

L-1011 TESTING WITH
RELAXED STATIC STABILITY

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Wind tunnel and flight tests indicate that fuel savings of 2 percent can be achieved by c.g. management for an L-1011 with the current wing configuration. The normal c.g. location is at 25 percent MAC as shown in figure 1. The maximum fuel saving occurs for a c.g. location of 35 percent MAC. However, flight at 35 percent requires that the c.g. range be extended aft of the 35-percent point. Flight at c.g. locations aft of 35 percent requires a pitch active control system (PACS) so that handling qualities are not significantly degraded. Figure 1 shows that the near-term PACS was flight tested with the c.g. at 39 percent MAC.

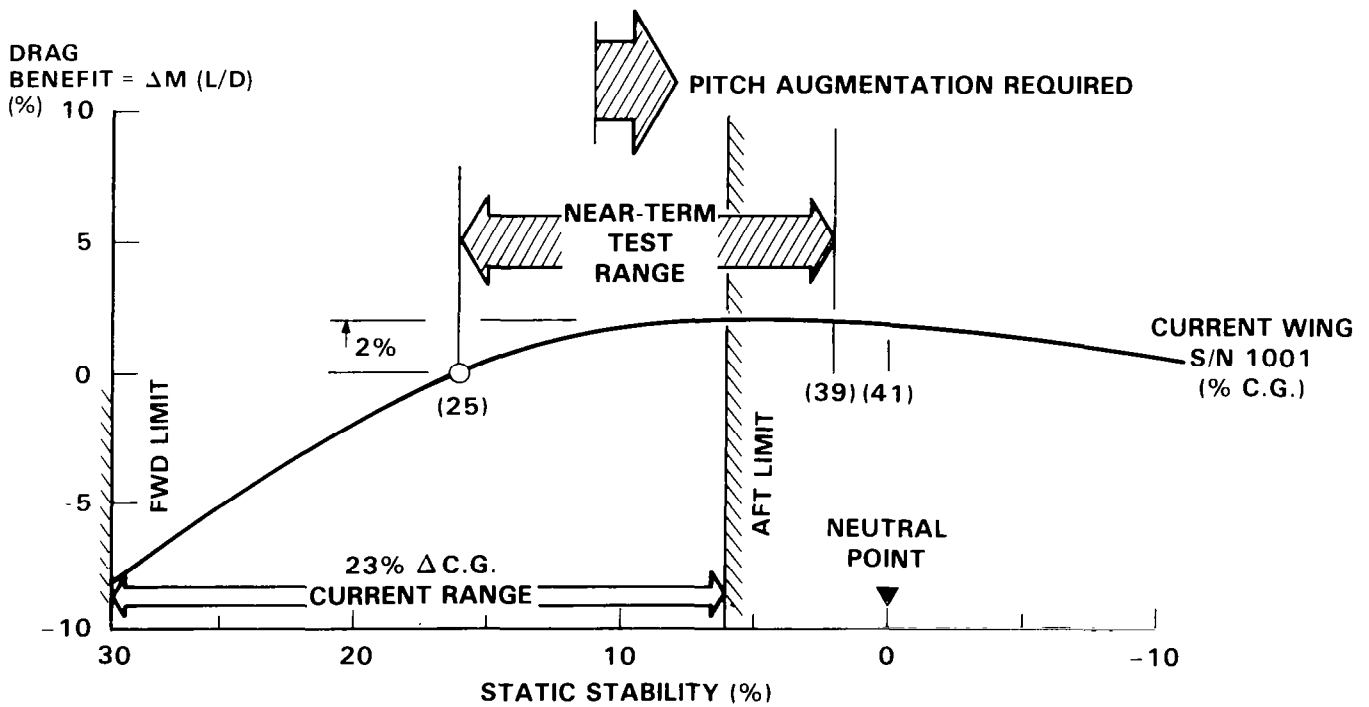


Figure 1

The near-term pitch stability augmentation system consists of a lagged pitch rate damper with washed-out column feed-forward loop. The damper serves to provide the necessary short-period frequency and damping characteristics while also suppressing turbulence effects, and the feed forward was designed to "quicken" the pitch rate response and reduce stick force gradients without affecting system stability. A block diagram of the system is shown in figure 2.

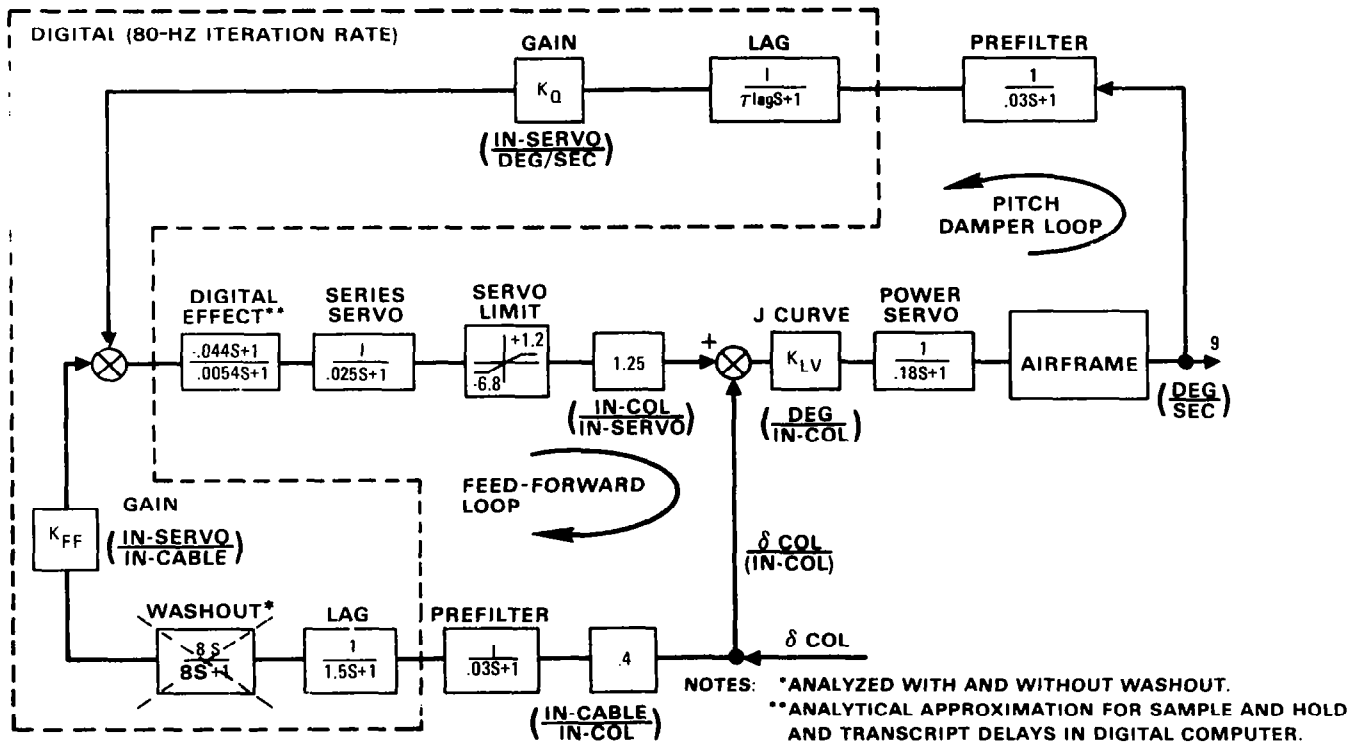


Figure 2

The schedules of pitch rate feedback gain and lag time constant were chosen so that the augmented stability L-1011 has good short-period frequency and damping characteristics for the complete center-of-gravity range (25 to 39 percent \bar{c}) investigated in flight test. The gain and lag schedules are defined as a function of calibrated airspeed. Characteristics with and without augmentation are shown in figure 3.

