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16. ABSTRACT

A study was conducted to investigate Relaxed Static Stability (RSS) and stability augmentation with active controls applied to subsonic transport aircraft. Analytical and simulator evaluations were done using a contemporary wide body transport as a baseline. Criteria for augmentation system performance and unaugmented flying qualities were evaluated. Augmentation control laws were defined based on selected frequency response and time history criteria. Flying qualities evaluations were conducted by pilots using a moving base simulator with a transport cab. Static margin and air turbulence intensity were varied in tests with and without augmentation. Suitability of a simple pitch control law was verified at neutral static margin in cruise and landing flight tasks. Neutral stability was found to be marginally acceptable in heavy turbulance in both cruise and landing conditions.

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ACCELERATED DEVELOPMENT AND FLIGHT EVALUATION
OF ACTIVE CONTROLS CONCEPTS FOR SUBSONIC TRANSPORT AIRCRAFT

VOLUME 2 - AFT C.G. SIMULATION AND ANALYSIS

LOCKHEED-CALIFORNIA COMPANY
COORDINATED BY: D. M. URIE

SUMMARY

This task entailed simulation of Relaxed Static Stability (RSS) configurations of a contemporary wide body subsonic transport, the Lockheed L-1011. Task objectives were to select criteria for augmentation system performance and unaugmented flying qualities and to define control laws for an augmentation system suitable for a derivative L-1011 configuration with a smaller horizontal tail. These objectives have been attained.

Design of augmentation control laws was accomplished using frequency response criteria. These criteria used the current transport modal characteristics as a standard for acceptable performance. Control laws so defined were then evaluated against normalized time history response envelopes of the current airplane.

Pilot-in-the-loop flight simulations were conducted on a moving base simulator with an L-1011 cab. Static margin and air turbulence intensity were varied with and without augmentation. These tests showed that lagged pitch rate damper provided flying qualities equivalent to the baseline airplane at aerodynamic stability levels down to neutral in heavy turbulence. Modified control laws resulting in quicker and slower time response to control input were evaluated. No clear preference was found, thus indicating that there is wide latitude in satisfactory dynamic control response.

Unaugmented simulations demonstrated that flying qualities of configurations with as little as 3 percent static margin are acceptable in cruise and approach flight conditions even with heavy turbulence.

The aft C.G. simulation results provide sufficient basis for proceeding to flight evaluation of the defined augmentation control laws with RSS and a small horizontal tail.

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LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOL	DEFINITION
C*	Cockpit Normal Acceleration plus U_C Times Pitch Rate Divided by Gravitational Acceleration
$\overline{c}$	Mean Aerodynamic Chord (MAC)
c.g.	Center of Gravity
E_{LOC}, $E_{G.S.}$	Localizer and Glideslope Errors
EPR	Engine Pressure Ratio
F_{COL}	Column Force
H	Altitude
IFR	Instrument Flight Rules
K	Stabilizer Feed Forward Gain
K_Q	Pitch Damper Gain
L_u,L_w	Specified Altitudes Used to Define Turbulence Properties
M	Mach Number
N_Z	Normal Load Factor at the c.g.
PLA	Engine Power Lever Angle
PLADOT	Rate of Change of Engine Power Lever Angle
Q	Aircraft Pitch Rate
R_T	Yaw Rate
S	Laplace Operator
SAS	Stability Augmentation System
S_H	Horizontal Tail Area

SYMBOL	DEFINITION
T	Engine Thrust
TURBU TURBV TURBW	Disturbance Velocities from Turbulence in the Forward, Side and Vertical Directions Respectively
U, V, W	Forward, Side, and Vertical Components of the Aircraft velocity vector
U_c	Constant Velocity in C*
V_e	Equivalent Airspeed
W	Aircraft Gross Weight
δ_{AT}	Aileron Deflection
δ_{COL}	Column Deflection
δ_F	Flap Deflection
δ_H	Stabilizer Deflection
δ_R	Rudder Deflection
δ_{SP}	Spoiler Deflection
δ_w	Control Wheel Angle
ζ	Damping Ratio
θ	Aircraft Pitch Attitude
τ_{LAG}	Lag Time Constant
τ_{wo}	Washout Time Constant
ψ	Heading
ω_d	Damped Frequency
ω_n	Natural Frequency

SECTION 1

INTRODUCTION

Contract NAS1-14690 is a program whereby Lockheed is investigating the use of active controls in the L-1011 for increased energy efficiency with applications in the commercial air fleet as early as 1980. The program investigates the use of maneuver load control, elastic mode suppression and gust alleviation with increased wing aspect ratio; and of augmented stability with more aft c.g. and smaller horizontal tail. The augmented stability permits relaxation of conventional static stability margins leading to the use of a substantially smaller tail, with significant weight and drag savings. The expected energy efficiency improvement attributable to the small tail is 3% to 3-1/2%.

Three tasks are defined for the contracted program:

- Task 1 - Flight Testing of load alleviation systems on an L-1011 aircraft.
- Task 2 - Design and pilot-in-the-loop simulator testing of a longitudinal stability augmentation system. Includes development of criteria for systems-off characteristics.
- Task 3 - Flight testing and evaluation of a modified L-1011 with extended wing tips and active controls.

Results of the aft C.G. simulation study, Task 2, are reported in this volume of the final report. Results of Tasks 1 and 3 are reported in Volume 1.

In this task three versions of the L-1011 aircraft are utilized. The current L-1011-1 is used as a basis for flying qualities evaluations. This configuration is depicted in Figure 1-1. The baseline aircraft for determining the direct effects of the tail size reduction is the shorter bodied L-1011-500 with extended wing tips. The reduced energy L-1011-RE shown in Figure 1-2 is the increased span airplane with a smaller horizontal tail. Table 1-1 lists the dimensional data of the L-1011-1 and the L-1011-RE. The aerodynamic data representing these configurations

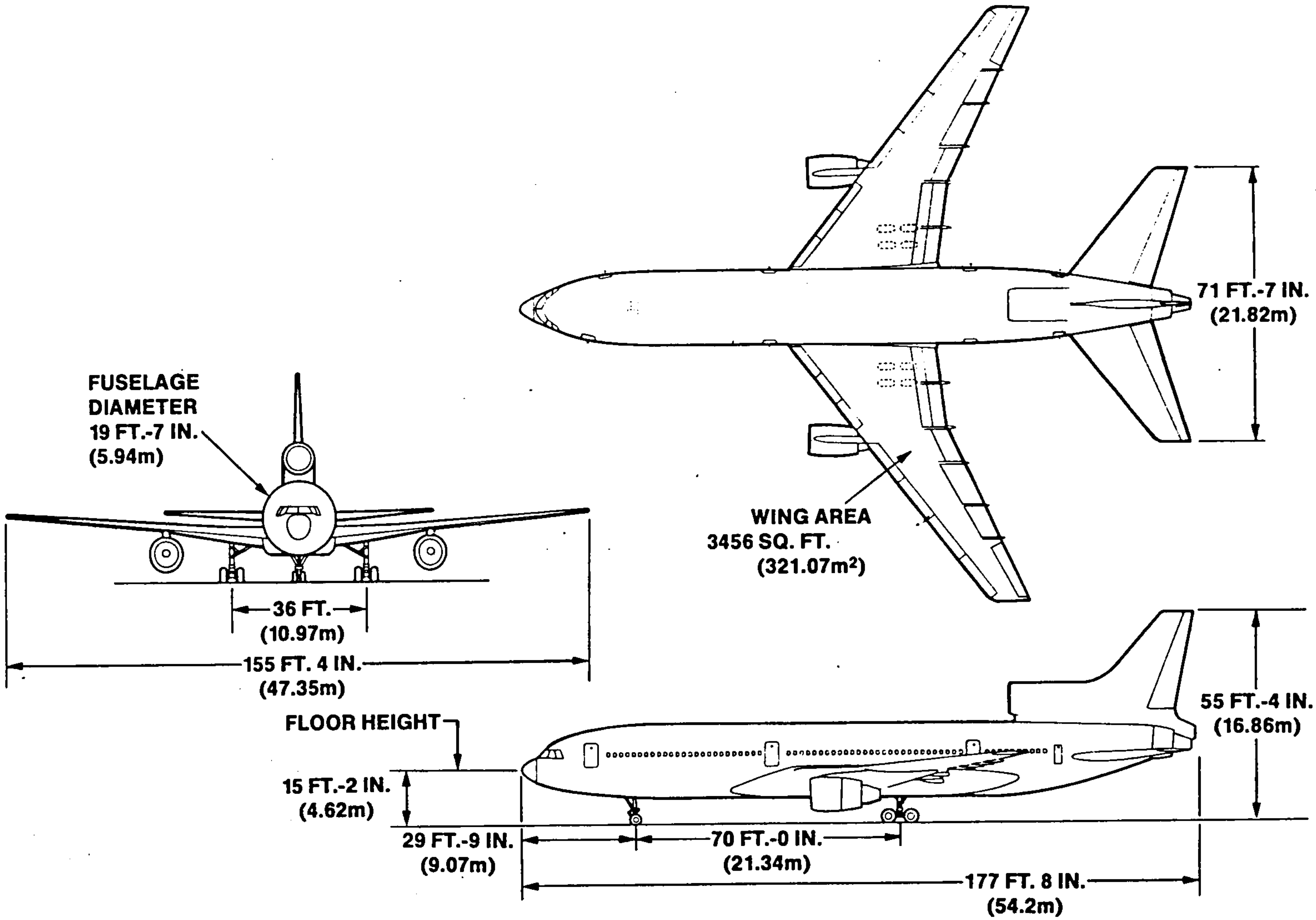


Figure 1-1. L1011-1 General Arrangement

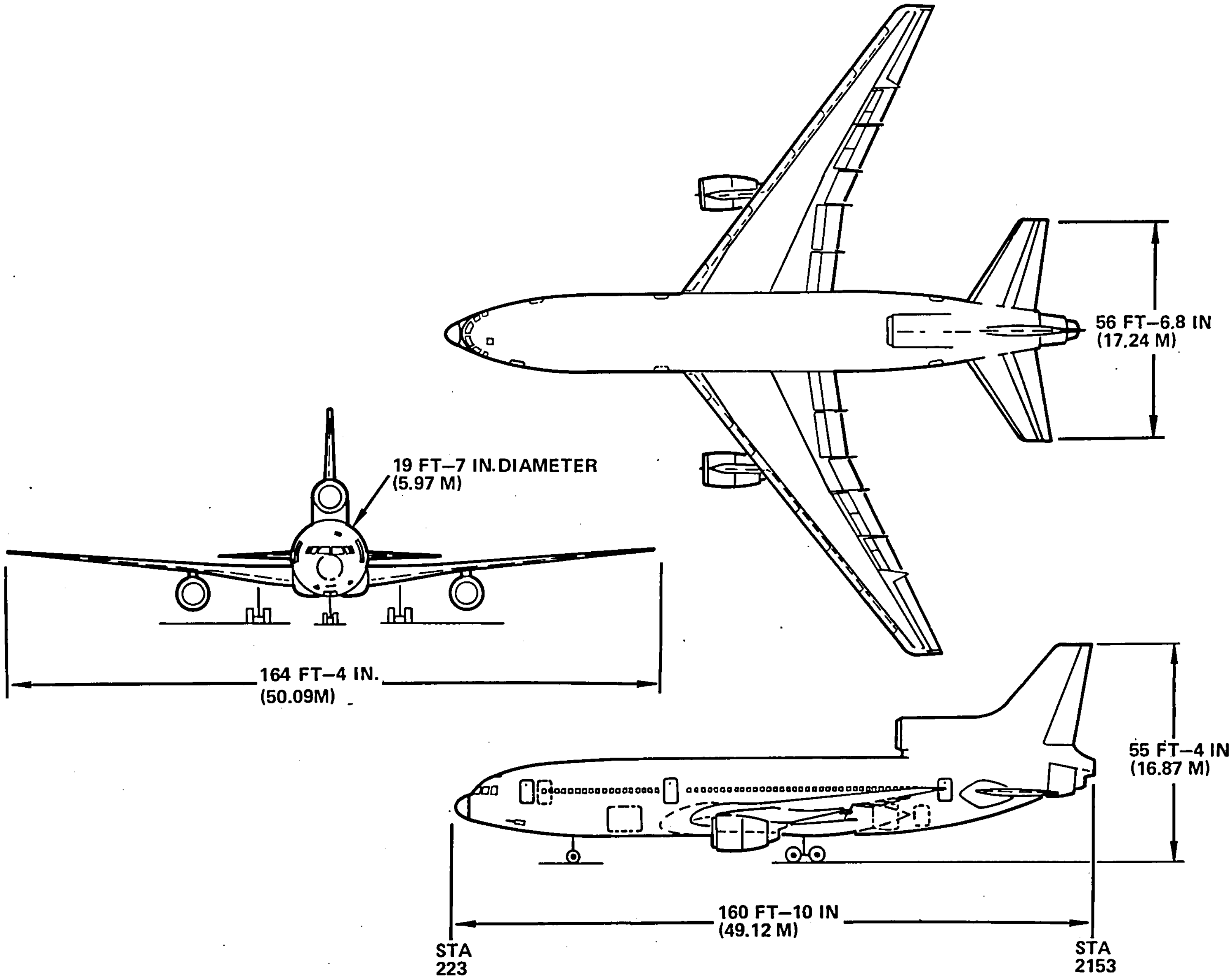


Figure 1-2. L-1011-RE General Arrangement

TABLE 1-1. AIRPLANE GEOMETRY

	L-1011-1	L-1011-RE
WING		
*Reference Area, S_W	321.07 m^2 (3456 $ft.^2$)	328.97 m^2 (3541 $ft.^2$)
*Reference Wing Chord, $\bar{c}_w$	7.455 m (24.46 ft.)	Not defined
*Reference Wing Span, b_w	47.24 m (155.0 ft.)	50.09 m (164.33 ft.)
Aspect Ratic, AR_w	6.95	7.63
Taper Ratio, λ_w	0.3	0.26
Geometric Dihedral, Γ_w	7°31' inb'd. 5°30' outb'd.	7°31' inb'd. 5°30' outb'd.
Wing Sweep at 0.25c, Λw	35.0 deg.	35.0 deg.
HORIZONTAL TAIL		
Reference Area, S_h	119.1 m^2 (1282 $ft.^2$)	74.32 m^2 (800 $ft.^2$)
Reference Chord, $\bar{c}_h$	5.92 m (19.42 ft.)	4.65 m (15.27 ft.)
Reference Span, b_h	21.82 m (71.58 ft.)	17.24 m (56.57 ft.)
Aspect Ratio, AR_h	4	4
Horizontal Tail Volumn, $\bar{V}_h$	0.919	0.573
ELEVATOR		
Reference Area (included in S_h), S_e	11.85 m^2 (127.5 $ft.^2$)	8.05 m^2 (86.6 $ft.^2$)
Span per side, b_e	9.33 m (30.6 ft.)	7.04 m (23.1 ft.)
VERTICAL TAIL		
Reference Area (Above WL 325), S_v	51.1 m^2 (550 $ft.^2$)	51.1 m^2 (550 $ft.^2$)
Reference Chord, $\bar{c}_v$	6.19 m (20.3 ft.)	6.19 m (20.3 ft.)
Reference Span (Above WL 325), b_v	9.05 m (29.7 ft.)	9.05 m (29.7 ft.)
Aspect Ratio, AR_v	1.6	1.6
Vertical Tail Volume, $\bar{V}_v$	0.066	0.060

*Although actual wing dimensions are different for the L-1011-RE, L-1011-1 reference dimensions were retained for aerodynamic computations.

are the flight validated L-1011-1 data plus supplementary data from Lockheed funded wind tunnel tests of the extended wing span and the small horizontal tail.

Lockheed preliminary design studies of several advanced subsonic cruise aircraft have shown that for a usefully wide c.g. range with a horizontal tail sized for nose-up and nose-down control power, the aft c.g. static margin will be approximately zero. This led to the concentration in this task on c.g. locations ranging from 25% MAC to slightly aft of the neutral point.

All work done in this task was performed using conventional engineering units. Results are presented in the international system of units except where instrumentation output is reproduced directly. Output from these sources and their working units are identified in Tables 2-2, 2-3 and 2-4. Elements of the L-1011 primary longitudinal control system whose rigging relationships are defined in engineering units are also shown in their original form.

SECTION 2

DISCUSSION

2.1 AUGMENTATION SYSTEM DEVELOPMENT

2.1.1 Criteria

The approach to developing an augmentation system for the small-tail L-1011 active controls airplane was to use the current L-1011 in the manual control mode as the standard of acceptable performance. The small-tail configuration with augmented stability (L-1011-RE) was designed such that handling qualities are at least as good as those of the current L-1011.

The L-1011 is designed to meet Part 25 of the Federal Air Regulations. This specification tends to be of a qualitative nature, however; so a number of other references are used to formulate a more quantitative set of design criteria. Among the more widely recognized criteria are:

- Military Specification, Flying Qualities of Piloted Airplanes, MIL-F-8785B(ASG).
- SAE Design Objectives for Flying Qualities of Civil Transport Aircraft, Aerospace Recommended Practice, ARP 842B.
- Naval Air Development Center, Proposal for a Revised Military Specification, Flying Qualities of Piloted Aircraft, NADC-ED-6282.
- Wright Air Development Center, Flight Evaluation of Longitudinal Handling Qualities in a Variable Stability Jet Fighter, WADC TR 55-299 and TR 57-719.

These references are used as a source for defining dynamic response requirements, and in particular the modal characteristics (e.g., short-period and phugoid frequency and damping).

The technique of identifying dynamic characteristics in terms of well-separated second-order modes of motion has come under criticism with the development of highly augmented control systems. This has brought about the development of time history criteria. Some of the well known time history criteria include:

- C* Time Response Criterion for Fighter Aircraft, Boeing Report D6-17841 T/N.
- Longitudinal Handling Qualities Criteria for Large Advanced Supersonic Aircraft, NASA CR-137635.

The philosophy adopted in this study is to develop an augmentation system which generally satisfies all of the above listed criteria. Therefore, the following handling qualities were considered in the development: 1) pitch rate and C* time histories for comparison with the current L-1011 short-period response to a step input; 2) frequency response criteria to ensure that oscillatory characteristics are within accepted guidelines and compare favorably with other transports; 3) the time-to-double amplitude criterion which governs long term pitch instability and is of primary concern in the case of an augmentation system failure; and 4) 4.45 Newtons (one pound) column force per six knots speed change away from trim, which is required by Federal Aviation Regulations.

Development of the augmentation system concentrates on the flight conditions of primary concern in the simulation study. These conditions are cruise and the landing approach. Although augmentation system design and analysis is restricted to these flight conditions, handling qualities can be evaluated at any flight condition, since a complete flight regime aerodynamic model has been programmed. This allows investigation of handling qualities at other flight conditions that may be critical.

The L-1011 landing gear balance requirements dictate an aft c.g. limit of $0.35\bar{c}$ for takeoff and landing, although in-flight c.g. locations aft of this limit are possible for research purposes. For purposes of this study, the aft c.g. limit is defined by the neutral point location. Previous studies have shown that in cases of stability augmentation system failure in the landing approach, IFR handling qualities become unacceptable for negative static margins greater than 2 or 3%. Considering the destabilizing effect of the small tail and stabilizing effect of the extended wing tips, the net stability loss for the L-1011-RE compared to the current L-1011-1 is 5% at low-speed conditions and in cruise about 3% at M = 0.80 decreasing to no loss in stability at M = 0.90 and above. Corresponding neutral point locations are about $0.42\bar{c}$ for the landing configuration and in cruise from 0.38 to $0.41\bar{c}$. Since the purpose of this study is to investigate the effects of relaxed static stability, c.g. locations forward of $0.25\bar{c}$ were not planned for the flight simulation, and are therefore not considered at this stage of the augmentation system development. Therefore, the c.g. range of greatest interest in this study is 0.25 to $0.40\bar{c}$.

2.1.2 Mach Trim

Technically speaking the Mach trim system is part of the L-1011 augmentation system, although it is not considered to be in this analysis, inasmuch as the current L-1011 is equipped with Mach trim. Its purpose is to give a satisfactory stable stick force gradient with velocity at high speed to comply with the FAR Part 25 requirements, i.e., 4.45 Newtons (1 lb)/6 knots away from trim speed. For purposes of this analysis, the effects of the Mach trim system have been incorporated into the basic airframe speed derivatives.

2.1.3 Linear System Models

Control system analysis was performed using a linearized aerodynamic model. Figures 2-1 and 2-2 show that the linear system model gives an accurate representation of the airplane response at both low and high speed conditions. Pitch rate time histories obtained with the linear system models are nearly the same as those from digital computer program solutions with complete nonlinear aerodynamic model.

2.2 UNAUGMENTED CHARACTERISTICS

2.2.1 Time Histories

The C* and pitch rate time histories of the small-tail L-1011 were determined for comparison with criteria which were delineated as study guidelines. These guidelines are defined by time history envelopes which represent response characteristics of the current L-1011 for a wide range of flight conditions. The comparison is shown in Figures 2-3 through 2-6. These figures show that the time history characteristics of the small-tail L-1011 are generally within guidelines except for c.g. locations aft of 0.35 $\bar{c}$, where the response falls below the lower boundary.

2.2.2 Characteristic Roots

Characteristic roots of the standard-tail L-1011 were evaluated to establish minimum frequency and damping requirements of the L-1011-RE, and to determine stability characteristics of the baseline airplane for the c.g. range of interest

