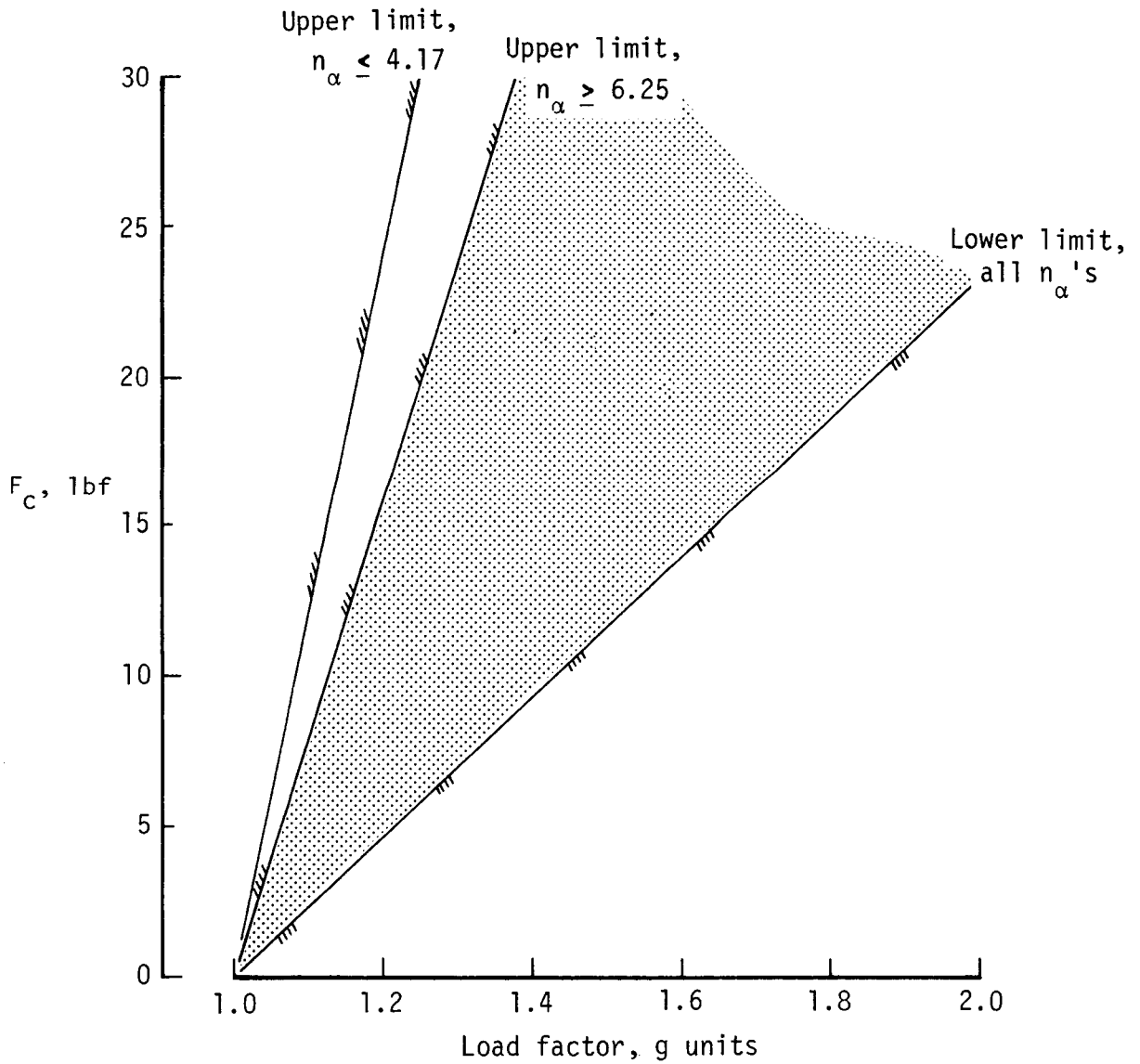
(b) Phugoid mode.

Figure 26.- Dynamic stability design objectives of advanced PACS.



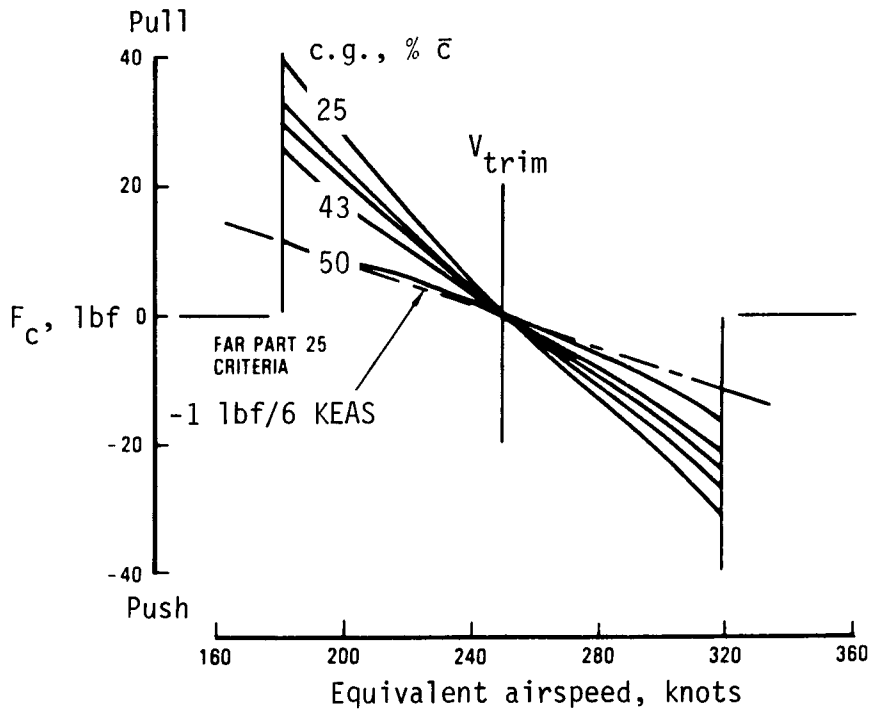
(a) MIL-F-8785C wheel control limits with $n_L = 2.5$.

Figure 27.- Pitch maneuvering force gradient limits.

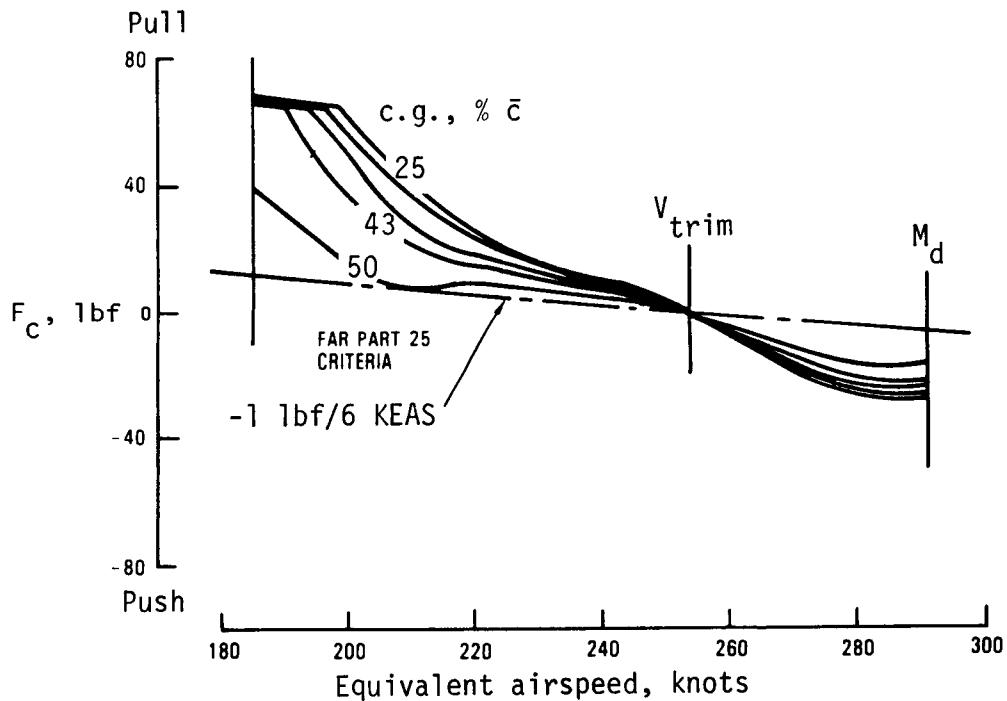


(b) Wheel control force gradient design objectives of advanced PACS.
MIL-F-8785C; Level 1.

Figure 27.- Concluded.



(a) Flight condition 17 (holding mode).



(b) Flight condition 7 (cruise mode).

Figure 28.- Typical speed stability column force characteristics for simulated L-1011 with advanced PACS operative.

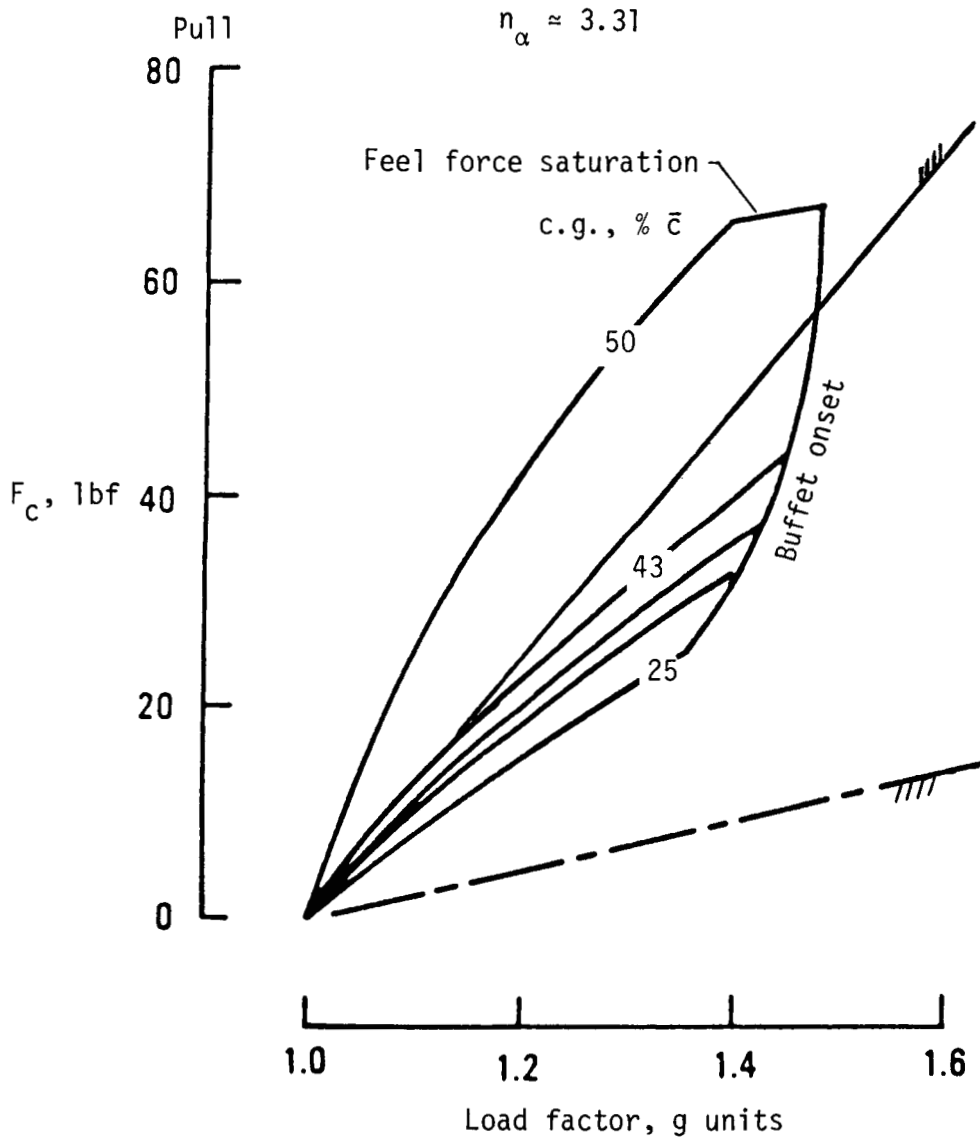


Figure 29.- Indication of maneuver stability characteristics of baseline L-1011 aircraft (PACS off; AACS on) in takeoff configuration. Indicated boundaries are from reference 4.

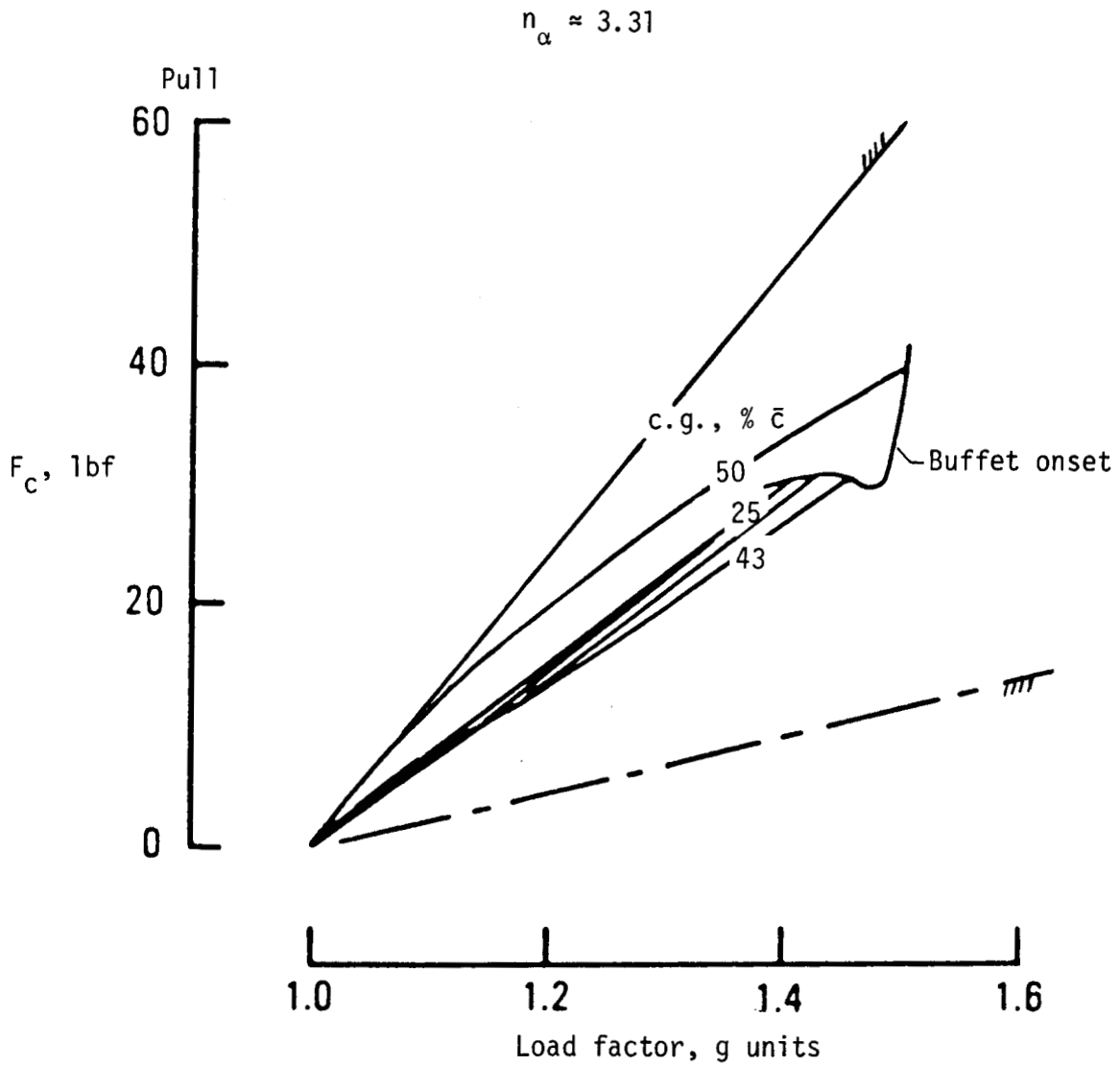


Figure 30.- Maneuver stability characteristics of advanced PACS configured aircraft in takeoff flight condition. Indicated boundaries are from reference 4.

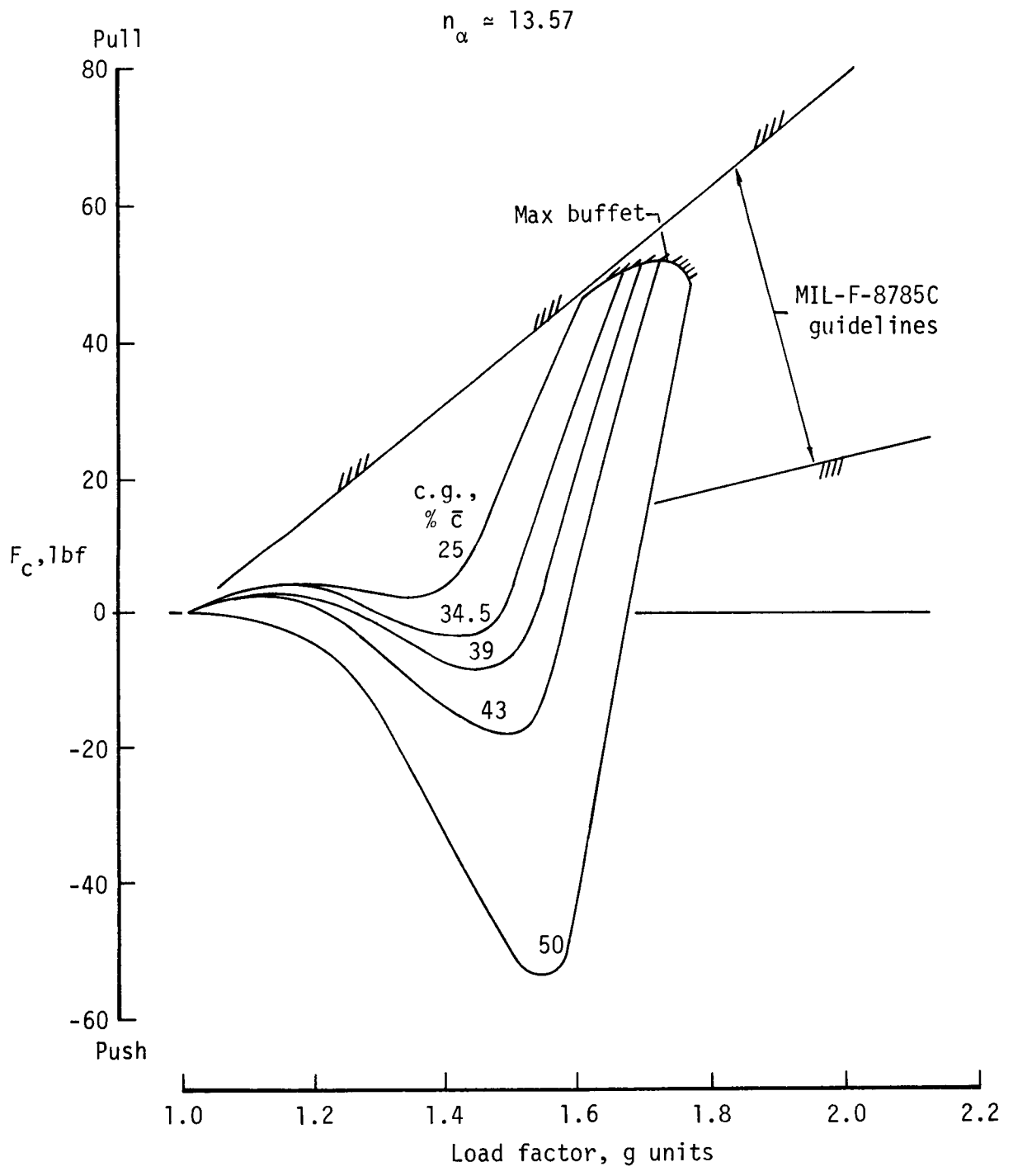


Figure 31.- Indication of maneuver stability characteristics of baseline L-1011 aircraft (PACS off; AACS on) in cruise configuration (flight condition 7).