$M = 0.83, h = 33,000 \text{ ft}, W = 360,000 \text{ lb}$

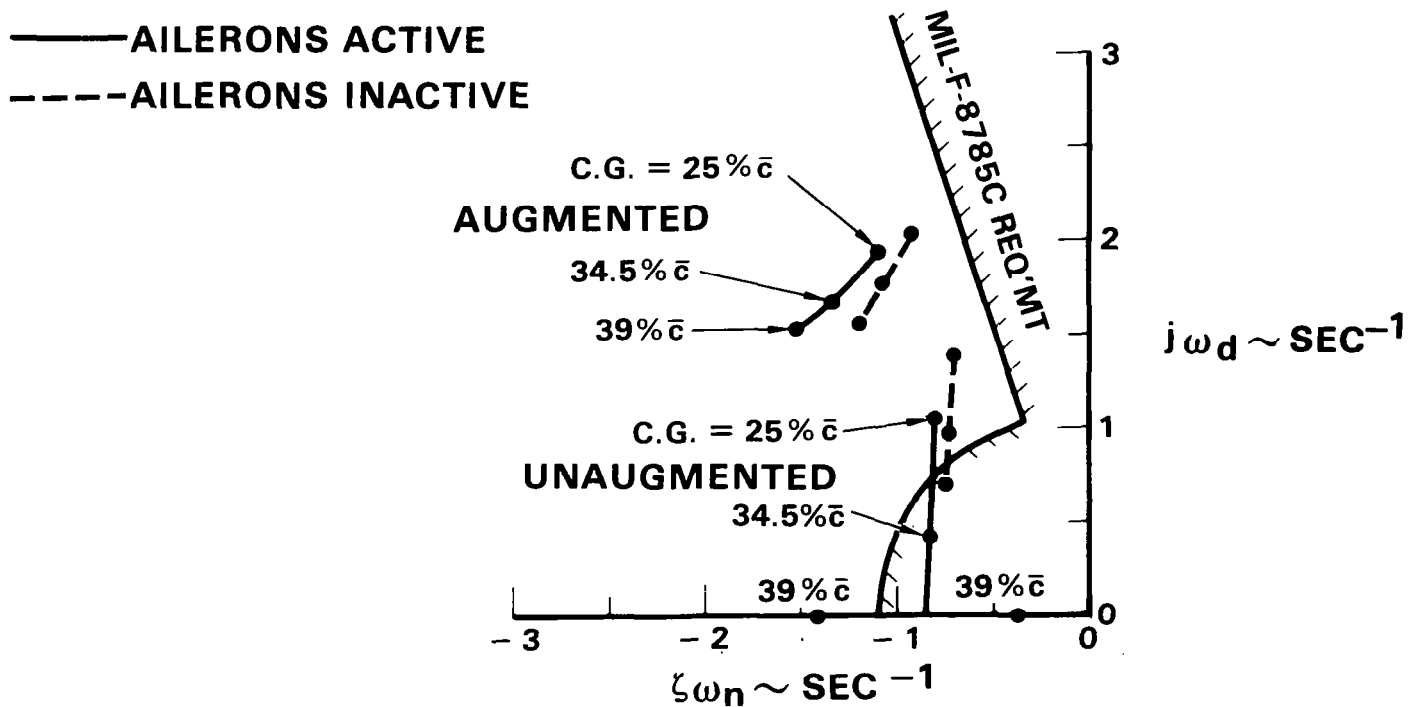


Figure 3

In cruise, the near-term augmentation system without feed-forward compensation provides slightly higher maneuver stability column force gradients at the relaxed static stability aft limit than the basic airplane has at mid c.g. without augmentation. The effect of feed-forward compensation is to reduce the column force gradients to levels comparable to the basic unaugmented airplane at typical c.g. locations. The initial force gradients comply with MIL-F-8785C (ref. 1) requirements; however, there is a deviation from linearity which results in a short-term negative gradient in the 1.6- to 2.0-g range which is unacceptable in terms of MIL-F-8785C requirements. These characteristics are shown in figure 4. While these negative gradient characteristics may not be desirable, they are not uncommon to Class III transport configurations which cruise at Mach numbers above 0.8. It is suggested that some narrow region of negative gradient may be acceptable as long as a substantial force level is maintained and there is adequate buffet onset or other warning prior to limit load factor.

M = 0.83, h = 33,00 ft, W = 360,000 lb

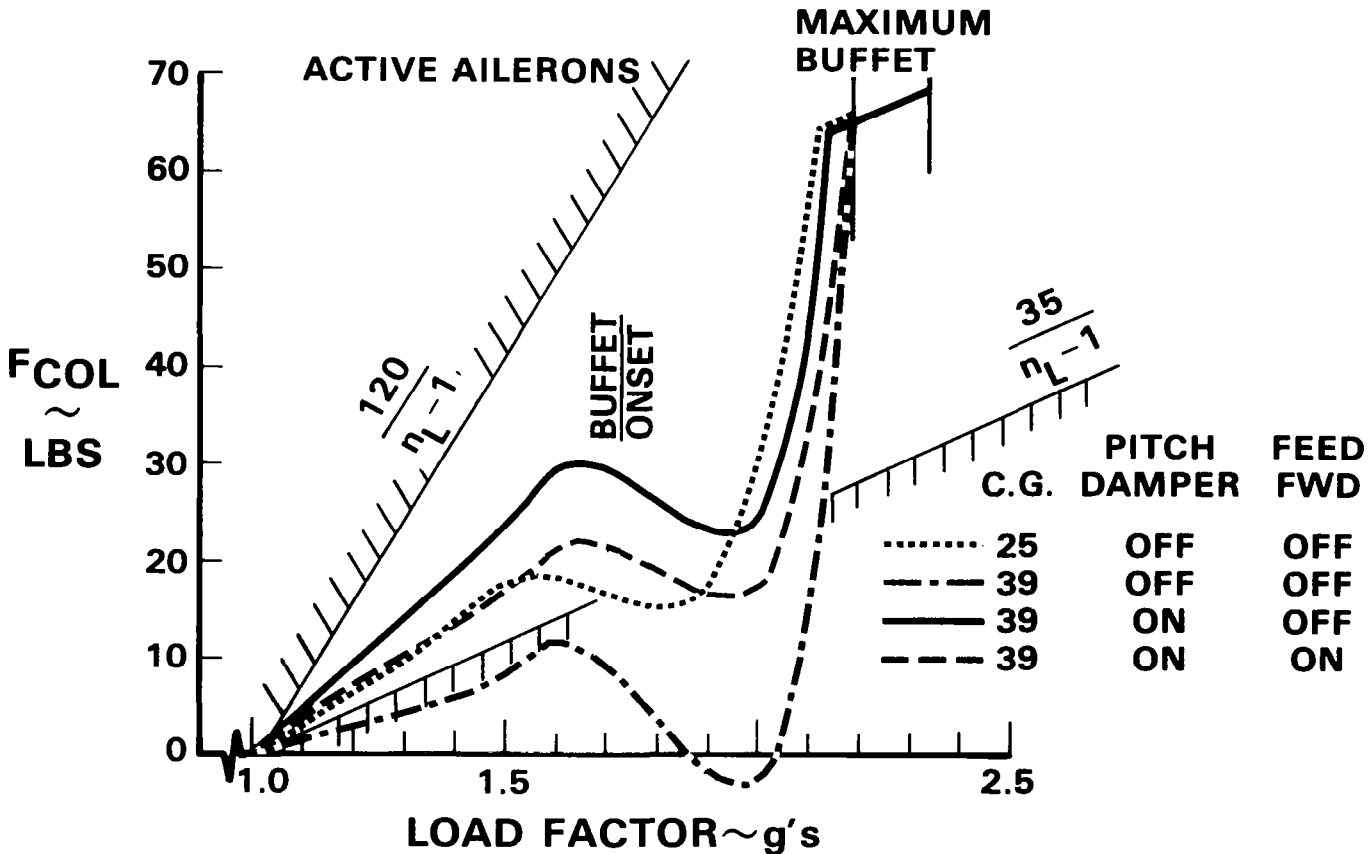


Figure 4

The near-term pitch active control system was ultimately evaluated in an actual flight test program utilizing the Lockheed in-house research airplane, L-1011 S/N 1001.

The near-term PACS flight test aircraft is fully instrumented for performance of flight test programs. This aircraft has been equipped with extended wing tips and an aileron active control system. The increase in wing aspect ratio increases the aerodynamic efficiency of the aircraft, and the aileron active control system provides wing load alleviation which results in lower structure weight. This increased aerodynamic efficiency and lower structural weight provide approximately a 3-percent fuel savings. A unique feature of the basic L-1011 longitudinal control system is the flying stabilizer with a geared elevator. Modifications made to the L-1011 for the near-term PACS program are shown in figure 5.

Three pilots participated in the evaluation, which concentrated on two cruise altitude conditions and an overspeed condition (V_{MO}) at high dynamic pressure. The test program covered 47 hours of flying, 14 for flutter clearance, and 33 for flying qualities evaluation. Flying qualities were evaluated at c.g.'s from 25 to 39 percent \bar{c} , where the airplane with active ailerons is close to being neutrally stable (1 to 2 percent static margin) at high-altitude trim conditions.

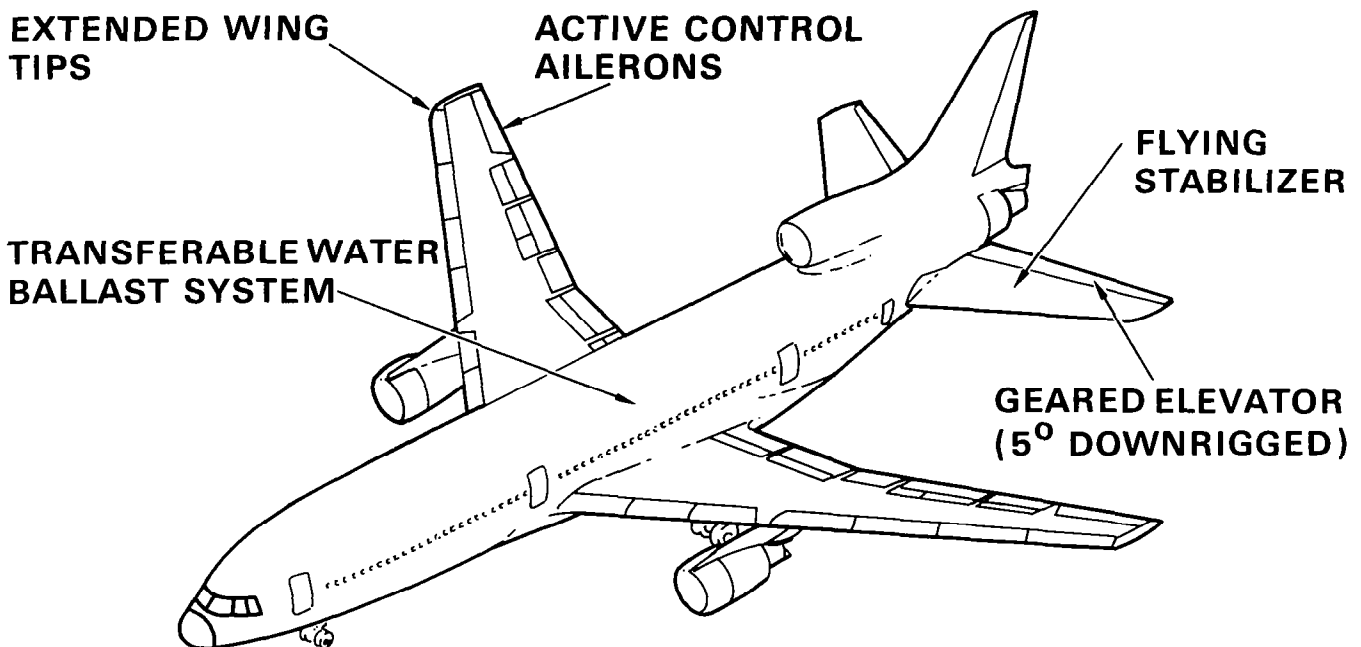


Figure 5

The pitch active control system utilizes a series servo which connects to the pitch control system in such a manner that the PACS commands are fed into the stabilizer power actuators without reflecting these commands into the pilot input control column. This is shown in figure 6.