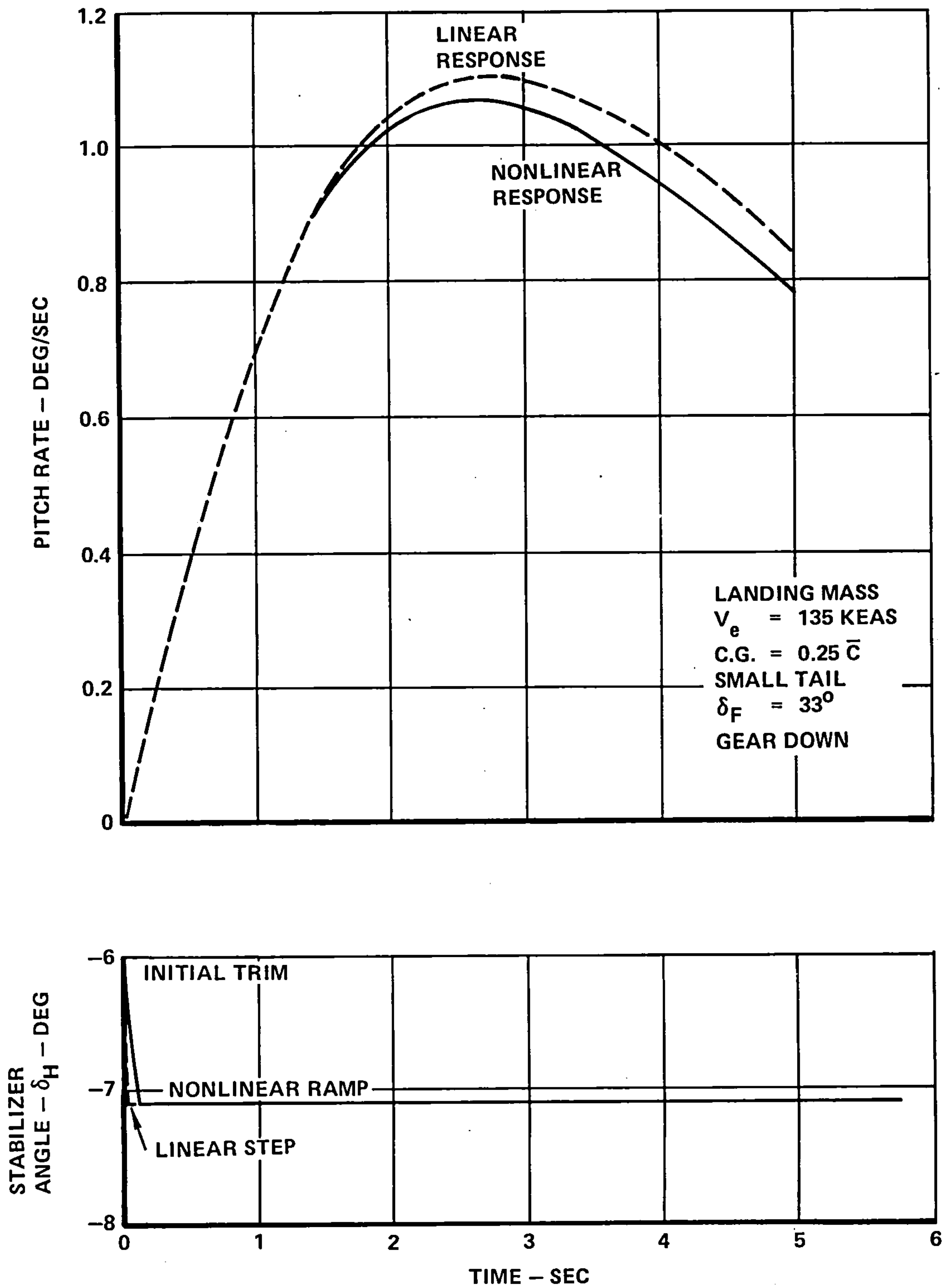


Figure 2-1. Linear Aerodynamic Model Accuracy: Approach Pitch Rate

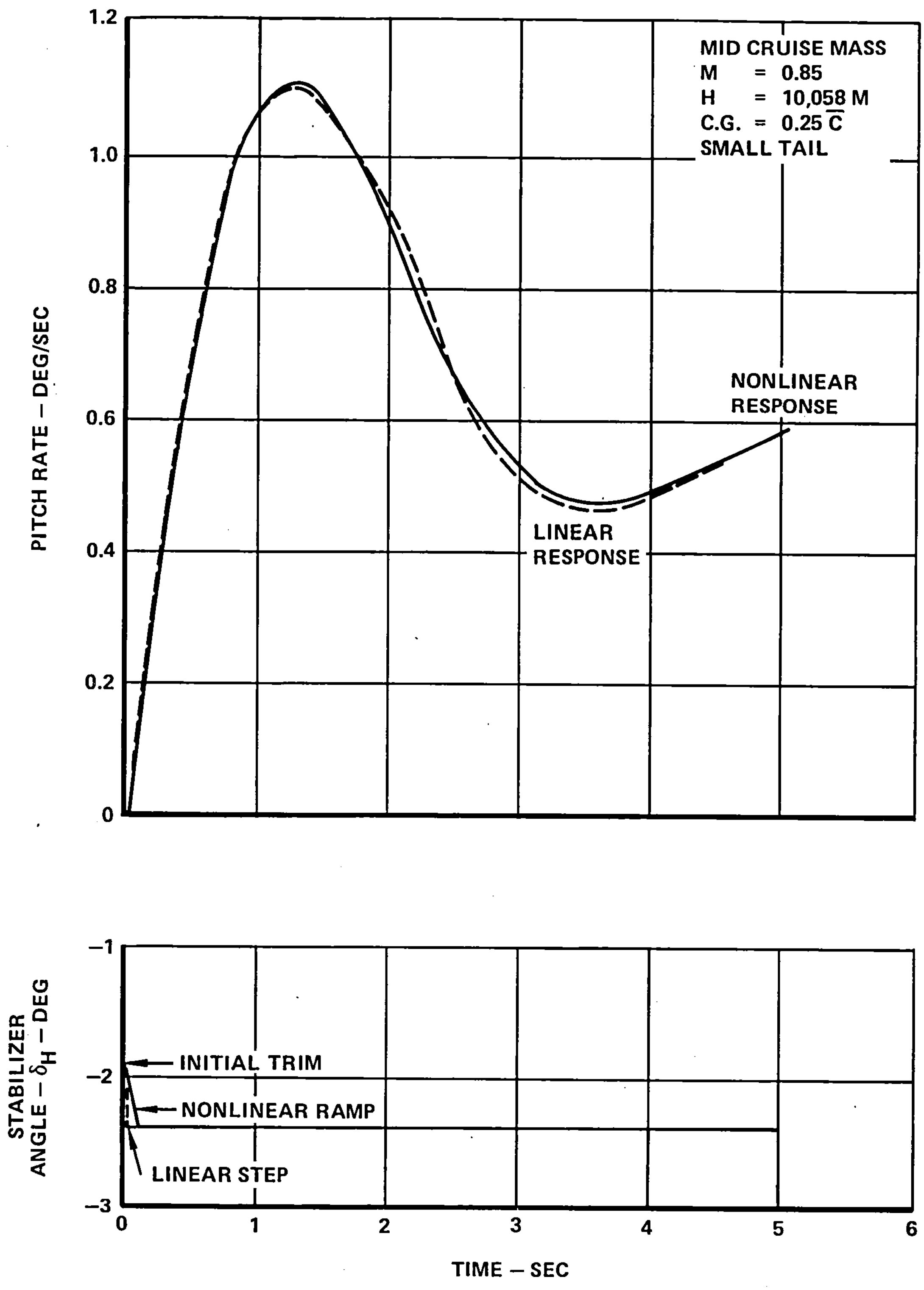


Figure 2-2. Linear Aerodynamic Model Accuracy: Cruise Pitch Rate

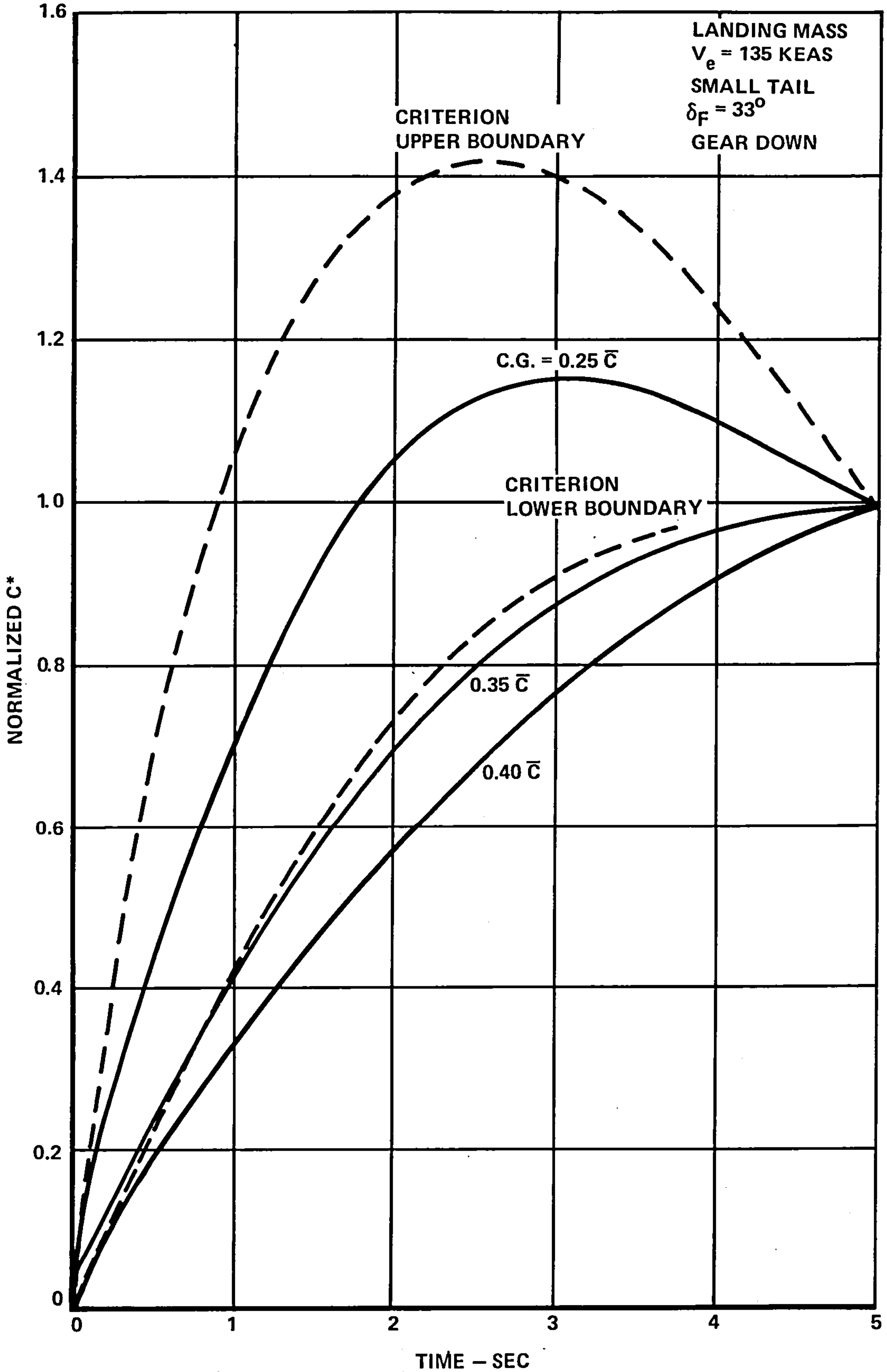


Figure 2-3. Small Tail C* Time History for the Unaugmented Approach

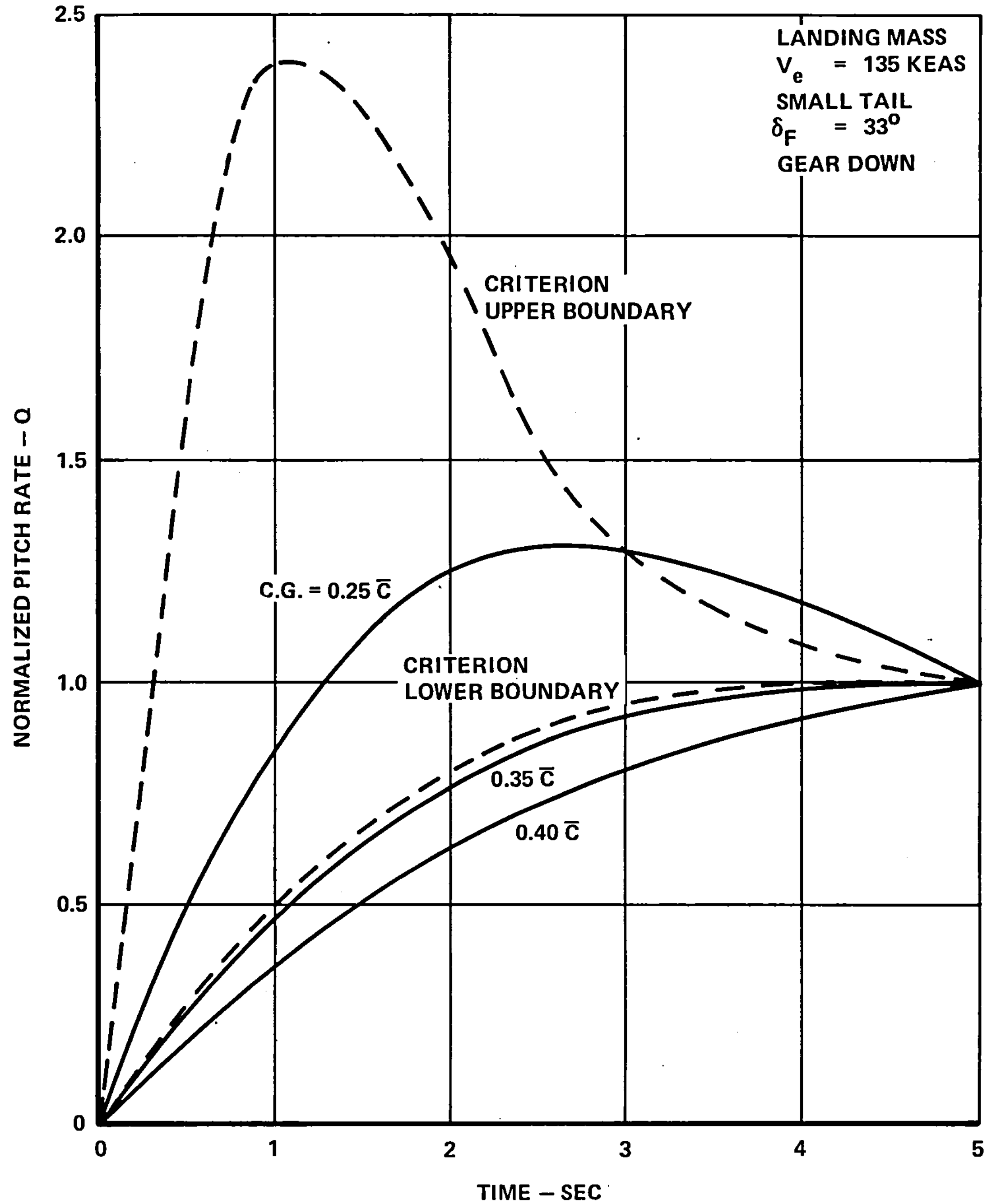


Figure 2-4. Small Tail Pitch Rate Unaugmented Approach

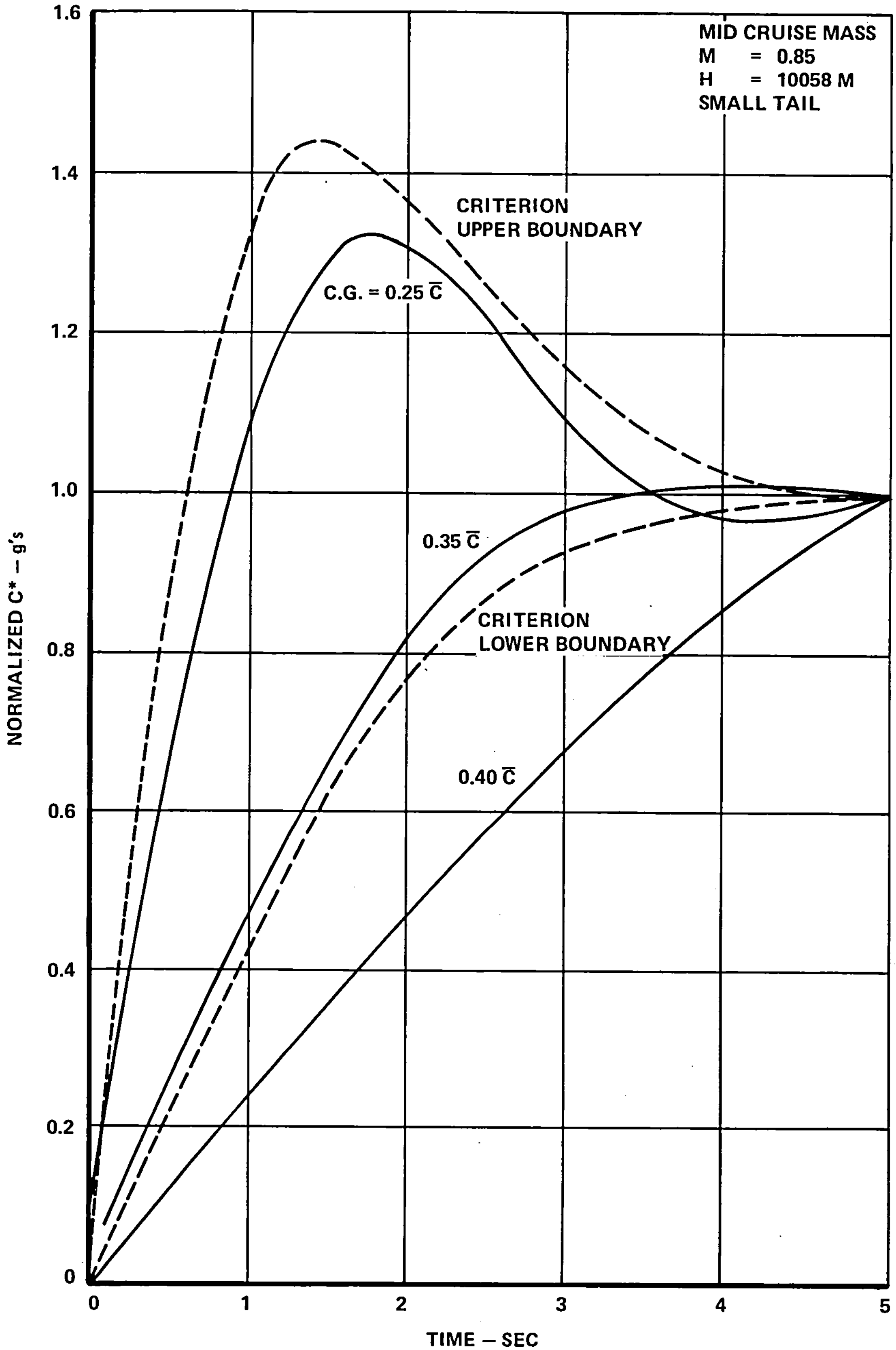


Figure 2-5. Small Tail C* Time History Unaugmented Cruise

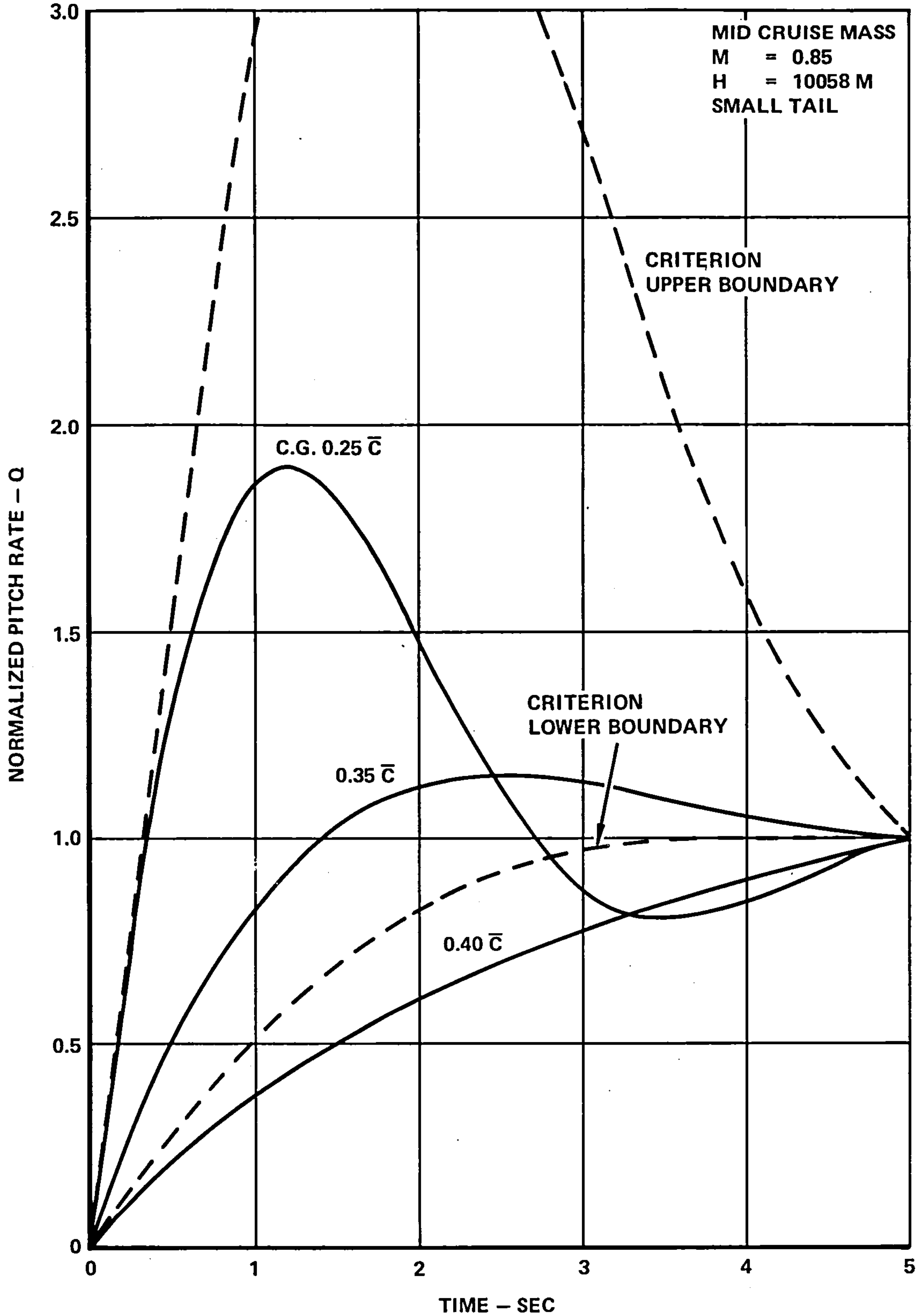


Figure 2-6. Small Tail Pitch Rate Unaugmented Cruise

in the flight simulation (0.25 to 0.50$\bar{c}$). Figures 2-7 and 2-8 show the effect of c.g. location on characteristic roots for the low and high speed conditions. The short-period frequency and damping values at mid c.g. were used as the minimum acceptable in the augmentation system design. Mid c.g. data for the landing approach (Figure 2-7) show a damping ratio of 0.57 and frequency of 0.86 rad/sec (0.14 Hz); corresponding values in cruise (Figure 2-8) show a damping ratio of 0.45 and frequency of 1.65 rad/sec (0.26 Hz). In the landing approach, unstable roots do not appear until the c.g. reaches 0.50$\bar{c}$, and in cruise a low frequency instability appears for c.g. locations aft of 0.40$\bar{c}$.

Figures 2-9 and 2-10 show the effects of c.g. location on characteristic roots for the unaugmented small-tail airplane. At the mid c.g. point damping values are essentially the same as for the standard-tail airplane; however, frequencies are somewhat reduced: 0.75 rad/sec (0.12 Hz) in the landing approach and 1.5 rad/sec (0.24 Hz) in cruise. In the landing approach, the configuration becomes increasingly unstable for c.g. locations aft of 0.40$\bar{c}$, and in cruise there is a low-frequency instability for c.g. locations aft of 0.37$\bar{c}$. These results suggest that 0.40$\bar{c}$ may be considered as an aft c.g. limit for the small-tail airplane.

2.3 AUGMENTATION SYSTEM DEFINITION

2.3.1 Design Approach

The design philosophy for the L-1011-RE augmentation system was based on consideration of the following characteristics of the unaugmented small-tail airplane:

1. With few exceptions, results from the piloted flight simulation show generally acceptable handling qualities (pilot rating ≤ 6.5) for c.g. locations as far aft as 0.40$\bar{c}$ in the landing approach and 0.35$\bar{c}$ in cruise. In cruise with the c.g. at 0.38$\bar{c}$, one pilot rated the airplane a 7 in all levels of turbulence and another pilot rated the airplane a 6.5. (See Section 2.10.)

2. Normalized time history characteristics are within the selected criteria boundaries except for c.g. locations aft of 0.35$\bar{c}$.

3. The angular frequency characteristics are unacceptably low at mid c.g., compared to the standard-tail L-1011, and continue to degrade as the c.g. moves aft.

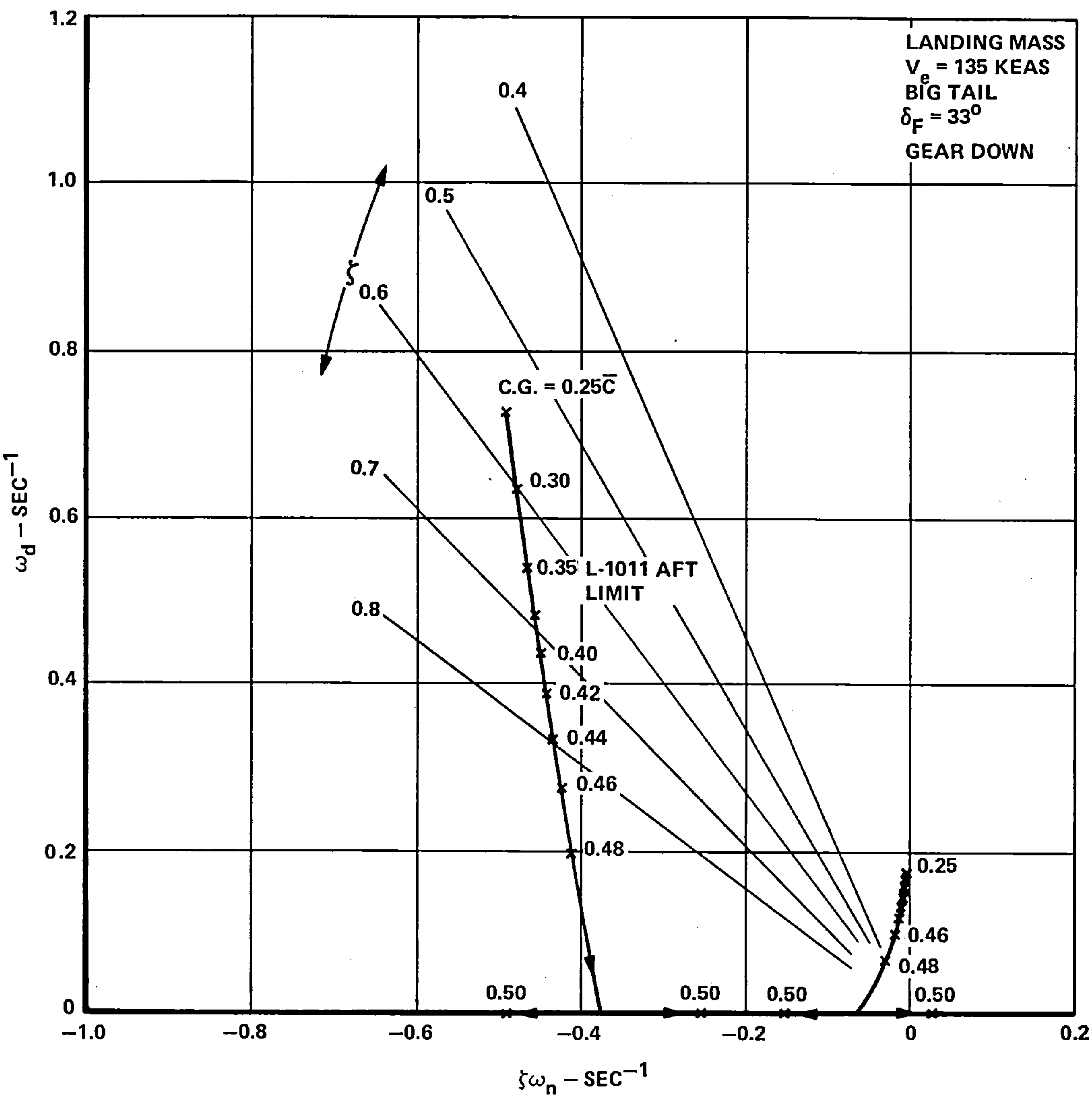


Figure 2-7. Characteristic Roots Unaugmented Standard Tail Approach

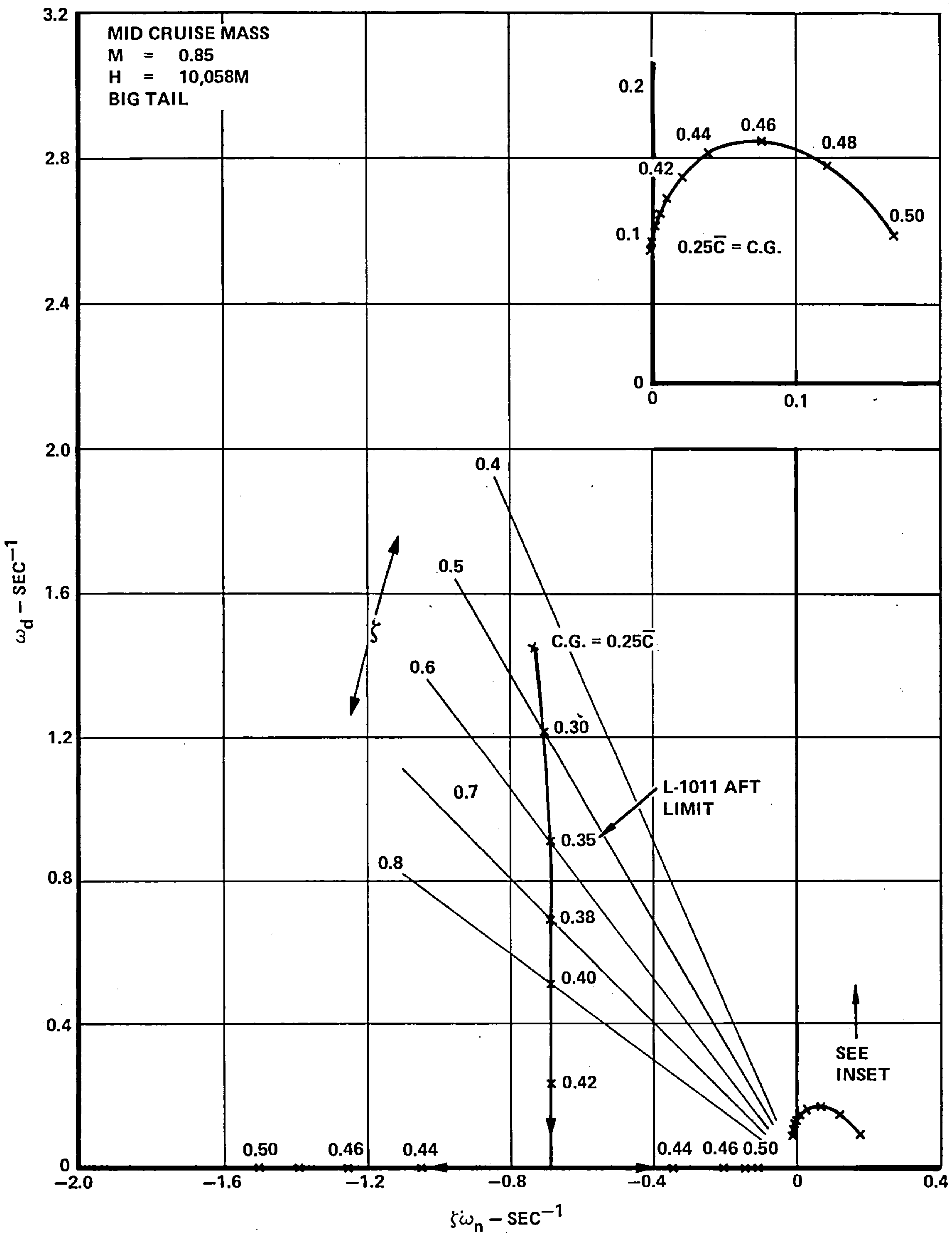


Figure 2-8. Characteristic Roots Standard Tail Cruise With Mach Trim

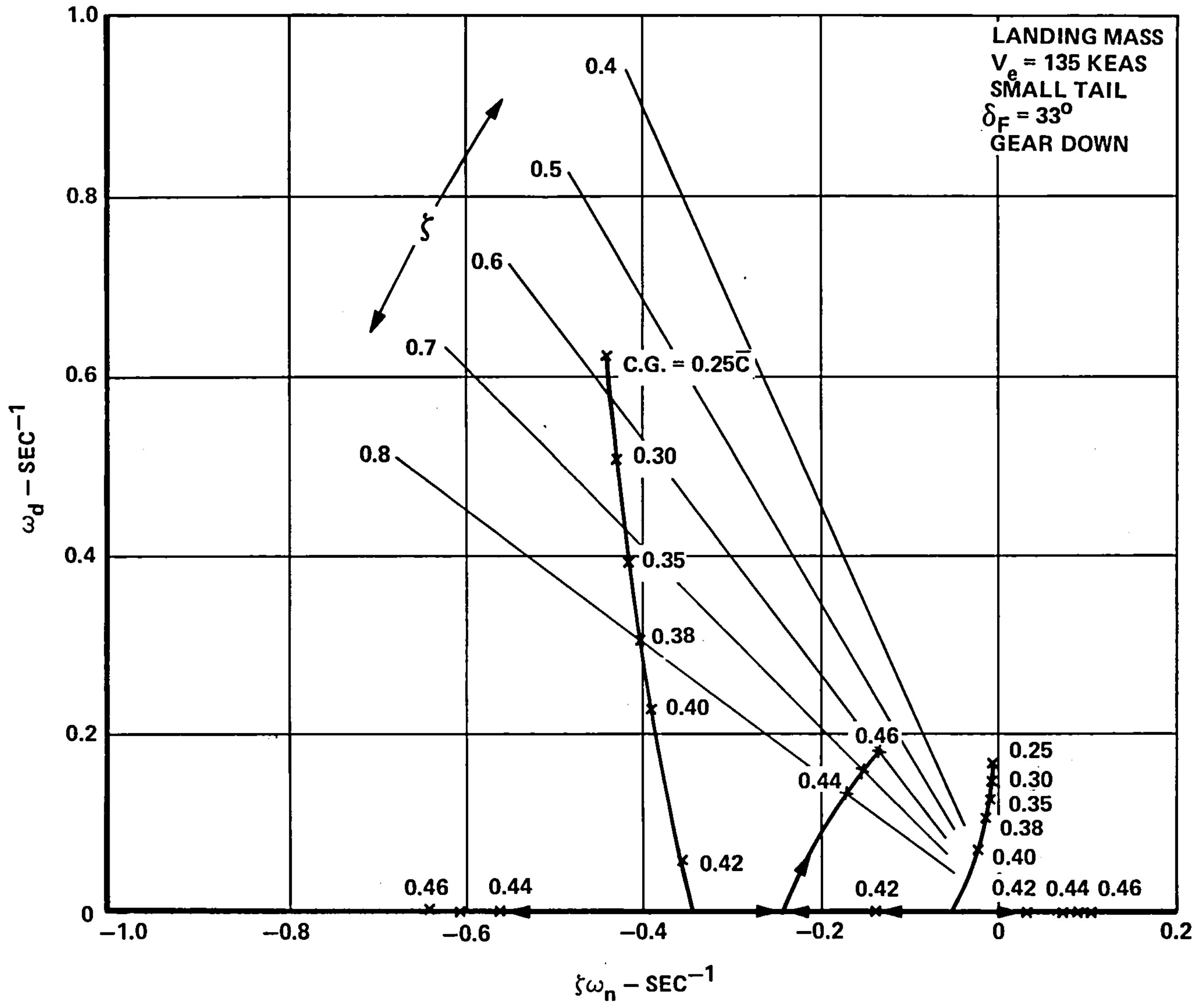


Figure 2-9. Characteristic Roots Unaugmented Small Tail Approach

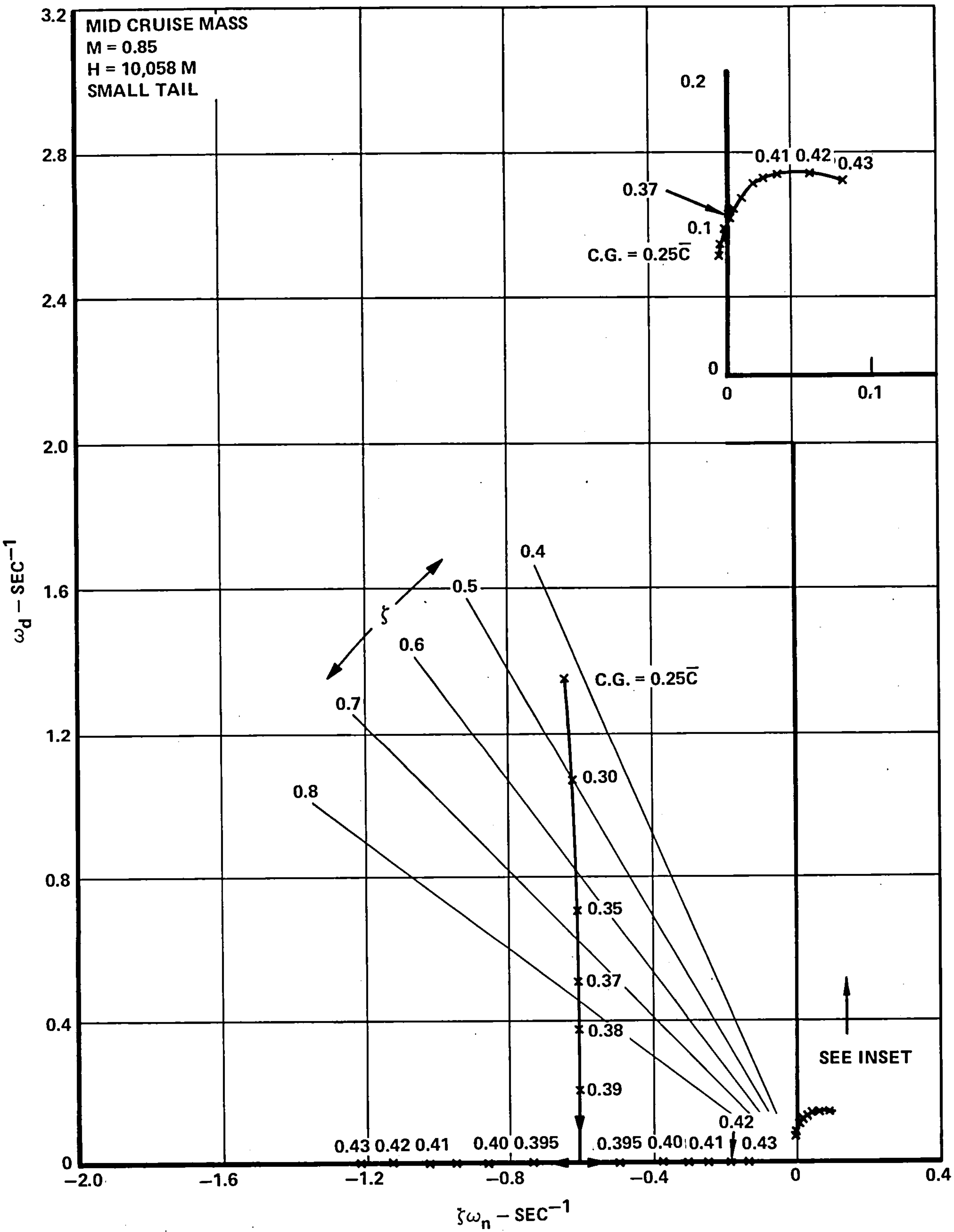


Figure 2-10. Characteristic Roots Unaugmented Small Tail Cruise With Mach Trim

Based on these findings, it was concluded that good handling qualities could be achieved with a simple augmentation system, which would be highly reliable. This system was conceived as a lagged pitch rate damper to provide the necessary short-period frequency and damping characteristics to suppress turbulence effects. In addition to this, a washed-out stick feed forward loop was designed to provide the flexibility of adjusting the C* and pitch rate time history characteristics without affecting system stability. A block diagram of the L-1011-RE augmentation system is shown in Figure 2-11.