$$n_{\alpha} \approx 13.57$$

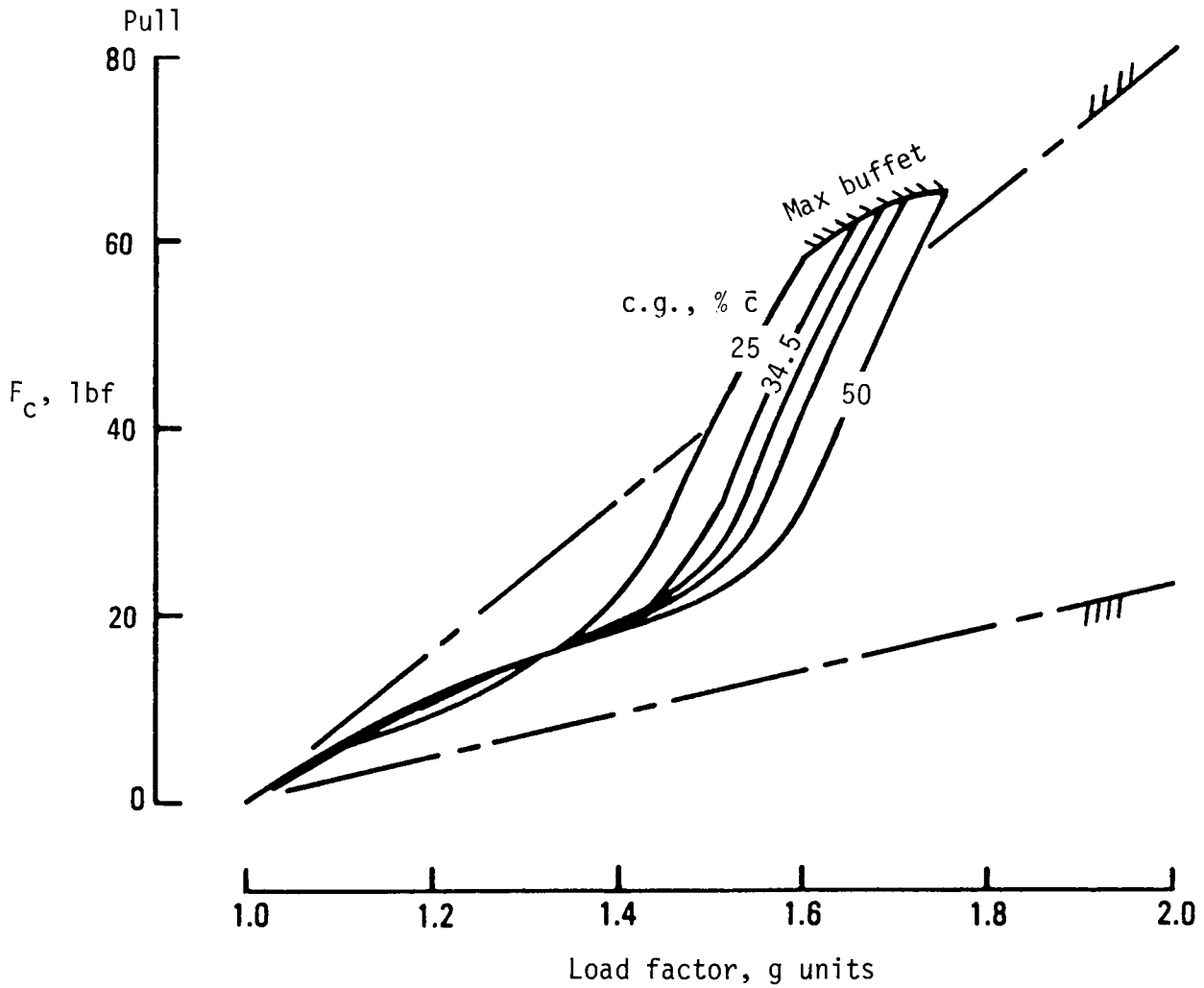


Figure 32.- Maneuver stability characteristics of advanced PACS configured aircraft for cruise flight condition 7. Indicated boundaries are from reference 4.

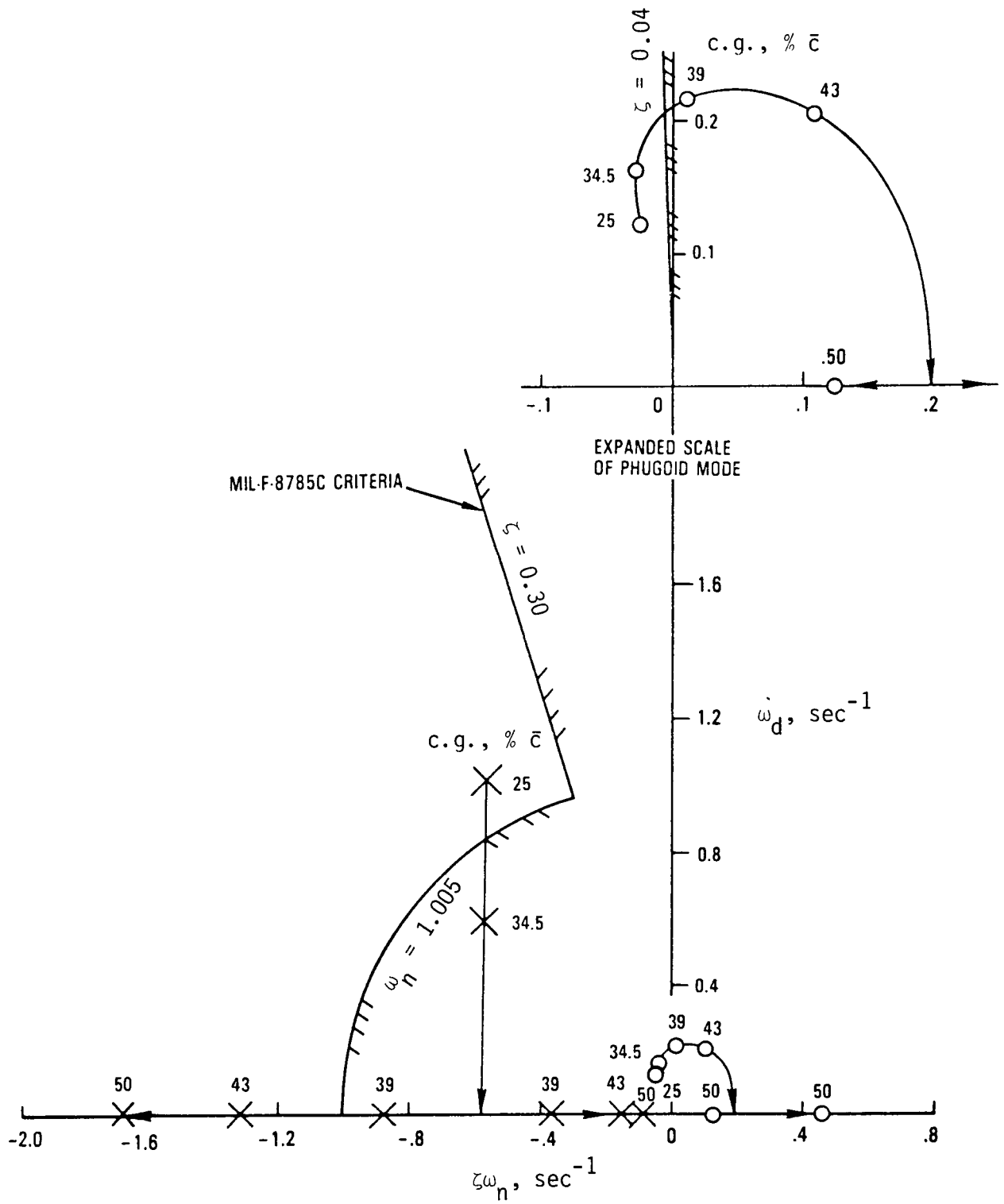
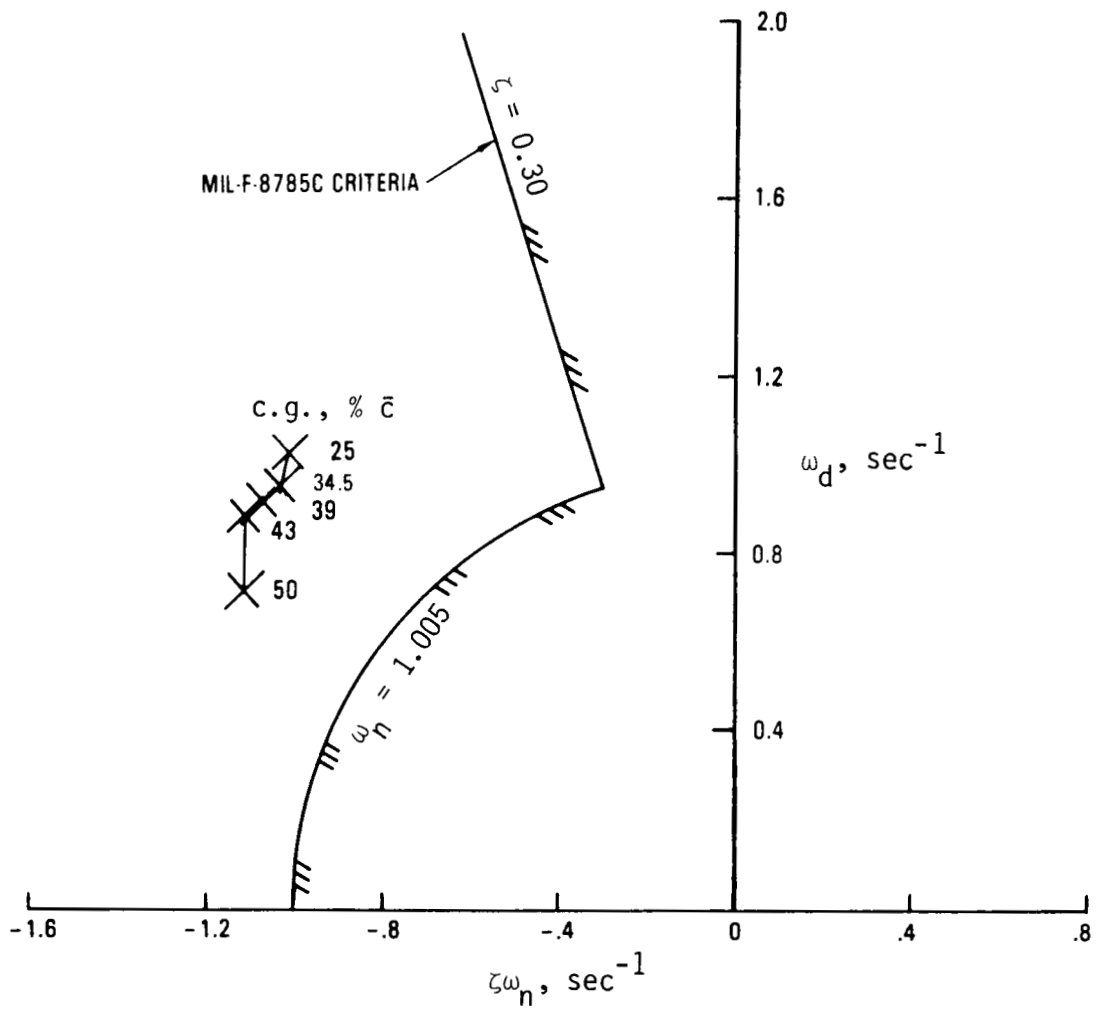
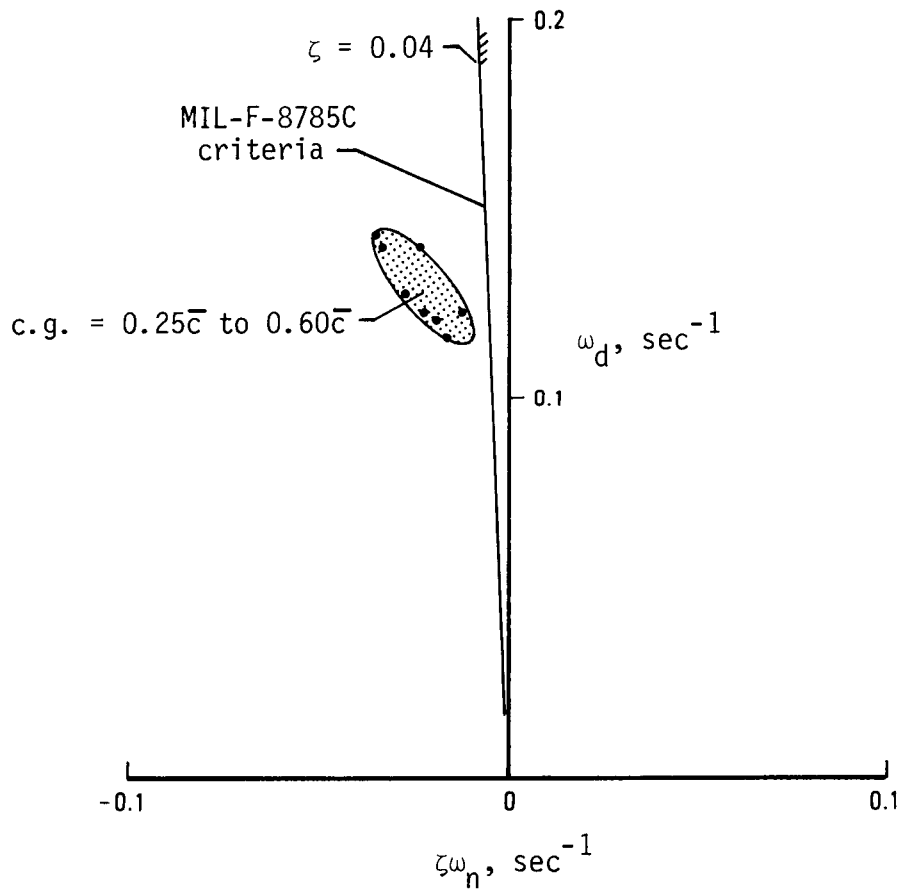


Figure 33.- Dynamic stability characteristics of baseline aircraft (PACS off; AACS on) for cruise flight condition 7.



(a) Short-period mode.

Figure 34.- Dynamic stability characteristics of cruise flight condition 7 with advanced PACS operative.



(b) Phugoid mode.

Figure 34.- Concluded.

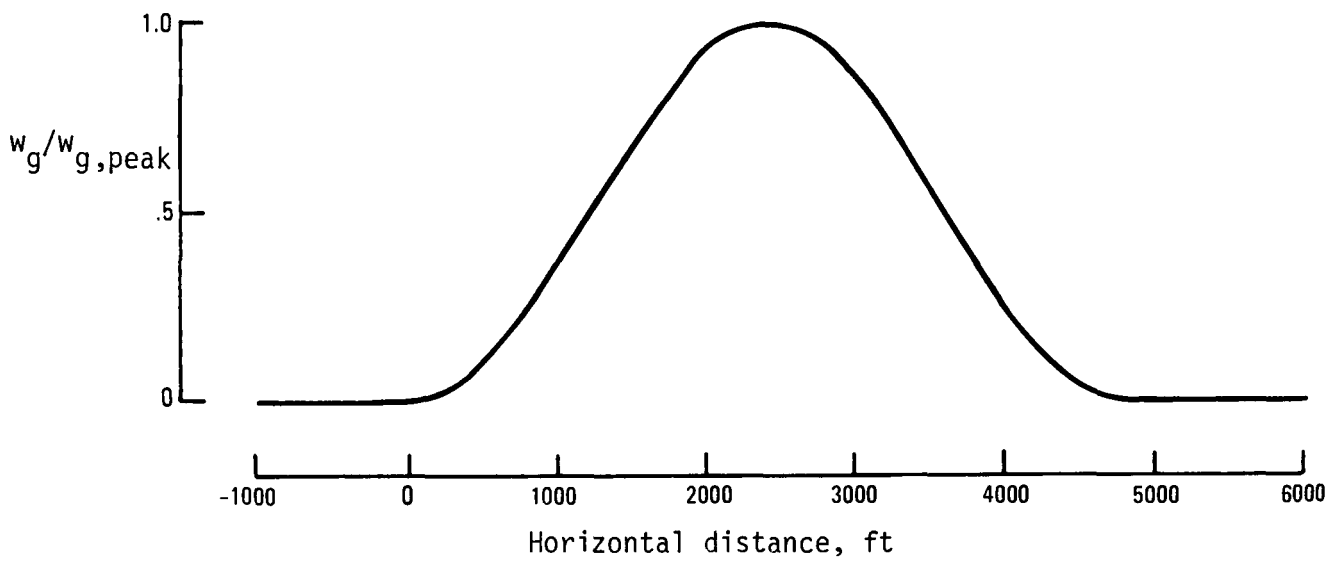
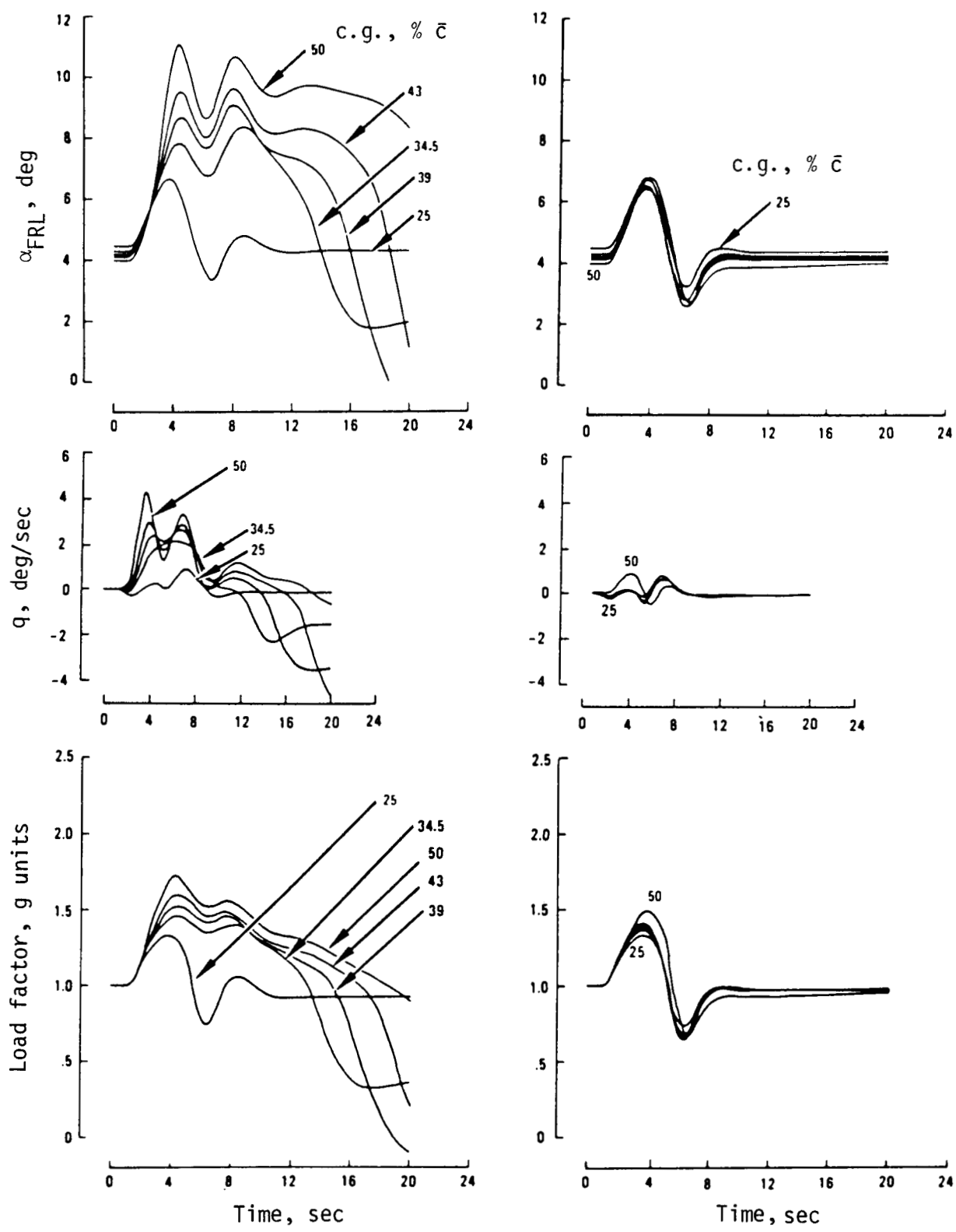


Figure 35.- Discrete gust model used in analysis of flight condition 7.