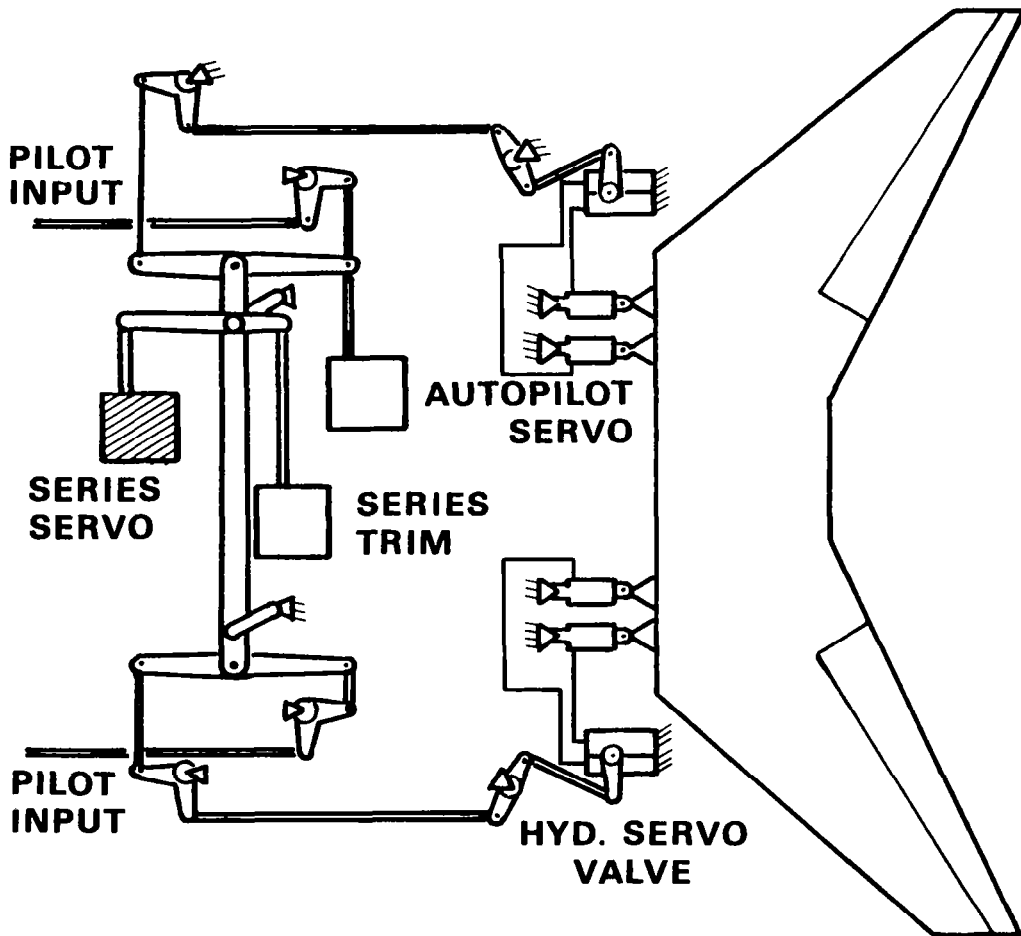


Figure 6

Flight test evaluation of the L-1011 with the near-term PACS operative shows a significant improvement in pilot ratings resulting in acceptable ratings to the flight test limit of 39 percent MAC which was 1 percent from the neutral stability point. The variations of pilot ratings with center-of-gravity locations with and without augmentation are shown in figure 7.

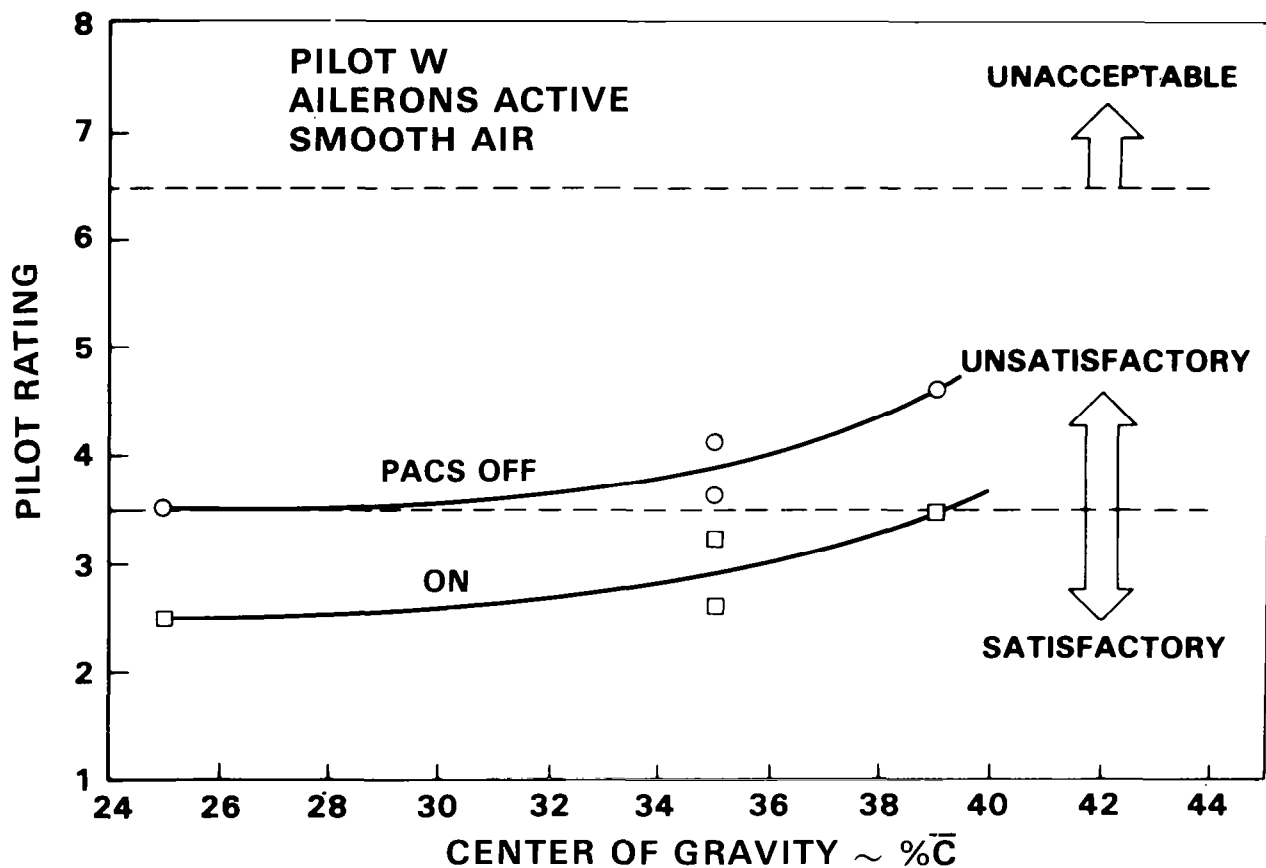


Figure 7

The fuel saving benefits to be gained by c.g. management are highly dependent on the aircraft wing configuration. Figure 8 shows that for advanced wing concepts aft movement of the c.g. location may result in fuel savings up to 4 percent. This 4 percent is based on increased aerodynamic efficiency determined by analyses and wind tunnel tests. The maximum benefits occur when the c.g. location is at approximately a -10-percent static stability margin. An advanced PACS that has a reliability of 10^{-9} is required for flight at this negative stability margin.

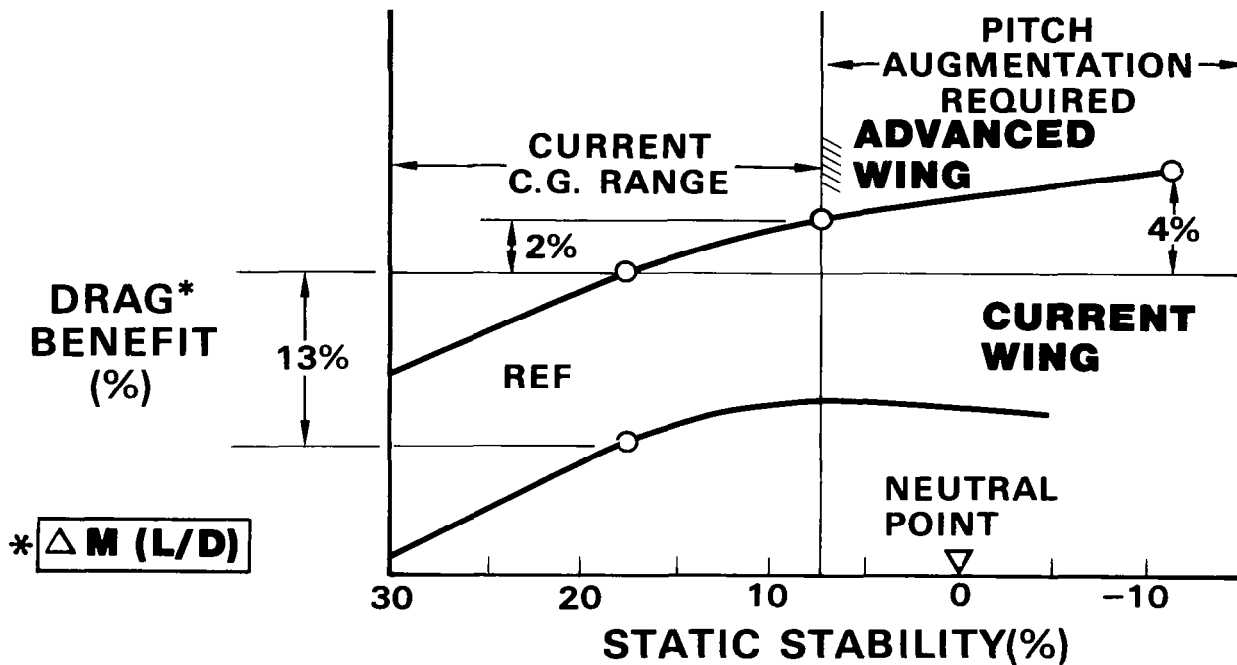


Figure 8

Figure 9 shows the control model used in an eigenstructure placement control law synthesis technique.