2.3.2 Modal Characteristics Procedure

The pitch damper was analyzed by plotting the locus of short-period characteristic roots as the damper gain and lag time constant were varied. Root loci were calculated for c.g. locations of 0.25, 0.35, and $0.40\bar{c}$. Results of these calculations are plotted in Figures 2-12 through 2-17. Data for the landing approach in Figures 2-12 through 2-14 show that a lag time constant of 0.8 seconds and a gain of at least 0.6 will give good frequency and damping characteristics for the c.g. range 0.25 to $0.40\bar{c}$. Corresponding data for cruise in Figures 2-15 to 2-17 show that a lag time constant of 0.4 seconds and a gain of at least 0.3 will be required.

Figures 2-18 and 2-19 summarize the effects of c.g. on the small-tail L-1011 with pitch damper lag time constant fixed at 0.8 seconds for the landing approach and 0.4 seconds for cruise, respectively. These data show that increased gain tends to decrease the effects of c.g. but at the same time degrades the damping. Using characteristics of the unaugmented standard-tail airplane as a reference, it was decided that a good compromise would be a gain of 0.8 for the landing approach and 0.4 for cruise.

Figures 2-20 and 2-21 show the effect of c.g. location on characteristic roots of the small-tail L-1011-RE with the basic augmentation system (System 1). These data show that the configuration has good short-period frequency and damping characteristics for the complete c.g. range, compared to the unaugmented standard-tail L-1011 with mid-c.g. ($0.25\bar{c}$). Also, all other roots are stable for c.g. locations aft to $0.40\bar{c}$. It is noteworthy that the augmentation system significantly increases the frequency over that of the unaugmented small-tail airplane, and also, because of the pitch damper lag, suppresses the low frequency instability of the unaugmented airplane in cruise.

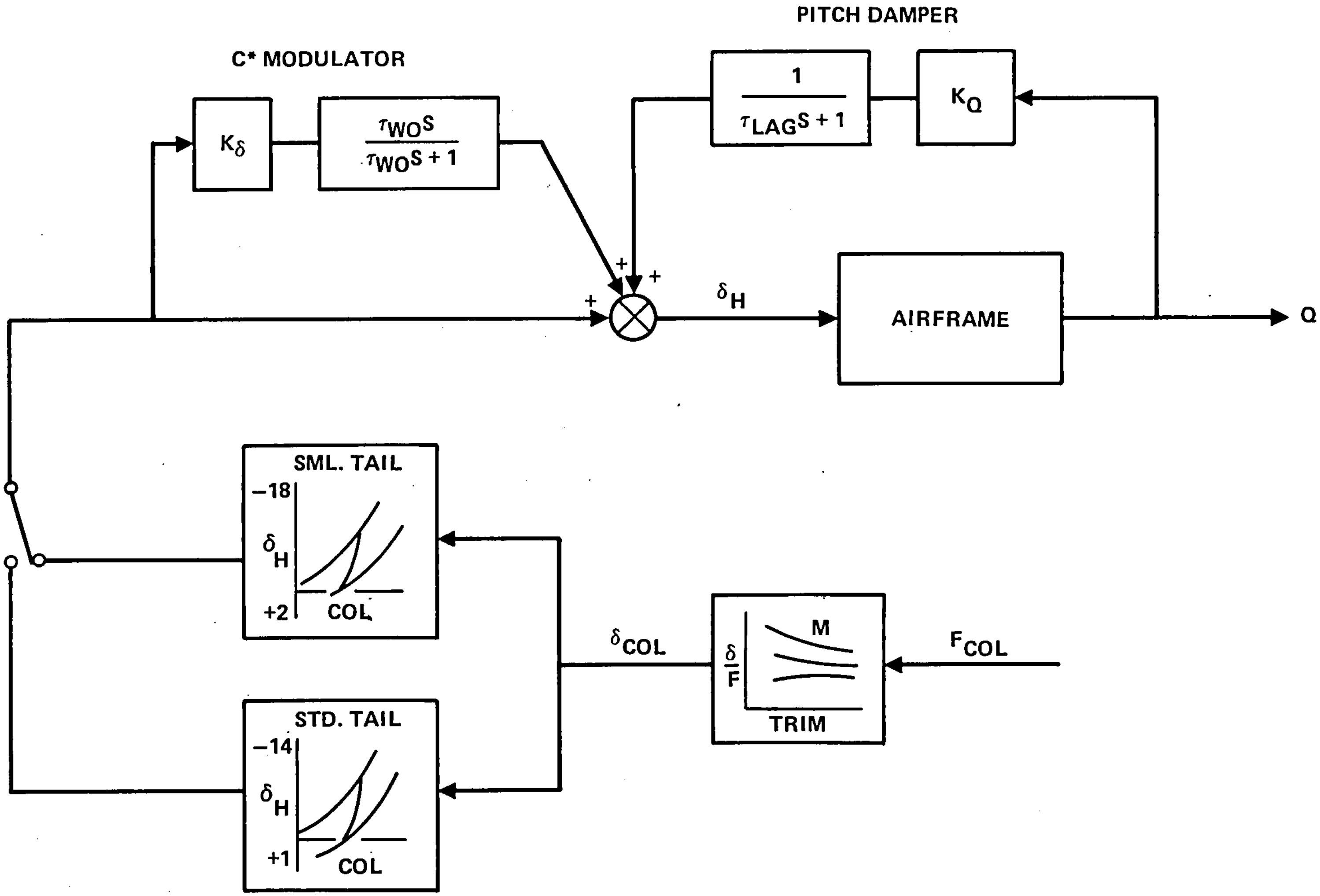


Figure 2-11. L-1011-RE Augmentation System Block Diagram

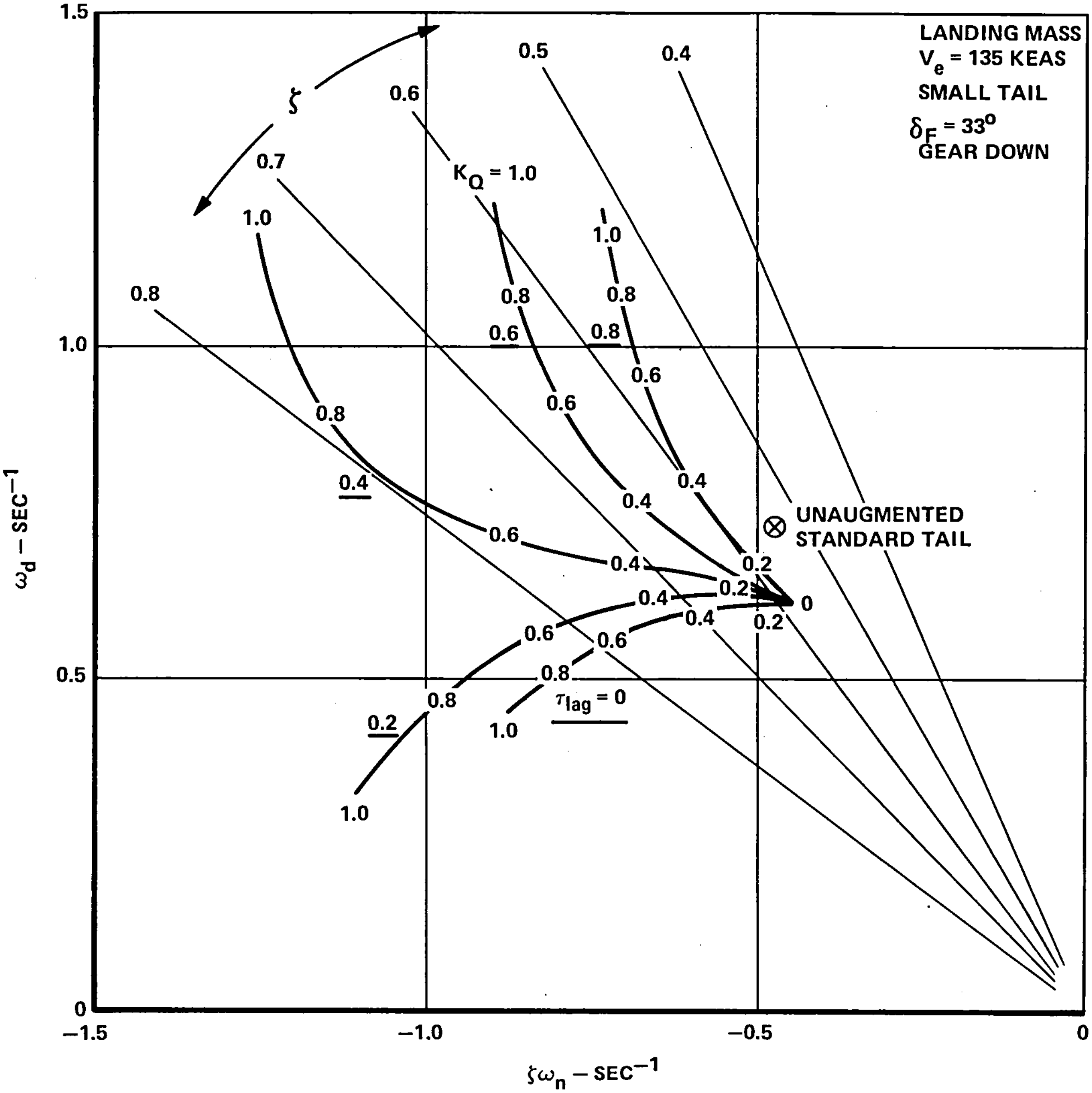


Figure 2-12. Effects of Gain and Lag Time Constant Approach C.G. at 0.25$\bar{c}$

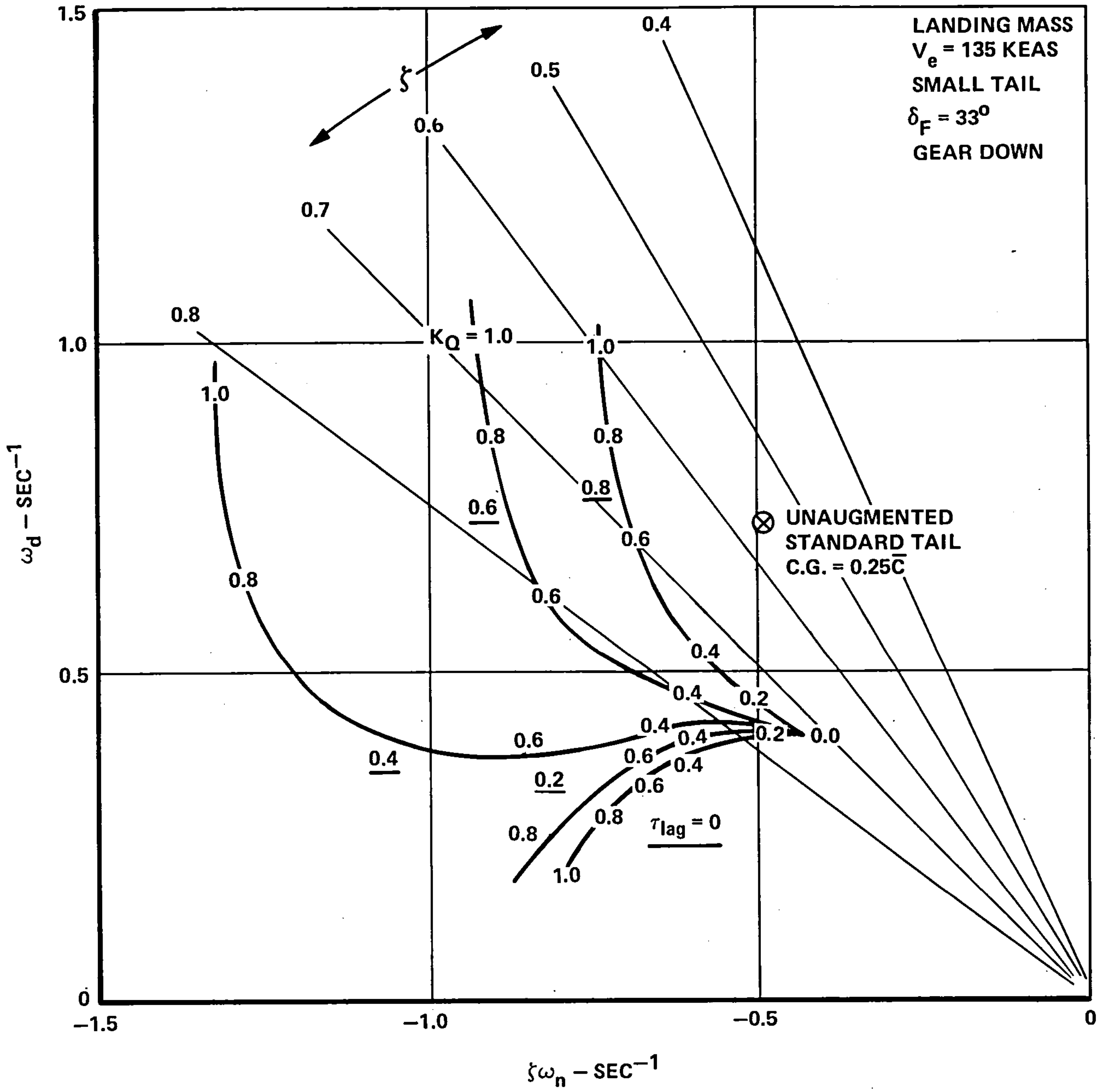


Figure 2-13. Effects of Gain and Lag Time Constant Approach C.G. at 0.35$\bar{c}$

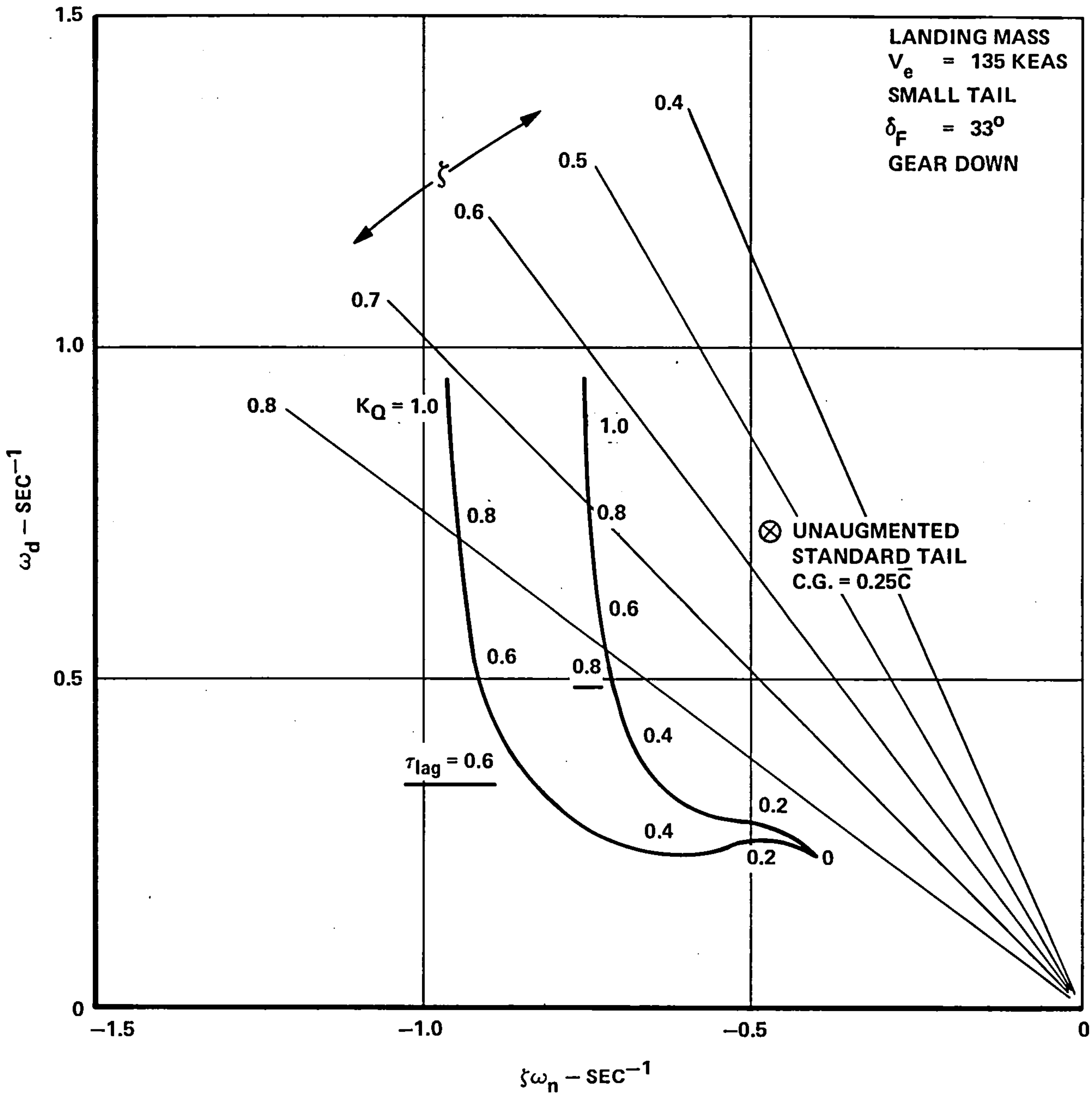


Figure 2-14. Effects of Gain and Lag Time Constant Approach C.G. at 0.40$\bar{c}$

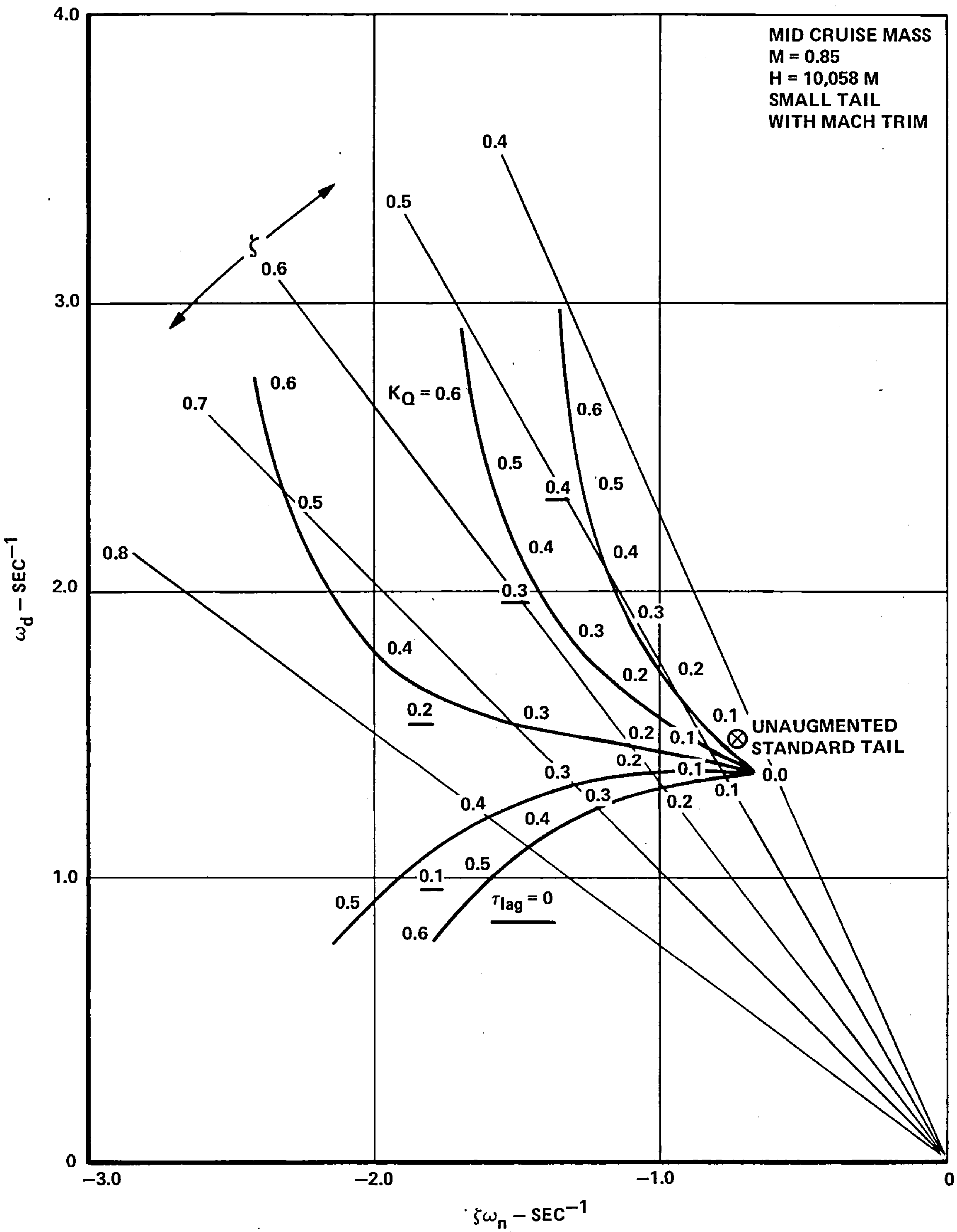


Figure 2-15. Effects of Gain and Lag Time Constant Cruise With C.G. at $0.25\bar{c}$