(a) Baseline aircraft (PACS off; AACCS on).

(b) Advanced PACS aircraft.

Figure 36.- Comparison of aircraft response, with and without PACS engaged, to a severe vertical gust for flight condition 7 with $w_{g,peak} = -54$ ft/sec.

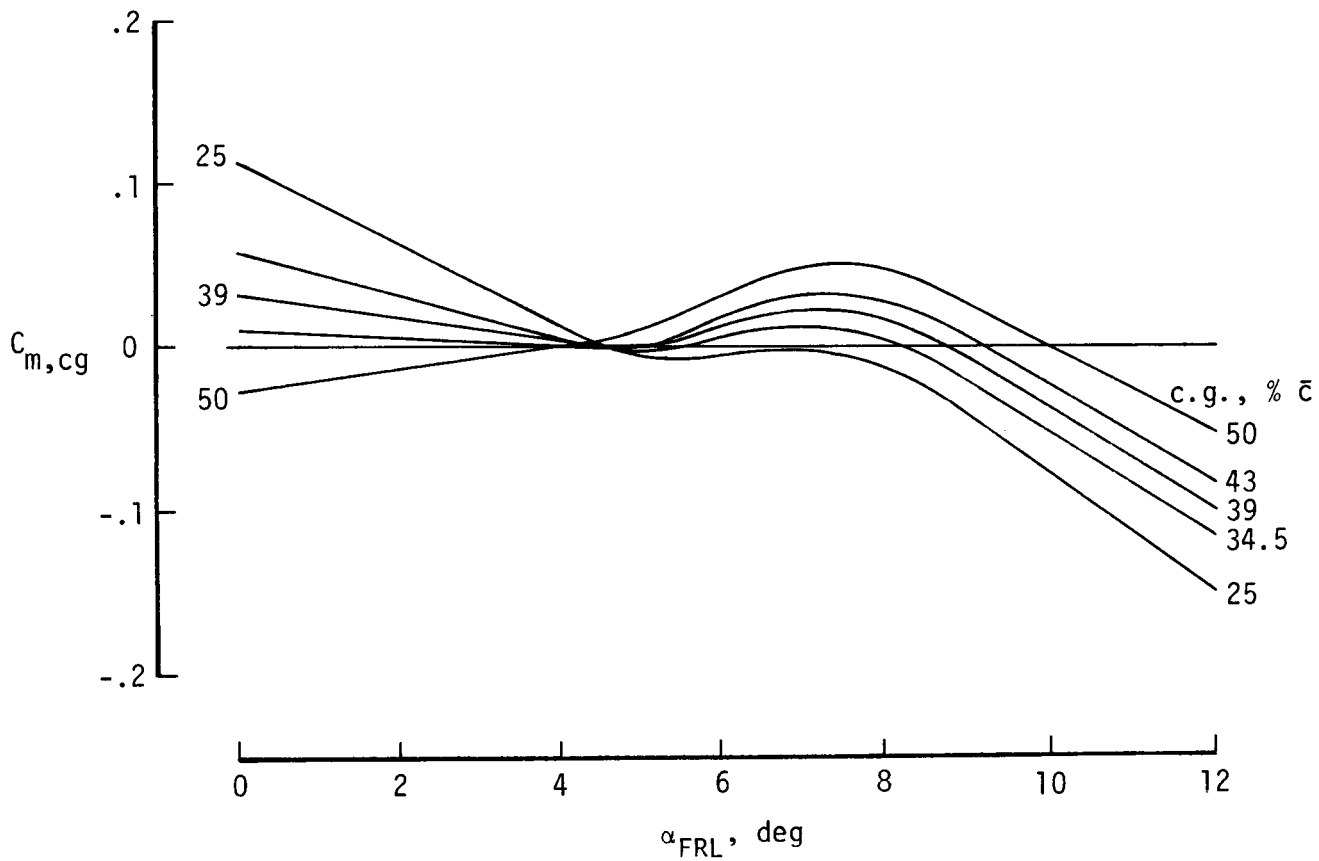
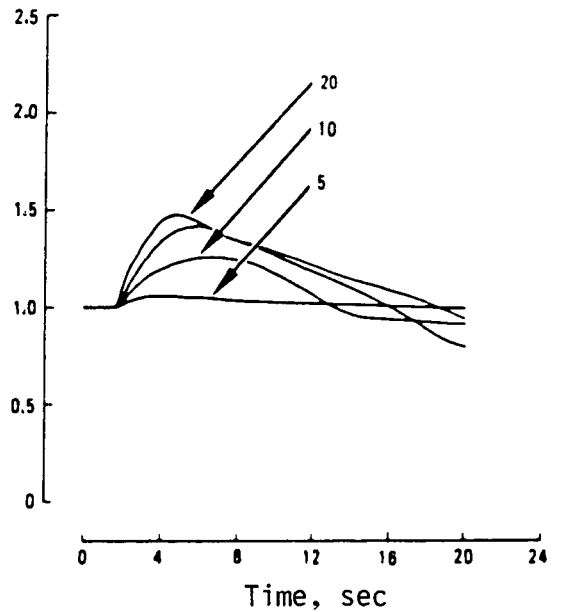
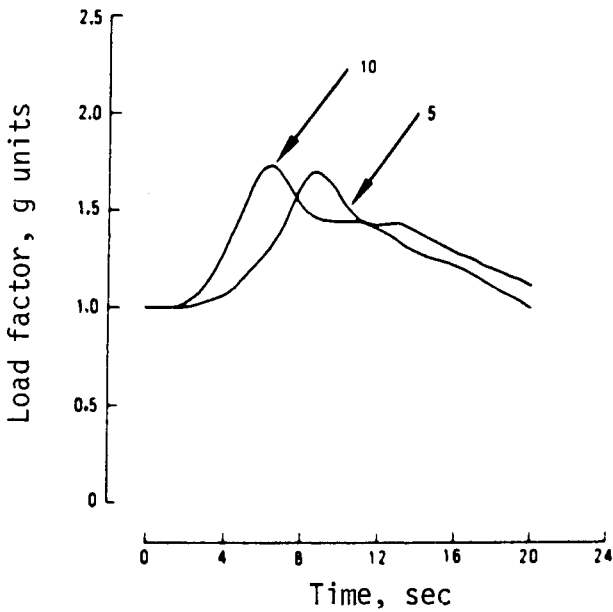
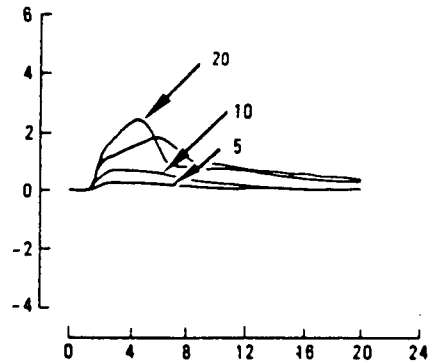
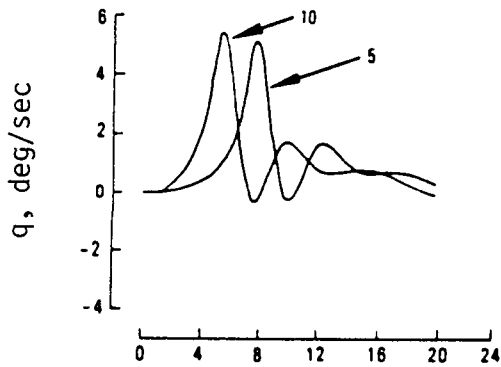
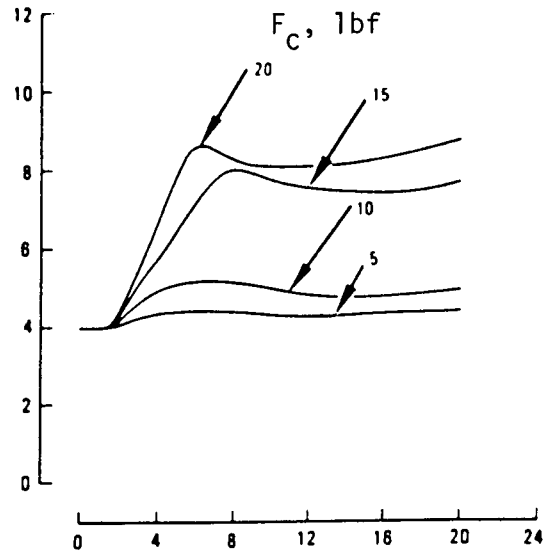
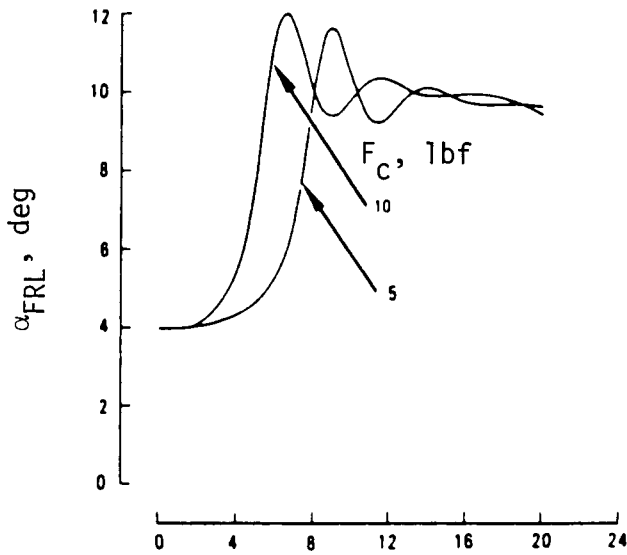


Figure 37.- Indication of aircraft static pitching-moment characteristics for flight condition 7.



(a) Baseline aircraft (PACS off; AACS on).

(b) Advanced PACS aircraft.

Figure 38.- Comparison of aircraft response, with and without PACS engaged, to various levels of control column step inputs for flight condition 7 with $c.g. = 0.50\bar{c}$.

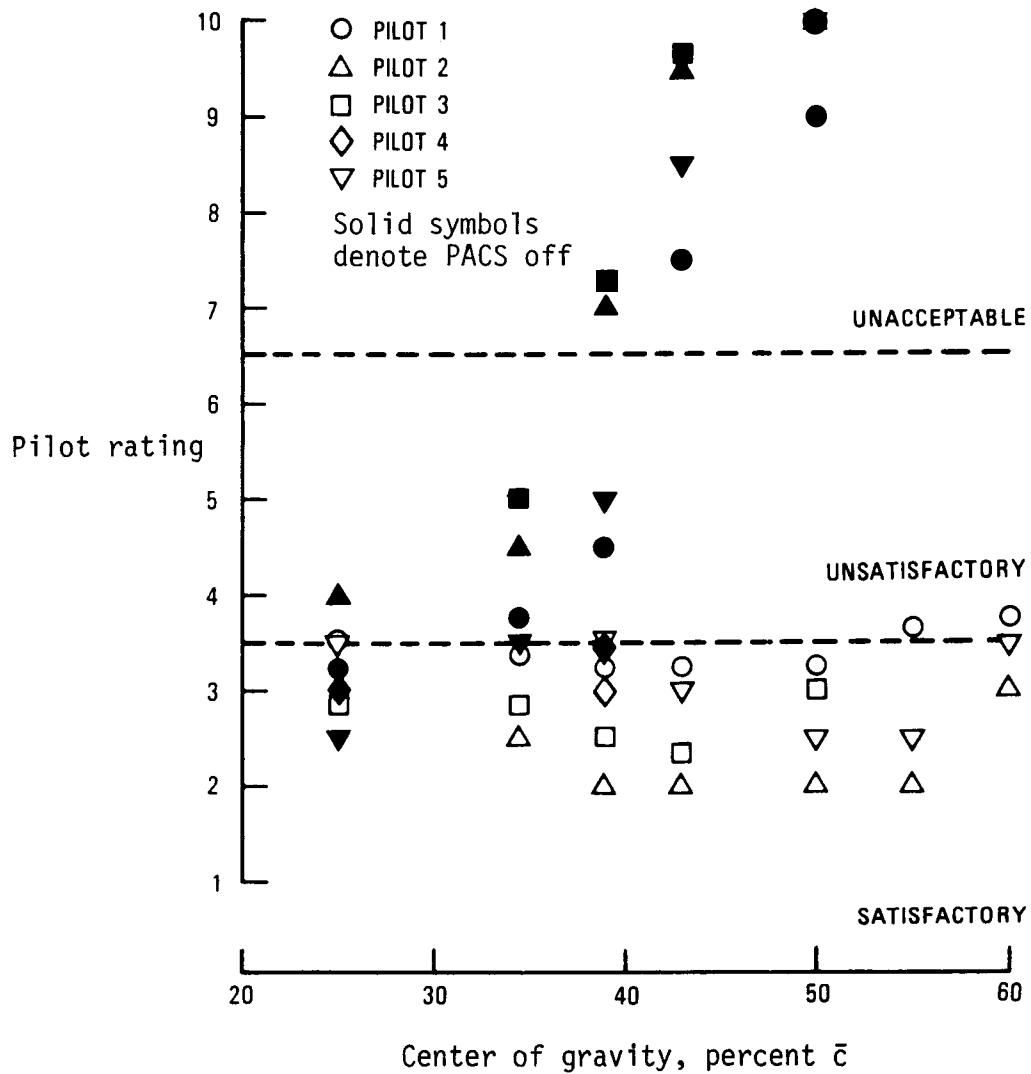


Figure 39.- Indication of effect of center-of-gravity position on pilot opinion with and without the advanced PACS engaged for cruise flight condition 10 in calm air.

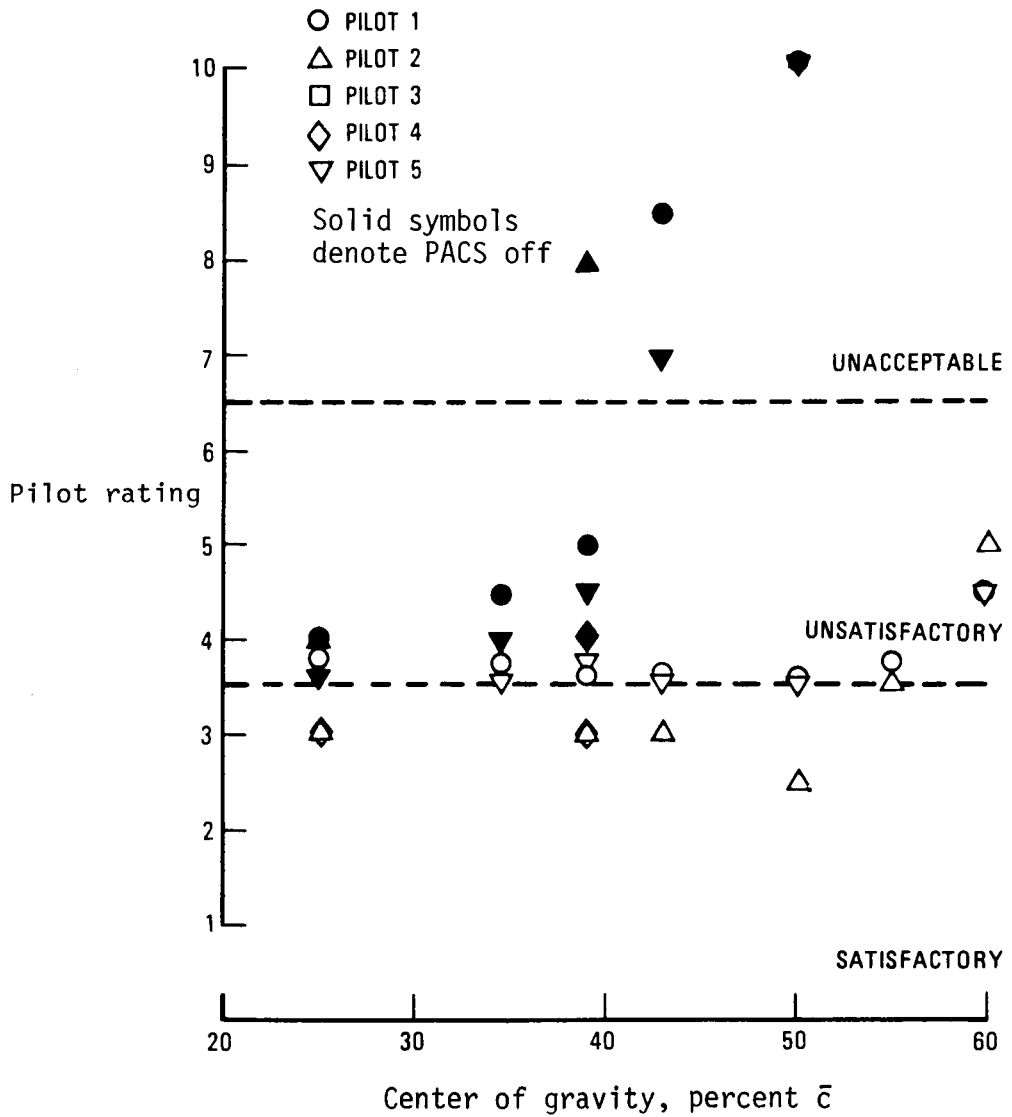


Figure 40.- Indication of effect of center-of-gravity position on pilot opinion with and without the advanced PACS engaged for cruise flight condition 10 in moderate turbulence.