With the feedback matrix $[F]$ closed, the state-space equation becomes

$$\{\dot{x}\} = [A + BFC] \{x\} + \{z\}$$

In the synthesis process, $[F]$ is computed such that the eigenvalues and eigenvectors of $[A + BFC]$ at any c.g. condition are nearly the same as those for $[A]$ with the c.g. at 25 percent \bar{c} .

$$[F] = [K_{\theta} \quad K_u \quad K_{NZ} \quad K_{\dot{\theta}}]$$

This set of gains operates on the four feedback signals: incremental pitch attitude, incremental speed, normal acceleration, and pitch rate.

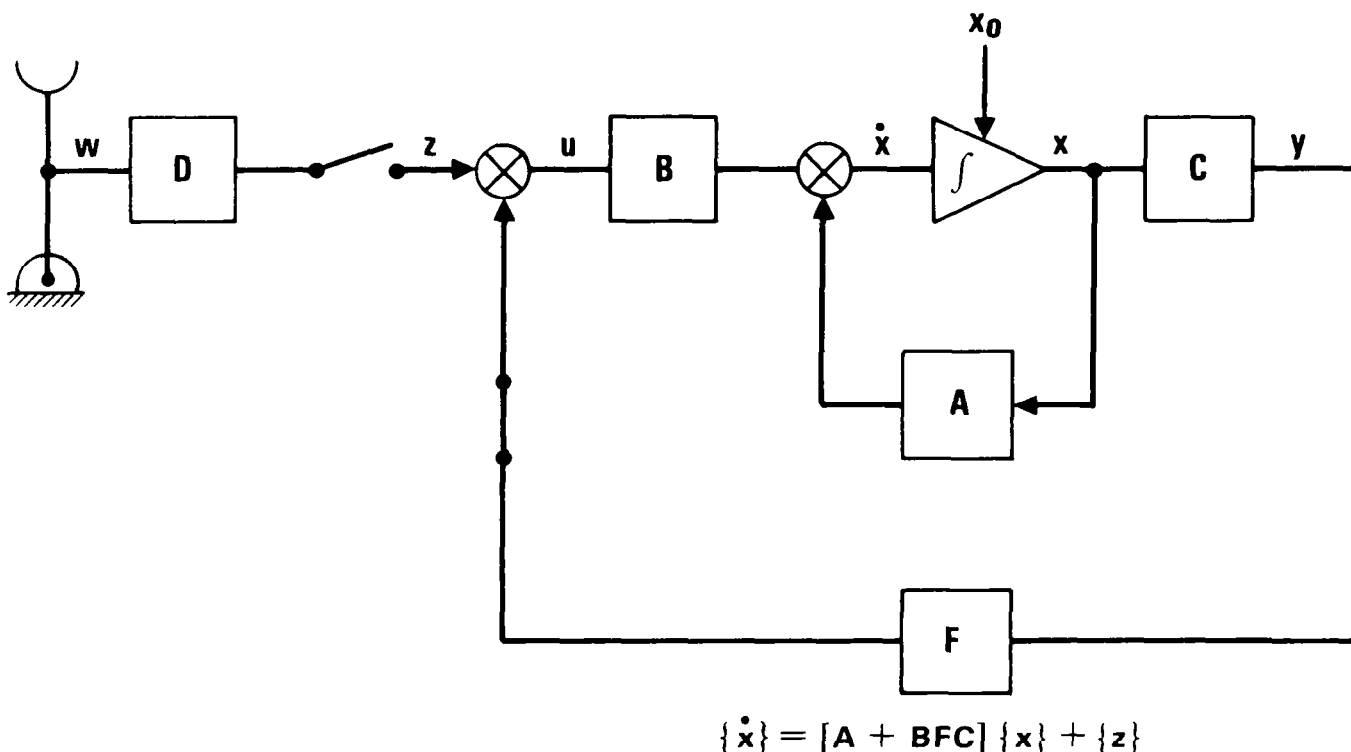


Figure 9

Plots of the feedback gains indicated that gain scheduling could be expressed as polynomial functions of dynamic pressure q and of horizontal stabilizer trim position δ_{HT} . Comparisons of least-mean-square (LMS) values determined the order of polynomials to be used for each set of curves. The second-order polynomial format

$$K = a + bq + cq^2 + d\delta_{HT} + e\delta_{HT}^2$$

was found to provide satisfactory curve fits for all gains. Pseudo-inverse matrix operations efficiently determined the coefficients to yield the least-squares fit for each set of gain values. Scheduled feedback curves of the pitch rate input are shown in figure 10.

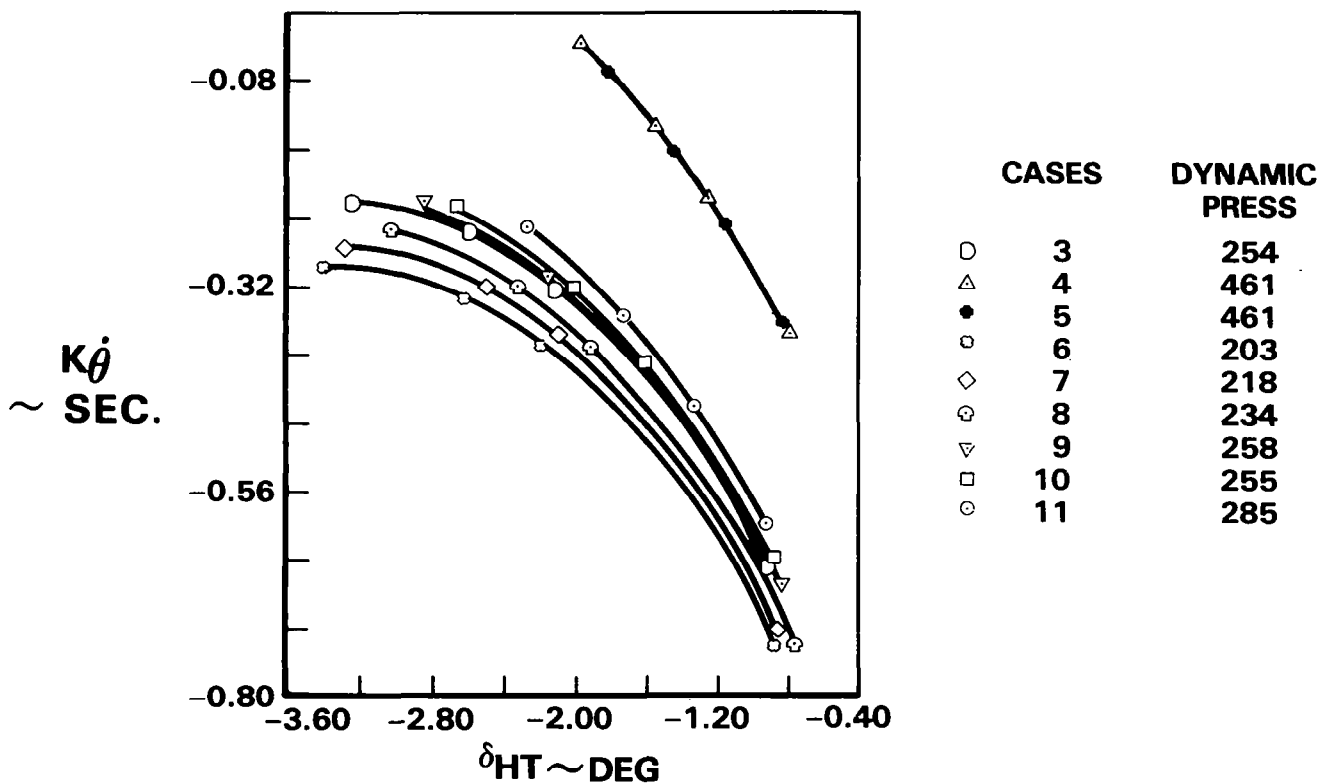


Figure 10

Figure 11 shows conglomerate short-period poles on the S-plane for all flaps-up flight conditions. Nearly all closed-loop poles fall within the objective boundaries:

- Short Period Mode
 - $\omega_0 \leq \omega_n \leq 2\omega_0$
 - $0.5 \leq \zeta \leq 0.8$

where ω_0 is the short-period frequency of the corresponding open-loop configuration at 25 percent \bar{c} . A few of the short-period damping ratios are higher than 0.8 but are considered to be acceptable.