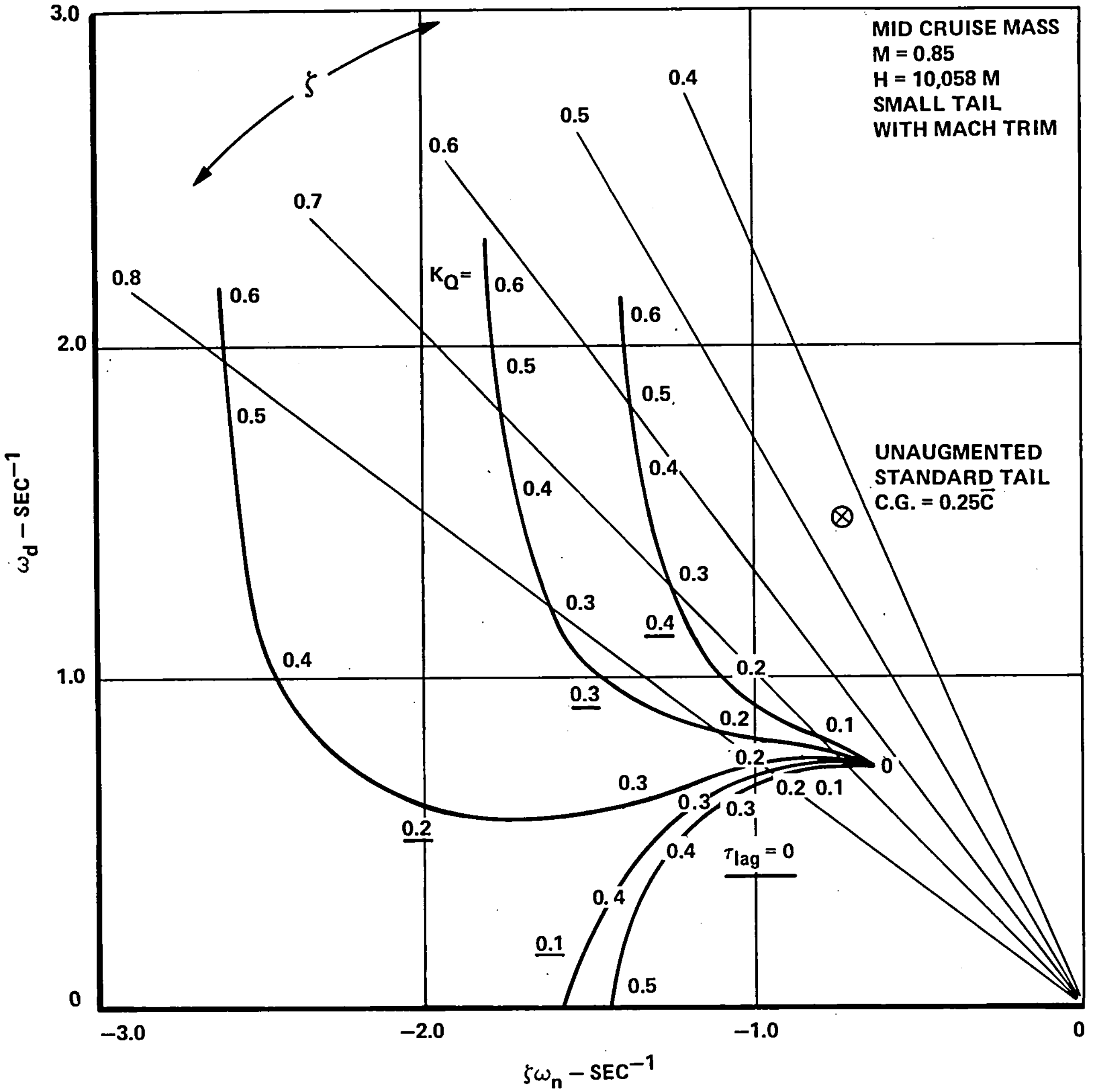


Figure 2-16. Effects of Gain and Lag Time Constant Cruise C.G. at 0.35c̄

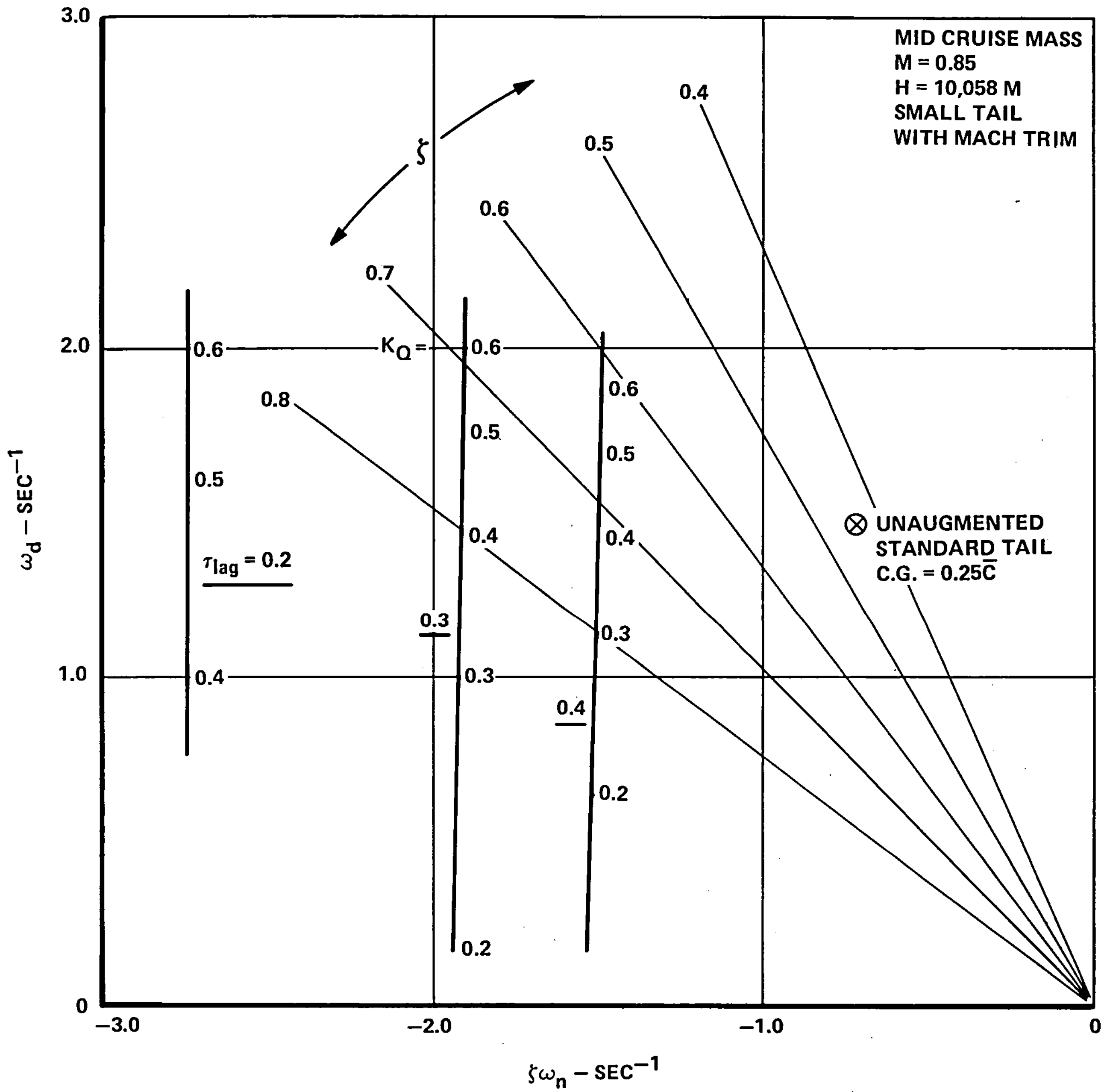


Figure 2-17. Effects of Gain and Lag Time Constant
Cruise C.G. at 0.40c

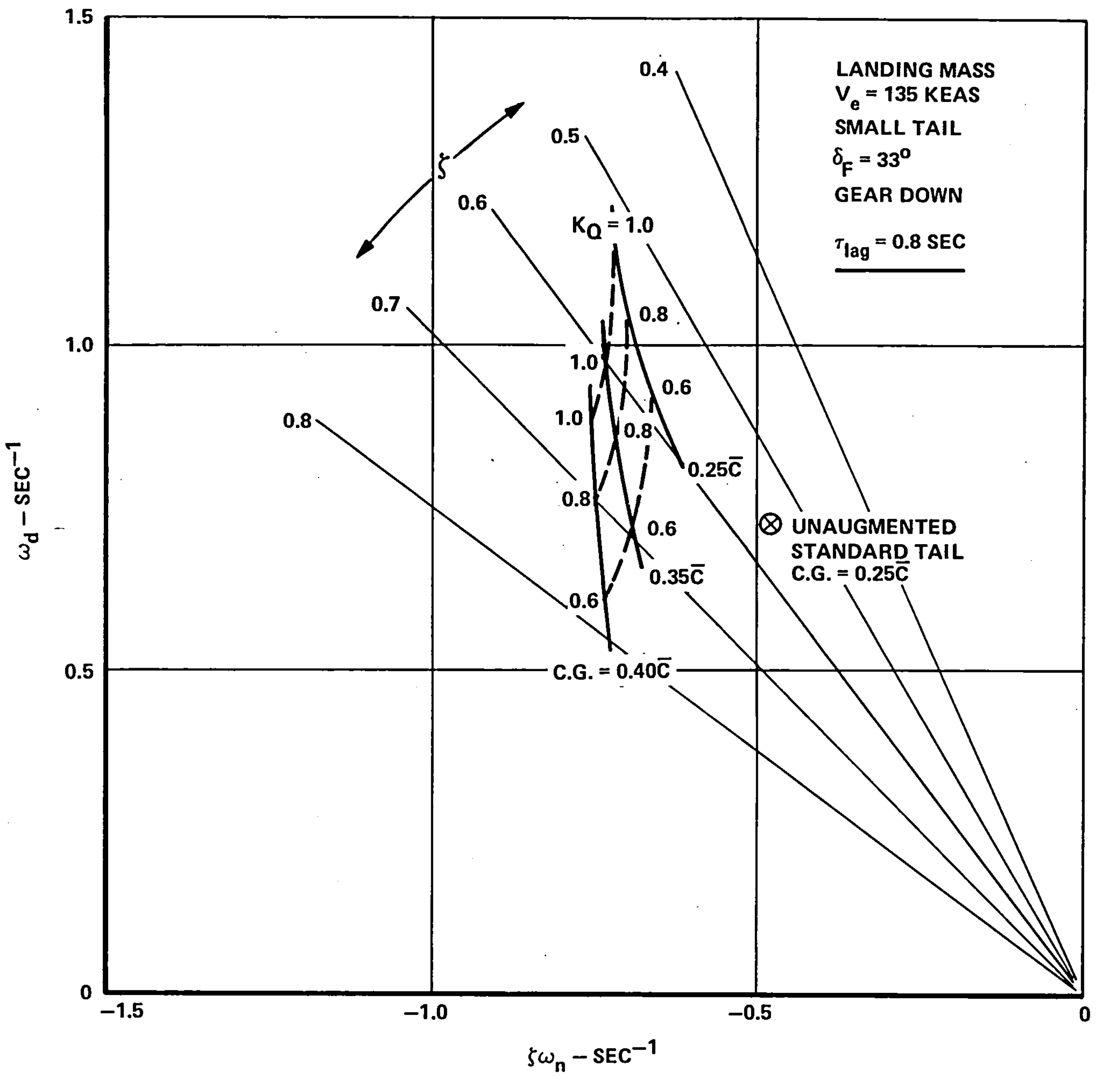


Figure 2-18. Effect of C.G. Approach Lag Time Constant = 0.8 Seconds

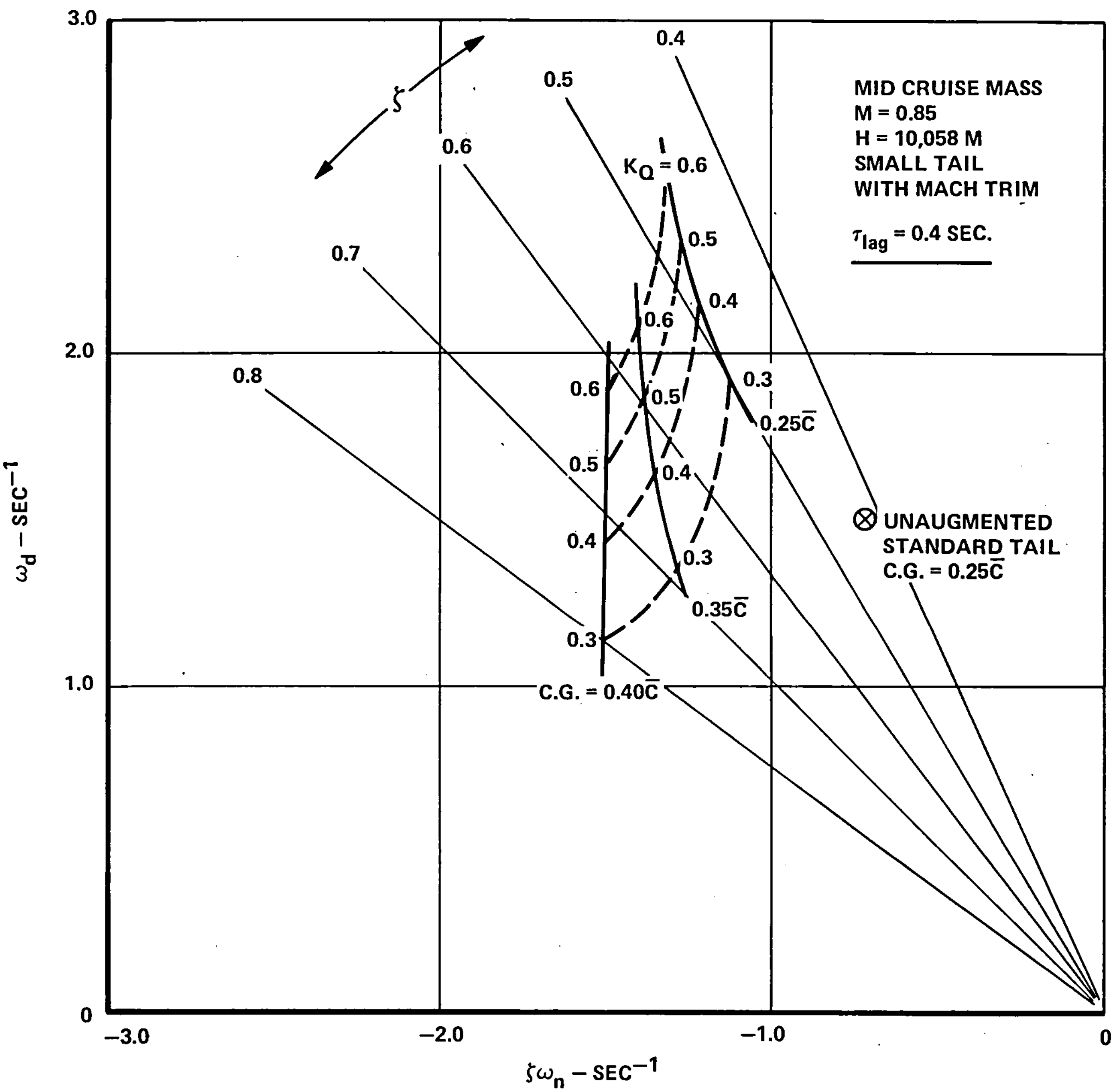


Figure 2-19. Effect of C.G. Cruise Lag Time Constant = 0.4 Seconds

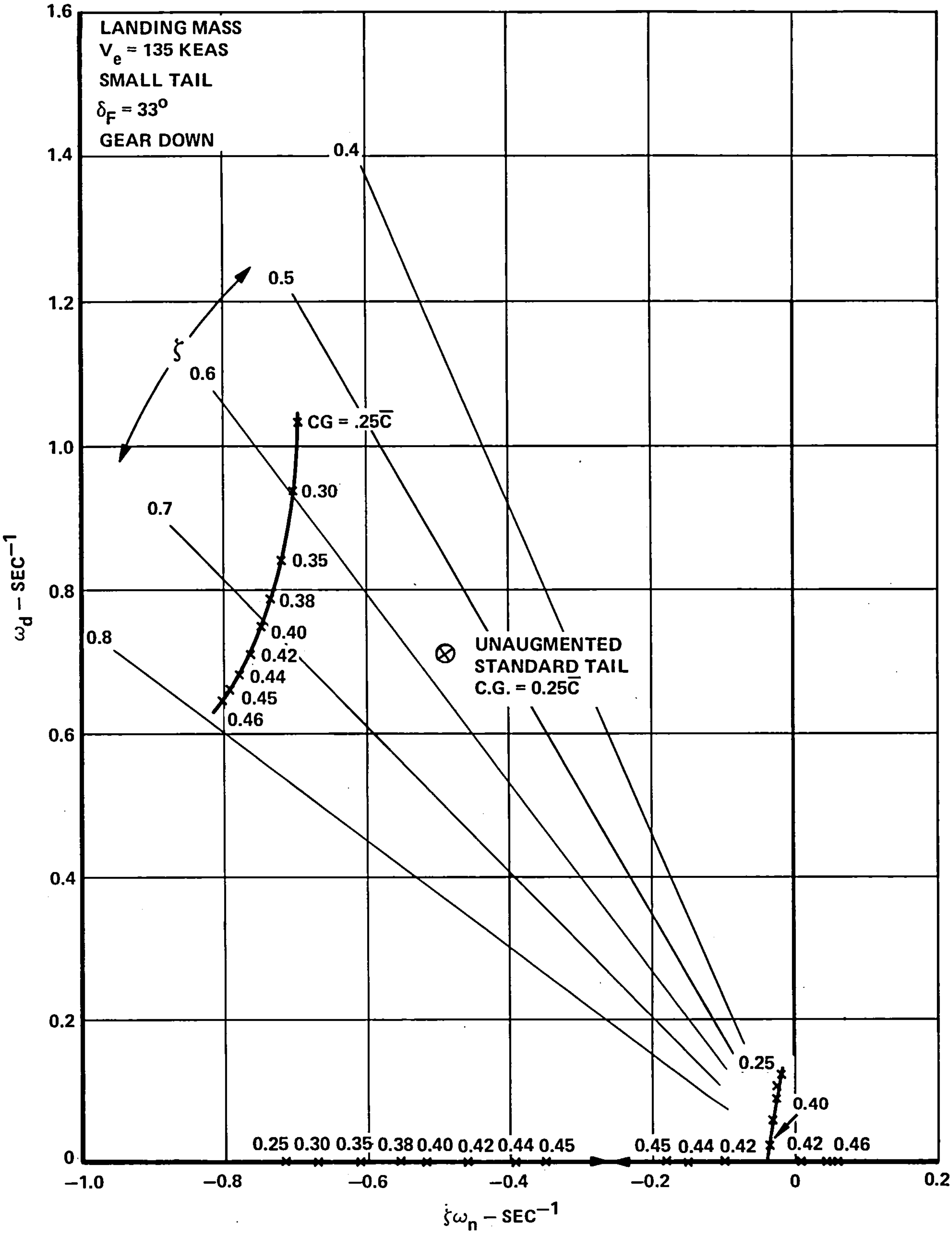


Figure 2-20. Effect of C.G. Approach System 1

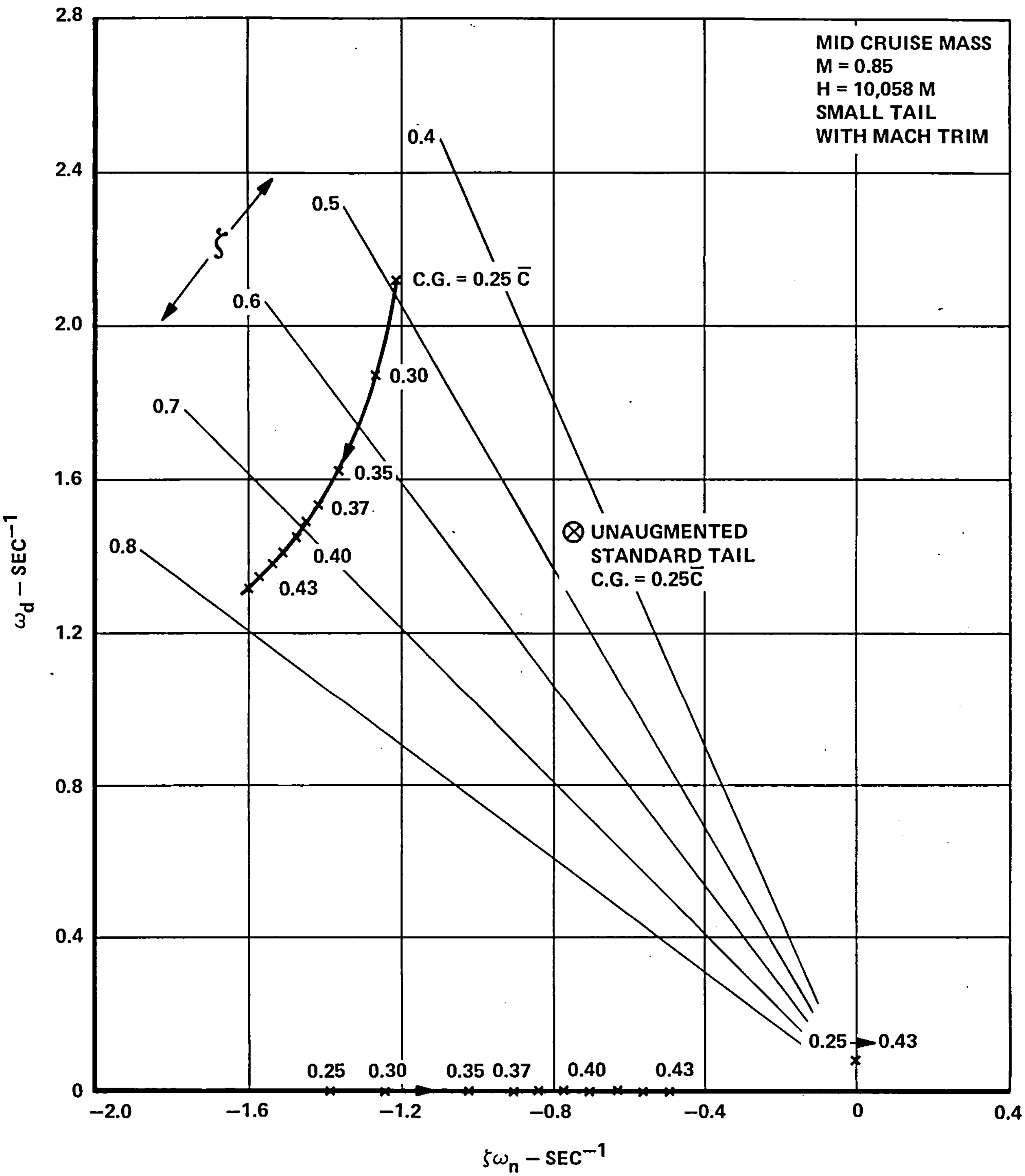


Figure 2-21. Effect of C.G. Cruise System 1

2.3.3 Time History Analysis

C* step response time history characteristics of the augmented system with the selected pitch damper gains and lag time constants are shown in Figures 2-22 and 2-23. Data for the landing approach in Figure 2-22 show the C* time histories are within the prescribed boundaries except for c.g. locations forward of $0.25\bar{c}$. Data for cruise in Figure 2-23 show the C* time histories are nearly centered between the upper and lower boundaries for intermediate c.g. positions. In order to evaluate the effects of C* in the flight simulation, an attempt has been made to match the upper and lower C* boundaries with the washed-out stick feed forward loop. In each case, that is for the landing approach and cruise, it was found that an upper boundary match was facilitated by reducing the pitch damper gain in addition to the stick feed-forward manipulation; gains and time constants for this system are identified as System 2. A lower boundary match was achieved by reducing slightly the stabilizer-to-column gain; this is identified as System 3.

Augmentation system characteristics are summarized in Table 2-1.

2.4 AFT C.G. FLIGHT SIMULATION OBJECTIVES

The L-1011-RE configuration has been developed to optimize performance and fuel economy. Flying qualities analysis and testing has been performed primarily to support the augmentation system design. Because of the lack of proven flying qualities design criteria for augmented aircraft and because of a need to establish minimum flying qualities requirements for the unaugmented aircraft, a flight simulation program was necessary to supplement the control system analysis.

Following is a list of the major objectives of the flight simulation program.

I. Evaluate minimum acceptable stability limits for operation with augmentation off.

   A. In high altitude cruise

   B. During landing approach

   C. In other flight conditions that may be critical

II. Evaluate augmentation system characteristics and optimize where possible.

   A. In high altitude cruise

   B. During landing approach

   C. In other critical conditions

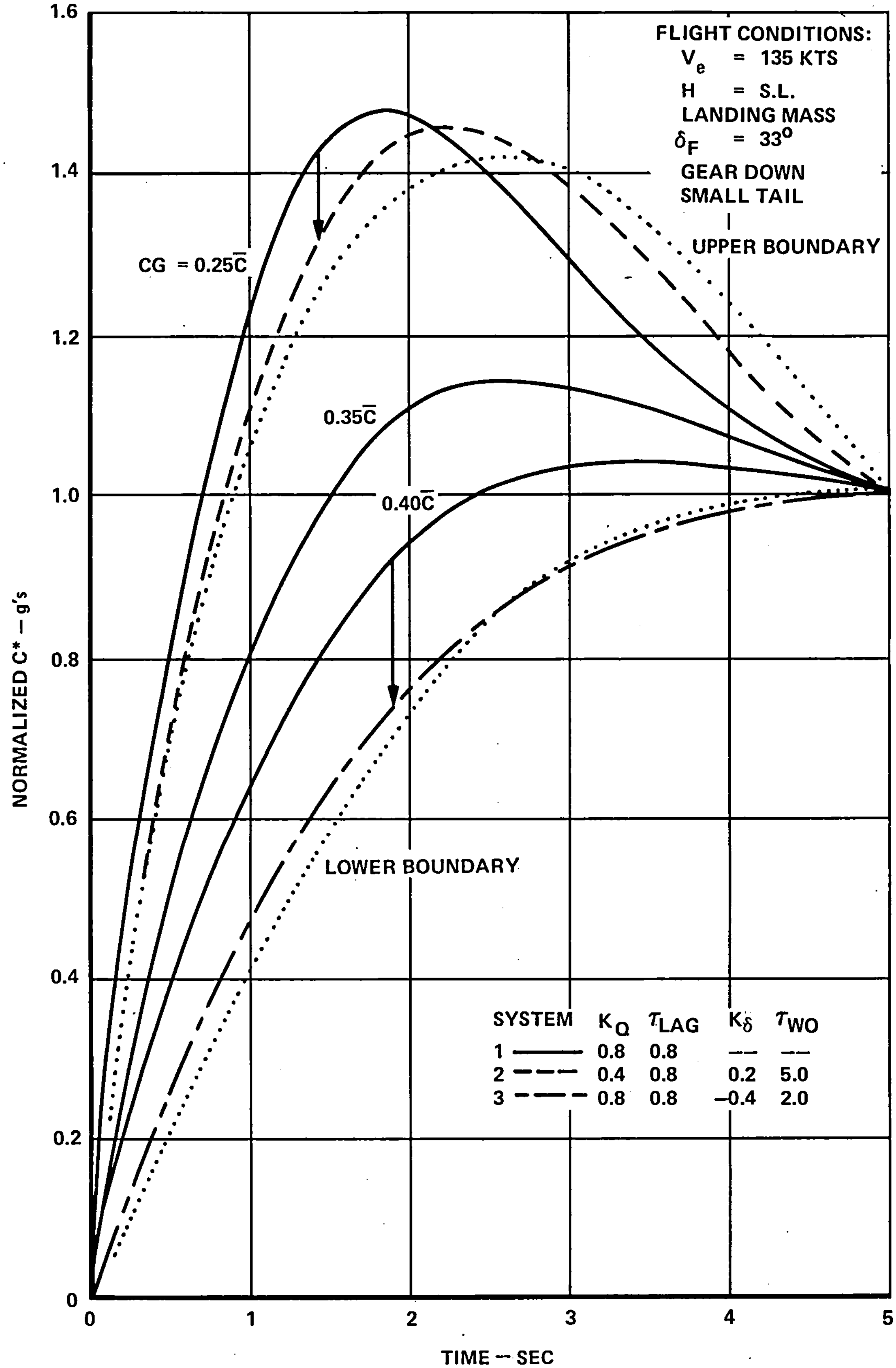


Figure 2-22. Landing Approach C*

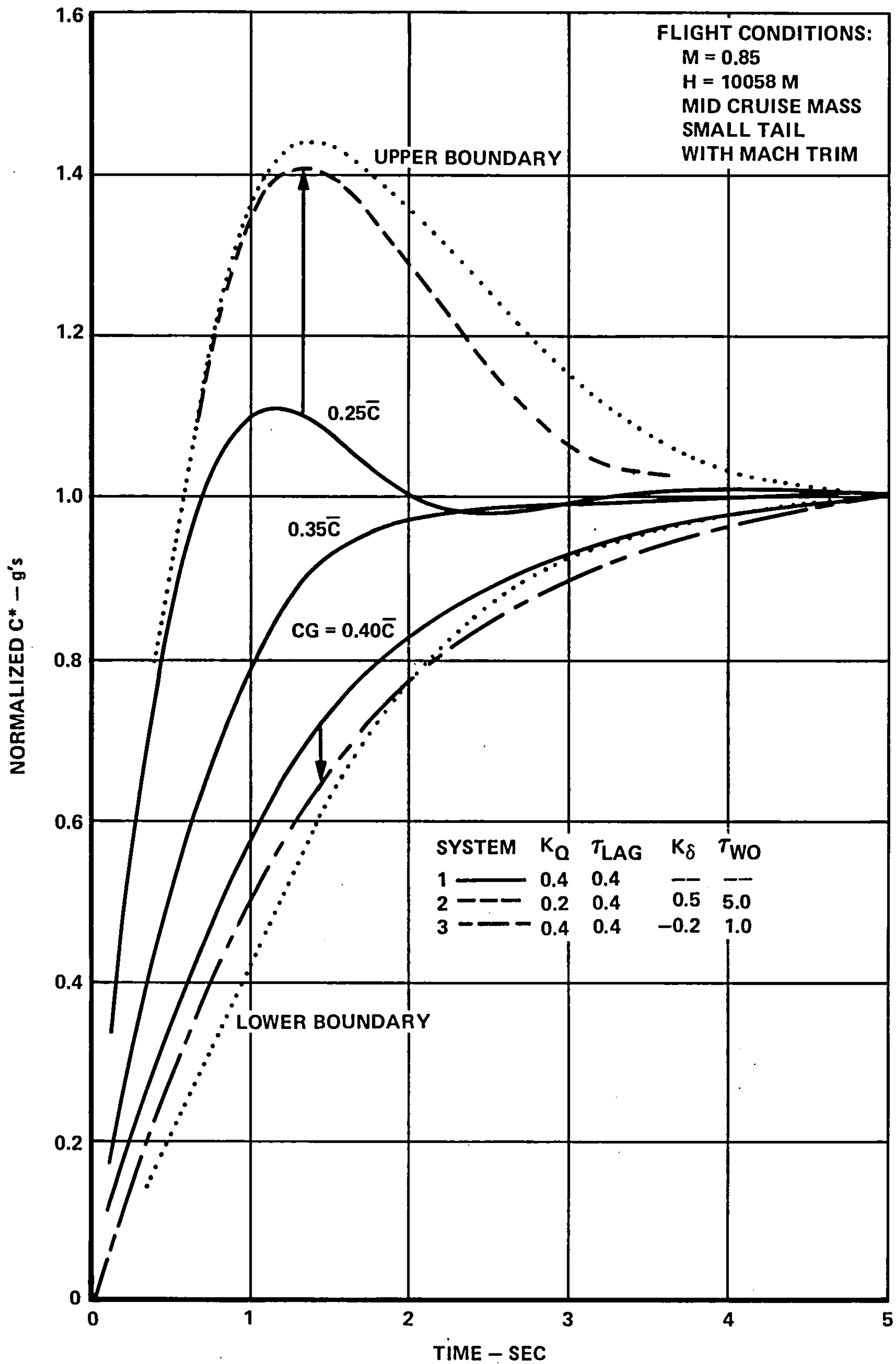


Figure 2-23. Cruise C*

TABLE 2-1. L-1011-RE AUGMENTATION SYSTEM CHARACTERISTICS

	LANDING APPROACH SYSTEM			CRUISE SYSTEM		
	1 PITCH DAMPER	2 UPPER C*	3 LOWER C*	1 PITCH DAMPER	2 UPPER C*	3 LOWER C*
K_Q – (SEC)	0.8	0.4	0.8	0.4	0.2	0.4
τ_{lag} – (SEC)	0.8	0.8	0.8	0.4	0.4	0.4
K_δ	––	0.2	–0.4	––	0.5	–0.2
τ_{WO} – (SEC)	––	5.0	0.2	––	5.0	1.0

III. Evaluate controlability of the transient response due to augmentation system failure.

IV. Evaluate the influence of atmospheric disturbances on flying qualities, both augmentation on and off.

V. Determine augmentation system authority requirements.

2.5 SIMULATION MATH MODEL

The simulation math model was programmed on a hybrid system using both analog and digital computing equipment. The digital computer was used for storage and retrieval of nonlinear aerodynamic and engine data and for integration of the equations of motion. The analog computer was used to simulate control system dynamics and cockpit control forces and to display the simulation outputs on strip chart recorders. Additional parameters were recorded digitally, such as touchdown conditions and RMS errors on final approach.

2.5.1 Aerodynamic Model

Aerodynamic data were input in the stability system of axes shown in Figure 2-24, with an indication of signs of the parameters. The various components of aerodynamic forces and moments were programmed over the complete range of airspeed and altitude within the operational limits of the airplane. A complete nonlinear flexible model of longitudinal aerodynamics was programmed, since the evaluation was concentrated on longitudinal flying qualities. A simplified lateral-directional model was employed, to be representative of the airplane response at the test conditions, but not containing a complete description of all systems.

Engine forces and moments were computed in the body system of axis, with each engine of the three controlled by a separate throttle. An engine dynamic model was programmed as shown in Figure 2-25, with time variations of Engine Pressure Ratio, EPR, adjusted to match flight-test-derived engine accelerations and decelerations. The variation of thrust with altitude and Mach number was also derived from flight test data. Aerodynamic forces and moments were transformed to body axis and combined with the engine effects and center-of-gravity corrections to compute the total body accelerations and moments using standard 6 degree-of-freedom equations of motion.

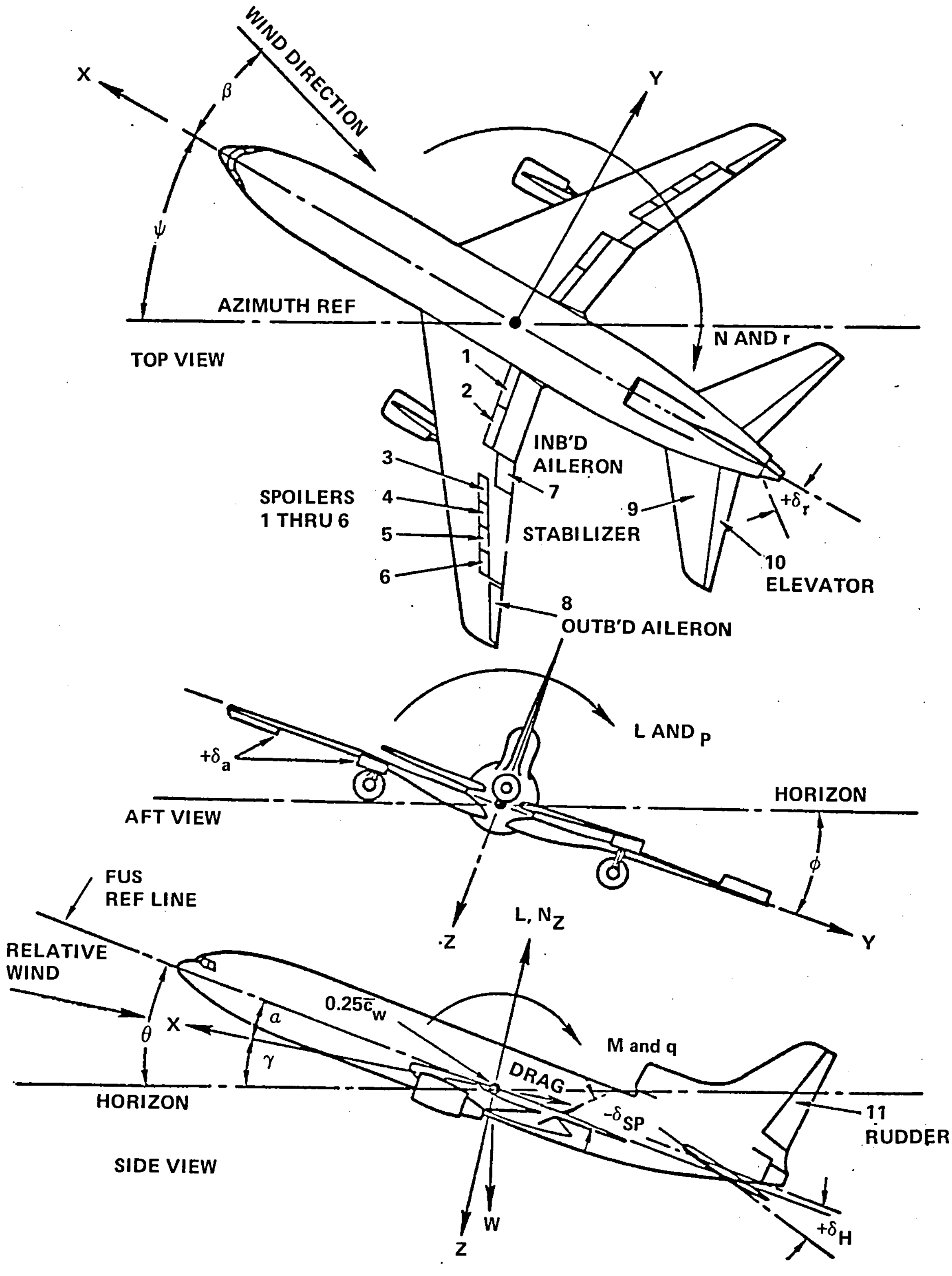


Figure 2-24. Control Surface Designation and Axes System

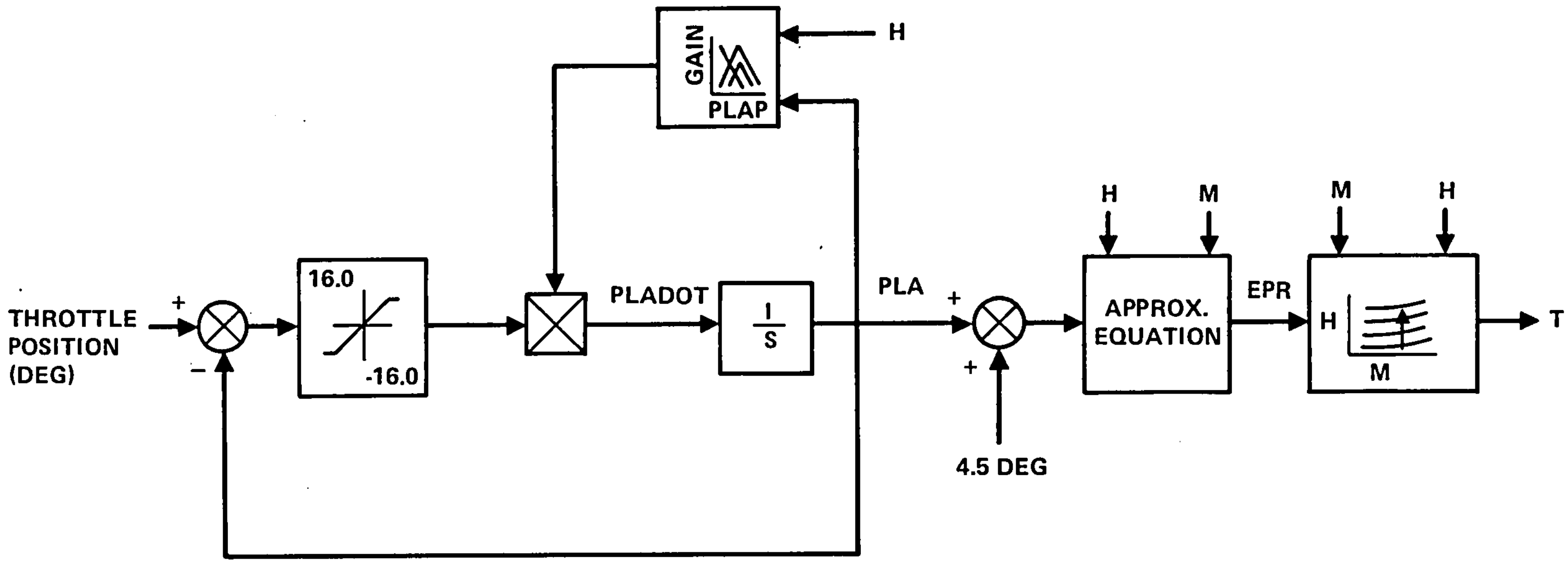


Figure 2-25. Engine Dynamics and Derivation of EPR and Thrust

Air turbulence was simulated by inserting random velocity inputs in the aerodynamic equations. Magnitudes and filtering of the input velocities were controlled according to the Dryden form of the random turbulence equations, presented in Figure 2-26. In the basic Dryden model the characteristic lengths are reduced as a function of height near the ground. In this study the lengths have been held at 305 m (1000 ft.). As a result the peak velocity gusts simulate vertical and horizontal wind-shear bursts on landing approach. Flying qualities were evaluated both in approach and cruise flight conditions in levels of turbulence from still air to heavy turbulence. Heavy turbulence is defined, for this study as 3.7 m/sec (12 fps) RMS in cruise and 2.7 m/sec (9 fps) in landing approach. These levels were obtained from various NASA simulation reports and from observation of the load factor and glide slope excurions caused by turbulence.