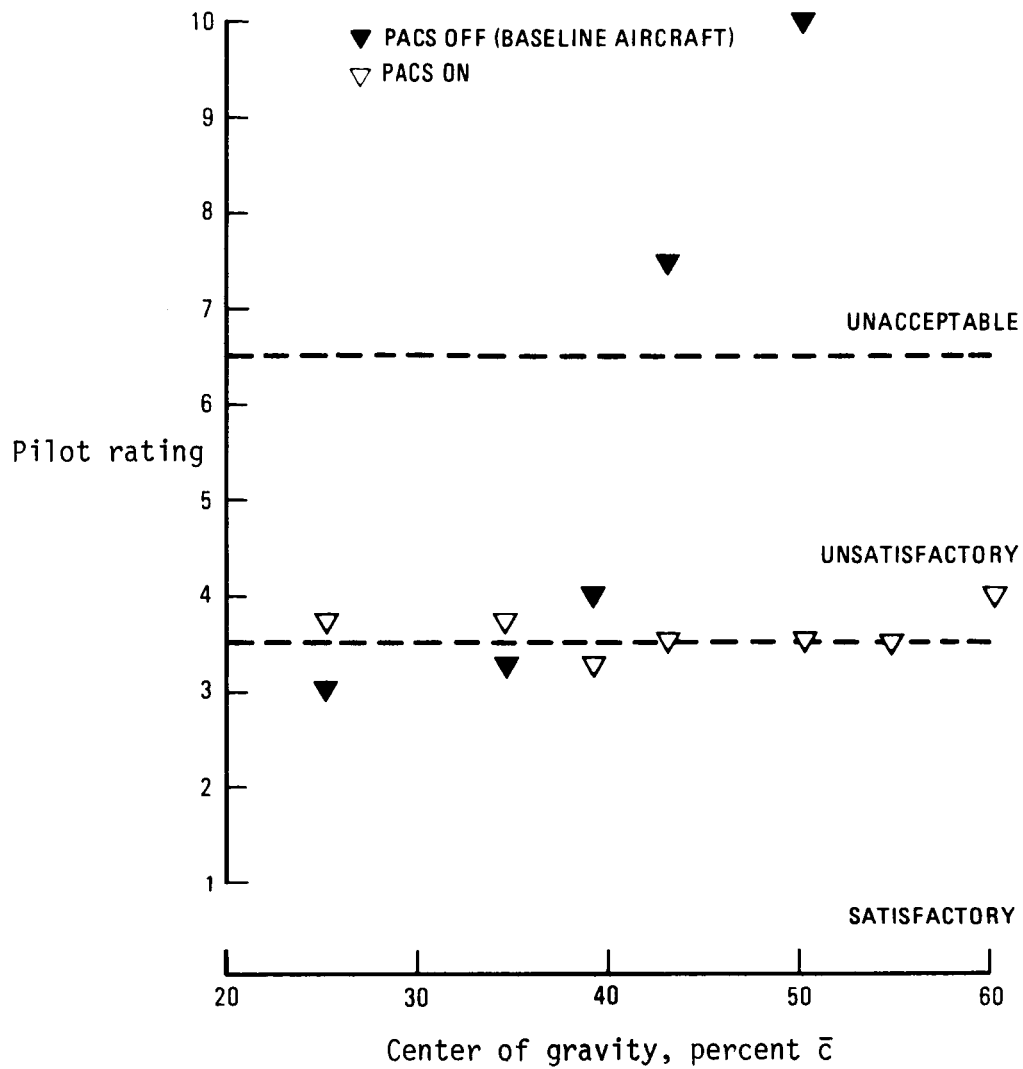


Figure 41.- Indication of effect of center-of-gravity position on pilot opinion with and without the advanced PACS engaged for cruise flight condition 15 in calm air.

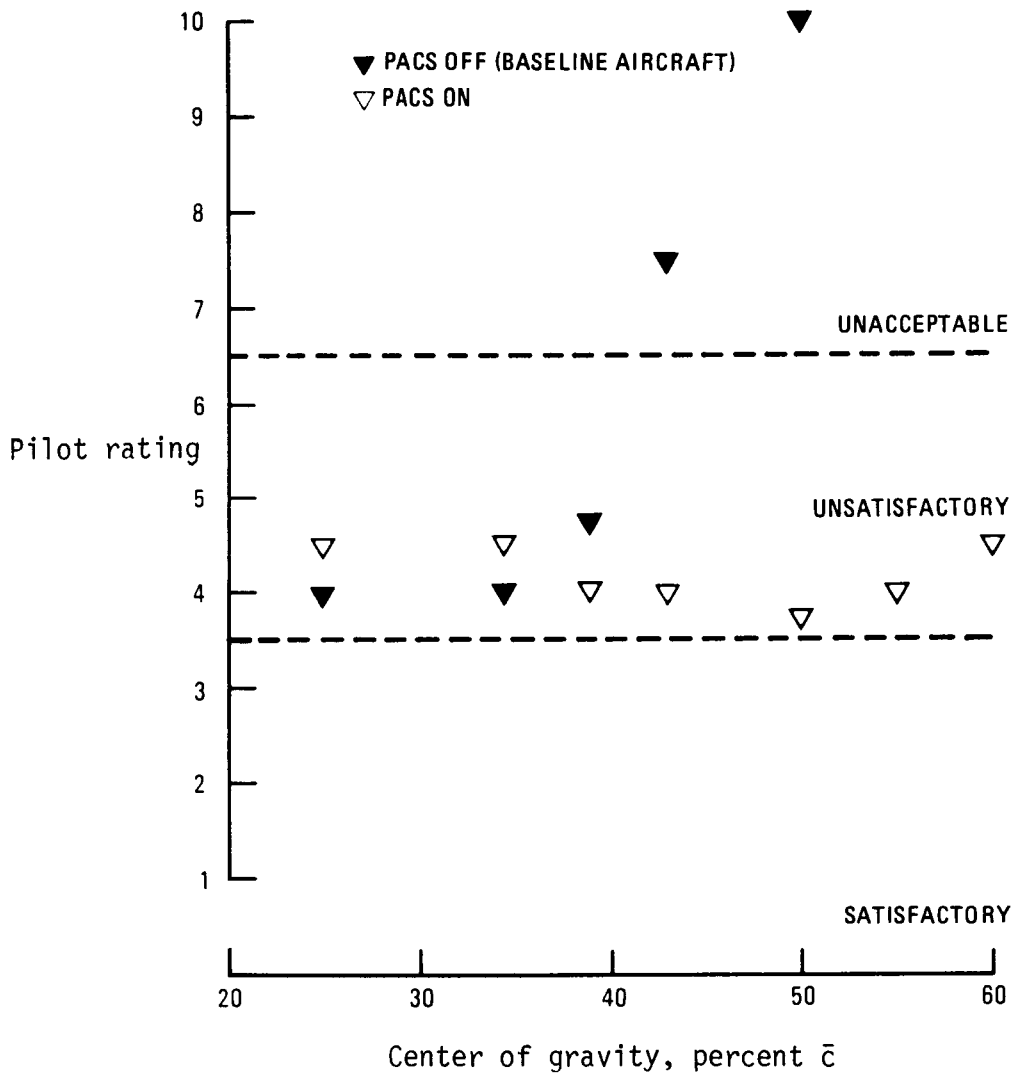


Figure 42.- Indication of effect of center-of-gravity position on pilot opinion with and without the advanced PACS engaged for cruise flight condition 15 in moderate turbulence.

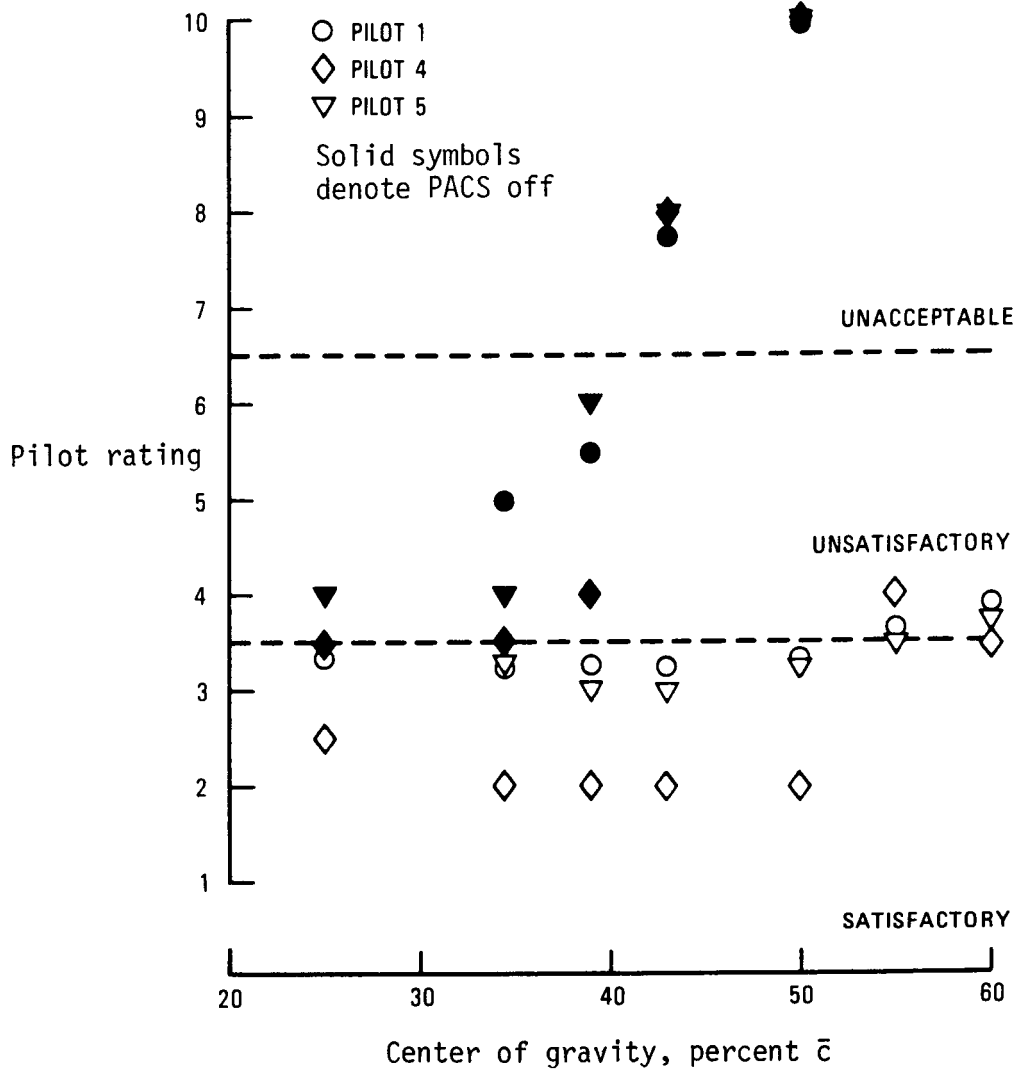


Figure 43.- Indication of effect of center-of-gravity position on pilot opinion with and without the advanced PACS engaged for cruise flight condition 7 in calm air.

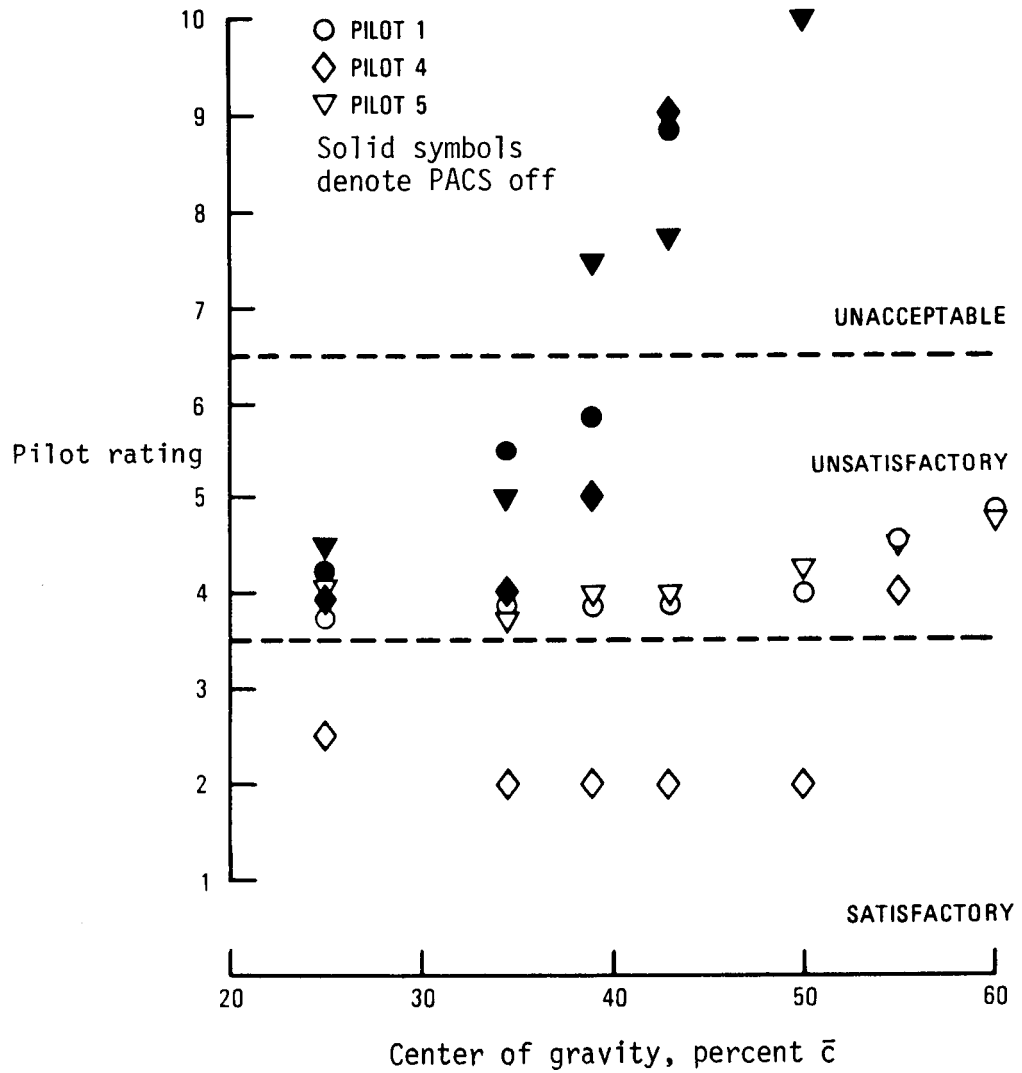


Figure 44.- Indication of effect of center-of-gravity position on pilot opinion with and without the advanced PACS engaged for cruise flight condition 7 in moderate turbulence.

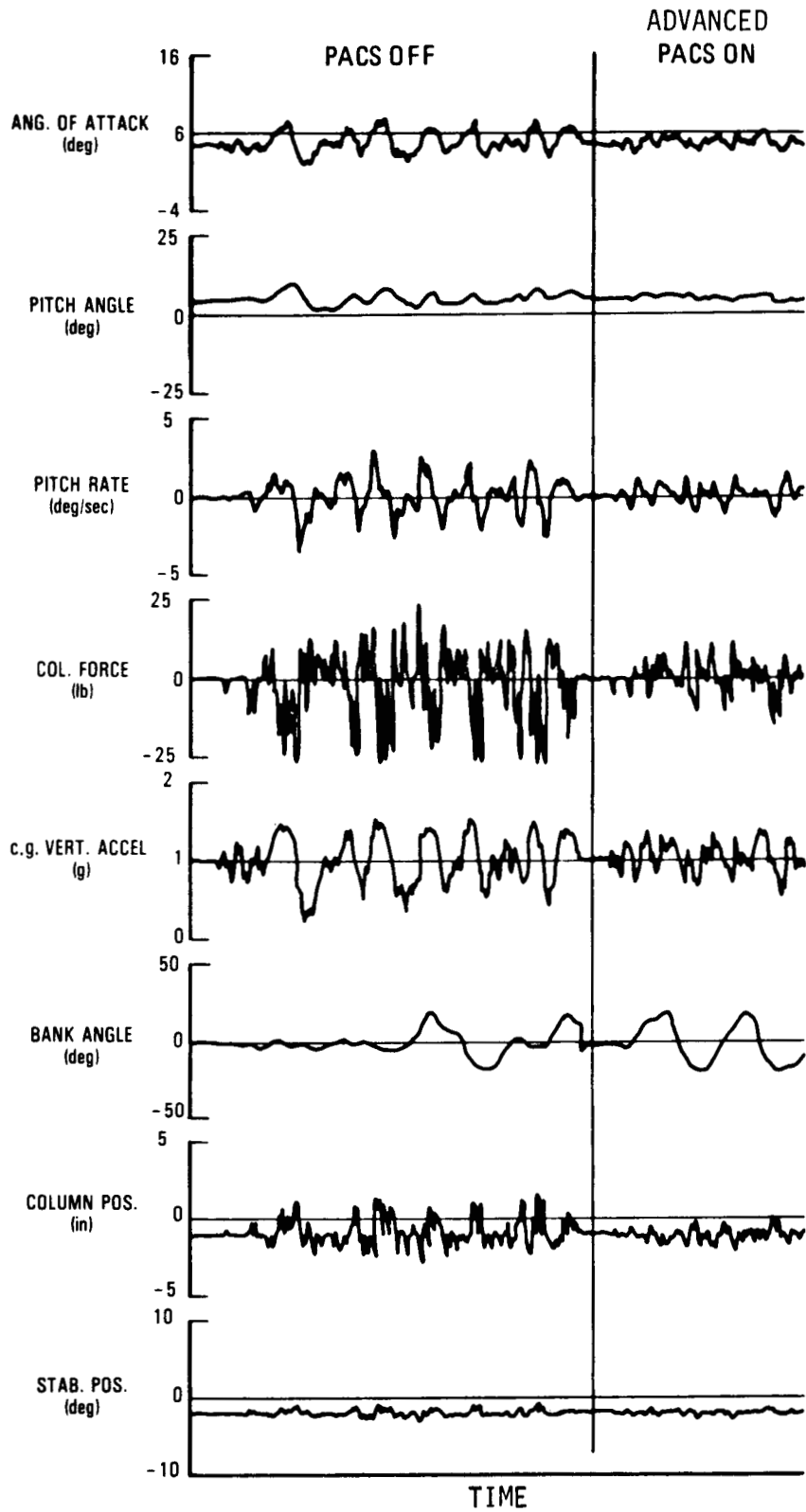


Figure 45.- Comparison of damping response characteristics of cruise flight condition 7 in moderate turbulence, with and without advanced PACS engaged, at c.g. = 0.39C.