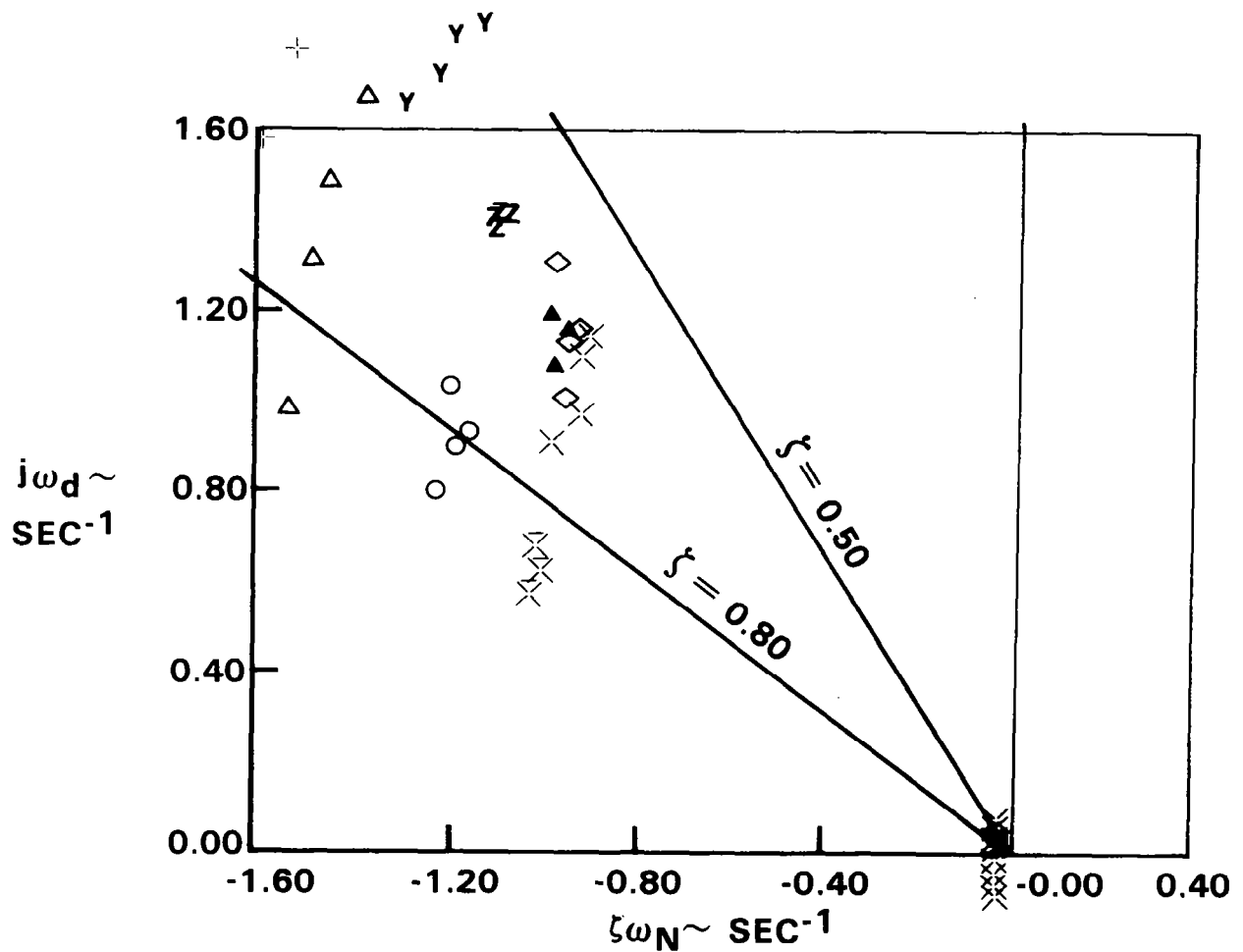


Figure 11

Control of the phugoid mode requires a velocity component, $K_u u$, in the feedback signal. Because of frequent velocity changes associated with changing trim conditions, however, use of a velocity sensor is undesirable. Knowledge of the transfer functions implicit in the equation

$$\{x\} = [IS-A]^{-1} [B] \{u\}$$

provides the transfer function relating u and θ , as shown in the figure. The composite signal β can be closely approximated by passing θ through a lag-lead network as shown in figure 12 resulting in the following:

$$\frac{\beta}{\theta} = \frac{K_3(\tau_1 s + 1)}{(\tau_2 s + 1)}$$

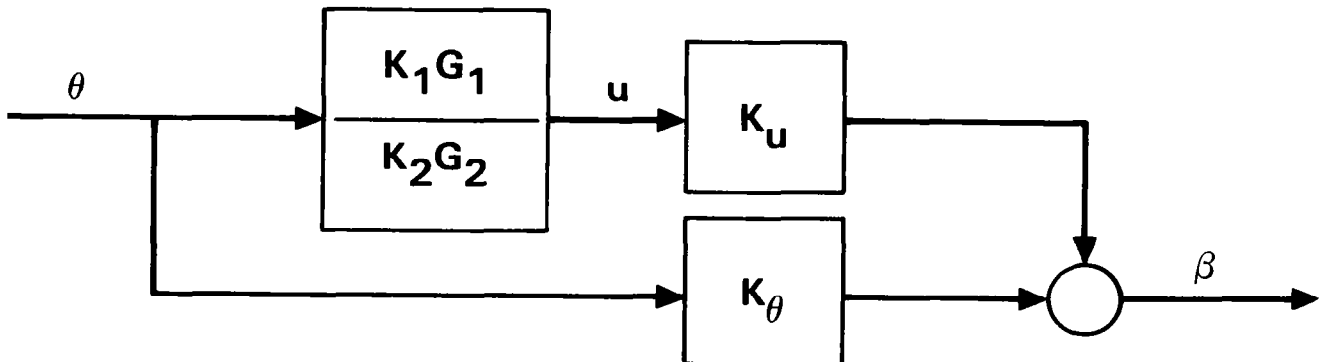


Figure 12

Figure 13 shows conglomerate phugoid poles on the S-plane for all flaps-up flight conditions. Nearly all closed-loop poles fall within the objective boundaries:

- Phugoid Mode
 $\omega_n \leq 0.16$ (40-second period)
 $0.1 \leq \zeta \leq 0.5$

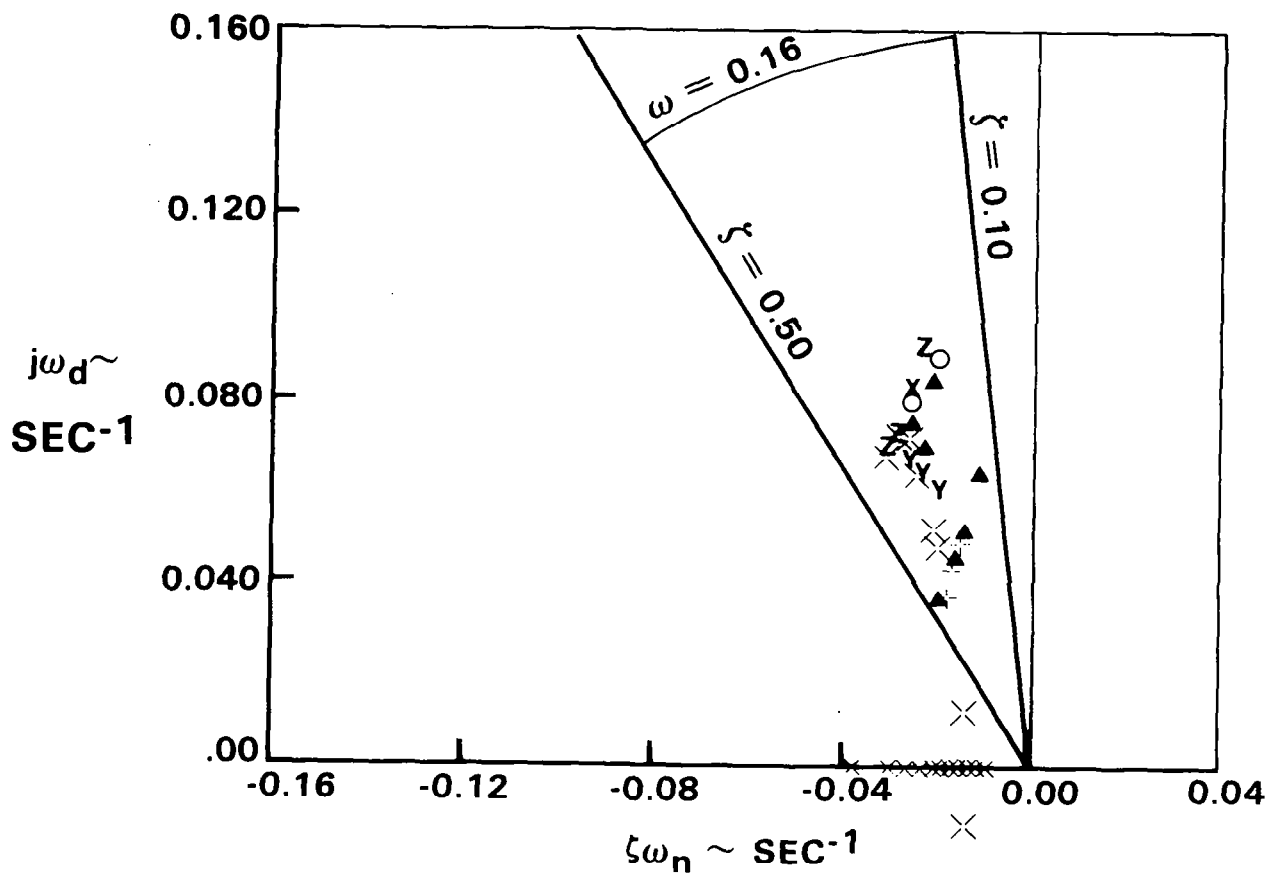


Figure 13

With the feedback and feed-forward loops closed, the system equation is

$$\{\dot{x}\} = [A + BFC] \{x\} + D\{w\}$$

where $\{w\}$ is the input vector comprising column displacement. Figure 14 shows the PACS control model with feed-forward loop closed.

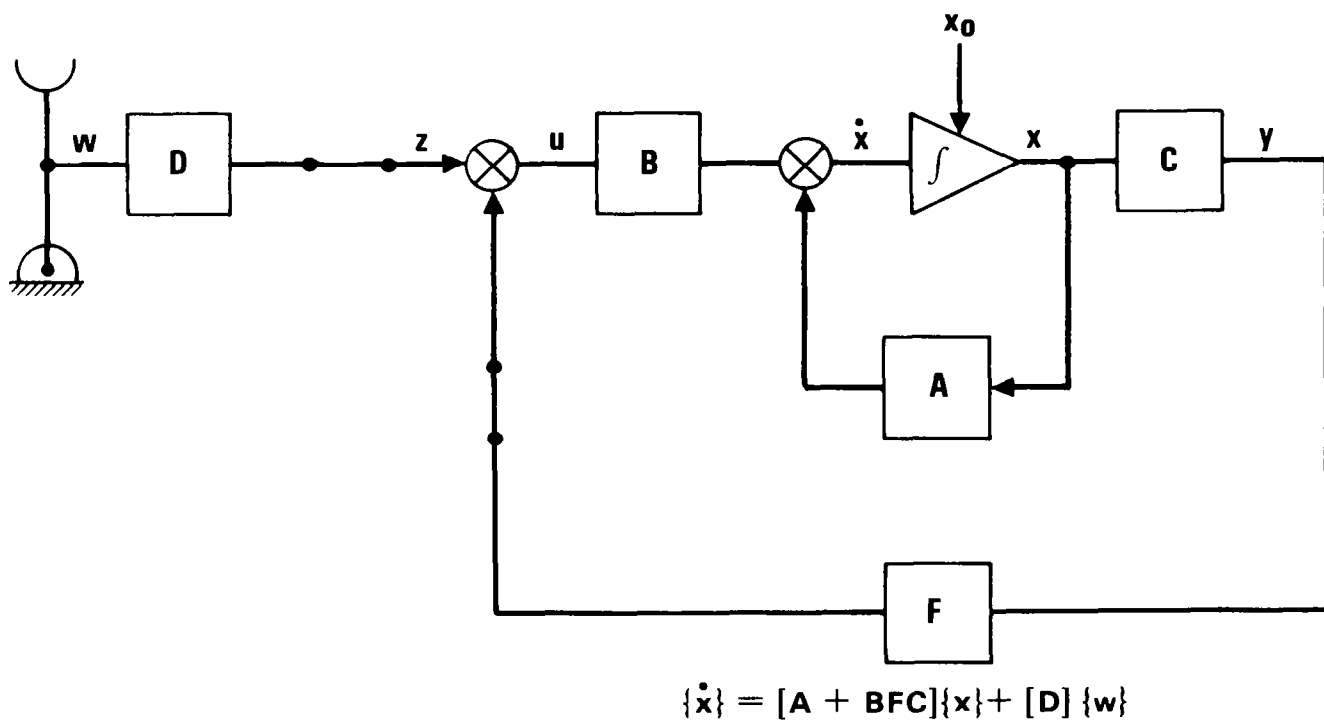


Figure 14

The feedback transfer function $K_{FB}G_{FB}(S)$ is a composite of all four feedback signals, as shown in the figure. It should be noted that the total transfer function from the input δ_H is the same regardless of which signal is designated to be fed back. This transfer function is

$$\frac{K_{NZ}N_{NZ}(S) + K_u N_u(S) + F_\theta N_\theta(S) + K_\dot{\theta} N_\dot{\theta}(S)}{D(S)}$$