2.5.2 Control System Model

The control systems programmed in the simulator included a complete dynamic model of the longitudinal control system, and a simplified model of the lateral and directional systems. Also included were trim controls, and flap and gear control systems. Figures 2-27 and 2-28 are block diagrams of the analog models of the three primary flight systems. The longitudinal system included the "J-curve" of stabilizer-to-column gearing of the L-1011-1 airplane for tests with standard tail size and modified "J-curve" with increased deflection limits (Figure 2-29) for tests with reduced tail size. All other components in the system were held constant, except for the addition of stability augmentation for some tests. The standard L-1011-1 trim system was used for all tests. The autopilot system was not simulated for these tests, since manual pilot control was assumed for all testing. It should be noted, however, that the autopilot provides a separate backup mode in the event of augmentation failure, and the augmentation-off conditions simulated in this program could occur only after complete failure of both autopilots as well as the augmentation system

2.6 SIMULATOR DESCRIPTION

2.6.1 Computing Equipment

The flight simulation equipment consisted of an Electronic Associates, Inc. 8400 digital computer, an Electronic Associates, Inc. 7800 analog computer, and a

LONGITUDINAL:

$$\text{TURBU} = \text{W.N.}\sqrt{\frac{2\,L_U}{\pi U}}\left(\frac{1}{1+\frac{L_U}{U}\,S}\right)$$

LATERAL:

$$\text{TURBV} = \text{W.N.}\sqrt{\frac{L_W}{\pi U}}\left(\frac{1+\frac{\sqrt{3}\,L_W}{U}\,S}{\left(1+\frac{L_W}{U}\,S\right)^2}\right)$$

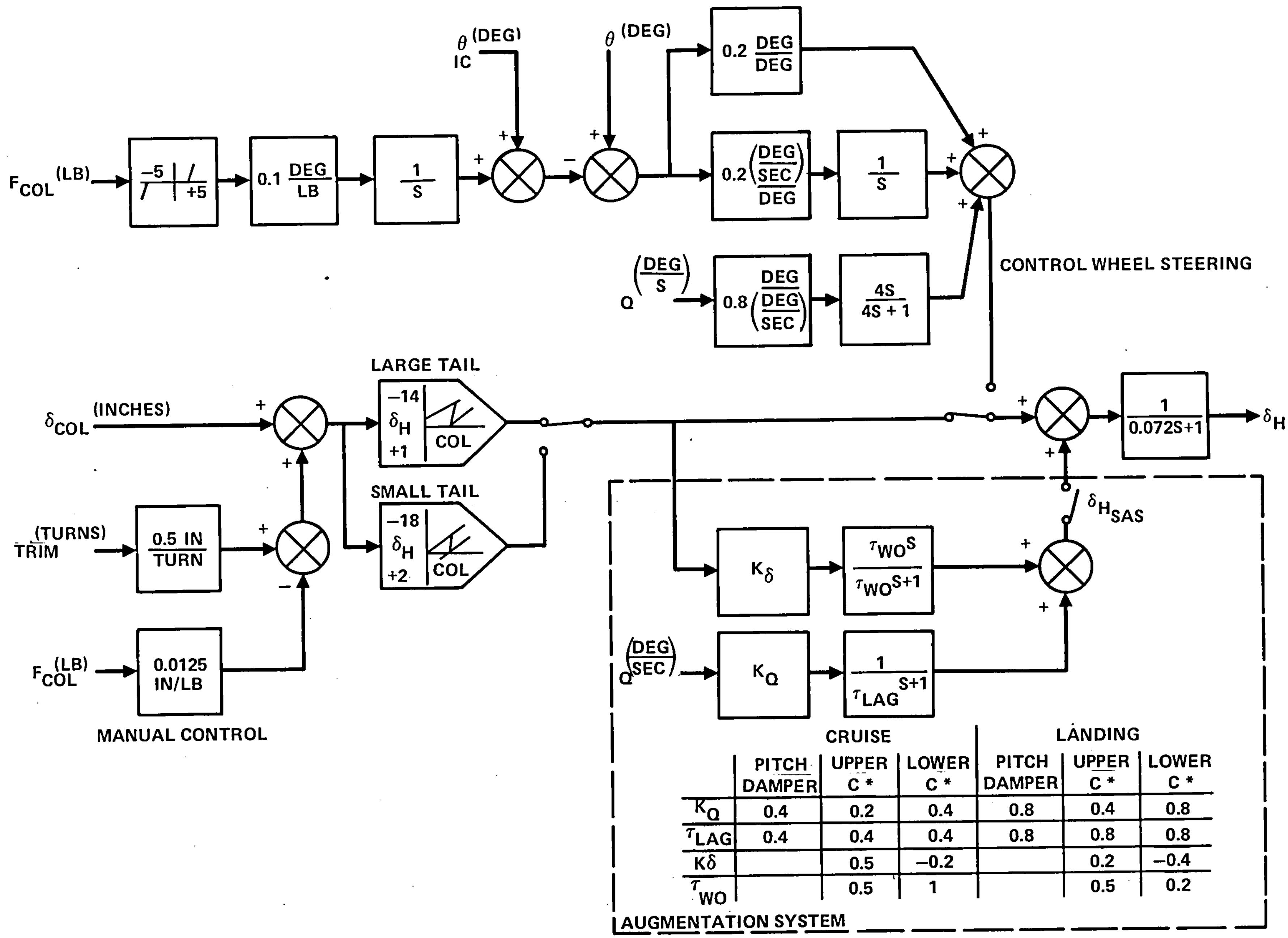
VERTICAL:

$$\text{TURBW} = \text{W.N.}\sqrt{\frac{L_W}{\pi U}}\left(\frac{1+\frac{\sqrt{3}\,L_W}{U}\,S}{\left(1+\frac{L_W}{U}\,S\right)^2}\right)$$

$L_U = L_W = 305$ M

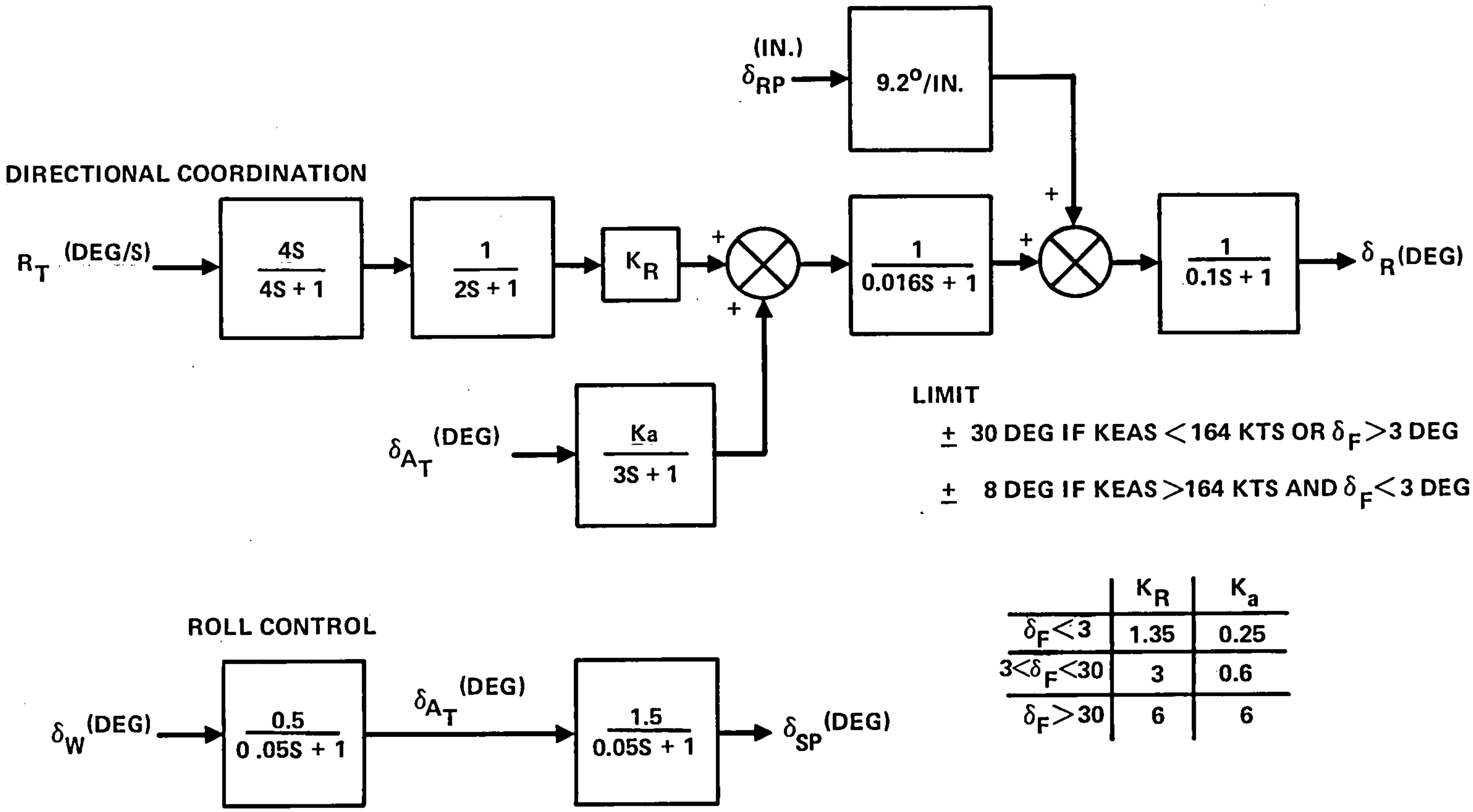
W.N. = WHITE NOISE

Figure 2-26. Turbulence Model



	CRUISE			LANDING		
	PITCH DAMPER	UPPER C *	LOWER C *	PITCH DAMPER	UPPER C *	LOWER C *
K_Q	0.4	0.2	0.4	0.8	0.4	0.8
τ_{LAG}	0.4	0.4	0.4	0.8	0.8	0.8
$K\delta$		0.5	−0.2		0.2	−0.4
τ_{WO}		0.5	1		0.5	0.2

Figure 2-27. Longitudinal Control Systems



LIMIT

$\pm$ 30 DEG IF KEAS $<$ 164 KTS OR $\delta_F > 3$ DEG

$\pm$ 8 DEG IF KEAS $>$ 164 KTS AND $\delta_F < 3$ DEG

	K_R	K_a
$\delta_F < 3$	1.35	0.25
$3 < \delta_F < 30$	3	0.6
$\delta_F > 30$	6	6

Figure 2-28. Lateral Control Systems

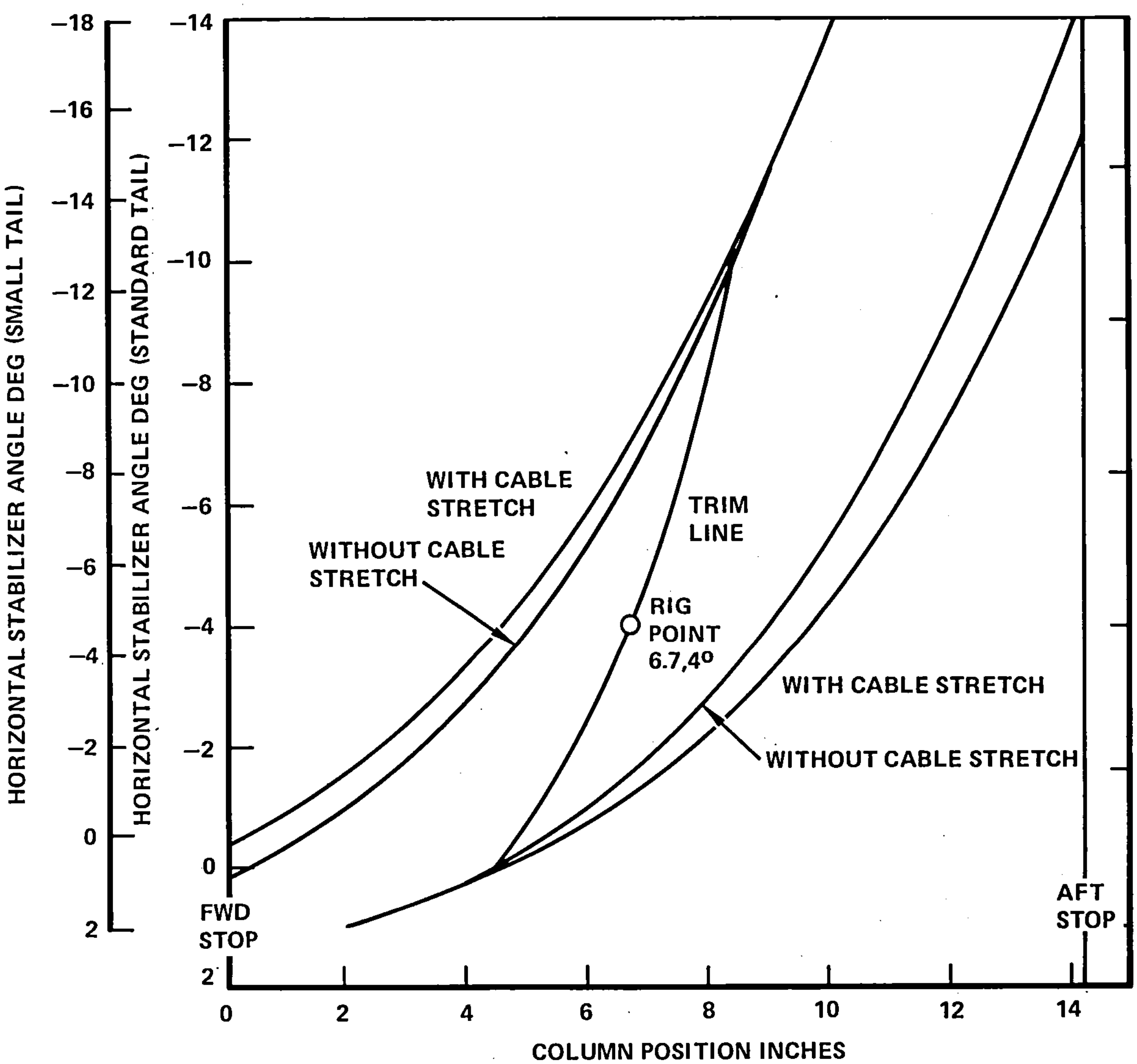


Figure 2-29. Column to Stabilizer Gearing (J Curve)

trunking rack to interconnect the computers and other peripheral equipment such as, a sound generator, visual system, motion system and the cockpit instrument and controls.

2.6.2 Motion System

The motion system used in this simulation is a four degree-of-freedom system, providing pitch, roll, vertical and lateral motions. The motion system provides completely independent motion in each degree of freedom, such that full excursion is available in any axis, independent of the excursions in the other axes. Deflection, rate and acceleration limits in each axis are presented in the following table.

	ACCEL	RATE	DEFL
PITCH	$\pm 25^\circ/sec^2$	$\pm 15^\circ/sec$	$\pm 15^\circ$
ROLL	$\pm 70^\circ/sec^2$	$\pm 15^\circ/sec$	$\pm 15^\circ$
VERTICAL	+0.8 g, -1.0 g	$\pm$0.3048 m/sec (1 fps)	$\pm$0.3048 m (1.0 ft.)
LATERAL	$\pm$0.2 g	$\pm$0.3048 m/sec (1 fps)	$\pm$0.3048 m (1.0 ft.)

Because of the importance of air turbulence in this evaluation, motion system gains were optimized to present the most realistic turbulence simulation possible within the limits of the actuators.

2.6.3 Control Column Force Simulation

The forces experienced by the pilot in the simulator are supplied by a hydraulic column-loader which is a conventional closed-loop servo system with position feedback and a high forward loop gain, to give high column response. The model consists of a second order system having position and rate feedback as follows:

$$\frac{F_P}{X} = \frac{S^2}{K} + S(K_V + K_C) + K_S + K_d$$

K_S = spring rate

K_d = detent spring rate

K_V = viscous friction

K_c = coulomb friction

$1/_K$ = system mass

X = stick position

F_p = pilot force

K_s was varied as a function of trim stabilizer position and Mach number, as shown in Figure 2-30. All other parameters were held constant throughout the analysis. Figure 2-31 presents a block diagram of the model used to generate column forces.

2.6.4 Cockpit Instrumentation

The flight instrument displays are situated in the pilot's station instrument panel as shown in Figure 2-32. Where possible actual aircraft instruments were used, and in other cases galvanometer and synchro-driven displays were used with instrument faces representative of flight hardware. Two displays not present in production aircraft, a feel force gauge and a vertical accelerometer, were included for evaluation purposes. For approach testing, a cross-pointer flight director display was available on the Attitude indicator. Equations used to drive the cross pointers are representative of the production L-1011 system and are shown in Figures 2-33 and 2-34.

2.6.5 Visual Display System

The visual system is a single-window television system with a 25-inch TV monitor mounted on the pilot's glare shield. The source of the displayed image is a three dimensional 1500:1 scale model of the Palmdale, California airport and surrounding terrain mounted on a continuous moving belt. The monitor image is generated by a closed circuit television channel, the camera of which is mounted on a servo-controlled carriage that moves across the width of the model belt and at right angles to its surface, thus providing lateral and vertical displacement of the image. These movements, along with model belt motion, present the true position of the aircraft, relative to the airport runway. A servo-controlled prism-mirror system, attached to the camera, provides pitch, bank, and heading displacements. Figure 2-32 shows the view presented to the pilot at a position 30.5 m (100 ft.) above the runway and 10 seconds from touchdown.

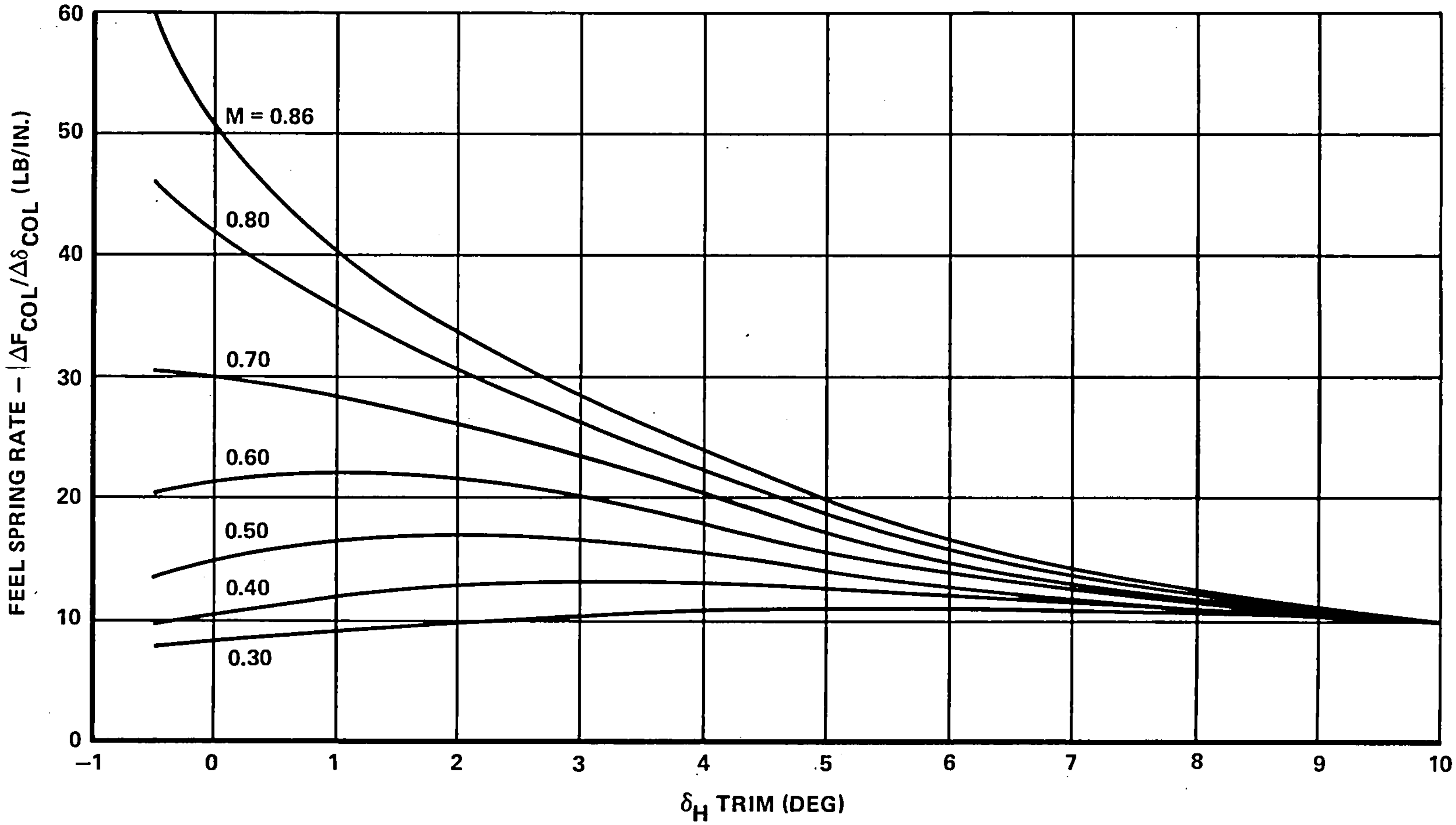


Figure 2-30. L-1011-500 Pitch Feel Spring Rate

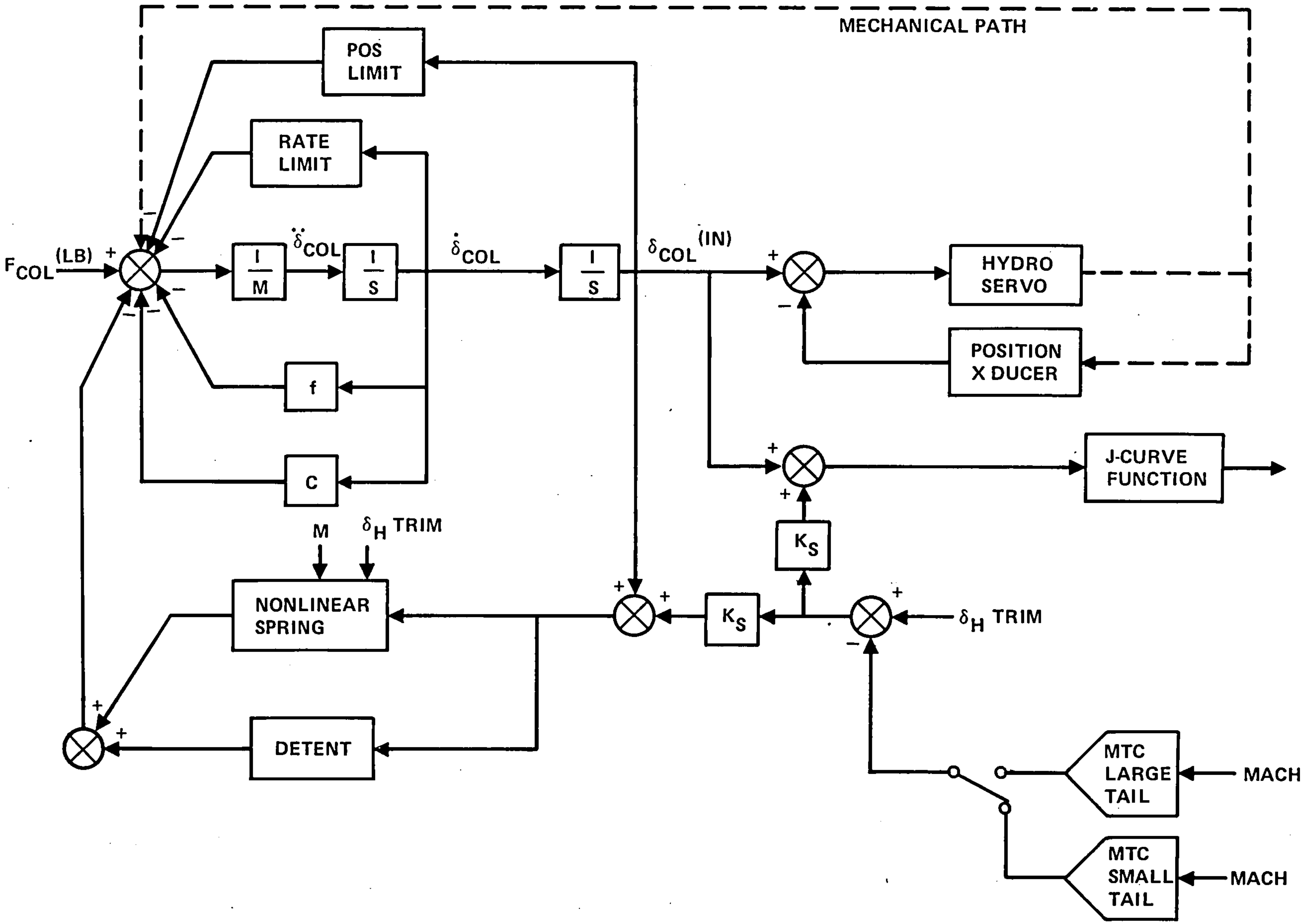
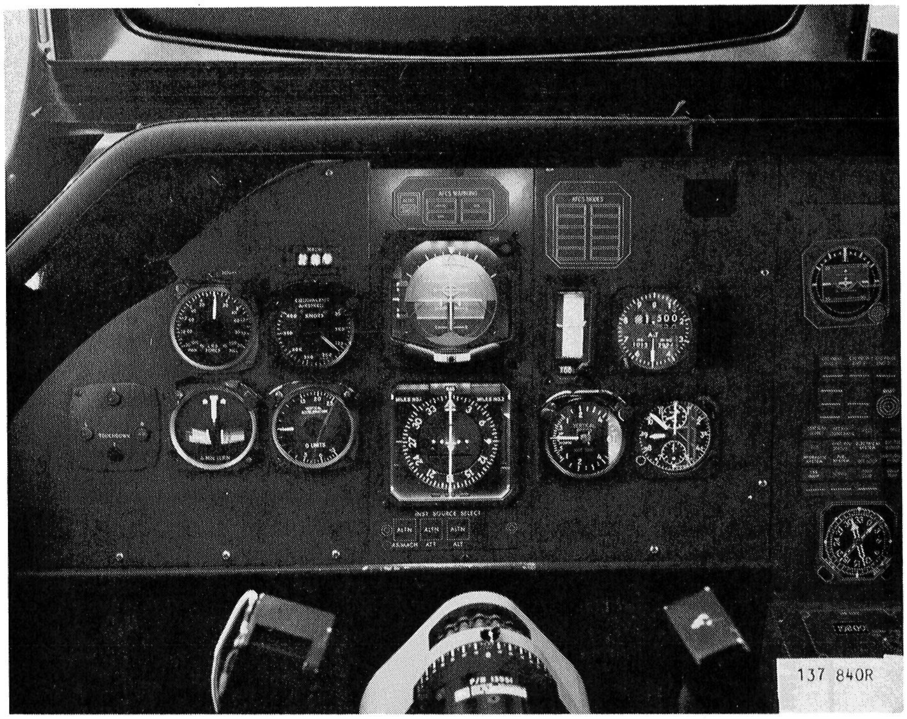