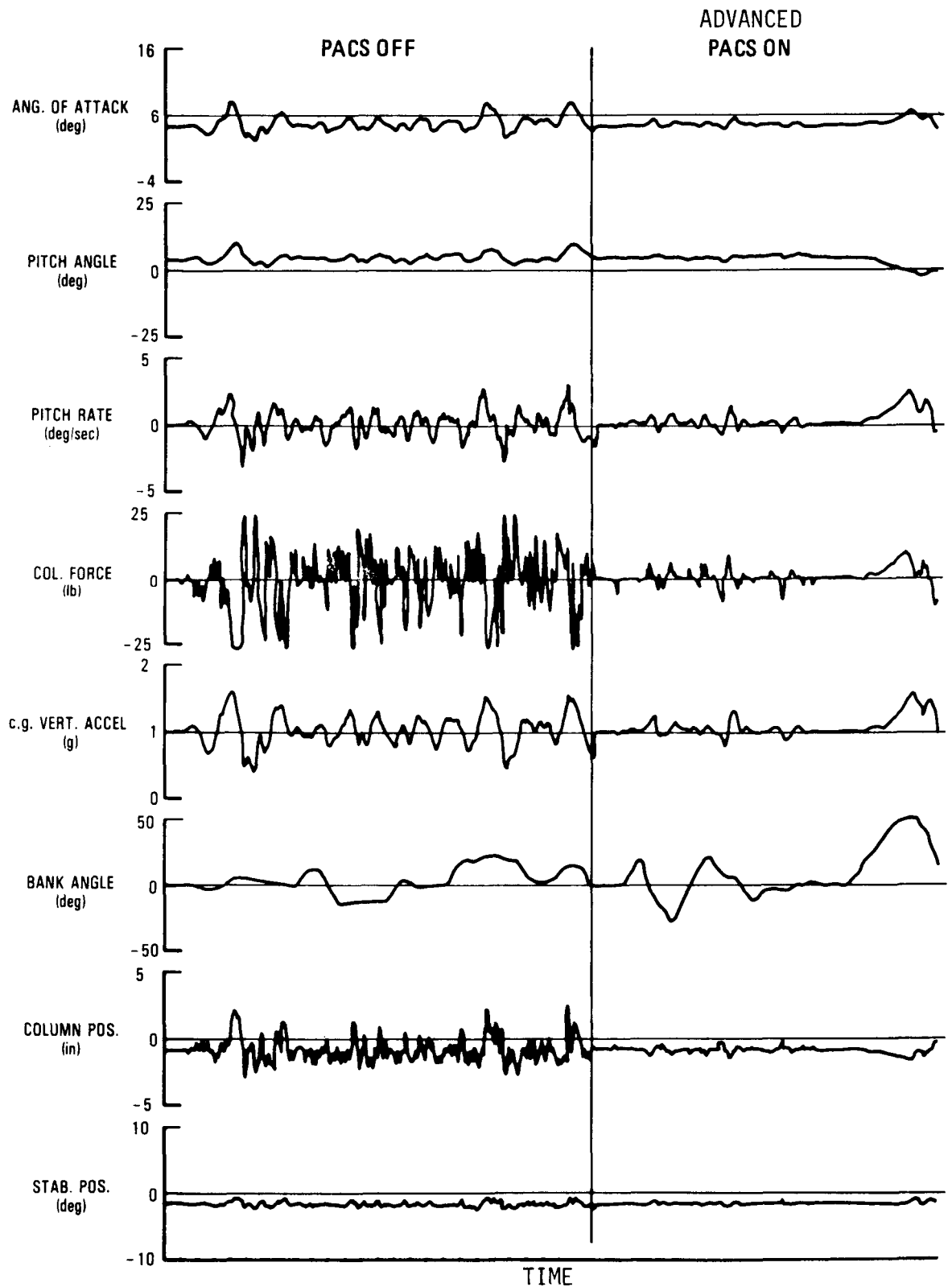


Figure 46.- Comparison of damping response characteristics of cruise flight condition 7 in calm air, with and without advanced PACS engaged, at $c.g. = 0.43\bar{c}$.

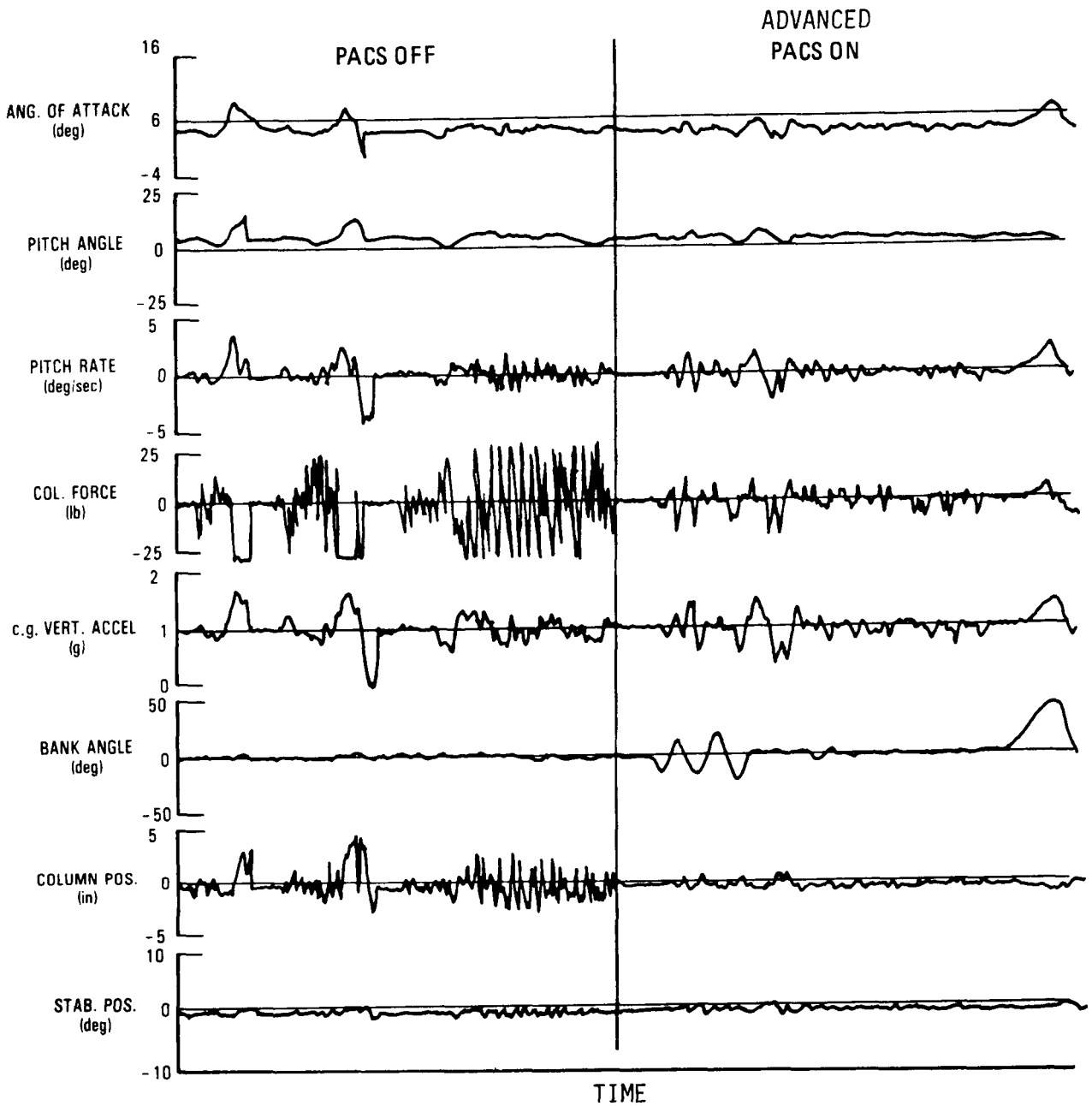


Figure 47.- Comparison of damping response characteristics of cruise flight condition 7 in calm air, with and without advanced PACS engaged, at $c.g. = 0.50\bar{c}$.

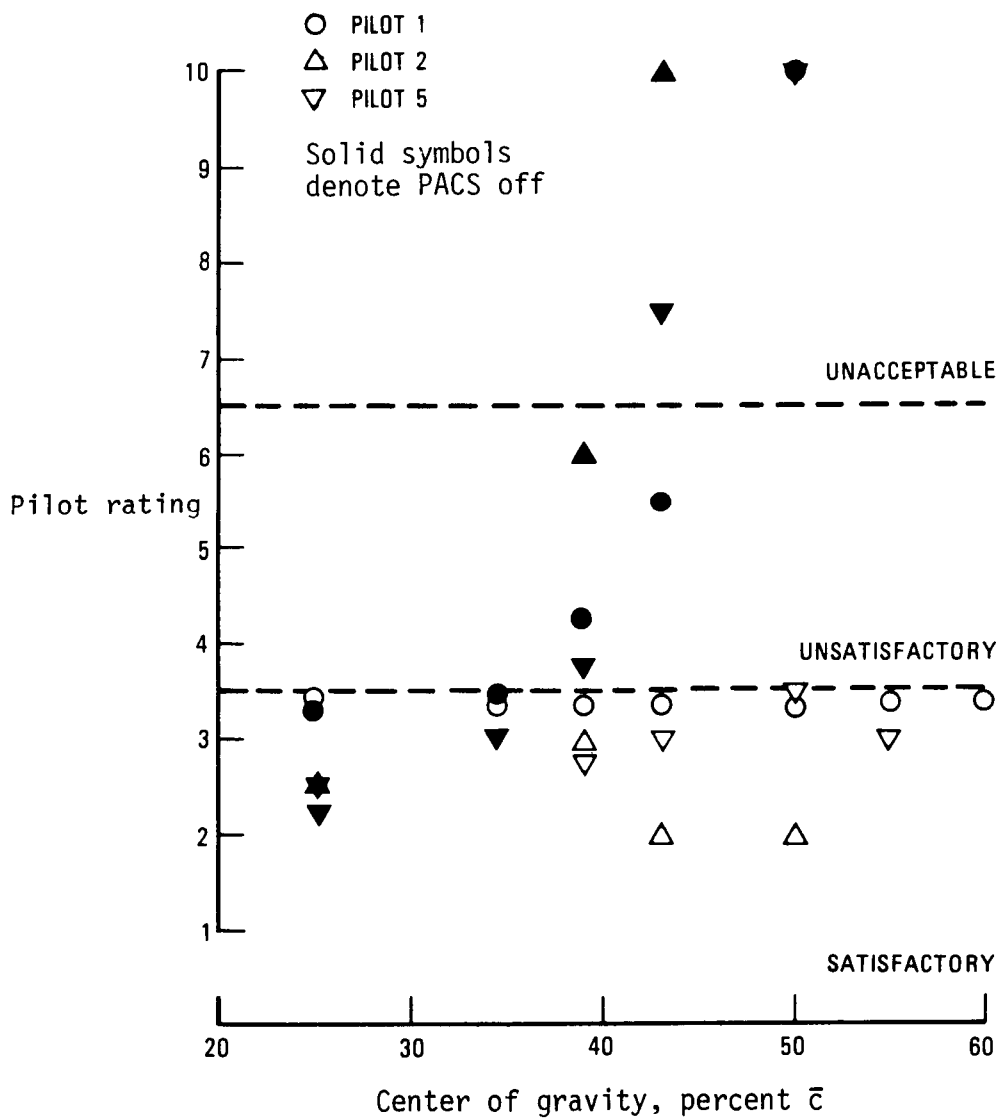


Figure 48.- Indication of effect of center-of-gravity position on pilot opinion with and without advanced PACS engaged for high-speed flight condition 16 in calm air.

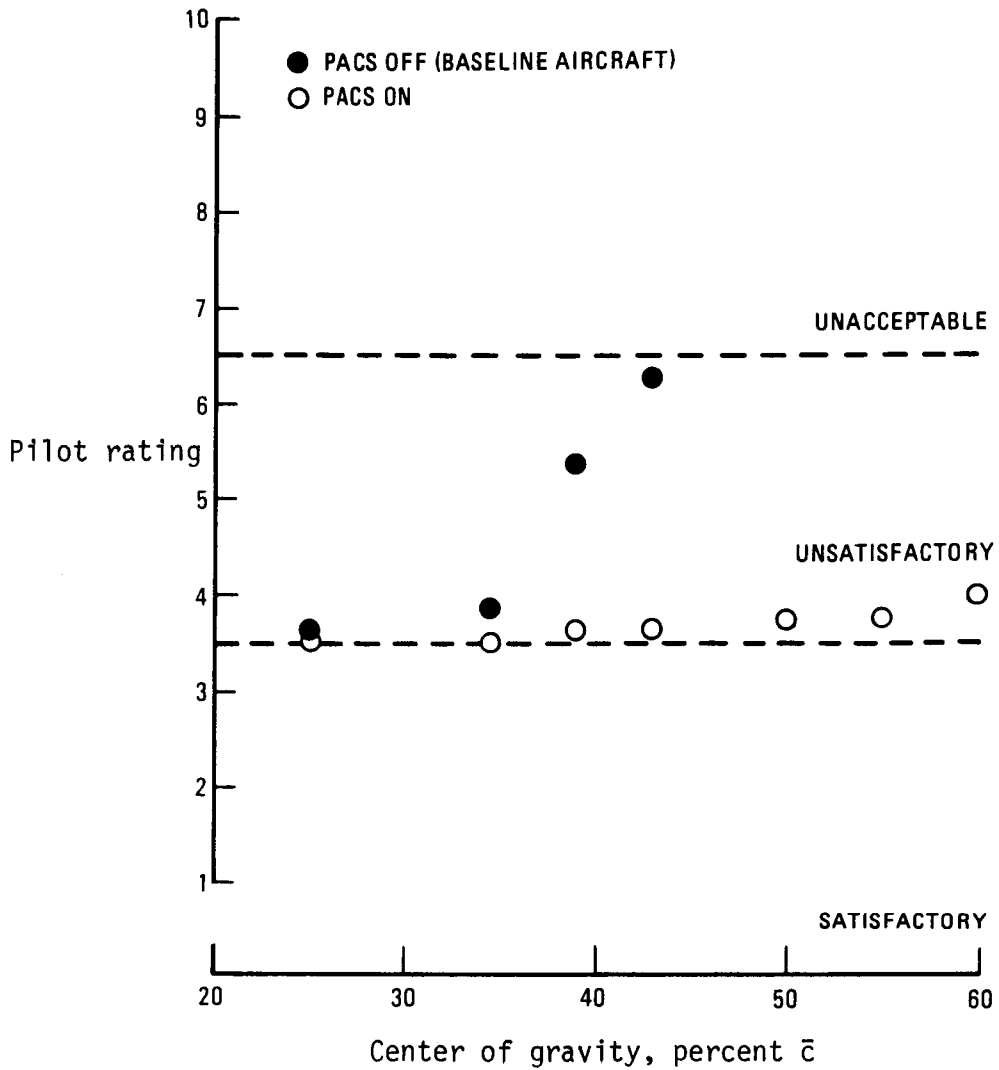


Figure 49.- Indication of effect of center-of-gravity position on pilot opinion with and without advanced PACS engaged for high-speed flight condition 16 in moderate turbulence.

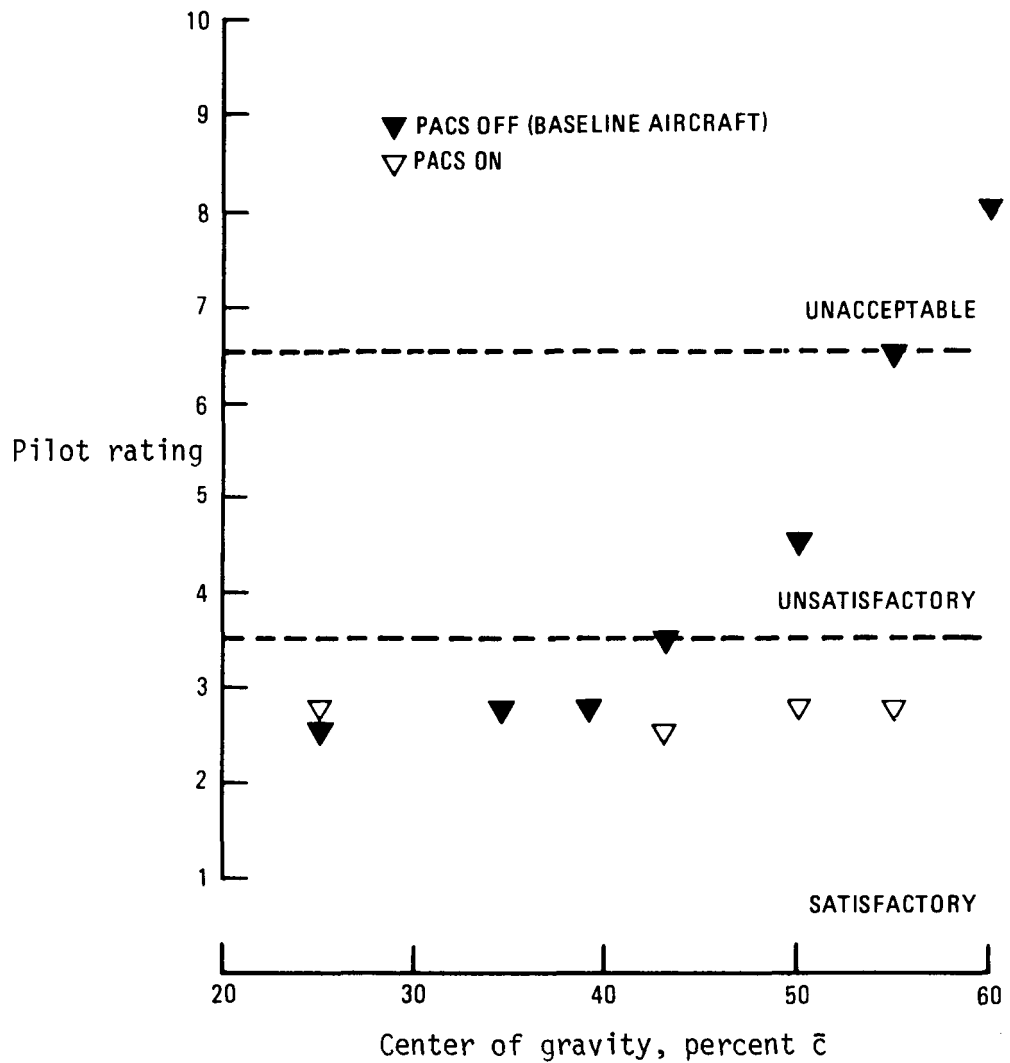


Figure 50.- Indication of effect of center-of-gravity position on pilot opinion with and without advanced PACS engaged for holding flight condition 17 in calm air.