The frequency variant part of this transfer function can be simplified for the purpose of computing $G_{FF}(S)$, because the PACS is not sensitive to this function. Simplifying assumptions permitted the approximation:

$$G_{FF} = 1/(S/\omega_{SP} + 1)$$

A block diagram of this logic is shown in figure 15.

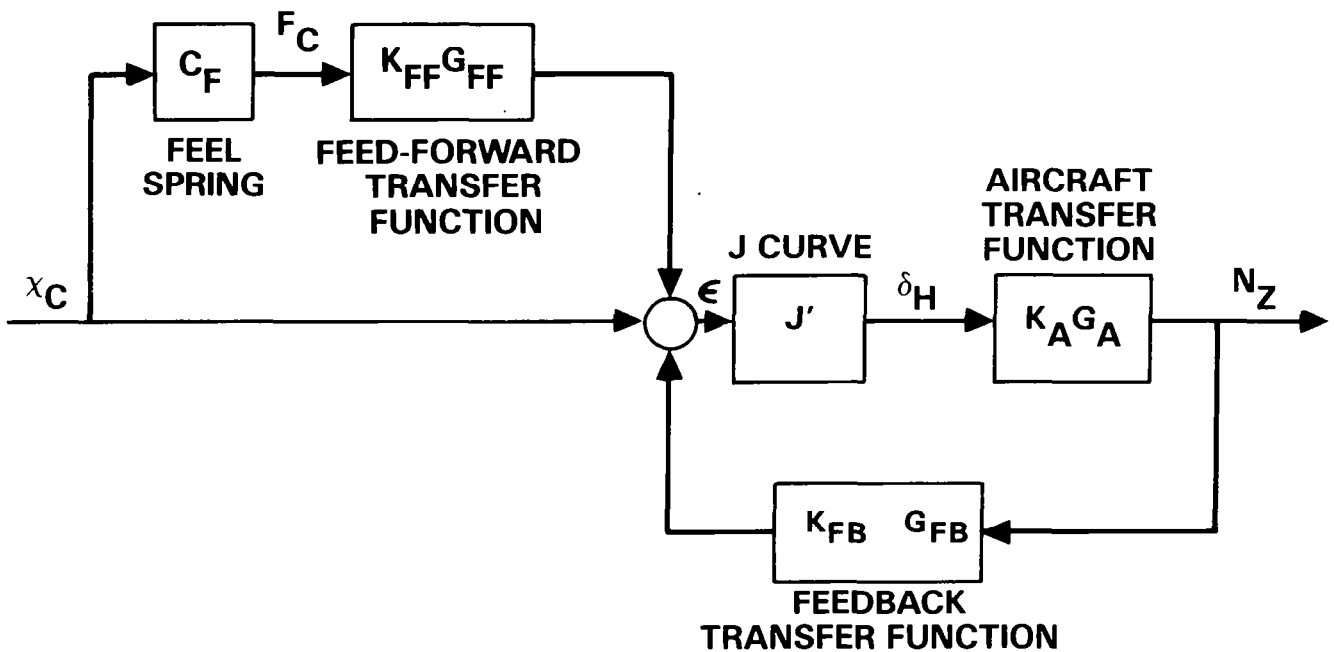


Figure 15

The secondary gain scheduling is used to compensate for:

- Pitch-up at high-mach/high-g flight conditions
- Outboard aileron symmetric effects when the aileron active control system (AACCS) is activated.

The secondary gain scheduling causes the system "to think" it has an additional c.g. aft increment by adding an increment to the stabilizer gain-scheduling signal, δ_{HT}^* . This occurs when the pitch-up phenomena or the AACCS mode is sensed in accordance with the block diagram of the secondary-gain controller. The increment produced by the bank angle ($C_{\theta}\delta_{HT}^2(1 - \cos \theta)$) is designed to "straighten" the force gradients during high-g turns. The secondary gain controller block diagram logic is shown in figure 16.

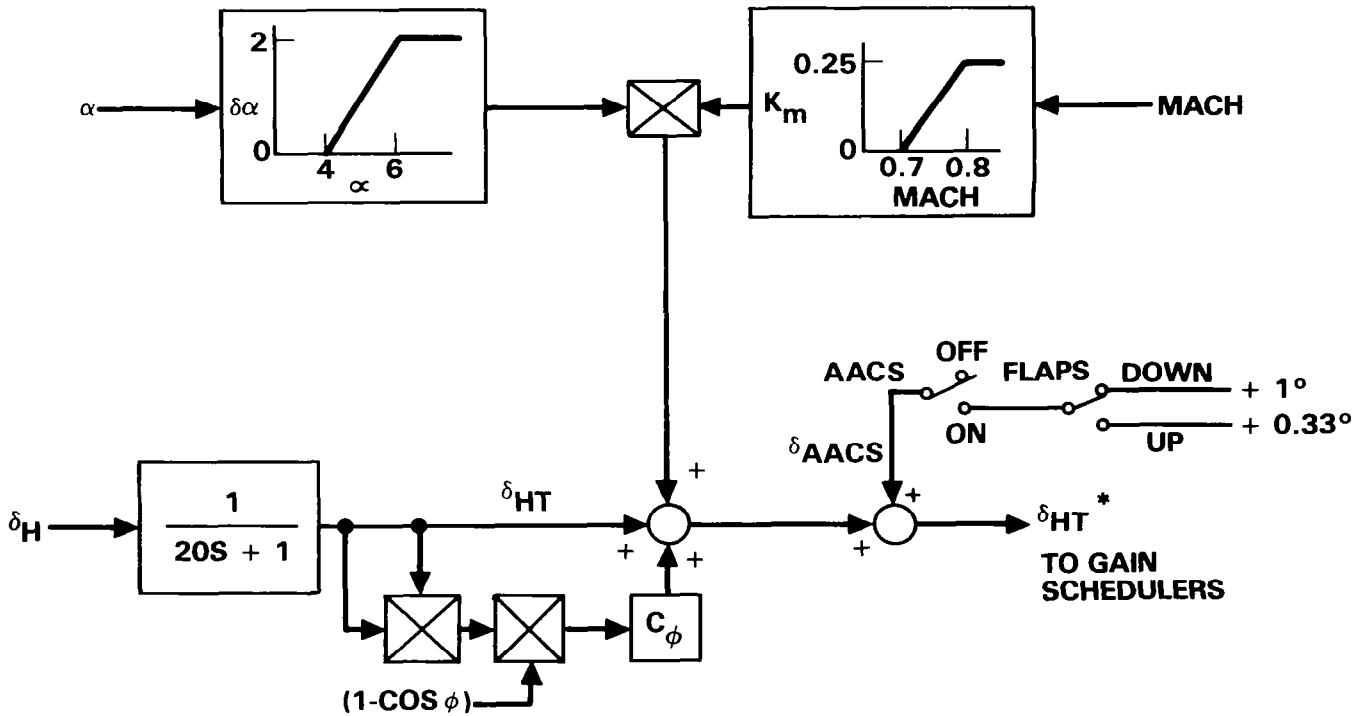


Figure 16

Figure 17 shows that the advanced pitch active control system with pitch excursion compensator completely removes the unstable dip in column dip force gradient characteristics. The data show that column maneuver force gradient characteristics are satisfactory for all c.g. locations. The initial force gradients are essentially the same for all c.g. locations, and they also fall in the middle of MIL-F-8785C specified design limits (ref. 1).