Figure 2-31. Pitch Feel Force System



FLIGHT INSTRUMENT DISPLAY

VISUAL RUNWAY DISPLAY

Figure 2-32. Cockpit Displays

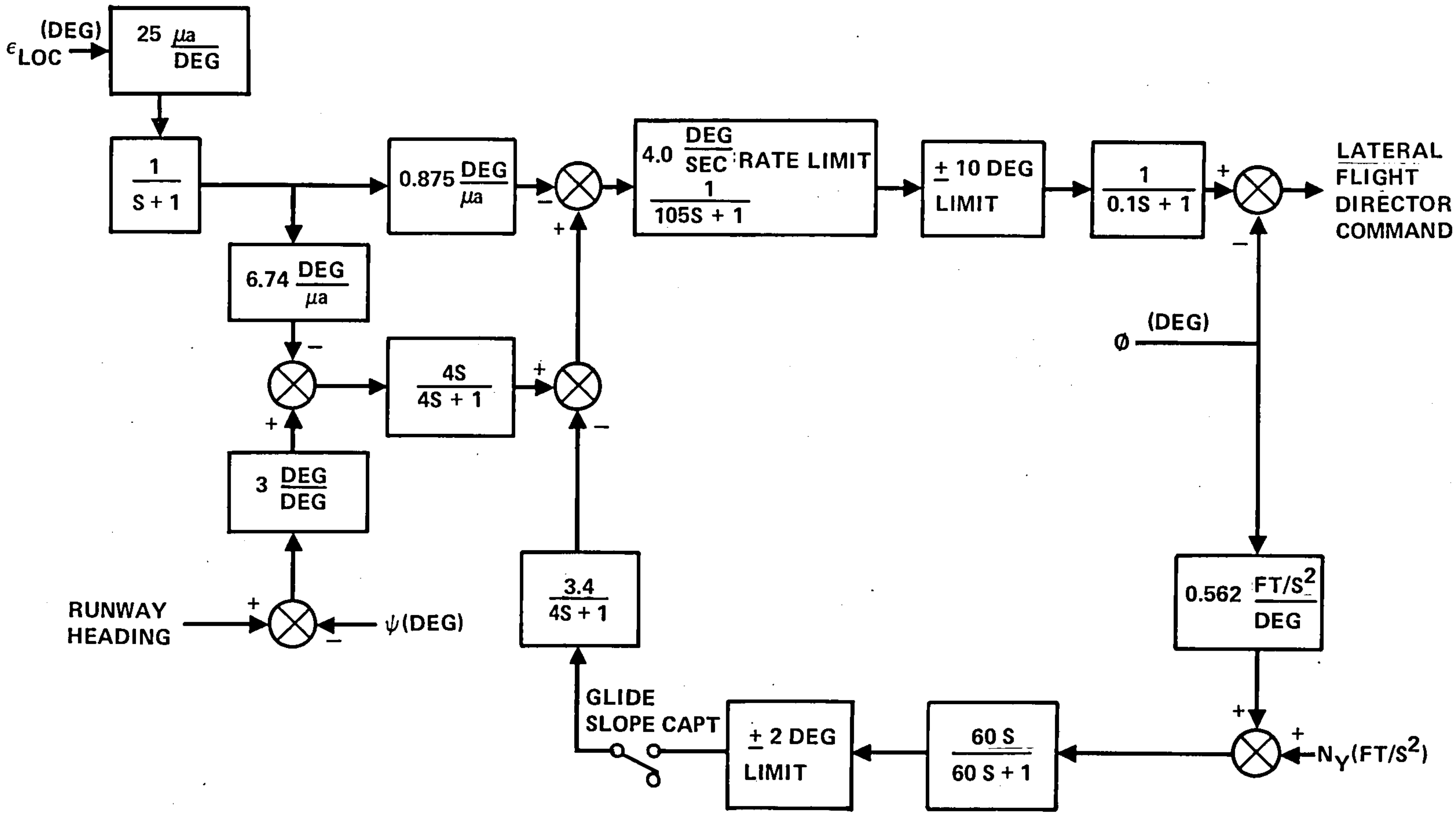


Figure 2-33. Lateral Flight Director

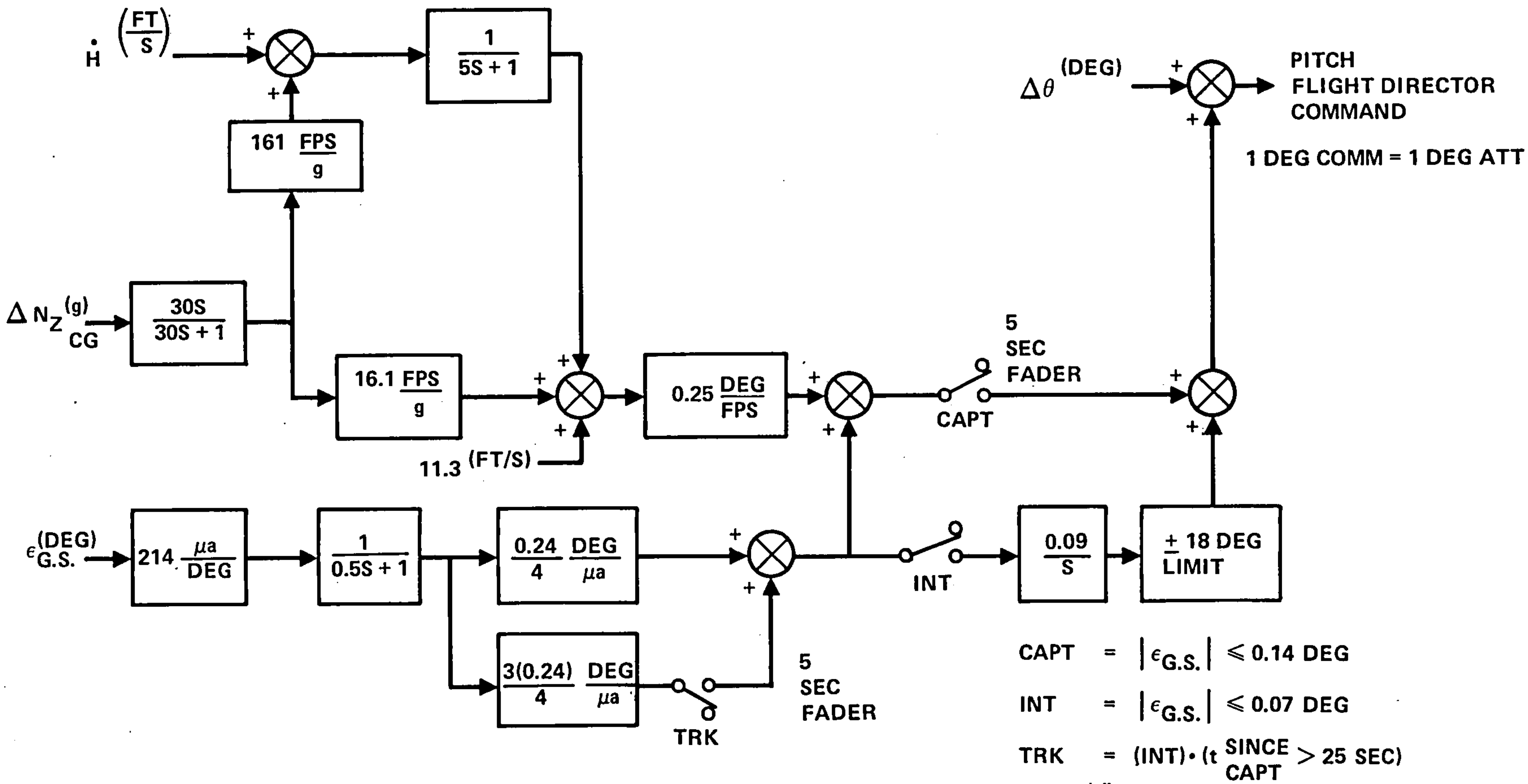


Figure 2-34. Longitudinal Approach Flight Director

2.7 DATA ACQUISITION

Output data from this evaluation are in the form of:

1. Pilot ratings and comments on the workload required to obtain satisfactory aircraft performance for the task being evaluated. Pilot ratings are recorded in terms of the Cooper-Harper handling qualities scale included as Figure 2-35.

2. Analog strip chart records of several parameters for each case evaluated.

3. Digital printout of several touchdown parameters for approach tests.

4. Statistical data computed during all approach tests and selected cruise tests.

Tables 2-2 and 2-3 present the parameters recorded on the analog strip charts and digital recorders, respectively, including symbols and units. Table 2-4 presents the parameters for which statistical data were computed for the approach tests.

2.8 DESCRIPTION OF TEST CONFIGURATIONS

In the flight simulation program three versions of the L-1011 aircraft were evaluated. To validate the simulation model, and to serve as a reference for pilot rating comparisons, the baseline L-1011-1 was evaluated in all flight conditions. The two primary test configurations were the L-1011-500 with extended wing tips designated herein as the baseline aircraft, and the L-1011-500 with extended wing-tips and reduced horizontal tail area, 74.3 m^2 (800 ft^2) vs 119.1 m^2 (1282 ft^2) for the baseline. This small tail configuration, designated L-1011-RE herein, was evaluated initially with no stability augmentation, and with three variations of automatic stabilization. Figures 1-1 and 1-2 present 3-view drawings of the -1 and the -RE configurations, respectively, and Table 1-1 presents a comparison of basic dimensional data for the two configurations. The baseline configuration dimensions are identical to those of the -RE except for the horizontal tail which is the same as that shown on the -1.

The stability augmentations system used in the evaluation, and a description of how it was developed is presented in Section 2-3 of this report.

2.9 TEST CONDITIONS

The flight simulator testing was concentrated on high altitude cruise and landing approach in varying levels of air turbulence from still air to heavy turbulence.

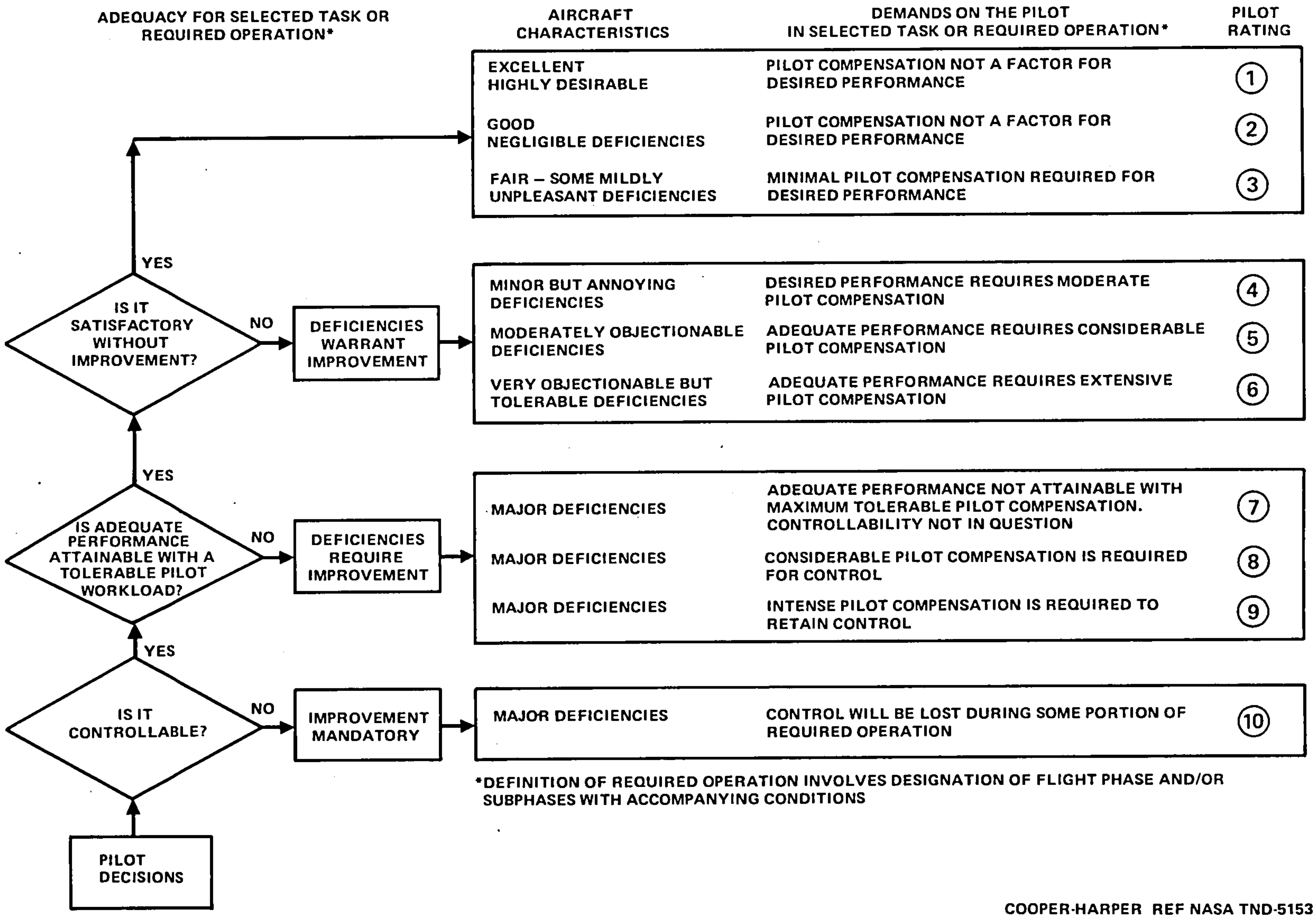


Figure 2-35. Handling Qualities Rating Scale

TABLE 2-2. RECORDED PARAMETERS - ANALOG STRIP CHART RECORDINGS

PARAMETER	SYMBOL	UNITS
Angle of Attack	α	degrees
Pitch Attitude	θ	degrees
Pitch Rate	q_B	deg/sec
Altitude	h	feet
Vertical Load Factor	n_{zB}	g's
Pilot Force on Column	F_c	lb
Column Position	δ_c	inches
Stabilizer Position	δ_H	degrees
Equivalent Airspeed	V_e	knots
Mach Number	M	--
Rate of Climb	R/C	ft/min
Throttle Position (#2 Engine)	δ_{th}	degrees
Engine Pressure Ratio (#2 Engine)	EPR	--
Throttle Thrust (All Engines)	THR	lb
* Glide Slope Error	GSE	degrees
Localizer Error	LOCE	degrees
* Distance from Runway Threshold	X_{rwy}	feet
Bank Angle	ϕ	degrees
Slide Slip Angle	β	degrees
Roll Rate	P_B	deg/sec
Yaw Rate	R_B	deg/sec
Lateral Load Factor	n_y	G's
Heading	ψ	degrees
Wheel Position	δ_w	degrees
Rudder Position	δ_R	degrees

NOTE: Additional parameters will be recorded if required to monitor augmentation system performance.

* These records are active only for approach testing.

TABLE 2-3. RECORDED PARAMETERS - DIGITAL LINE PRINTER RECORDING

PARAMETER	SYMBOL	UNITS
Test Number	Test	-
Run Number	Run	-
Elapsed Time (From Start of Run)	Time	seconds
Equivalent Airspeed	KEAS	knots
* Distance from Runway Threshold	XDIST	feet
* Distance from Runway Centerline	YDIST	feet
Rate of Climb	HDOT	ft/sec
Pitch Altitude	THETA	degrees
Roll Angle	Roll Angle	degrees
Vertical Acceleration	C.G. ACC	ft/sec^2
Total Thrust (All Engines)	THRJIP	
Angle of Attack	ALPHA	degrees
Center of Gravity Location	SCGTOT	%MAC/100
Stabilizer Position	DELH	degrees
Column Position	Stick	inches
Gross Weight	Weight	lb
Pitch Rage	Pitch Rate	deg/sec
Heading	Heading	degrees
Slideslip Angle	Slideslip	degrees

NOTE: The digital line printer records these data at the end of each run and on command from a cockpit switch.

* These records are active only for approach testing.

TABLE 2-4. STATISTICAL DATA PARAMETERS

CRUISE PARAMETER	UNITS
C.G. Load Factor	G's
Pitch Attitude	Degrees
Airspeed	Knots
Angle of Attack	Degrees
Altitude Rate	Ft/sec.
Stick Position	Inches
Stick Force	Lbs.
Pitch Rate	Deg/sec.
Stabilizer Position	Degrees
Roll Attitude	Degrees
LANDING APPROACH PARAMETER	**UNITS**
Glidescope error	Degrees
Pitch attitude	Degrees
Airspeed	Knots
Angle of Attack	Degrees
Altitude Rate	Ft/sec.
Stick Position	Inches
Stick Force	Lbs.
Pitch Rate	Deg/sec.
Localizer Error	Degrees
Roll Attitude	Degrees

A representative cruise condition, M = 0.83 at 10,058 m (33,000 ft.) altitude, was used for most of the cruise testing at an aircraft gross mass of 181,437 kg (weight of 400,000 lbs.). Other Mach-altitude combinations along the best-cruise speed line of Figure 2-36 were used in a limited evaluation of altitude effects on augmentation-off flying qualities. The pilots were instructed to attempt to maintain airspeed and altitude in turbulence and to attempt small heading and altitude changes for a qualitative evaluation of the workload associated with typical flight tests in cruise. Additionally, intentional upsets were introduced to evaluate their ability to recover to the initial flight conditions.

Landing approach testing was initiated at a distance of ten miles from the runway threshold in level flight at initial altitude of 457 m (1500 ft.) AGL. An instrument approach was flown to 91 m (300 ft.) AGL, at which time the visual presentation of the airport was available for final approach and touchdown. The initial aircraft configuration was gear up and flaps at 10°. The pilots flew level to glideslope intercept, at which time the landing gear were extended and flaps were extended to 22° and finally to 33° as the aircraft descended on the glideslope. A flight director representative of the L-1011 system was used for the IFR portion of the approach.

In both cruise and approach tests, aircraft center of gravity was varied from a mid-cg condition, 25% MAC, to a maximum aft location which was defined by unacceptable pilot ratings (>6.5) with the augmentation system off. The cg range thus defined, was then used for testing with augmentation on.

2.10 PILOT EVALUATION OF UNAUGMENTED FLYING QUALITIES

In order to determine the acceptable range of aircraft center of gravity in the event of complete augmentation system failure, center of gravity was moved aft from 25% MAC in small increments until unacceptable pilot ratings were obtained, both in cruise and in landing approach. This test method was repeated for three levels of air turbulence from calm air to heavy turbulence. Figure 2-37 presents pilot ratings of the L-1011-RE (small tail) configuration in cruise for the aforementioned conditions, for two pilots. Both pilots indicated that flying qualities were relatively good at centers of gravity forward of 30% MAC, but began to deteriorate aft of this point. At a center-of-gravity of about 38% MAC, both pilots felt that controllability of the aircraft required an unacceptably high workload for

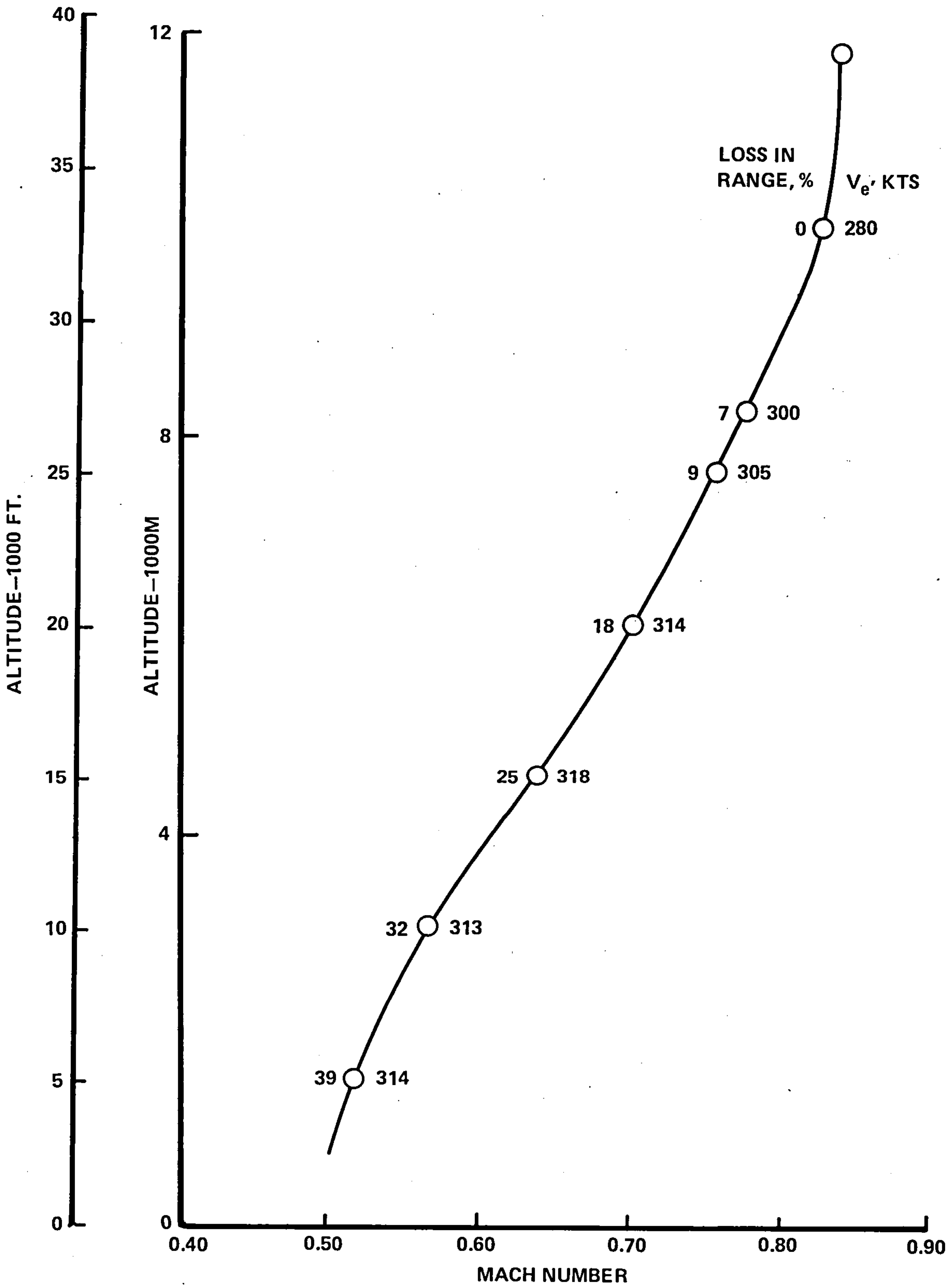


Figure 2-36. Reduced Altitude Best Cruise

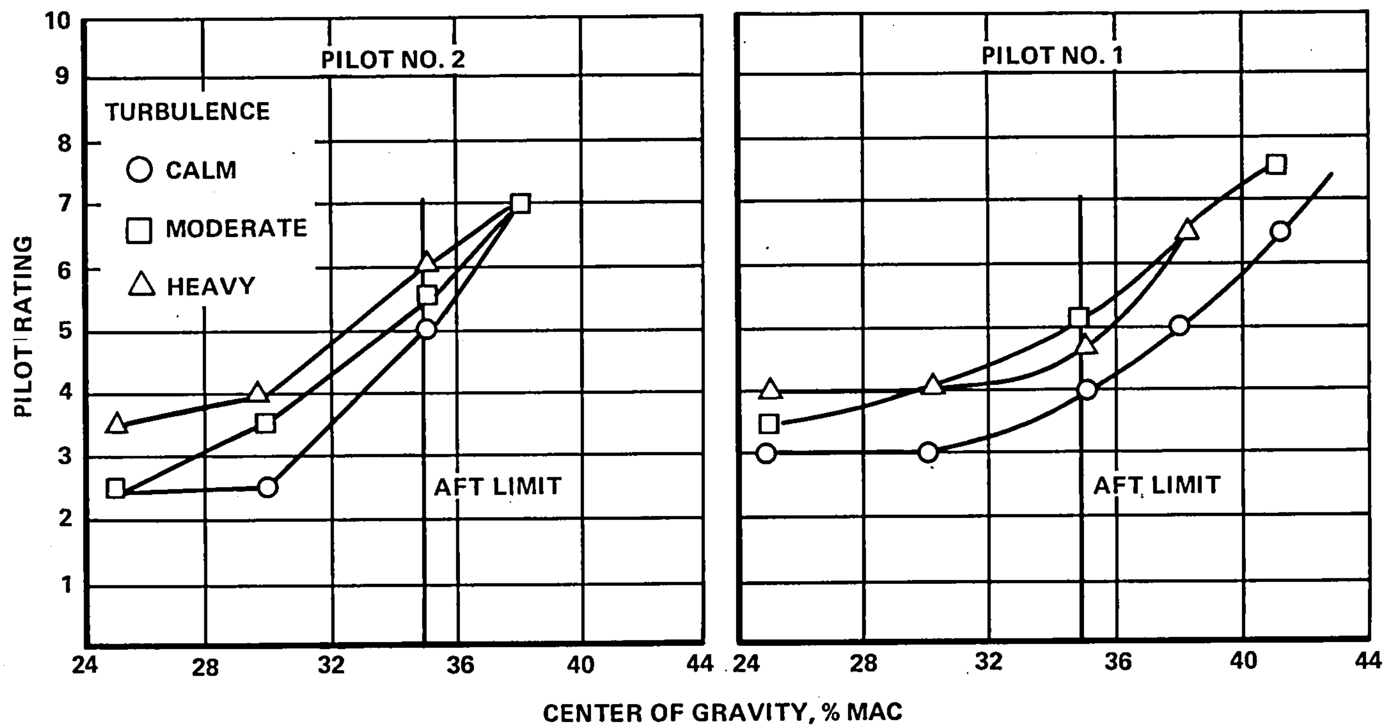


Figure 2-37. Cruise Flying Qualities L-1011-RE No Stability Augmentation

flight of long duration. Aircraft response became sluggish and pitch attitude or altitude control was extremely difficult. Turbulence did not have a significant influence on pilot ratings in the cruise condition. In general, ratings were degraded by one rating unit in heavy turbulence indicating that the sluggishness and inherent lack of stability of the aircraft was of more importance than disturbances from air turbulence.

The effect of cruise altitude on flying qualities with augmentation off was evaluated by simulated flight at Mach-altitude combinations along the best range line of Figure 2-36. As altitude was reduced from 10,058 m (33,000 ft.) to 4571 m (15,000 ft.), pilot ratings improved by two rating units, as shown in Figure 2-38 and the pilots reported a significant reduction in workload to maintain airspeed and altitude. There is a reduction in range associated with lower altitudes, also shown in Figure 2-36, which would dictate the altitude reduction available in any given situation, in the event of total system failure.

In landing approach, a similar test sequence was conducted for three levels of air turbulence. Figure 2-39 presents pilot ratings obtained from these tests. It can be seen that pilot ratings in the landing approach are relatively insensitive to center-of-gravity location compared to cruise results. Acceptable approaches were flown as far aft as 44% MAC (-2% static margin) in moderate turbulence. The most significant affect was found to be turbulence level, because of the effects of updrafts or downdrafts and horizontal wind shears on glidepath control. In heavy turbulence, acceptable glideslope control was marginal at any center-of-gravity, because of rapid excursions above or below the glideslope, which could not be controlled to an acceptable level. These results show that the cruise flight condition dictates the aft cg limits.