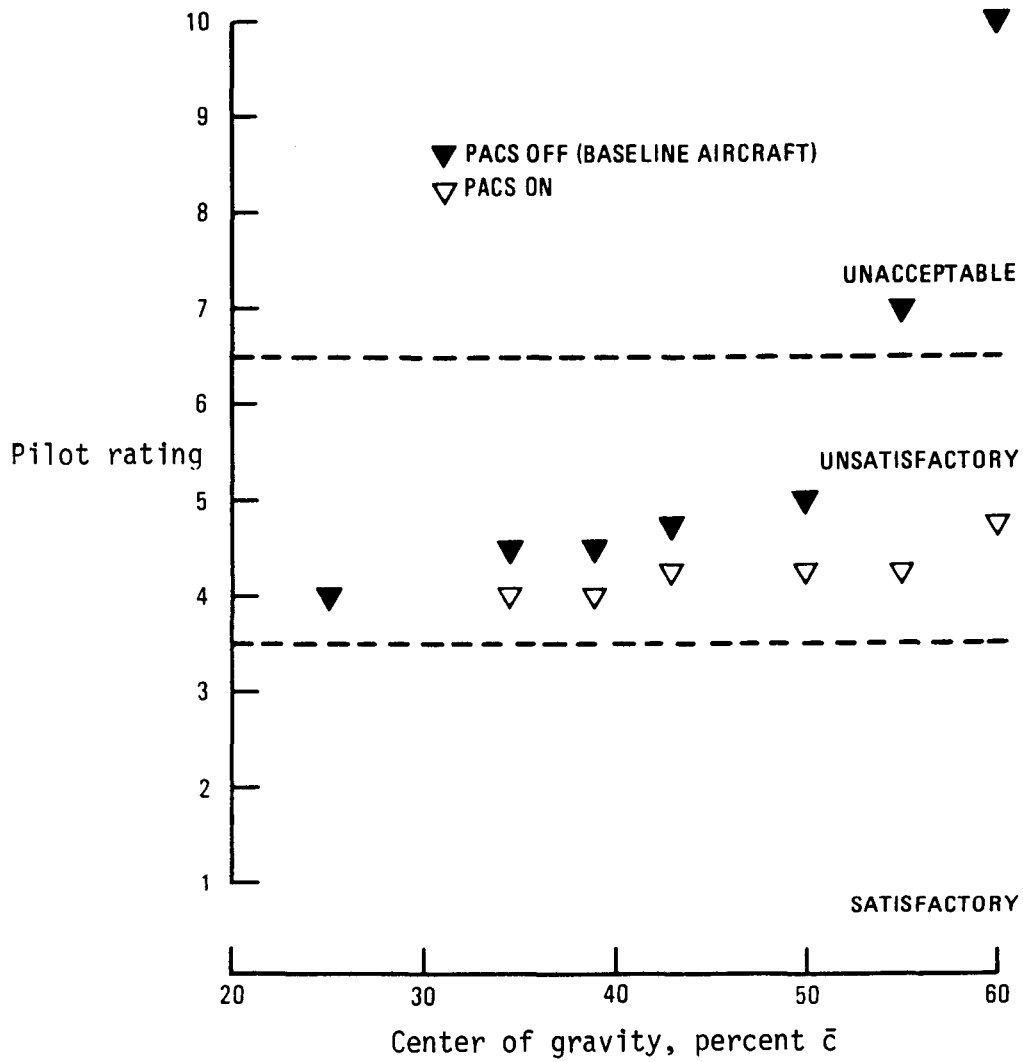


Figure 51.- Indication of effect of center-of-gravity position on pilot opinion with and without advanced PACS engaged for holding flight condition 17 in moderate turbulence.

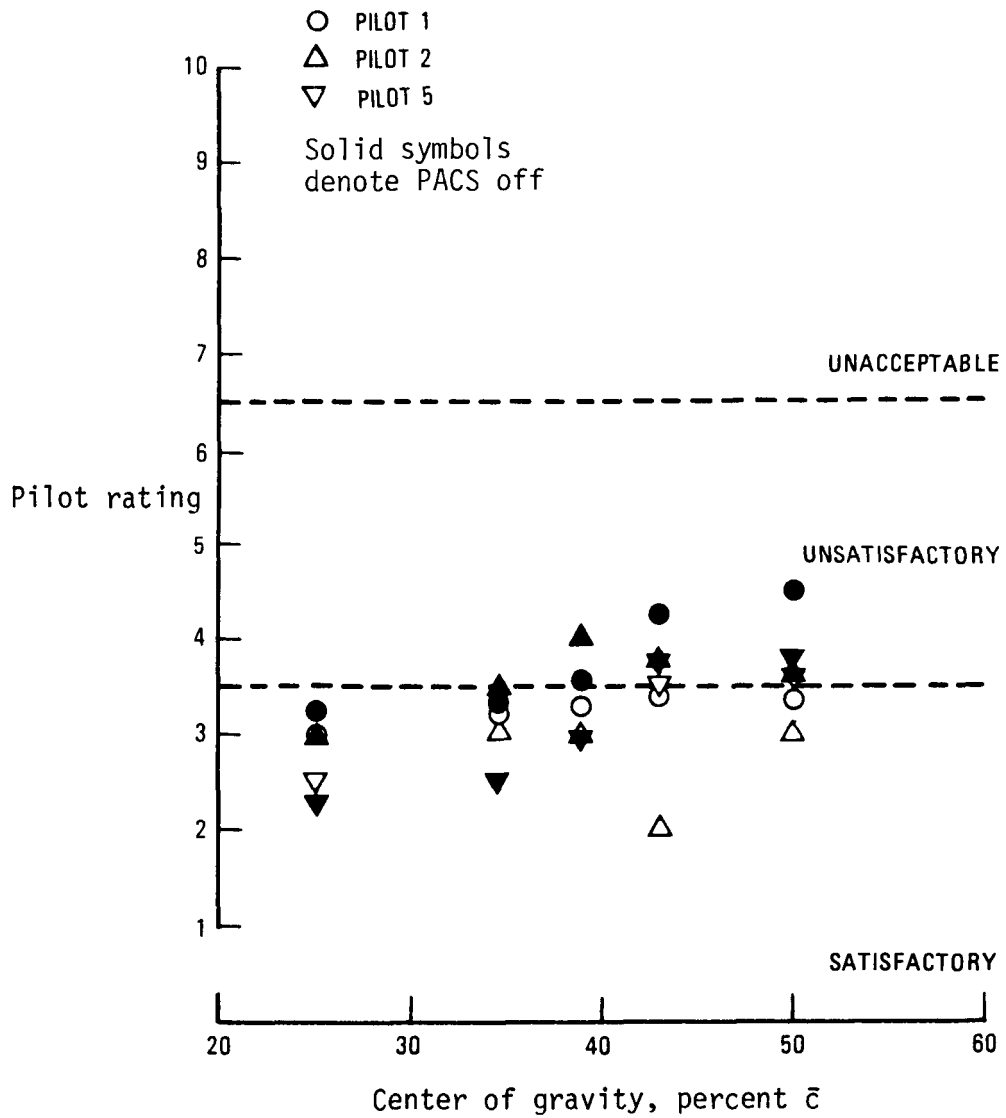


Figure 52.- Indication of effect of center-of-gravity position on pilot opinion with and without advanced PACS engaged for landing flight condition 18 in calm air.

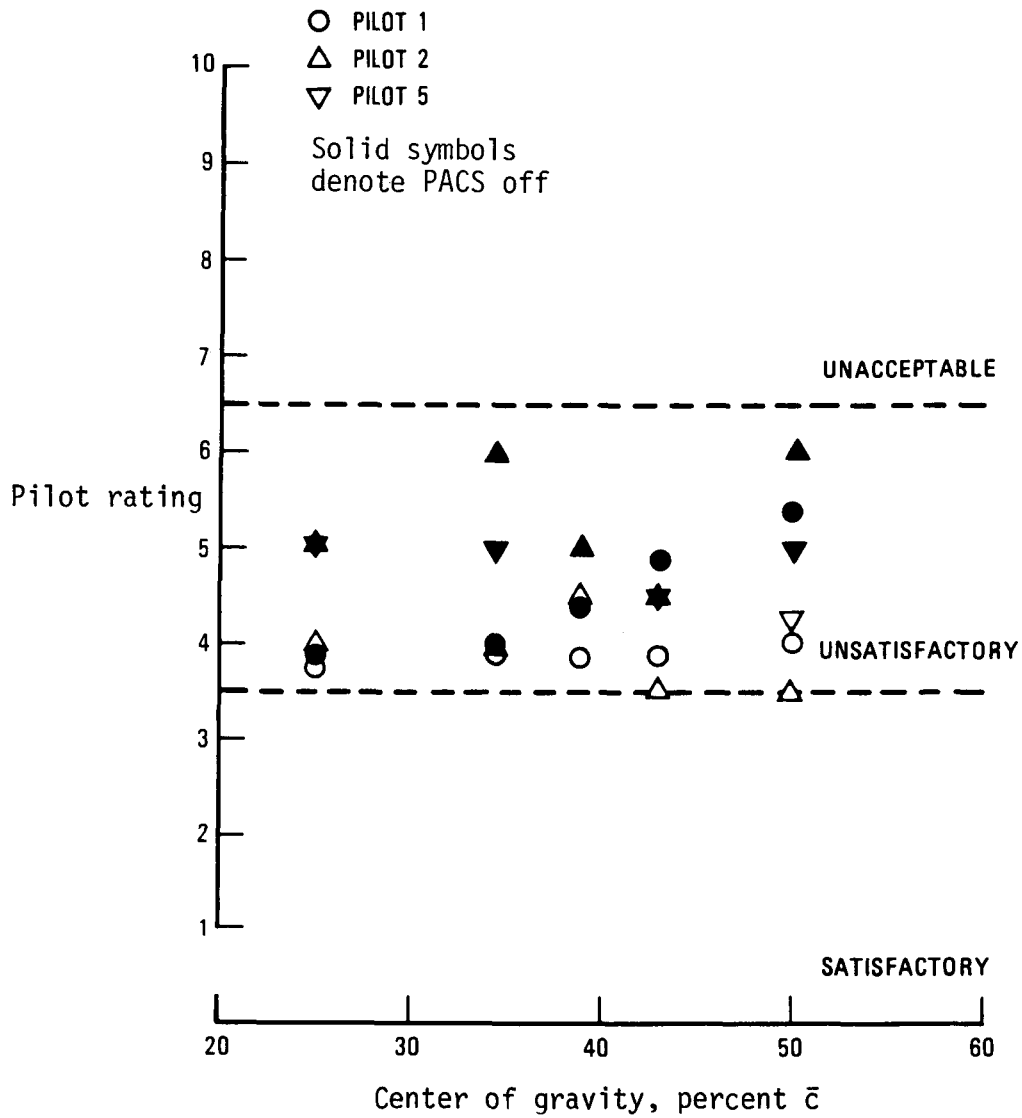


Figure 53.- Indication of effect of center-of-gravity position on pilot opinion with and without advanced PACS engaged for landing flight condition 18 in moderate turbulence.

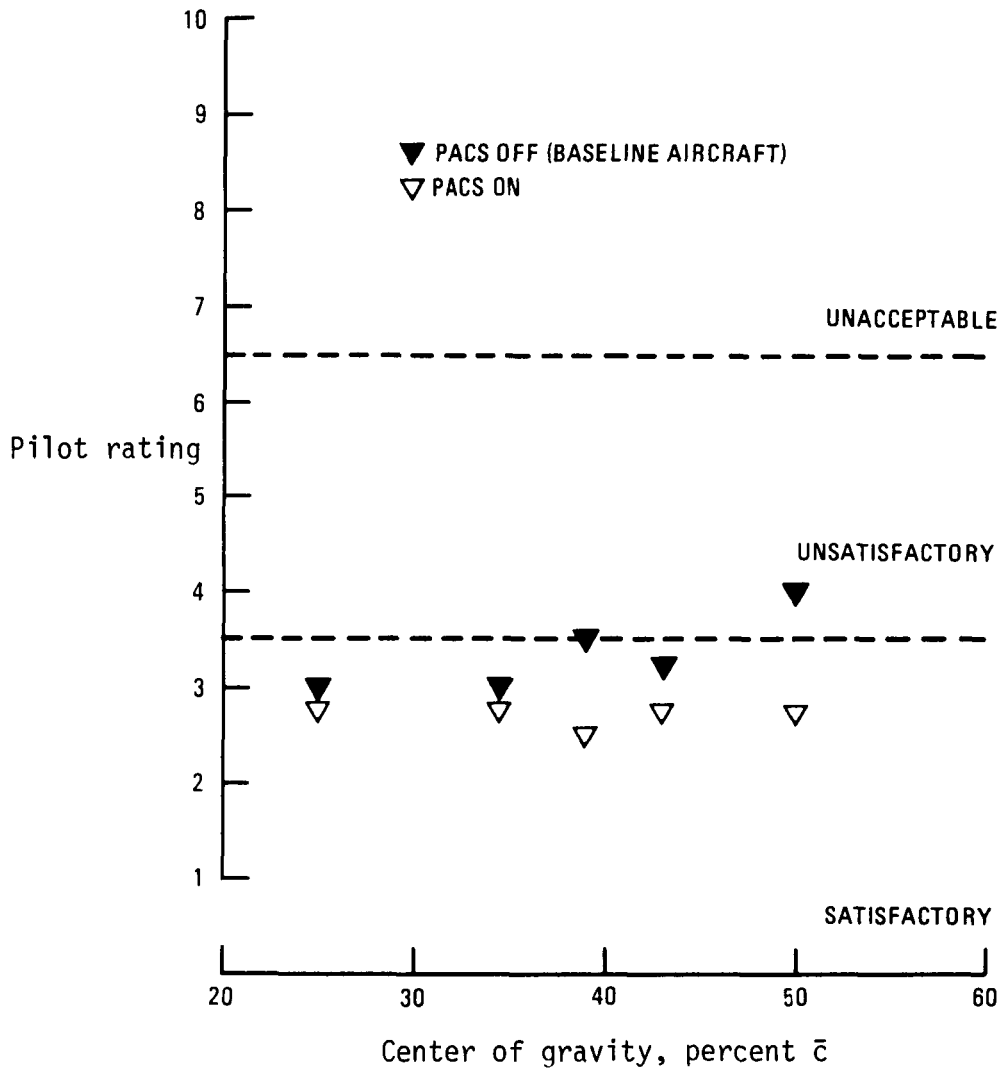


Figure 54.- Indication of effect of center-of-gravity position on pilot opinion with and without advanced PACS engaged for takeoff flight condition 19 in calm air.

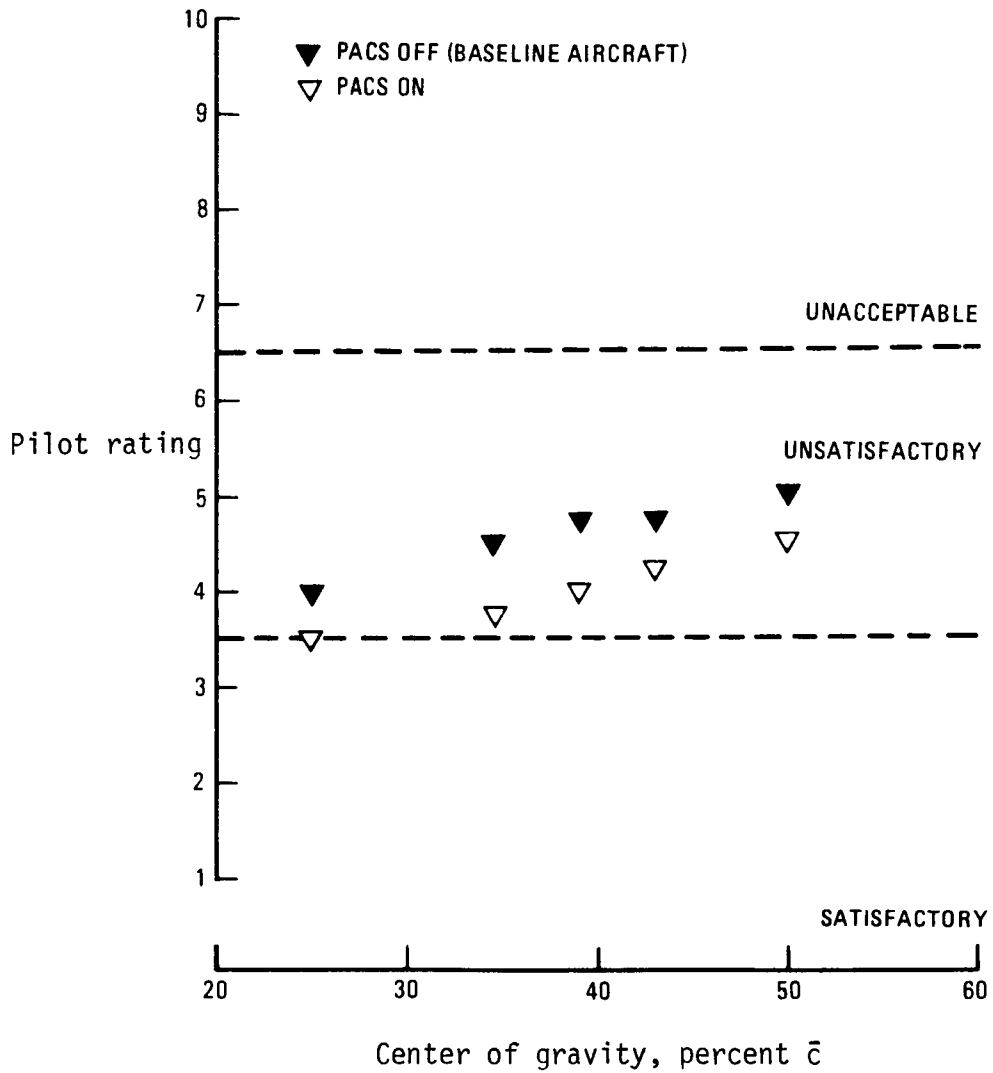


Figure 55.- Indication of effect of center-of-gravity position on pilot opinion with and without advanced PACS engaged for takeoff flight condition 19 in moderate turbulence.