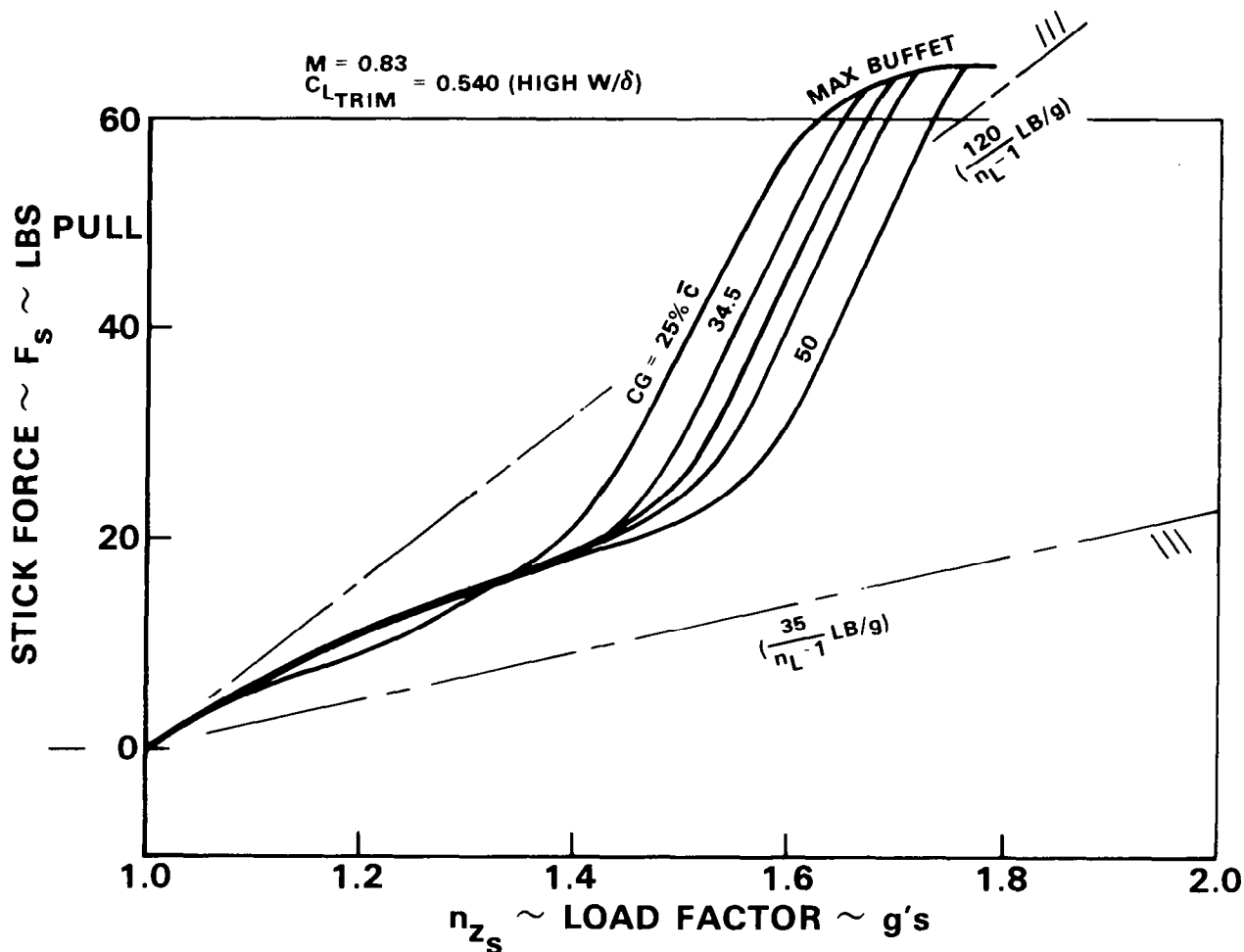


Figure 17

With the advanced pitch active control system engaged, the response of the airplane to a severe vertical gust (heavy thunderstorm magnitude of 54 fps) is shown in figure 18 to be essentially the same for all c.g.'s from 25 percent \bar{c} (15 percent stable) to 50 percent \bar{c} (10 percent unstable).

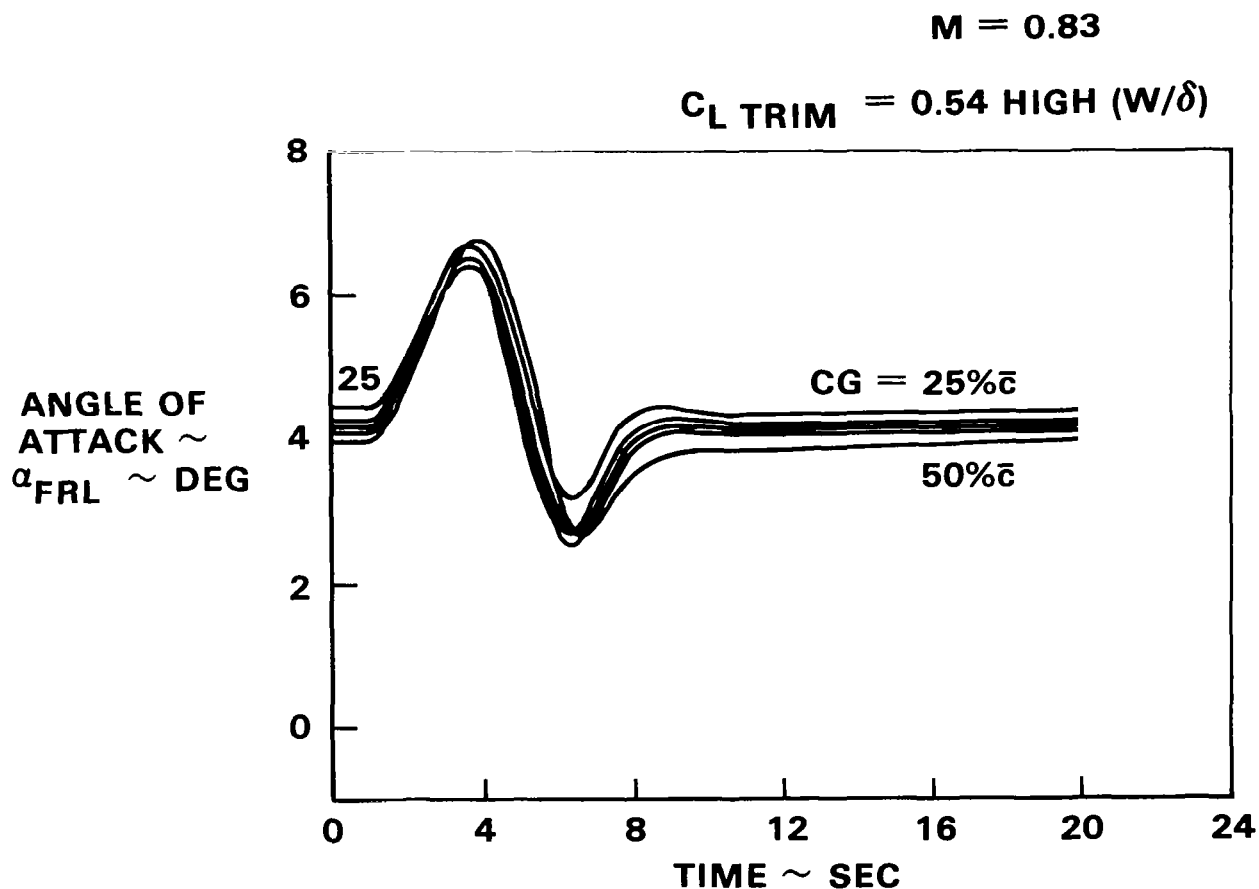


Figure 18

The advanced PACS signals can be grouped into four categories.

- Feedback signals to provide desired stability
- The feed-forward signal to provide the desired column-force gradient
- Primary gain scheduling signals to compensate for flight condition changes
- Secondary gain scheduling to provide additional stability compensation and force-gradient compensation during special flight conditions

Figure 19 shows these signals as used in the advanced PACS.

| SYMBOL | SIGNAL | TYPE | USE |
|-------------------------------------|---|---------------------------|--|
| F_C | COLUMN FORCE | FEED-FORWARD | COLUMN FORCE GRADIENT |
| N_Z $\dot{\theta}$ θ | NORMAL ACCELERATION PITCH RATE PITCH ATTITUDE | FEEDBACK | SHORT PERIOD MODE PHUGOID MODE |
| q δ_{HT}^* S_F | DYNAMIC PRESSURE HORIZONTAL STABILIZER TRIM FLAP SWITCH | 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 OPERATIONS |

Figure 19

The advanced PACS is shown by the solid lines in figure 20. Inputs to the controller are:

Feedback

N_z = Normal acceleration

θ = Pitch attitude

$\dot{\theta}$ = Pitch rate

Feed forward

F_c = Column force

Primary gain scheduling

q = Dynamic pressure

δ_{HT} = Stabilizer trim angle

Secondary gain scheduling

α = Angle of attack

ϕ = Bank angle

m = Mach number

The controller output is provided in this planned flight test mechanization to two series servos which have position-summed outputs that limit hardover stabilizer deflections to $\pm 3/4$ degree if one series servo fails. The total PACS authority is ± 1.5 degrees of stabilizer authority.

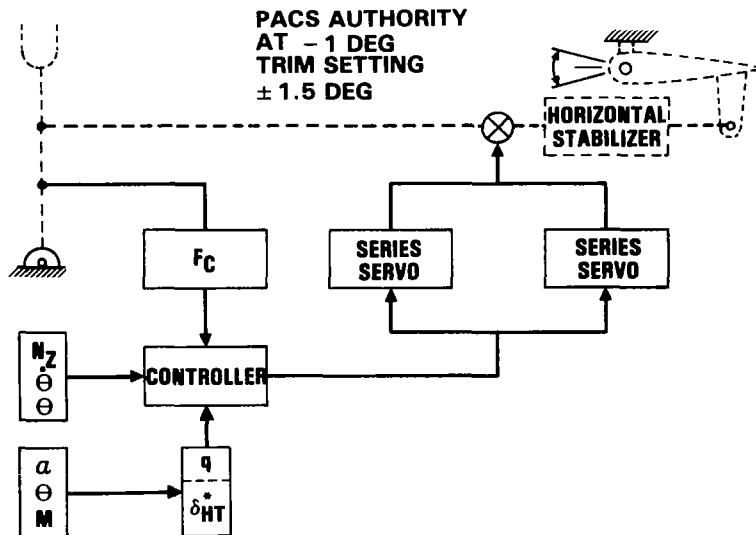


Figure 20

The purpose of the pitch-attitude synchronizer is to remove bias offsets from the pitch-attitude signal, and thus to avoid saturating the series servos. The integrator provides a reference level which tends to command the airplane as if it were in an attitude-hold mode. It has two modes of operation which are pilot optional: (1) fixed reference, or (2) controlled reference, selected by the switch S_2 , as shown in the circuit below. With $S_2 = \bar{C}$, the system is in the fixed reference mode and provides a reference attitude θ_R equal to the aircraft trim attitude θ_T . A block diagram of the pitch synchronizer function is shown in figure 21.