In order to determine if tail size effects were restricted to static stability differences only, the baseline configuration (with large horizontal tail) was evaluated at comparable stability levels by flying at more aft centers of gravity. Figures 2-40 and 2-41 present pilot ratings from tests of both configurations plotted as a function of static margin (rather than center-of-gravity). In landing approach with no turbulence, pilot ratings appear to be a function of static margin only, but in cruise an additional effect is present. The large-tail aircraft has improved flying qualities at a comparable stability level relative to

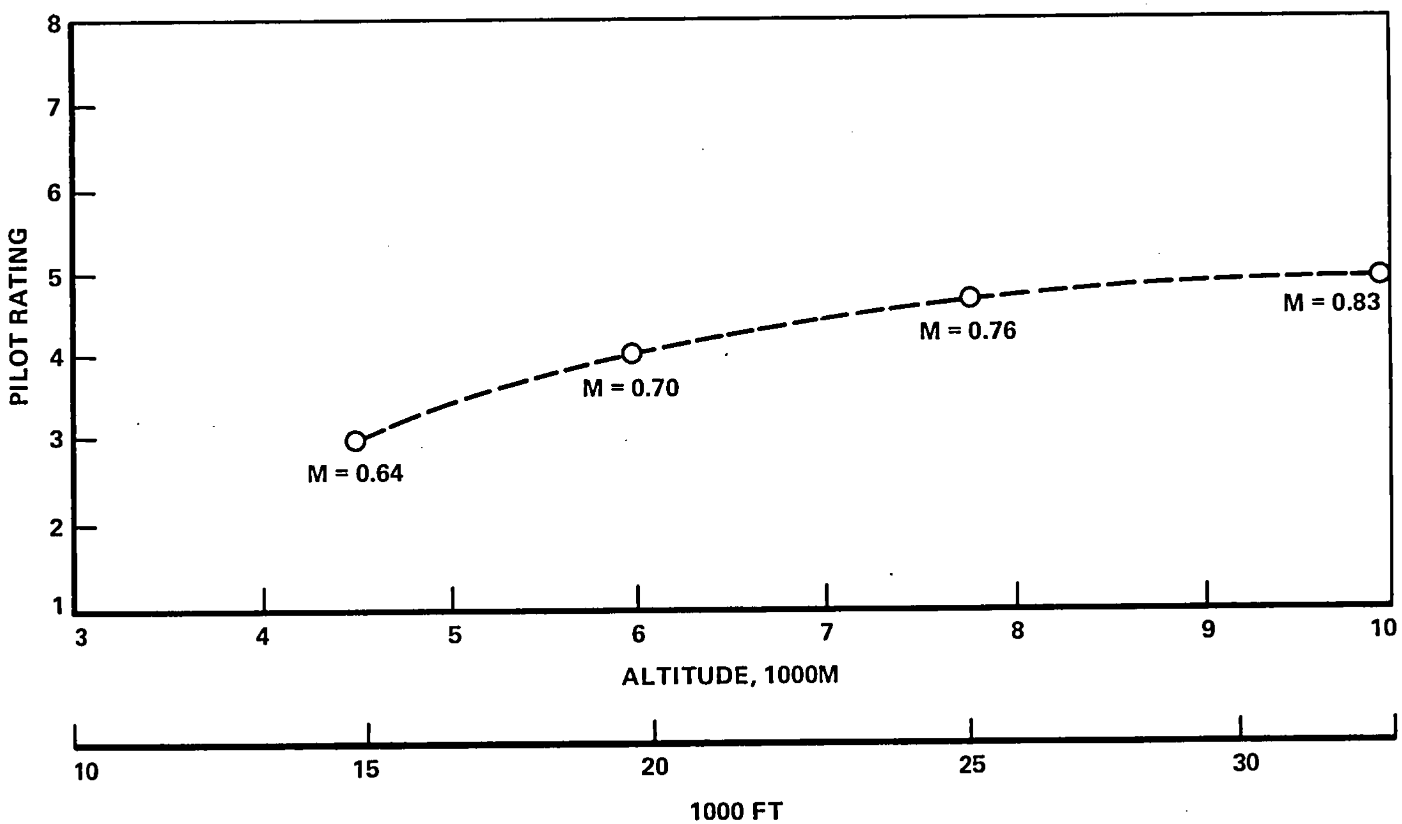


Figure 2-38. Effect of Altitude on Cruise Flying Qualities

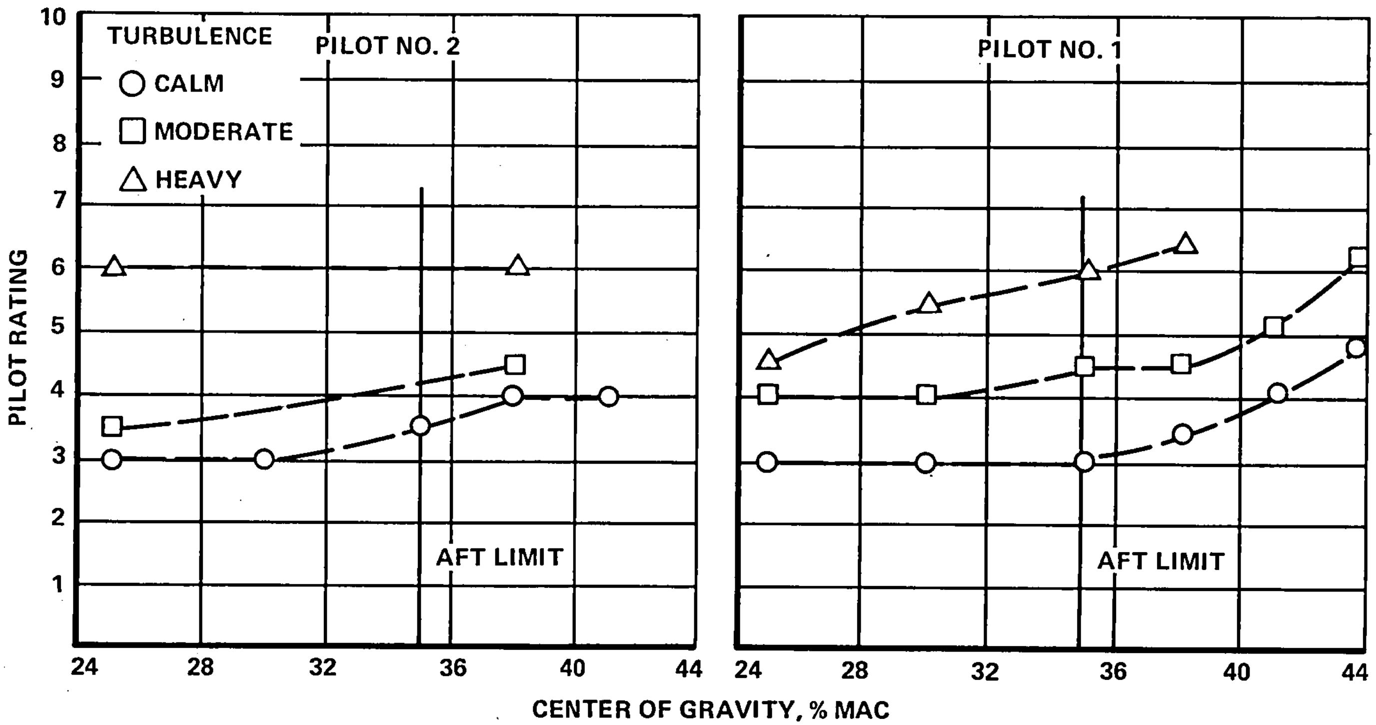


Figure 2-39. Approach Flying Qualities L-1011-RE No Stability Augmentation

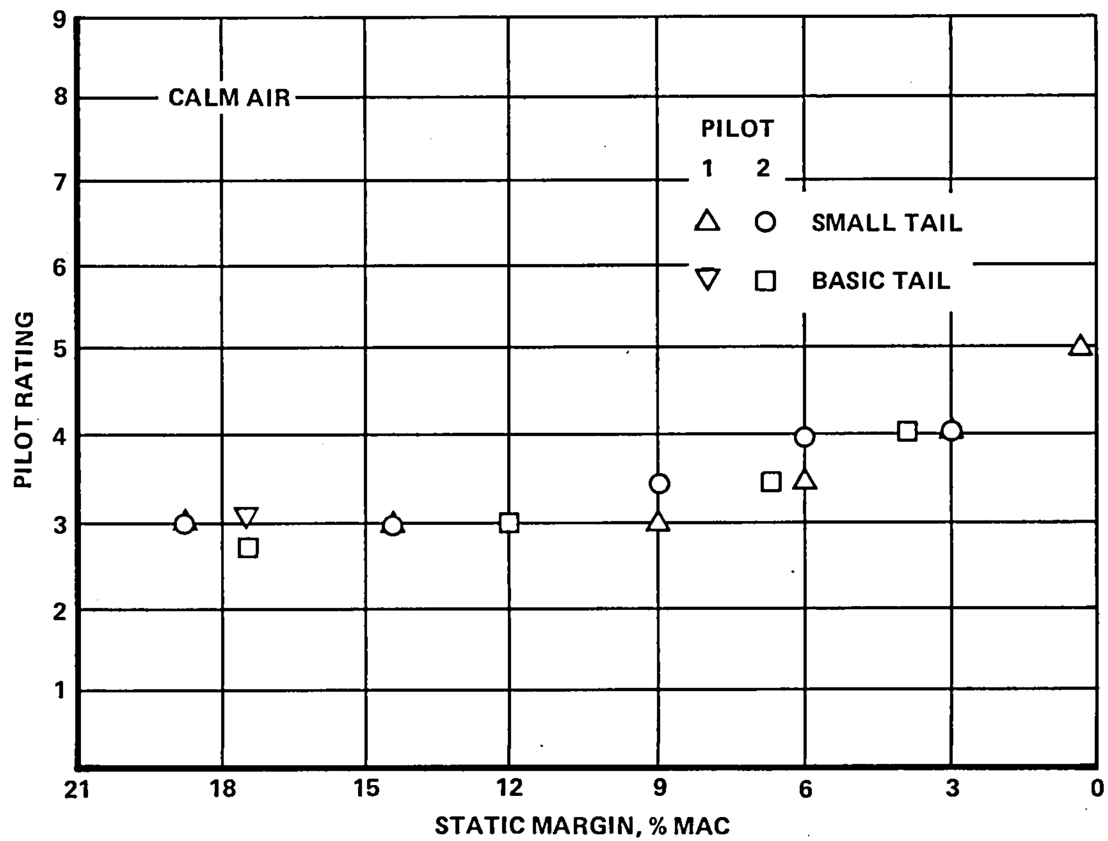


Figure 2-40. Approach Flying Qualities (Unaugmented)

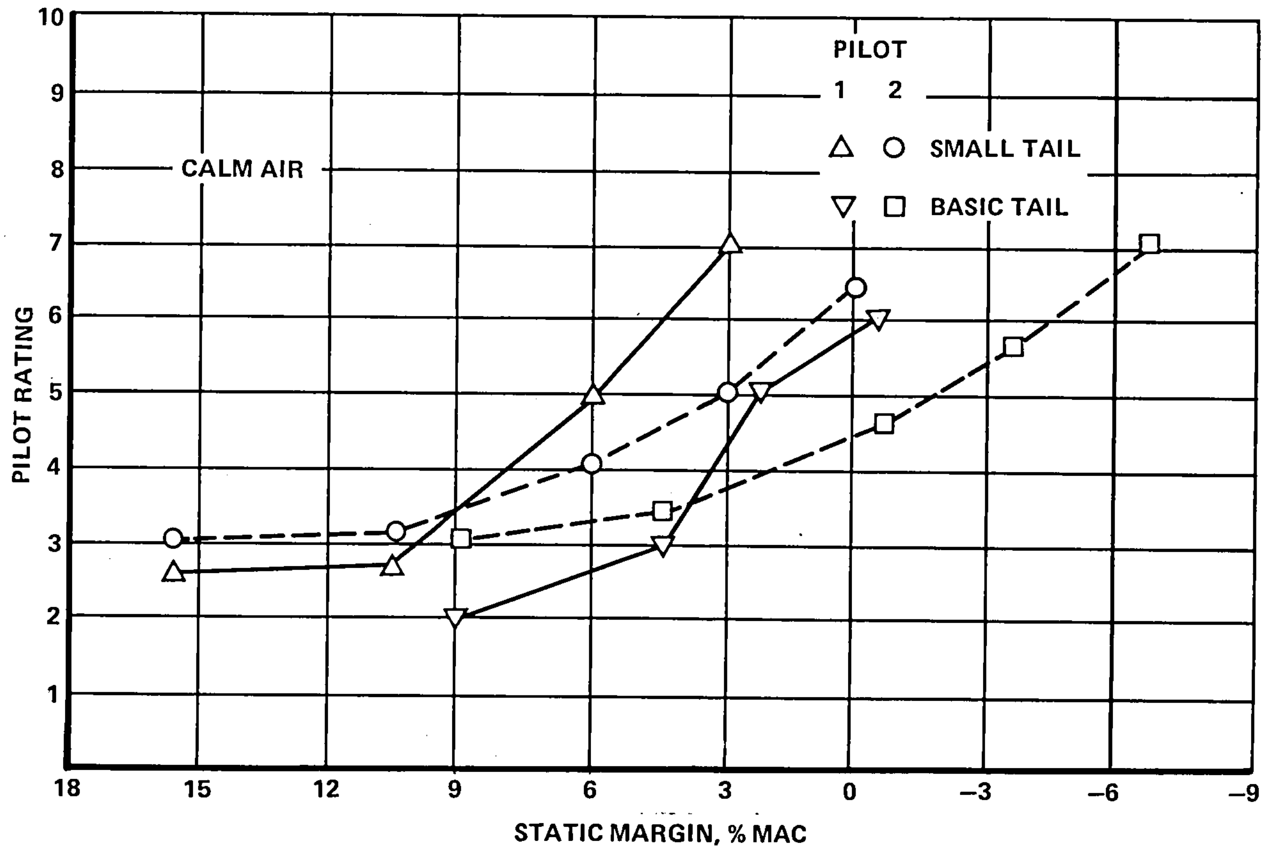


Figure 2-41. Cruise Flying Qualities (Unaugmented)

the small-tail aircraft, particularly at lower stability levels. The increased pitch damping provided by the larger horizontal tail is believed to be the primary reason for improved controllability in this configuration.

2.11 PILOT EVALUATION OF FLYING QUALITIES WITH AUGMENTATION

2.11.1 Augmentation Performance

The augmentation system developed for this evaluation, described in detail in Section 2.3, is a lagged pitch damper with stick quickening for pitch response adjustability. The three systems designated herein as #1, #2, and #3 are:

#1 - lagged pitch damper only

#2 - lagged pitch damper with increased pitch response (C*)

#3 - lagged pitch damper with reduced pitch response (c*)

Each configuration was evaluated in calm air and in heavy turbulence and compared to the augmentation-off case by three pilots. Figures 2-42 through 2-44 present pilot ratings for the cruise flight condition. All pilots reported that the augmentation provided a significant improvement in controllability at aft centers of gravity in both levels of air turbulence. There is no clear-cut preference for one system over another, which suggests that the improvement in pitch damping provided by all systems is more significant than differences in aircraft control response. The pilots commented that, although they may have preferred the response of one system over another, they could quickly adapt to any of the systems evaluated.

Figures 2-43 and 2-44 show a direct comparison between the L-1011-1 with the current operational tail size and the small tail L-1011-RE, for identical flight conditions flown "back-to-back". In both cases, the L-1011-RE, with the preferred augmentation system engaged, was rated equivalent to the L-1011-1 in calm air and slightly better than the L-1011-1 in heavy turbulence. Figure 2-45 is a time history of a segment of simulated flight in the cruise flight condition in heavy turbulence, taken from a strip chart recorder. The effect of stability augmentation on several flight parameters is shown, demonstrating the reduction in aircraft disturbance and pilot workload required for control of air speed and altitude.

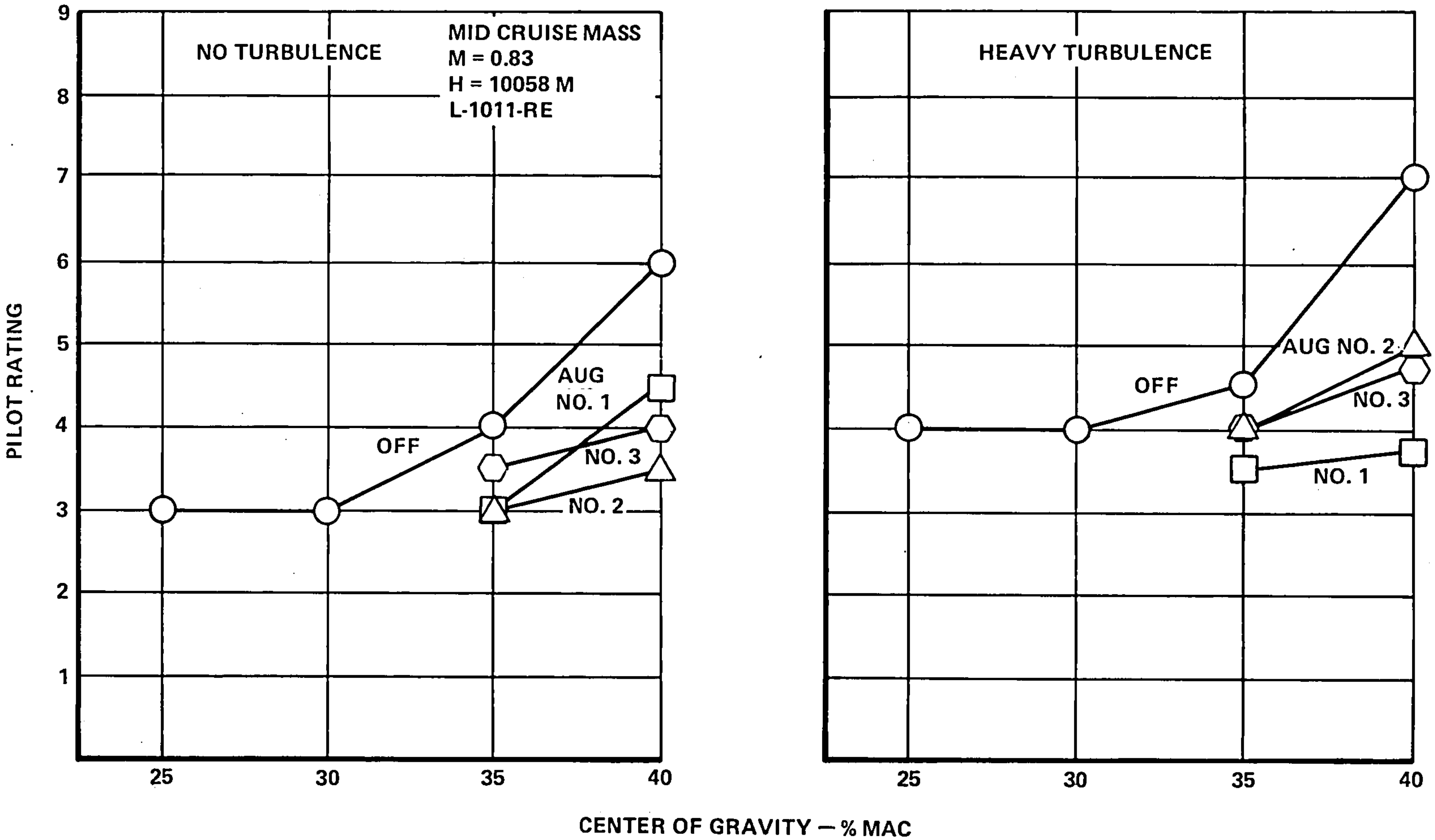


Figure 2-42. Pilot No. 1 Evaluation of Cruise Augmentation

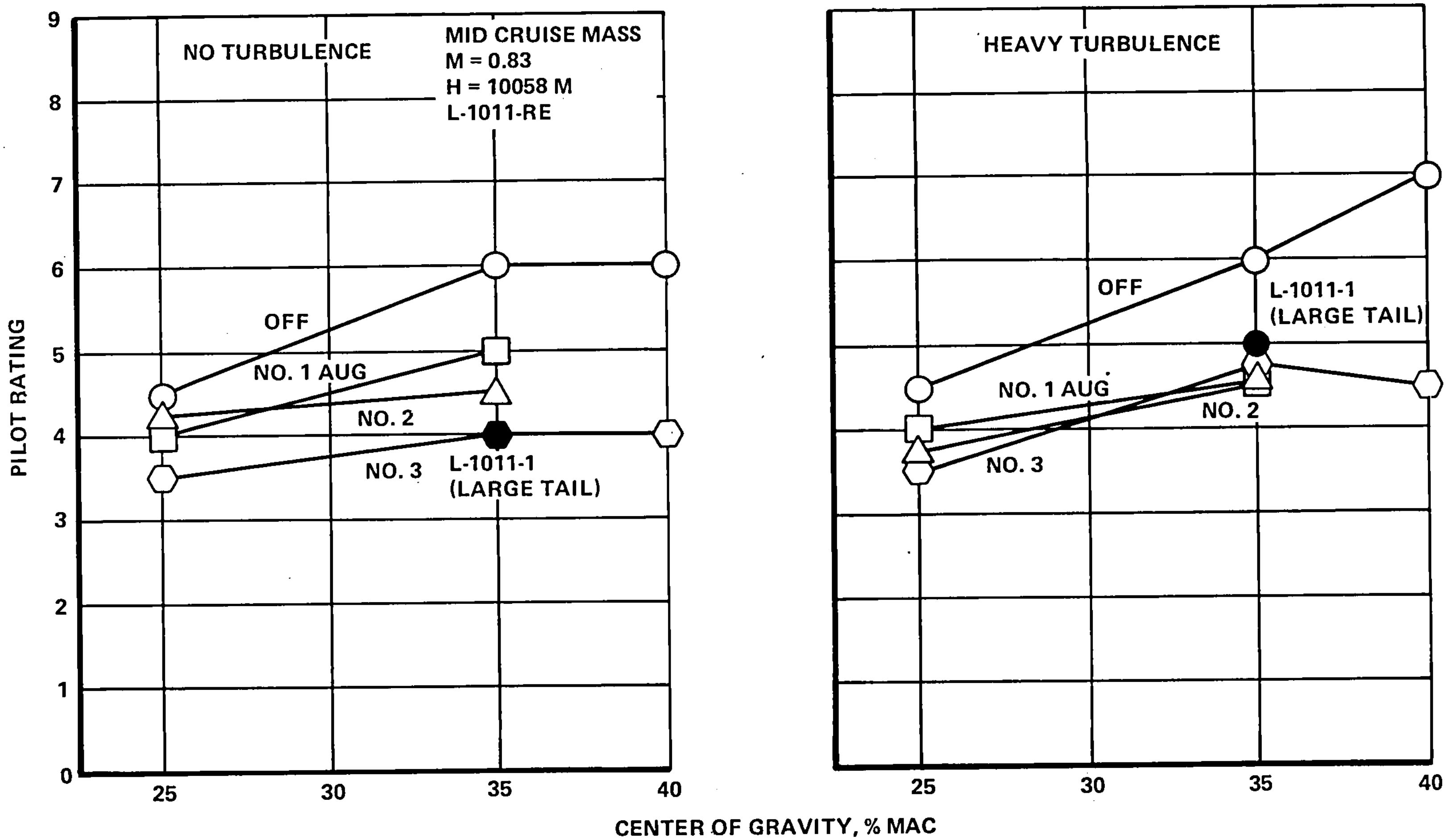


Figure 2-43. Pilot No. 2 Evaluation of Cruise Augmentation

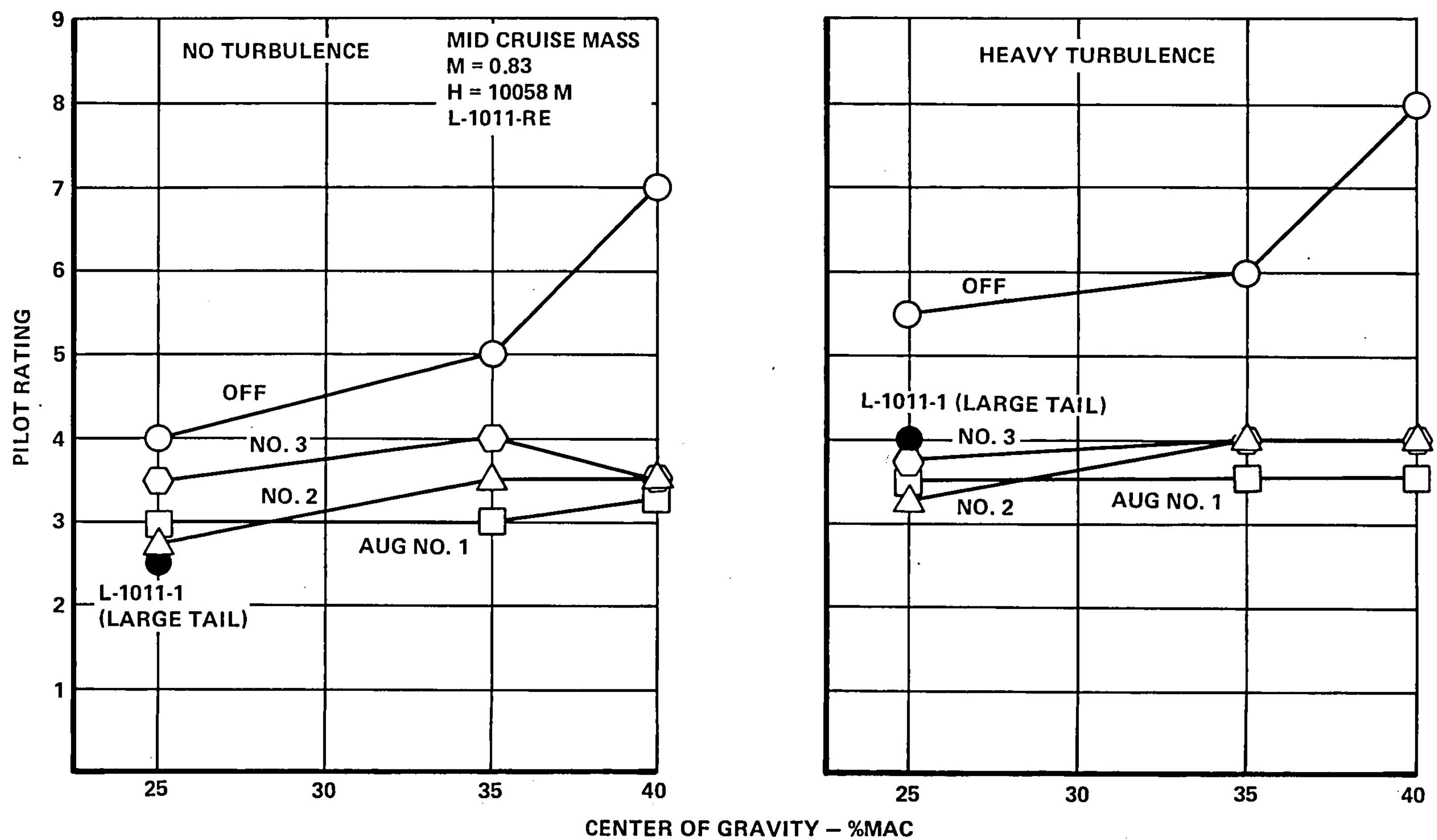


Figure 2-44. Pilot No. 3 Evaluation of Cruise Augmentation

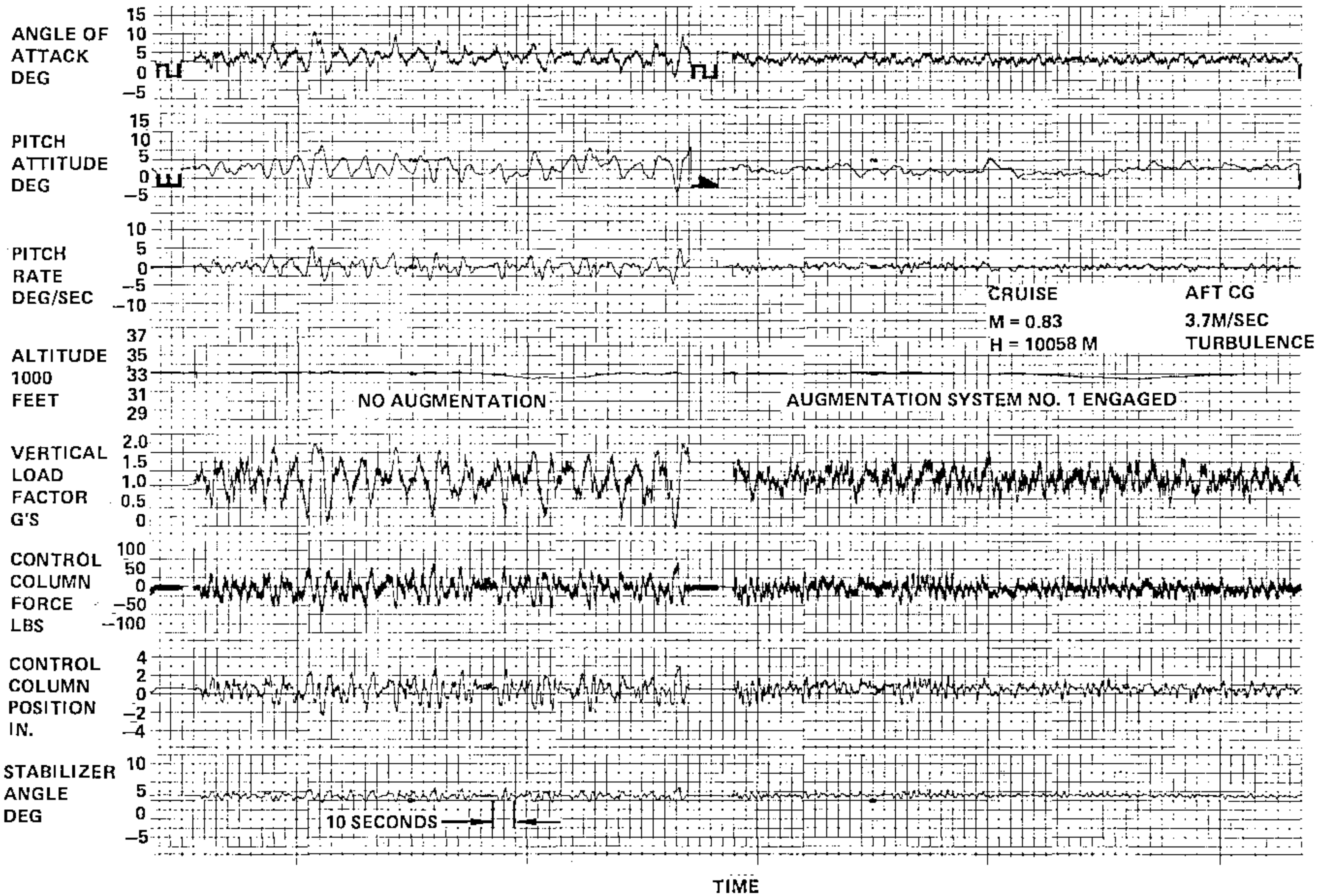


Figure 2-45. Simulated Flight in Turbulence; Effect of Augmentation

Figures 2-46 and 2-47 show a comparison of several statistical parameters for the L-1011-1 and L-1011-RE in cruise. These data are in agreement with both the pilot ratings and time history data in showing a reduction in workload with augmentation on.

Figures 2-48 through 2-50 present pilot ratings of flying qualities during an IFR approach and landing in varying conditions of center of gravity and air turbulence. In calm air, a slight improvement in controllability was noted, but because the unaugmented small tail aircraft was relatively easy to fly, the rating improvement was small. In heavy turbulence, a significant improvement in flying qualities was observed at all centers of gravity. The pilots were able to capture and track the glide slope with an acceptable level of work load, even in the severe turbulence conditions. As in the cruise condition, a "back-to-back" comparison of the L-1011-1 and the L-1011-RE with augmentation engaged showed the two configurations to be equivalent in calm air and the augmented L-1011-RE to be easier to fly in turbulent air.

2.11.2 Augmentation System Failure

The effect of a sudden failure of the stability augmentation system both in cruise and in IFR approach conditions was evaluated at aft centers of gravity in heavy turbulence. In no case was any unacceptable aircraft transient or change in required pilot technique observed. In some cases the failure was initiated without a cue to the pilot, and a few seconds elapsed in each instance before the pilot became aware that the failure had occurred. It should be noted, however, that these failures were all of the "soft" type where the augmentation input to the stabilizer failed to a null condition. Additional analysis is necessary to determine the possible effects of failures that could cause a "hard-over" input to the stabilizer from the augmentation system.