C-2

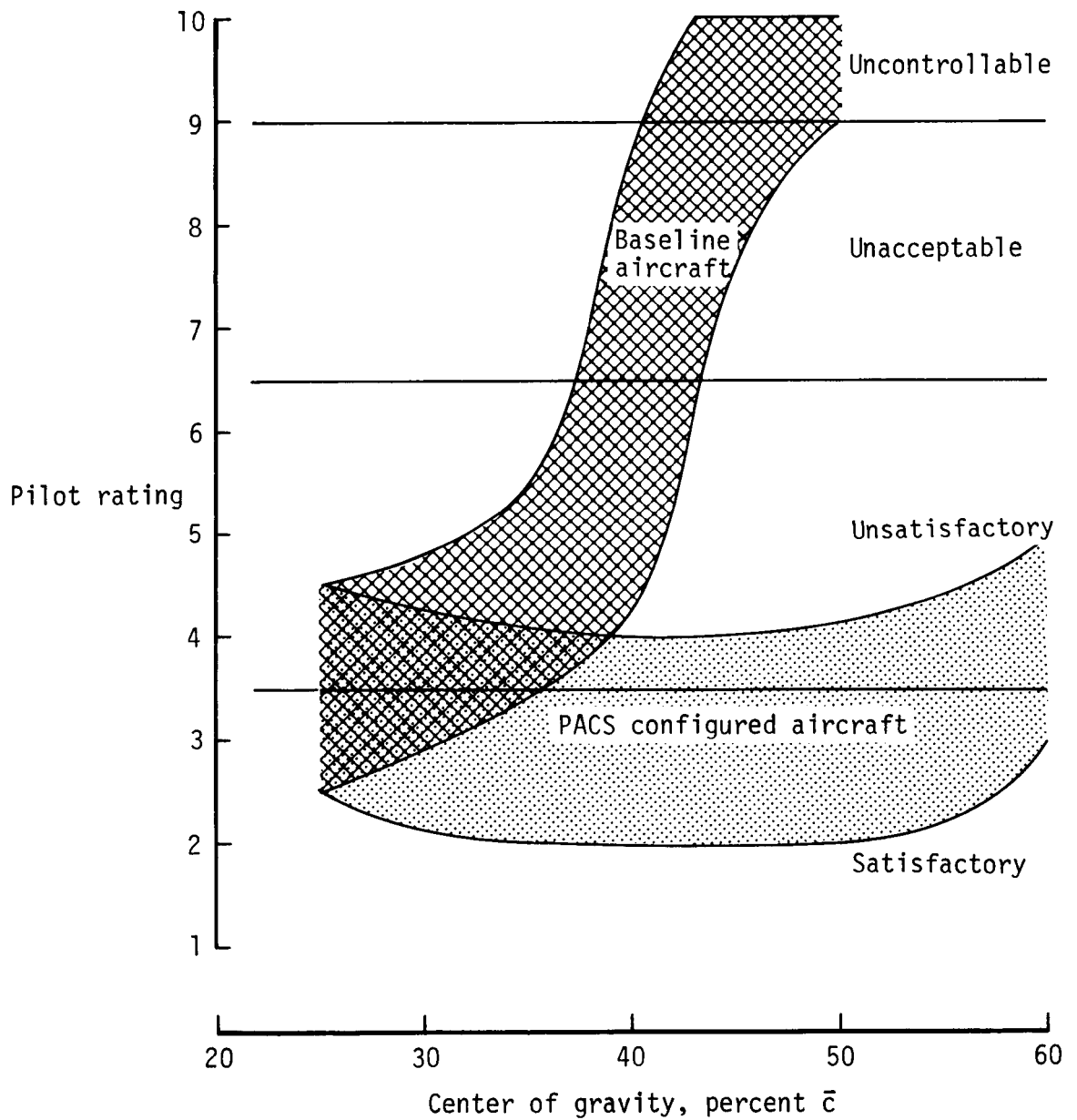
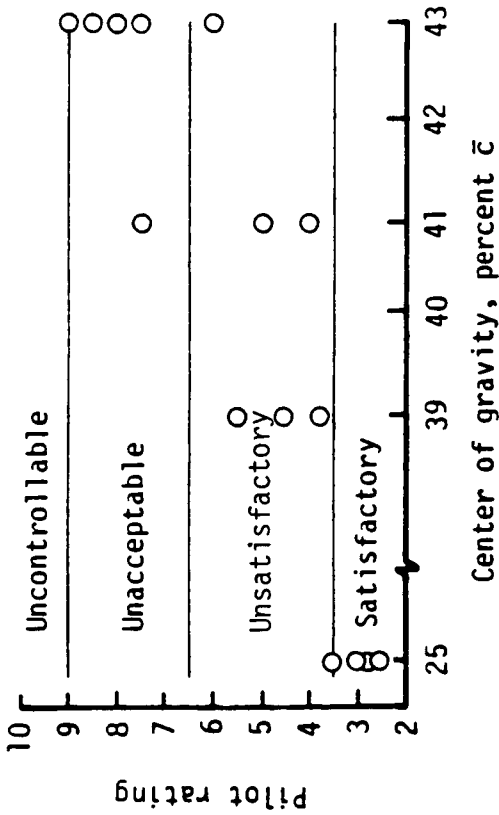
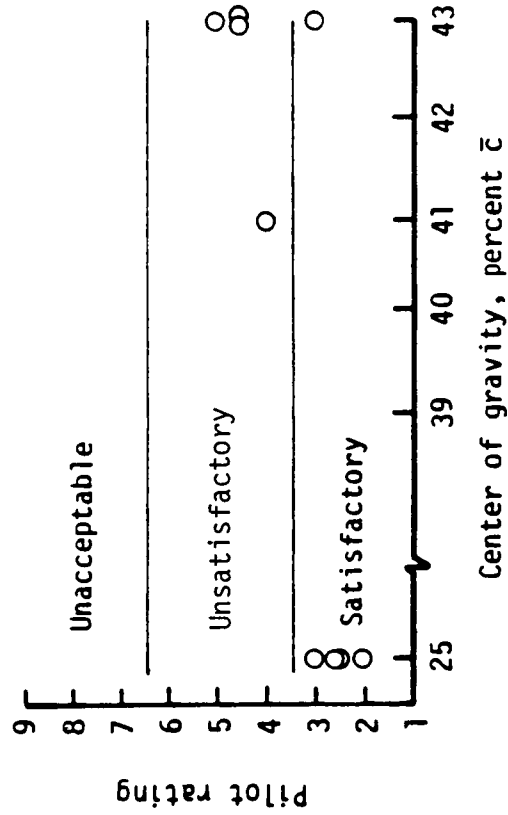


Figure 56.- Summary of effect of center-of-gravity position on pilot opinion, with and without advanced PACS, for the cruise and high-speed flight conditions evaluated. Both calm air and turbulent conditions are included.

Simulation



(a) Aileron active control system (AACCS) on.



(b) Aileron active control system (AACCS) off.

Test airplane

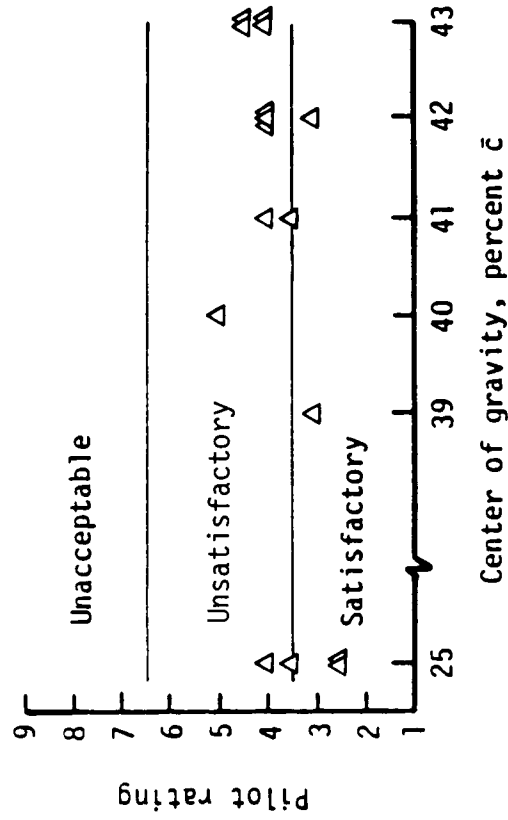
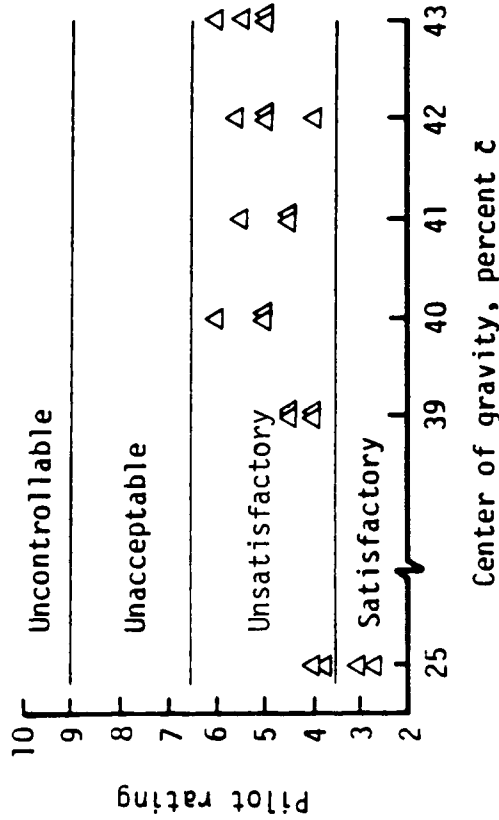


Figure 57.- Comparison of pilot ratings between simulator and flight test aircraft with PACS off for cruise flight condition 10.

Open symbols represent flight test results
 Solid symbols represent ground-based simulation results

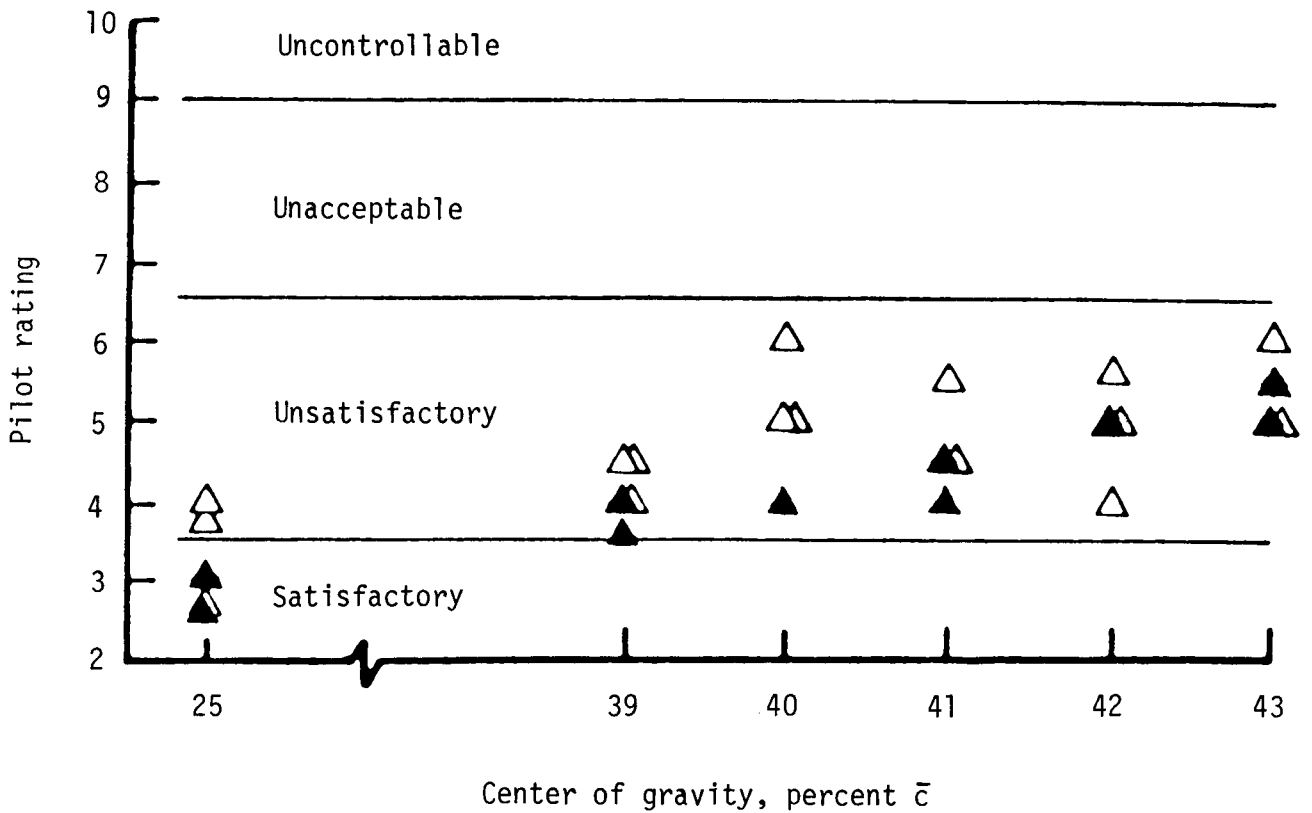


Figure 58.- Comparison of pilot ratings between simulator and flight test airplane for baseline airplane (PACS off, AACS on). Piloting procedures are same for both tests.

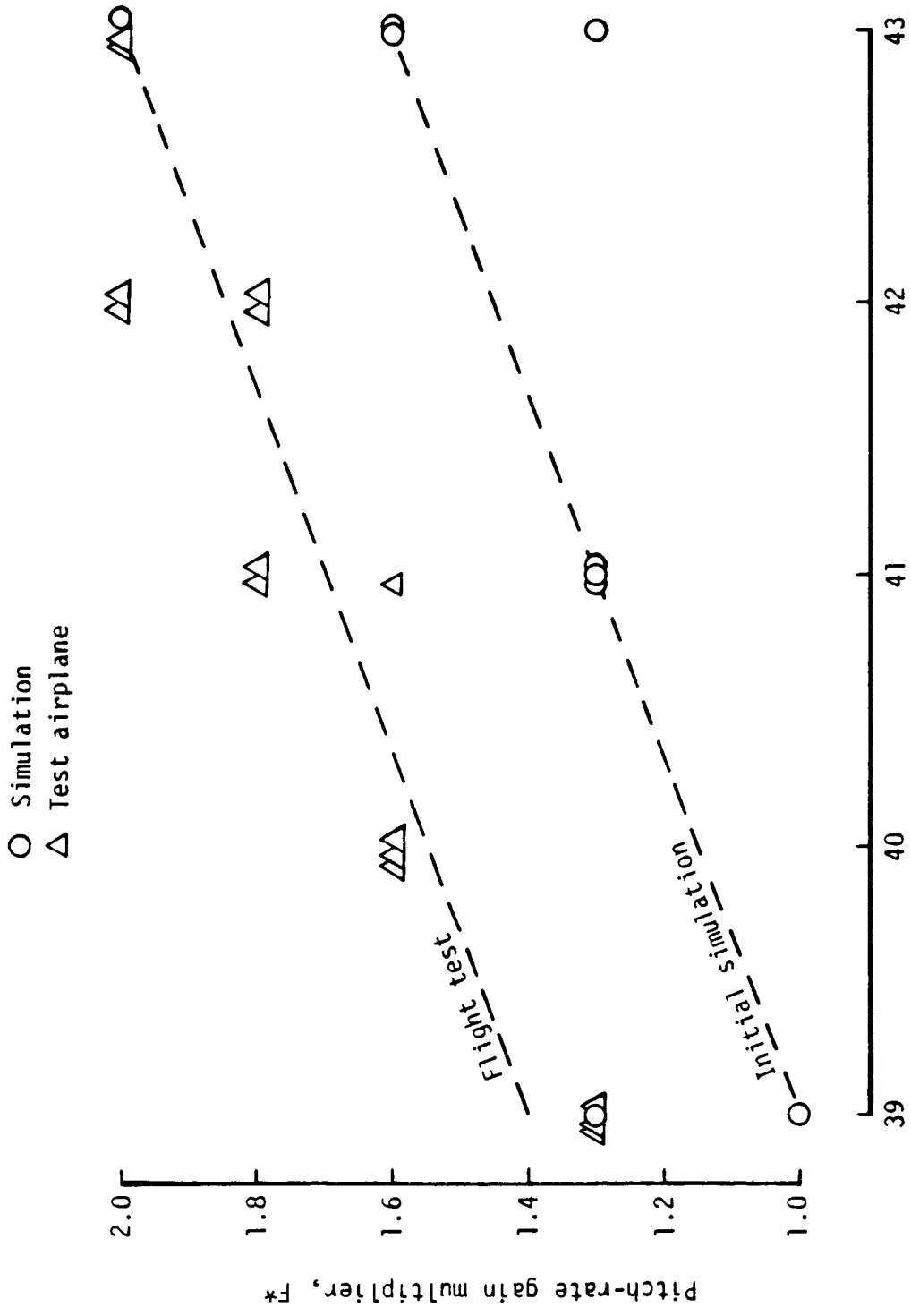


Figure 59.- Comparison of preferred pitch-rate feedback gains between simulator and flight test airplane. (Flight condition 10; AACCS on; PACS with full feedforward.)

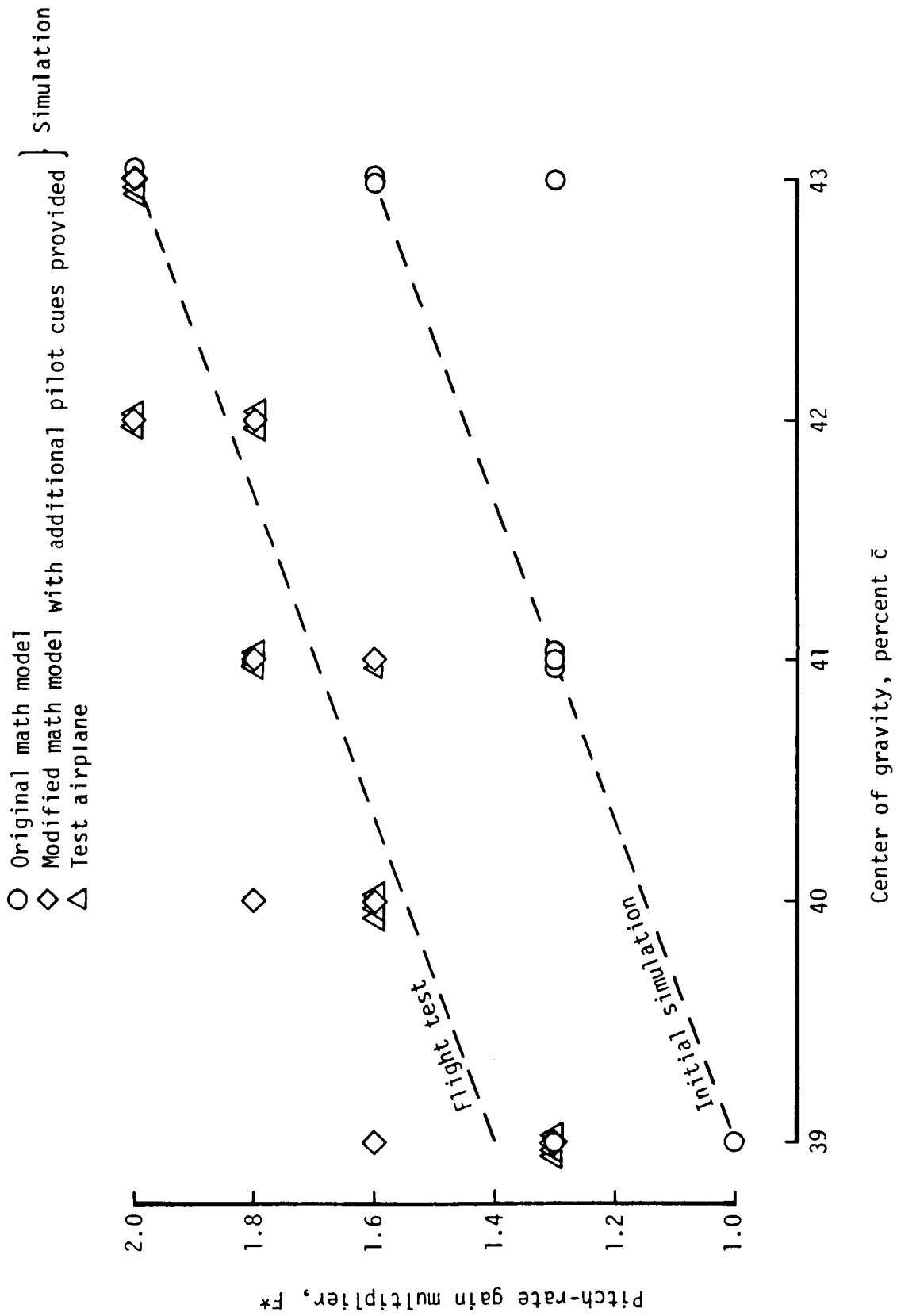


Figure 60.- Indication of effect of supplying pilot with sufficient cues during simulation tests.