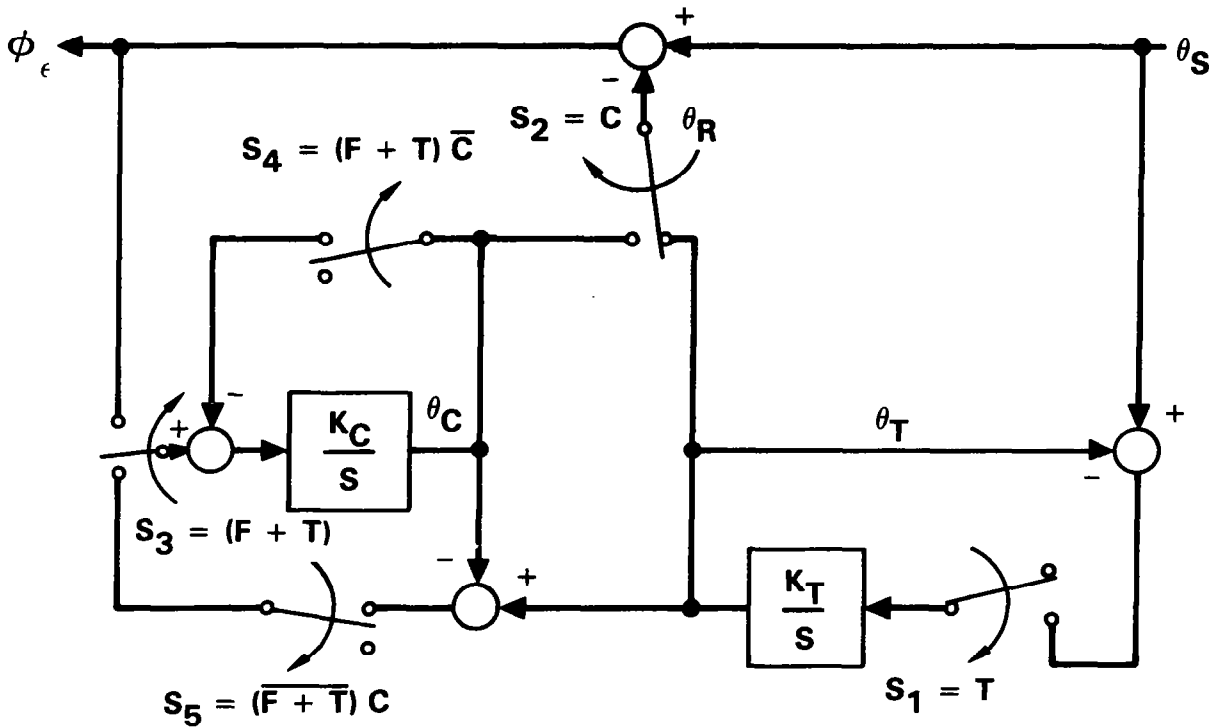


Figure 21

The advanced pitch active control system was evaluated on the Langley visual motion system (VMS) simulator pictured in figure 22. This is a general purpose simulator consisting of a two-man cockpit mounted on a six-degree-of-freedom synergistic motion base. Motion cues are provided by the relative extension or retraction of the six hydraulic cylinders of the motion base. Washout techniques are used to return the motion base to the neutral point once the onset motion cues have been commanded.

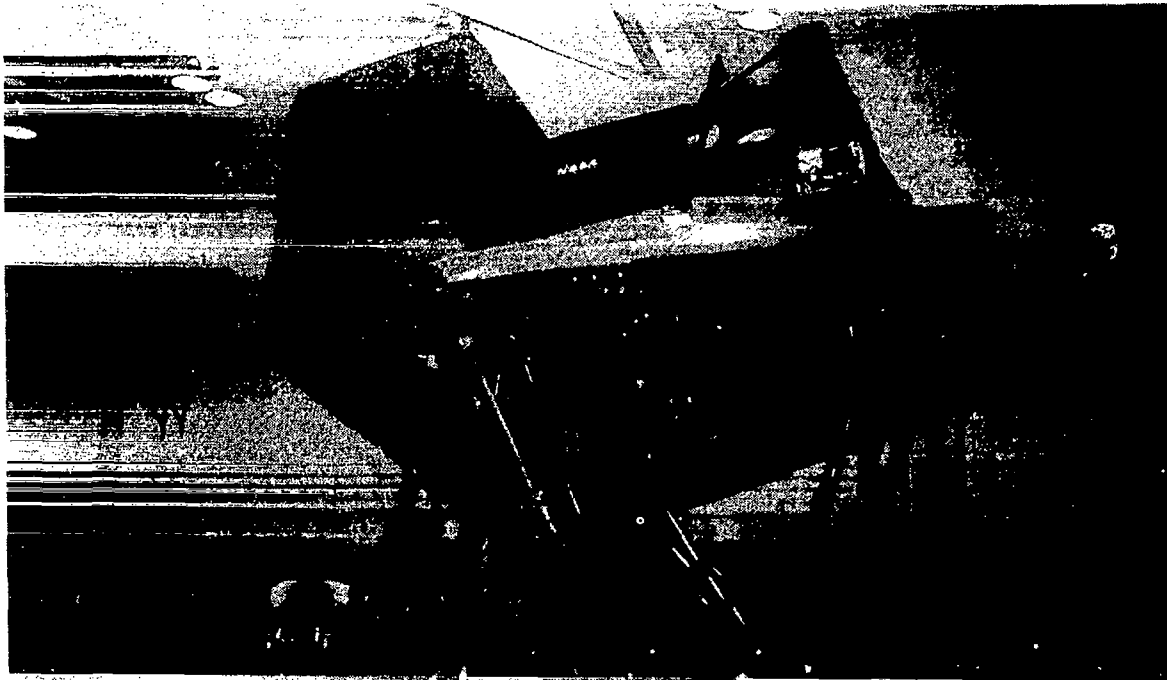


Figure 22

The handling qualities evaluation at each flight condition covered the c.g. range from 25 to 50 percent \bar{c} , for which the control law was designed; this represents a stability range in cruise of 15 percent positive static margin to 10 percent unstable.

Results of the simulation in figure 23 show that the advanced flight control system completely fulfills the function for which it was designed. Pilot ratings indicate that handling qualities of the augmented airplane with c.g. at 25 percent \bar{c} (10 percent statically unstable) are as good as the basic unaugmented airplane with c.g. at 25 percent \bar{c} (15 percent statically stable). The results are most impressive at high-speed conditions where handling qualities of the unaugmented airplane quickly degrade to unacceptable levels for c.g.'s aft of 40 percent \bar{c} .

Flight condition 10 is an intermediate altitude cruise condition. At this condition, maneuvering stability about trim is essentially linear.

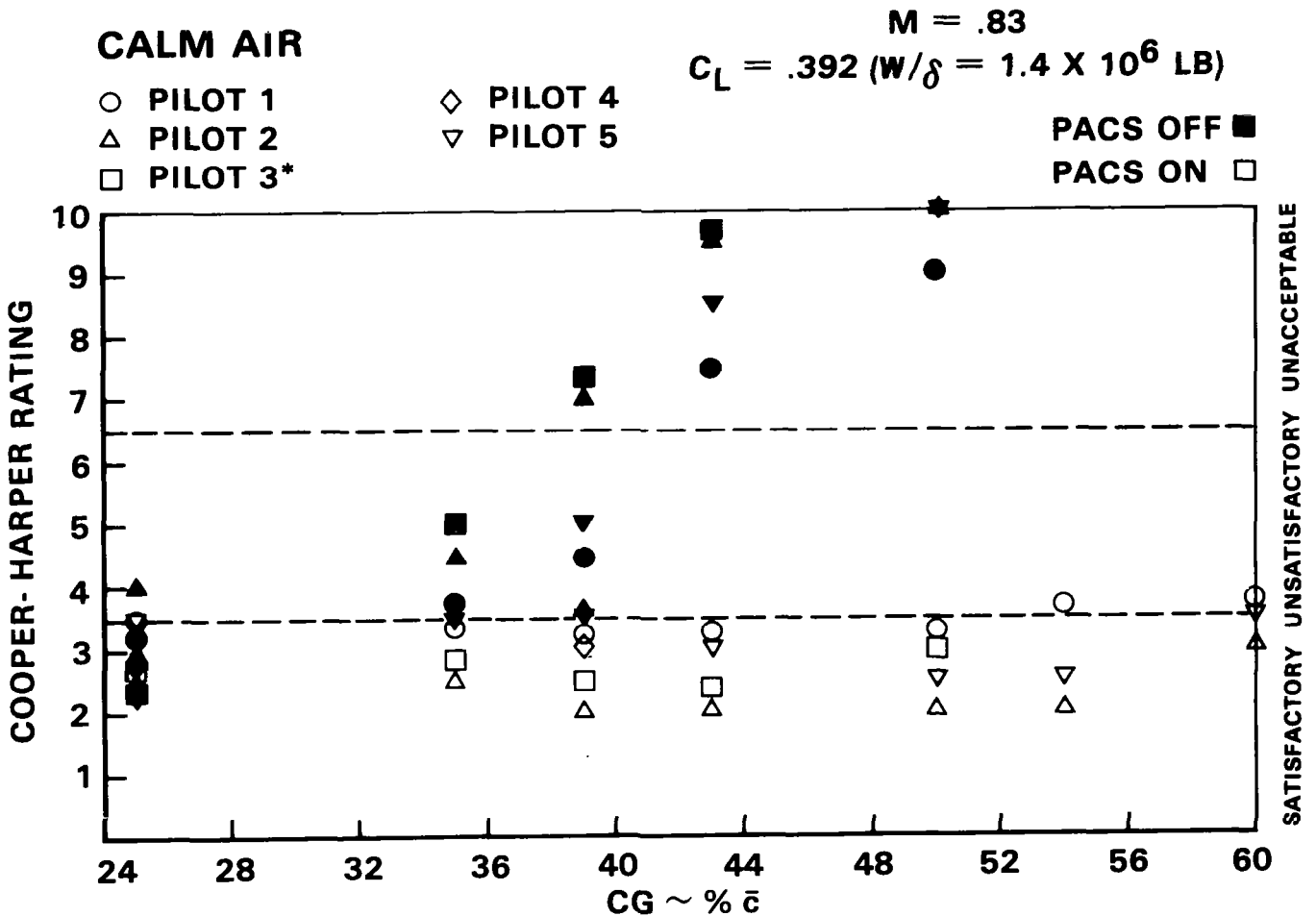


Figure 23

REFERENCE

1. Military Specification, Flying Qualities of Piloted Airplanes, MIL-F-8785C, November 1980.