2.11.3 Augmentation System Authority Requirements

The testing discussed in previous paragraphs was conducted with no constraints on augmentation system authority or control surface rates other than those of the primary control system. To determine the limits of authority required from the system, several simulator runs were conducted in cruise and landing approach in calm air and in heavy turbulence. Figure 2-51 shows augmentation system input time

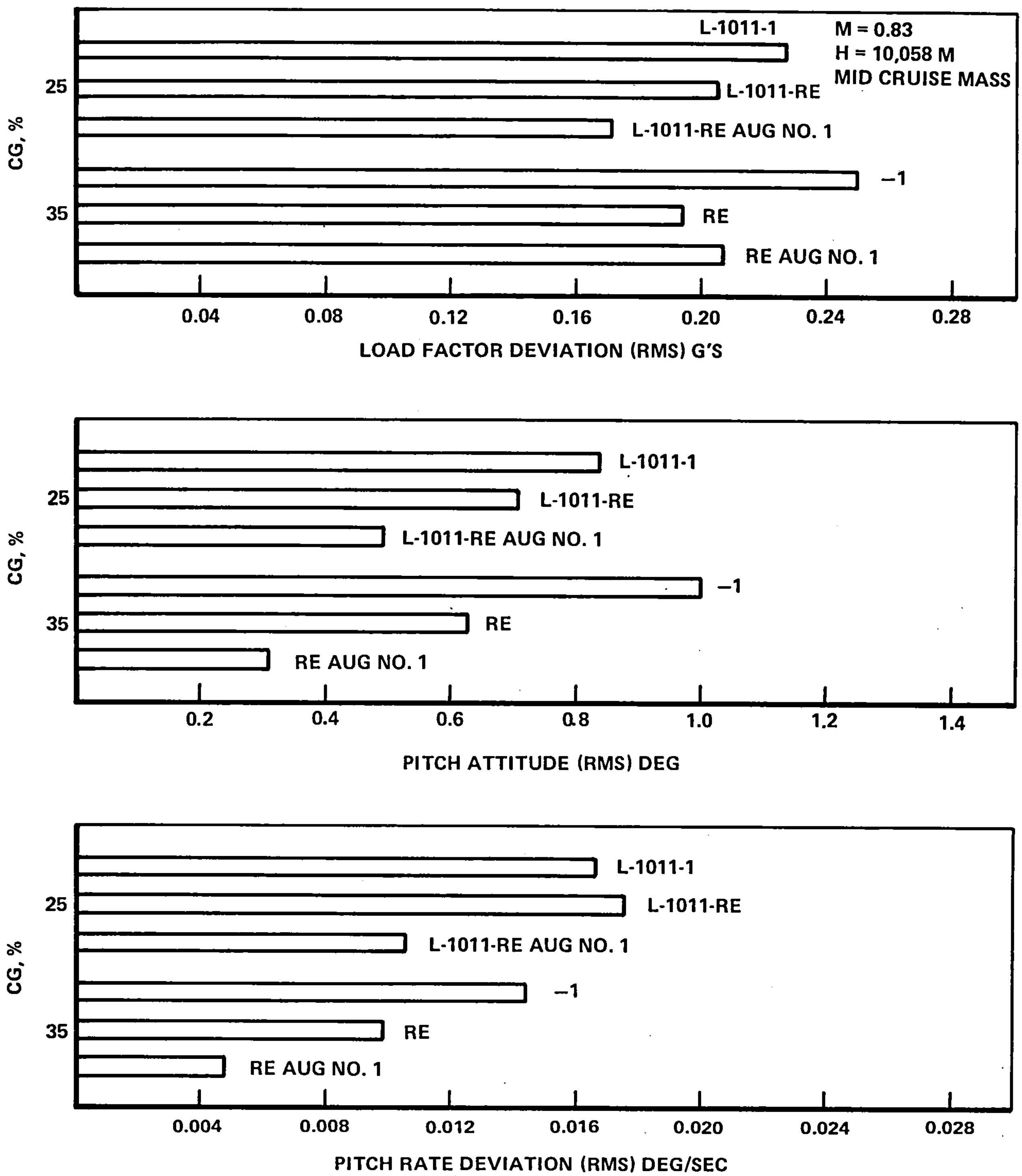


Figure 2-46. Aircraft Response to Heavy Turbulence, Cruise Configuration

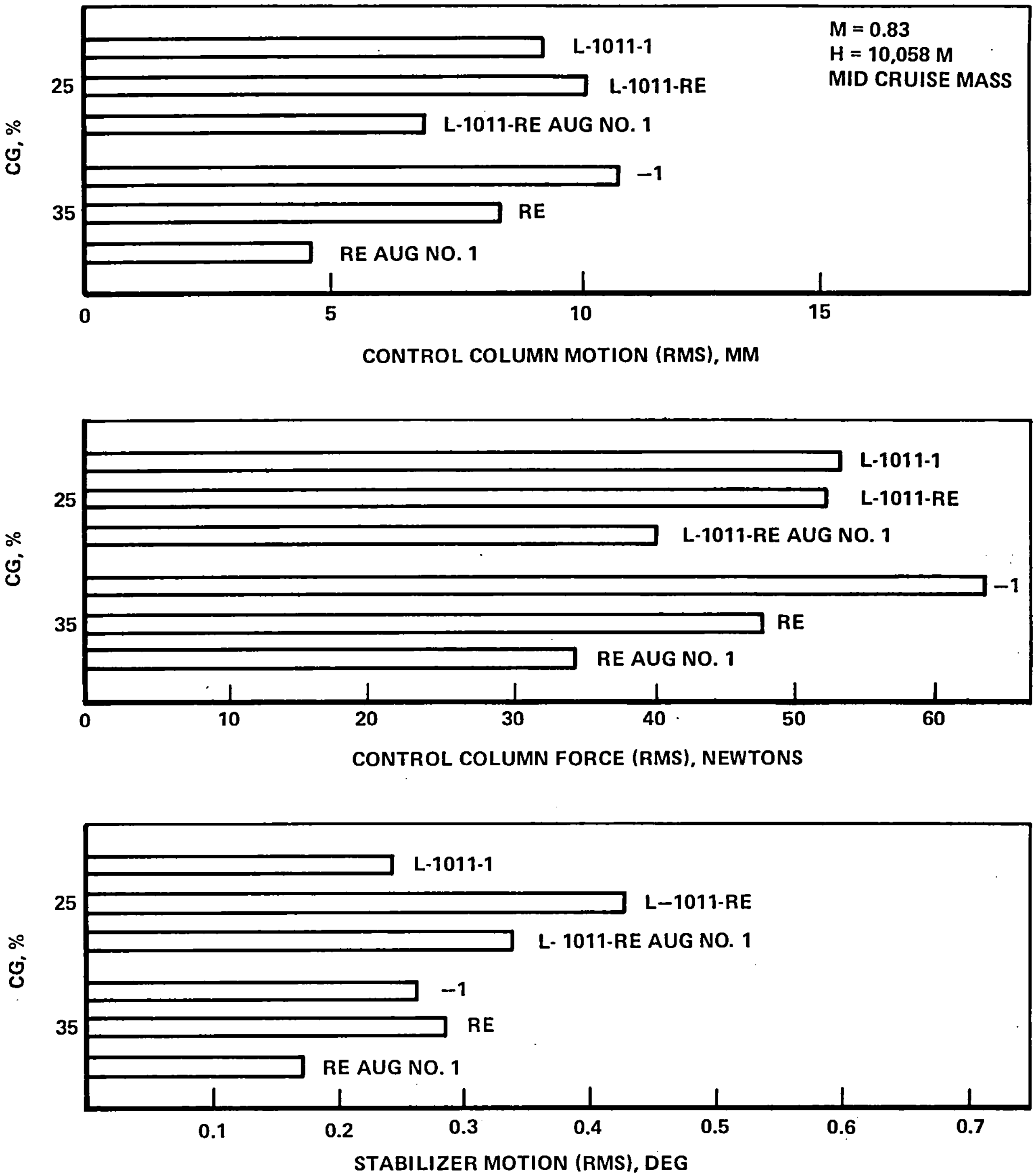


Figure 2-47. Control Activity in Heavy Turbulence, Cruise Configuration

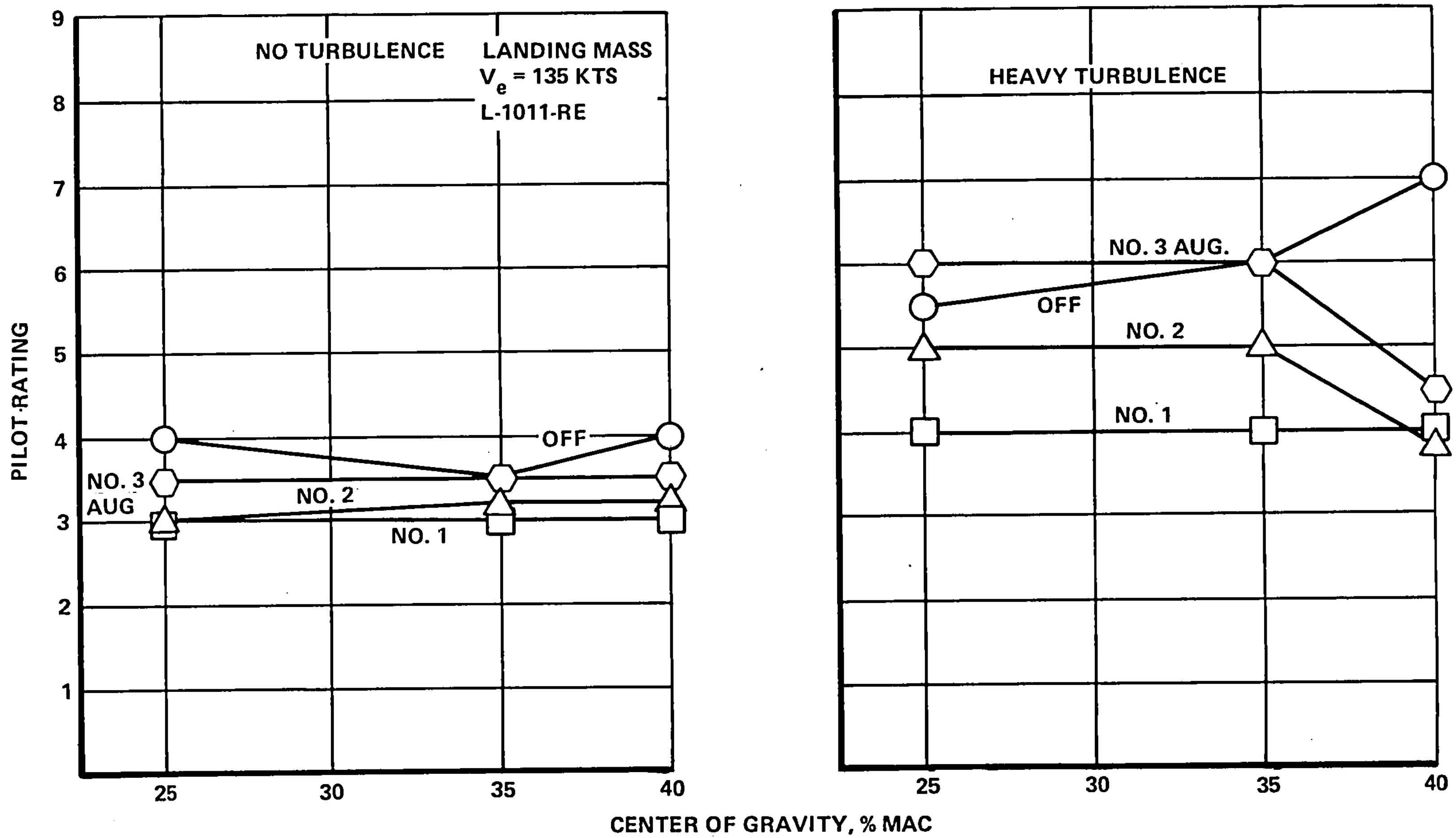


Figure 2-48. Pilot No. 1 Evaluation of Approach Augmentation

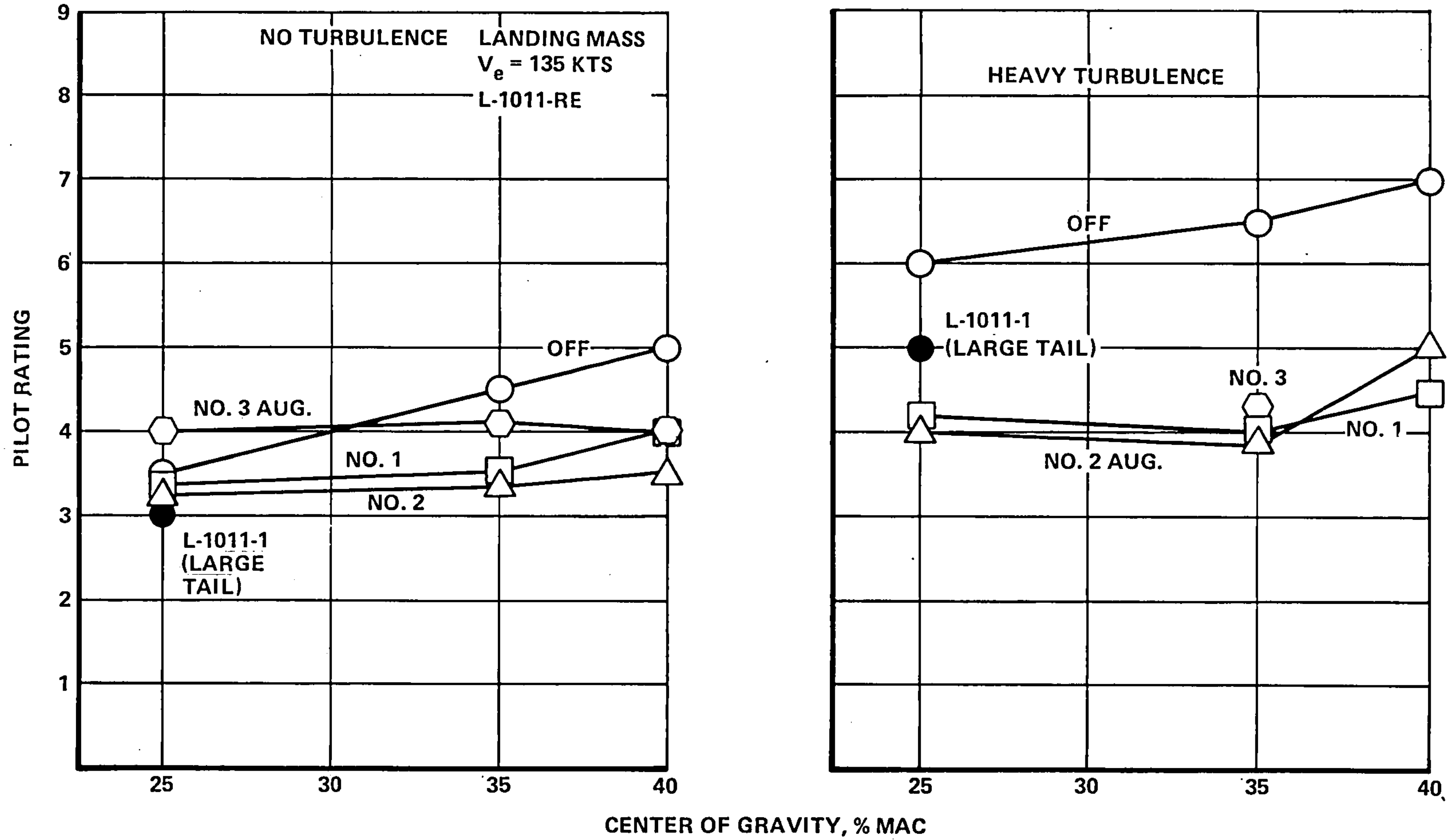


Figure 2-49. Pilot No. 2 Evaluation of Approach Augmentation

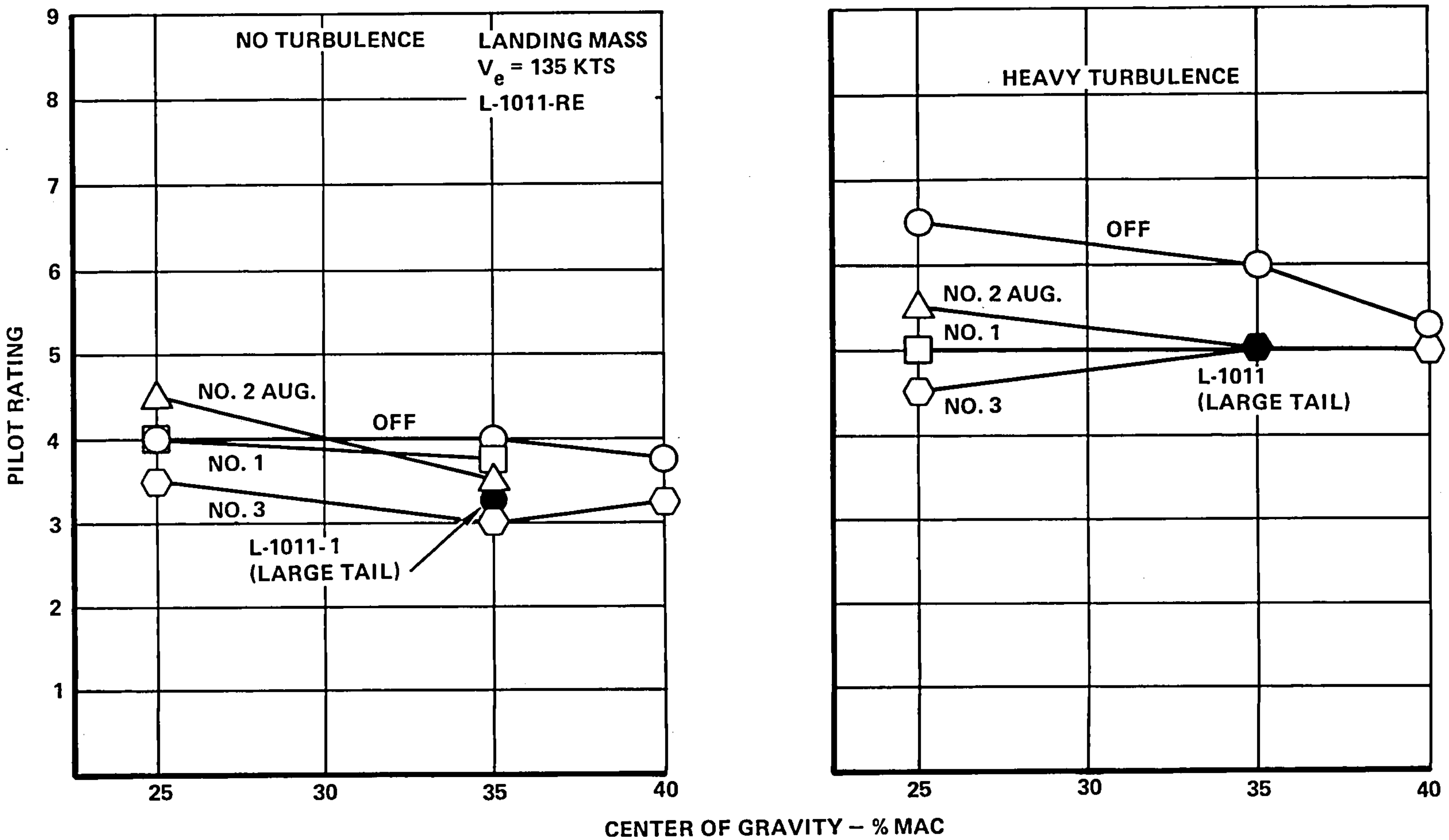


Figure 2-50. Pilot No. 3 Evaluation of Approach Augmentation

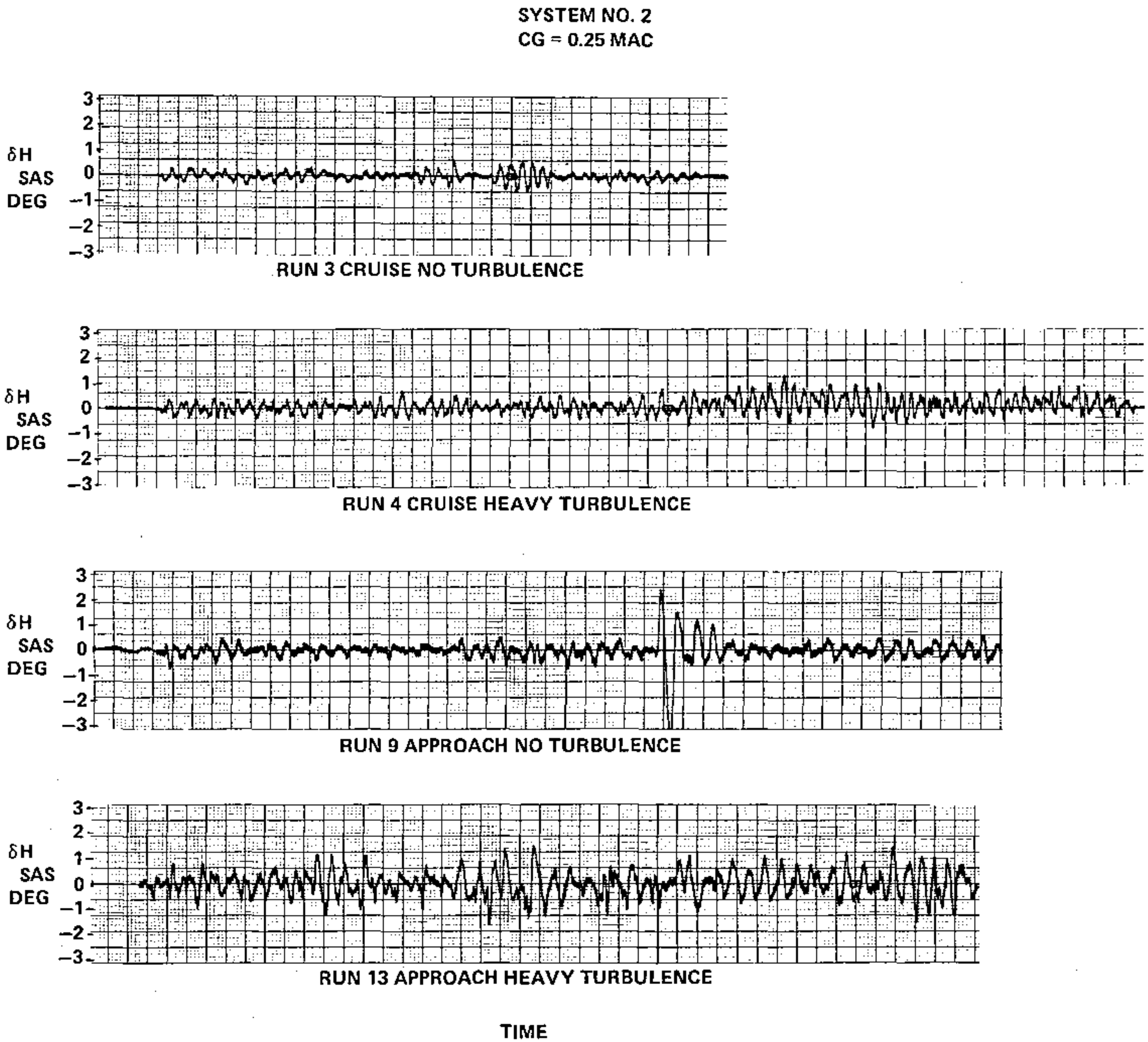


Figure 2-51. Augmentation System Authority Requirements Data

histories from four simulator runs. The two upper curves were obtained in simulated cruise conditions, while the lower curves came from simulated landing approaches, starting at ten miles from the airport and continuing to touchdown. The maximum deflections occur during the approach condition, as expected and significantly lower amplitudes are required in cruise. Based on these tests, authority limits of at least $\pm$ 1-1/2° in approach and $\pm$ 3/4° in cruise are required for adequate stabilization in heavy turbulence levels.

2.12 AUGMENTATION RELIABILITY

The methodology for determining the acceptability of augmented relaxed static stability within the philosophy of equivalence must rely on probabilistic analysis. One approach for relating unaugmented static margin and augmentation performance with numerical probability is demonstrated in Figure 2-52. This figure presents the landing approach simulation pilot rating data in terms of probability of exceedance per flight. Probability is associated with pilot rating by correlating the simulator ratings as a function of turbulence RMS velocity with a probability of exceedance gust model of the atmosphere at low altitude. These data were plotted for the reference big-tail configuration with 12% static margin, for the small tail configuration with neutral static stability and no augmentation, and for the small tail with pitch damping operating full time.

The maximum turbulence intensity in which the simulator test pilots say they would continue a landing approach is 2.7 m/sec (9 fps) RMS. The gust model indicates a probability of approximately 10^{-4} of encountering turbulence exceeding this level on one landing approach of about 4 minutes duration. A current unaugmented airplane with an aft c.g. minimum static margin in the approach configuration (12% MAC) would receive a pilot rating of 5 in that turbulence based on Task 2 simulation data.

Using 5 as a baseline value for approach handling qualities pilot rating, it can be determined from a weighted sum of the unaugmented and 100% augmented simulation data that an augmentation failure rate of 3% would provide a probability of exceedance equivalent to that of the conventionally stable airplane. That is, the probability of refusing a landing due to handling qualities difficulty would be no greater for the small tail airplane with zero static margin and 97% reliable augmentation than for the big tail airplane having 12% static margin. In light of

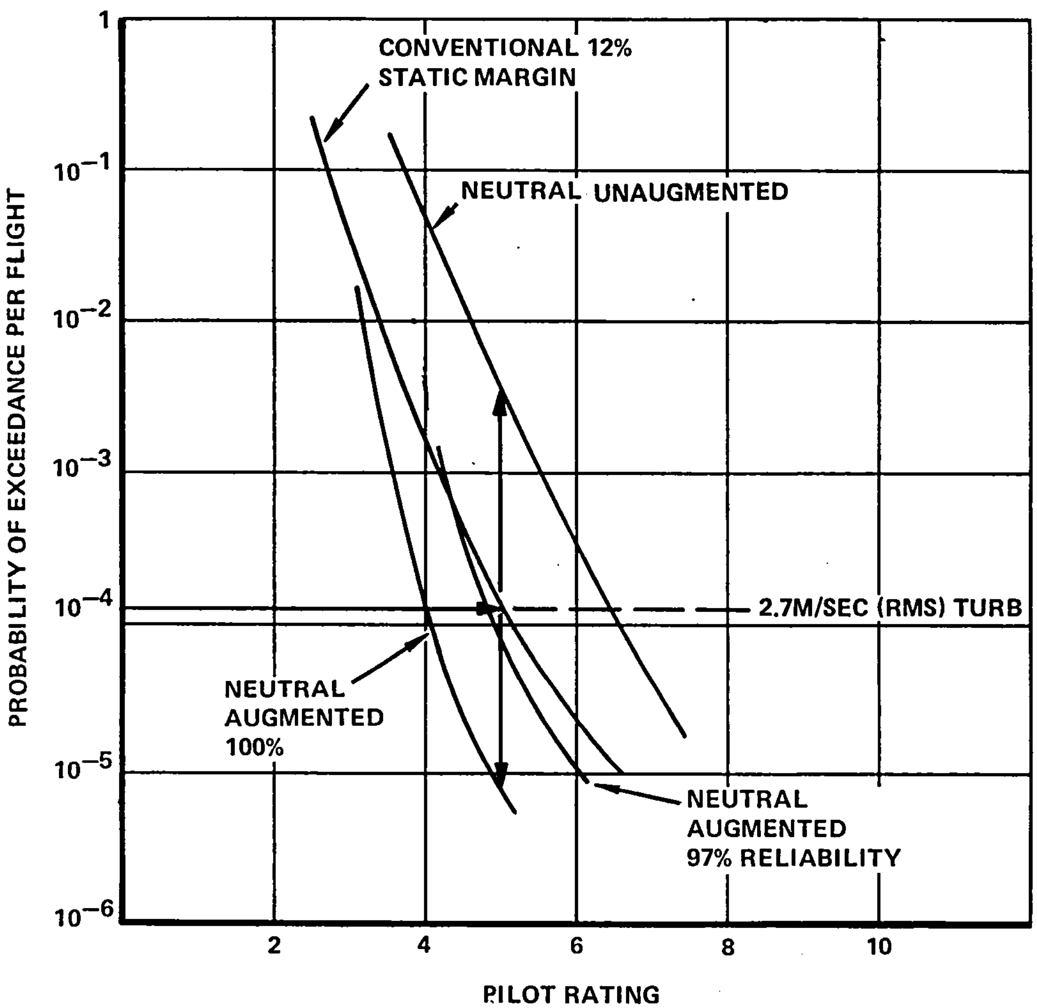


Figure 2-52. Probability Approach-Handling Qualities Equivalence

years of operational experience with the existing L-1011 yaw damper, 3% is an extremely conservative assumption for failure rate. A more realistic value for a dual/dual system utilizing state-of-the-art avionics would be 10^{-4} to 10^{-5}. This level of augmentor reliability would make the neutrally stable augmented airplane an order of magnitude less likely to encounter degraded handling qualities leading to a wave-off decision by the pilot.

The preceding discussion is confined to the landing approach flight condition. The cruise condition would appear to be more demanding in terms of augmentation system reliability. This judgment is based on consideration of Figure 2-37 which shows the dependence of unaugmented handling qualities on static margin regardless of air turbulence intensity, and of Figure 2-41, which shows that static stability alone does not organize the simulator pilot rating data. The greater exposure time at cruise flight condition must also be taken into account. The cruise condition simulation data acquired in Task 2 are insufficient for application of this probabilistic technique to determination of augmentation reliability requirements in this more demanding flight condition. It is considered that the technique is valid based on the landing approach results and additional research into cruise is warranted.

2.13 STALL DYNAMICS

Continuous Systems Modeling Program (CSMP) study of aft c.g. stall recovery dynamics and their influence on augmentation design was originally envisioned as an element of this task. CSMP stall study would be of considerable value applied to augmented stability configurations having significantly large negative static margin (i.e., -5% MAC or more). However, it was determined that for the c.g. range of interest in the L-1011 derivative model of Task 2, stall recovery is essentially a static control power problem. Therefore, this element was deferred in favor of other flying qualities analysis.

SECTION 3

CONCLUSIONS

Based on results from Task 2 analytical and flight simulation studies, the following conclusions can be drawn concerning augmentation system design and unaugmented handling qualitites criteria.

For conventionally configured subsonic transport aircraft of approximately neutral static stability:

- The philosophy of providing handling qualities safety equivalent to that of current aircraft designed to conventional static stability margins is a workable guideline for augmented stability transport aircraft acceptability.
- Expression of current aircraft characteristics in terms of well known frequency response and time history parameters is suitable for augmentation system design criteria.
- Classical control systems analysis methods implemented on production computing techniques are adequate for design of stability augmentation.
- Flying qualities that meet or exceed equivalence criteria can be obtained with simple lagged pitch rate damping.
- Cruise flight is the condition where unaugmented handling qualities are most sensitive to relaxed static stability (RSS) and hence is the flight condition of primary interest in stability augmentation design.
- Handling qualities of unaugmented aircraft on landing approach are affected strongly by turbulence level but are relatively insensitive to RSS until static margin becomes negative.
- An RSS aircraft with pitch rate damping can have approach handling qualities better than current aircraft on landing approach.
- Airframe motion in turbulence is less for an RSS configuration with augmentation than for current transports.
- In turbulence, pitch control surface activity for an RSS aircraft with augmentation operating is less than with augmentation off, but more than for current unaugmented aircraft.

SECTION 4

RECOMMENDATIONS

On the basis of results from the flight simulator testing of an L-1011 derivative with a smaller horizontal tail and augmented stability, it is recommended that a flight test program be undertaken. Testing should be planned to validate unaugmented flying qualities, to test simulator defined control laws, and to demonstrate the acceptability of a smaller horizontal tail.