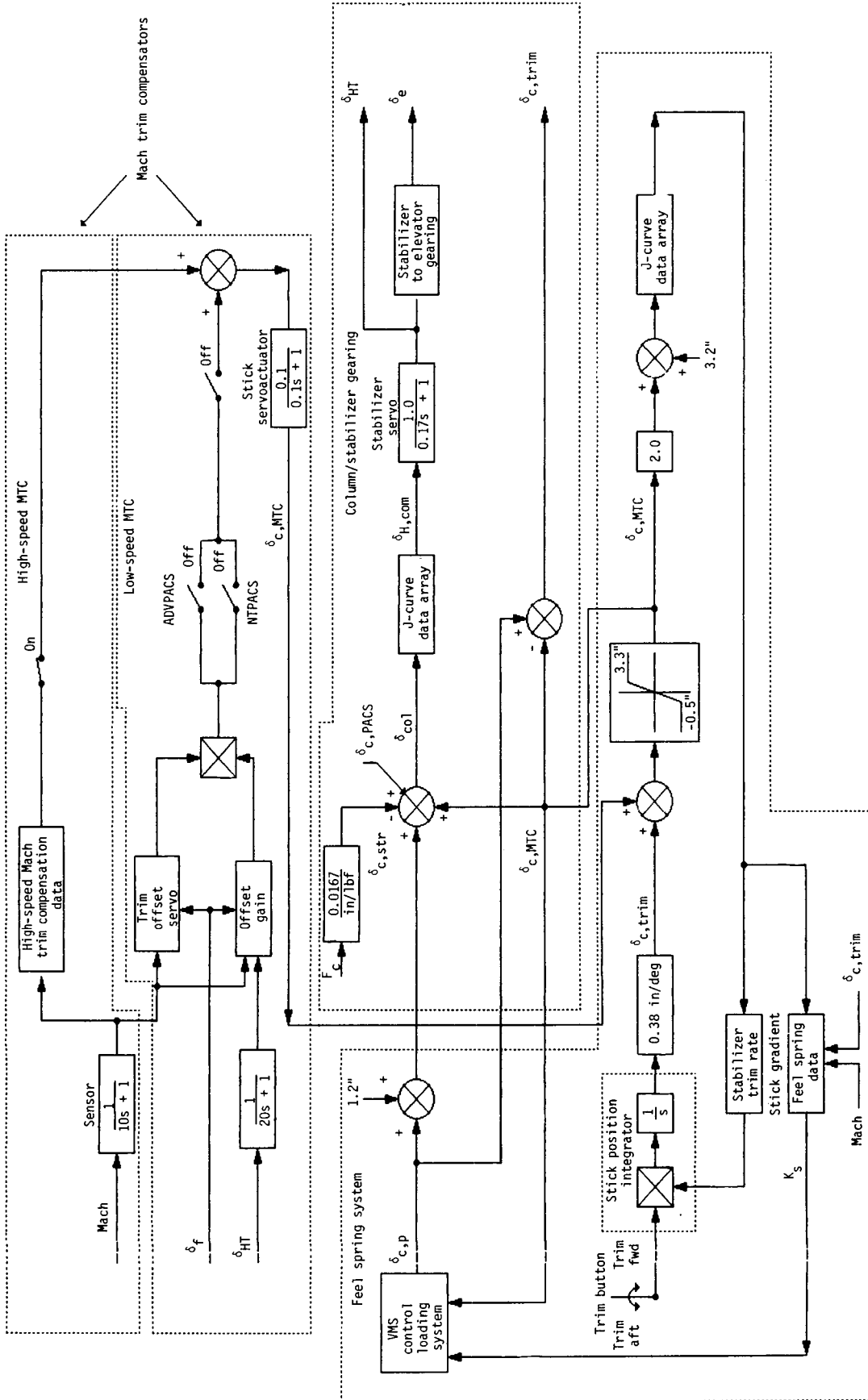


Figure 61.- Block diagram of basic longitudinal control system.

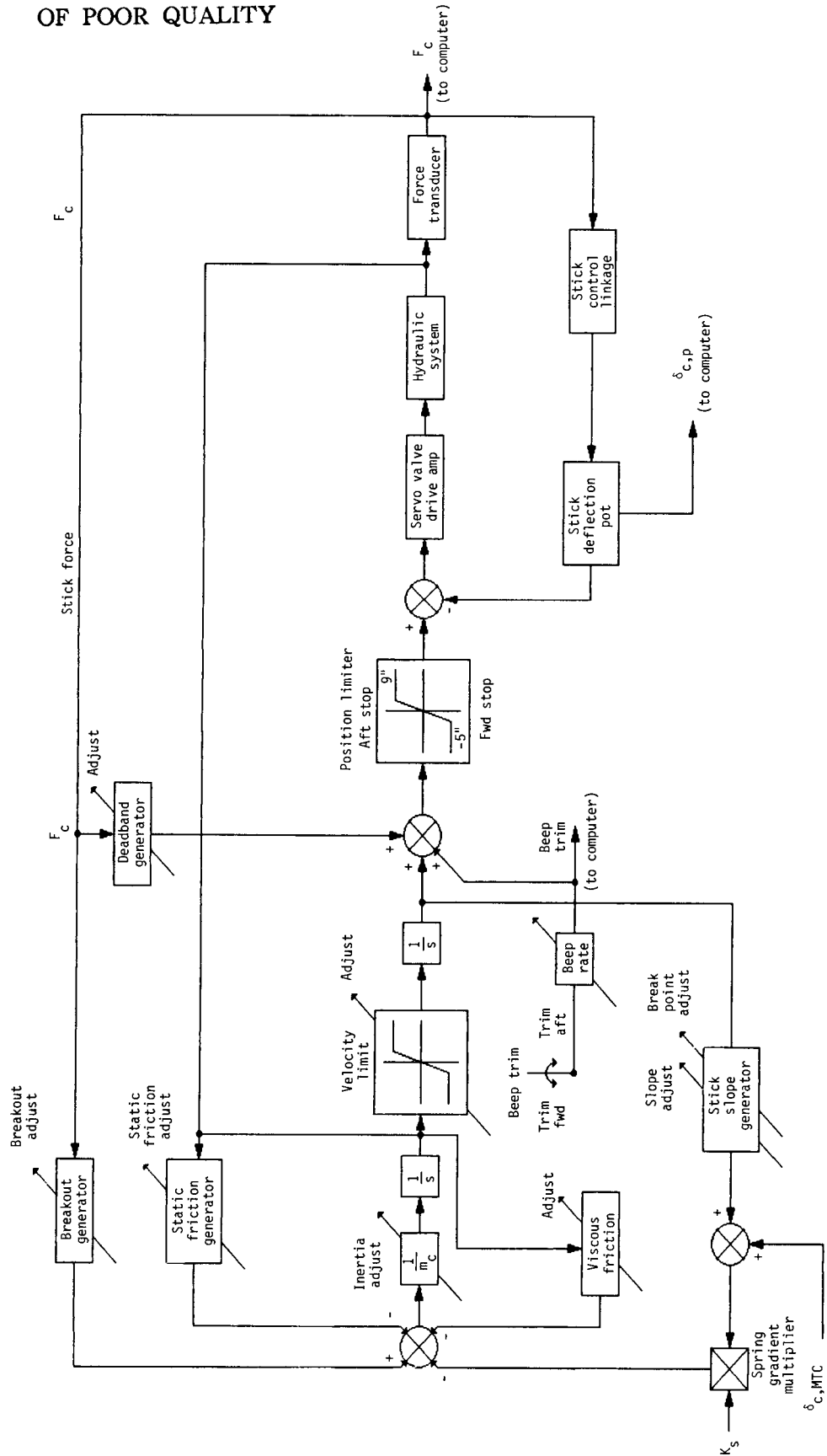


Figure 62.- Block diagram of longitudinal control loading system.

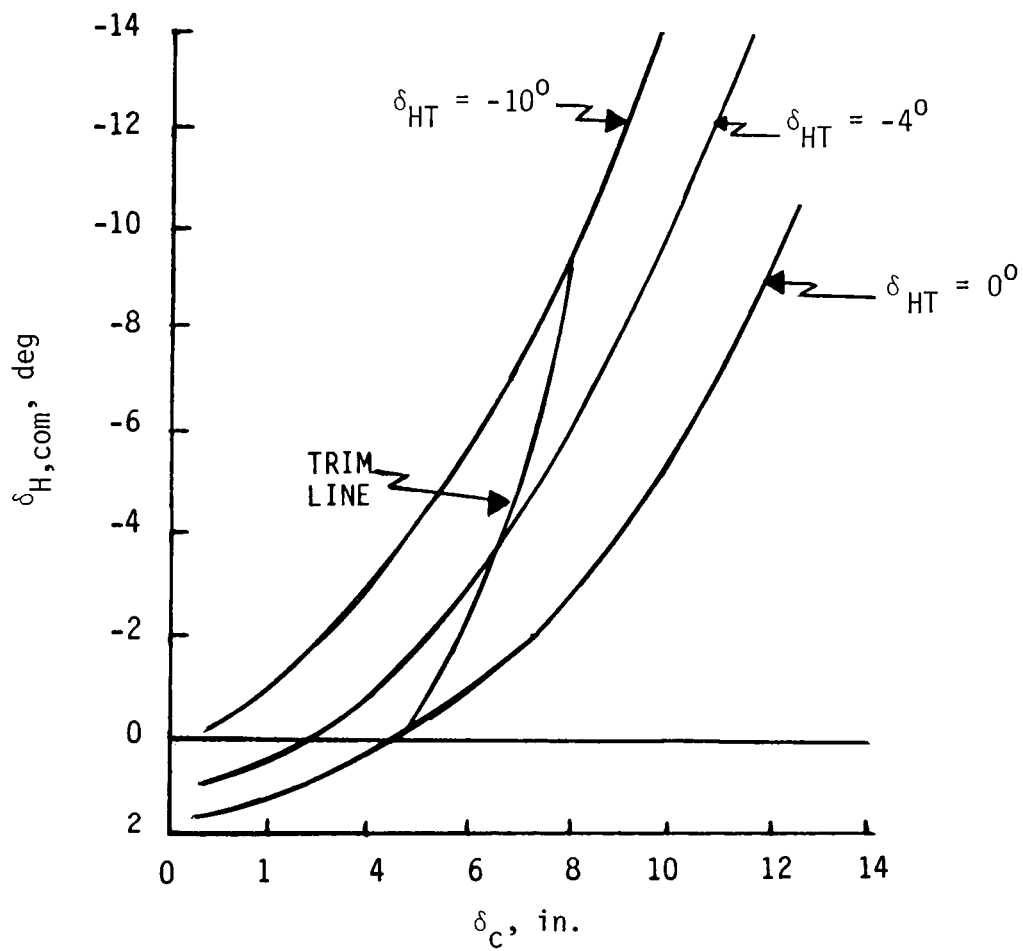


Figure 63.- Indication of nonlinear stabilizer/column gearing (J-curve).

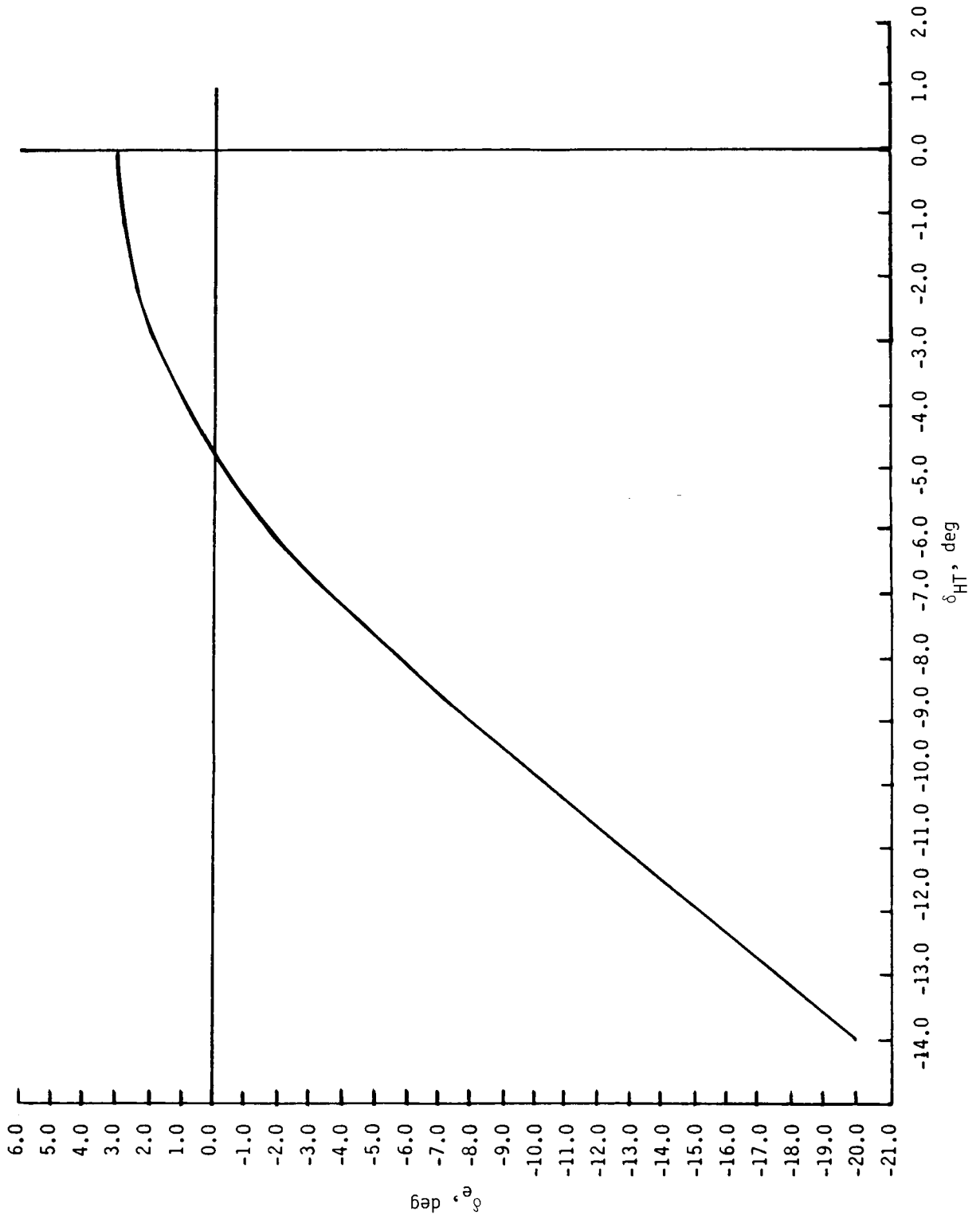
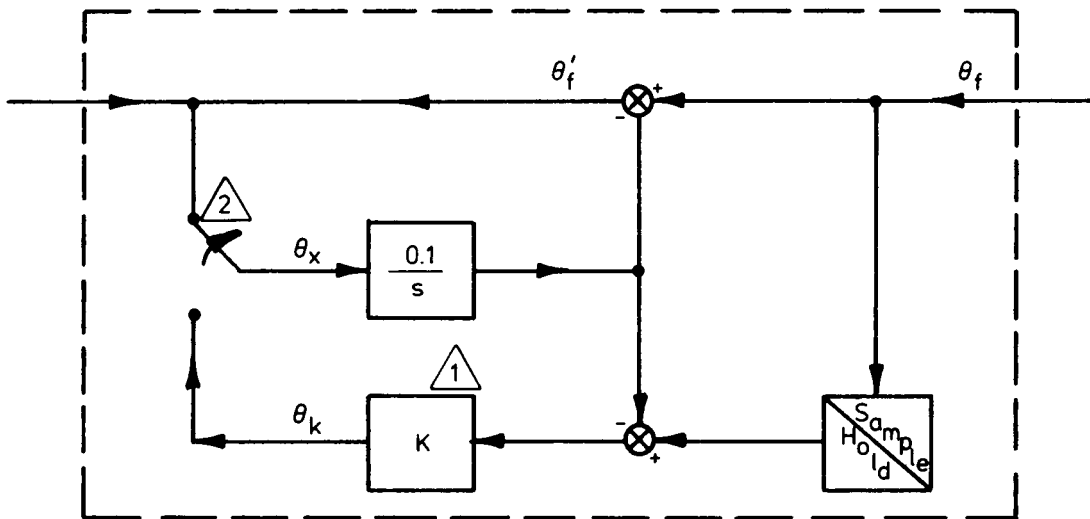


Figure 64.- Nonlinear gearing of elevator/stabilizer.



- $\triangle 1$ $K=0.0$ If $F \oplus T \oplus WOG$
 $K=1.0$ Otherwise
- $\triangle 2$ $\theta_x = \theta'_f$ If $F \oplus T \oplus WOG$
 $\theta_x = \theta_k$ Otherwise
- F = Pilot Applied Force
 T = Trim Button Commanded
 WOG = Weight on Gear
 \oplus = Logical Sum

Figure 65.- Advanced PACS pitch synchronizer circuit.

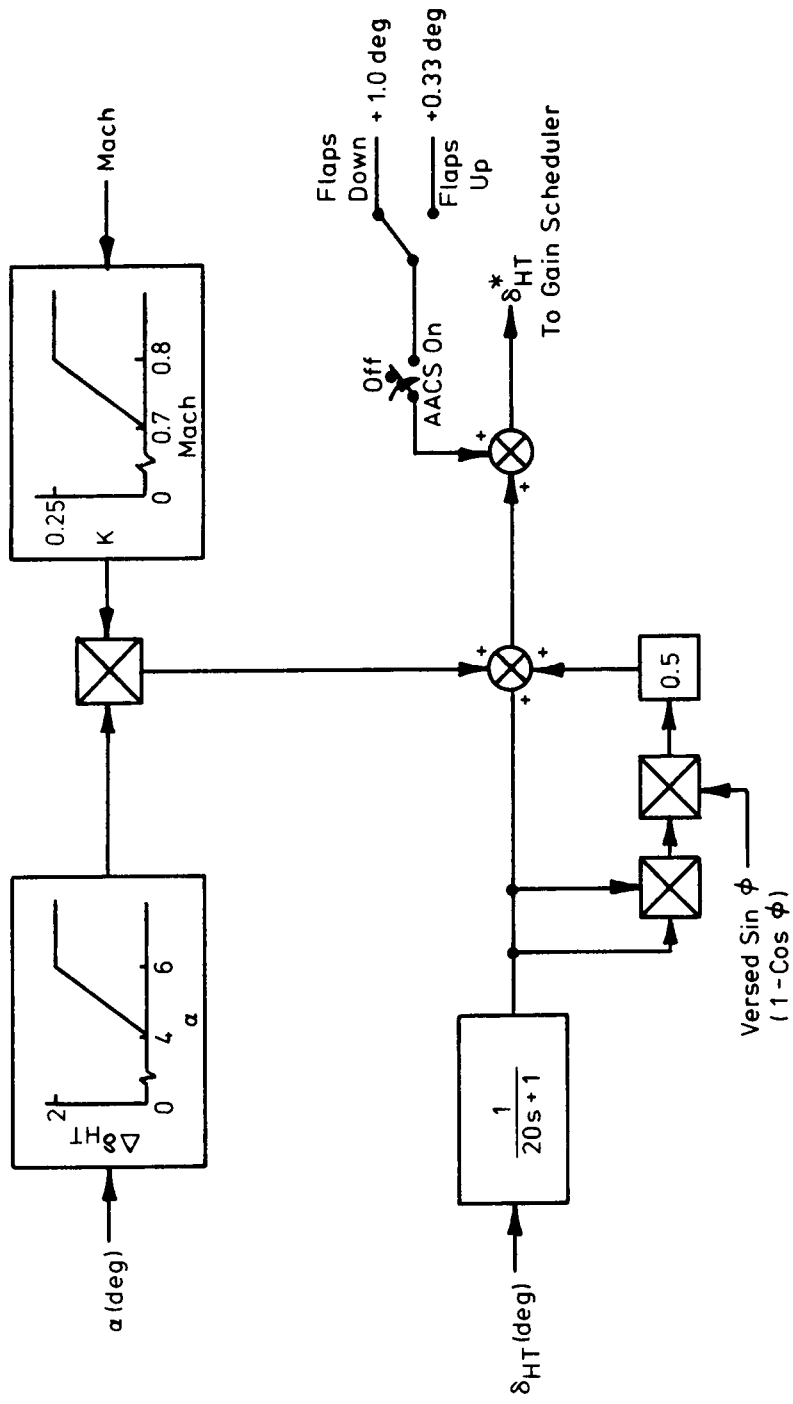


Figure 66.- Advanced PACS gain controller.