NASA Contractor Report 3660

Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project

Longitudinal Handling Qualities Study of a Relaxed-Stability Airplane

Staff of Boeing Commercial Airplane Company

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Staff of Boeing Commercial Airplane Company
Boeing Commercial Airplane Company
Seattle, Washington

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FOREWORD

This document constitutes the final report on the Longitudinal Handling Qualities Piloted Simulation Task of the Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project, one element of the NASA Aircraft Energy Efficiency/Energy Efficient Transport (ACEE/EET) Project. The report covers work performed from February 1981 through December 1981 under Contract NAS1-15325.

The NASA Technical Monitor for this task was D. B. Middleton of the ACEE/EET Project Office at Langley Research Center.

The work was accomplished within the Preliminary Design Department of the Vice President—Engineering organization of the Boeing Commercial Airplane Company. Key contractor personnel who contributed were:

G. W. Hanks	Program Manager
H. A. Shomber	IAAC Project Manager
C. C. Flora	Task Manager
W. F. Shivitz	Principal Investigator
D. J. Maund	Flight Controls Technology
S. R. Bowman	Simulation Programmer

During this study, principal measurements and calculations were made in customary units and were converted to Standard International units for this document.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

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1.0 SUMMARY

This report documents a piloted simulation study of a Boeing 757 airplane balanced at center-of-gravity (cg) locations that ranged from normal to extremely aft of normal and equipped with an Active Controls Technology (ACT) pitch augmentation system. The 757 airplane simulated characteristics were based on preflight predictions (viz, analytical calculations and wind-tunnel data). The primary goals were to (1) investigate longitudinal handling qualities at reduced levels of longitudinal stability and (2) establish cg limits that would ensure adequate handling qualities for safe continued flight and landing with the augmentation system off or failed during a subsequent flight test of an ACT system with the 757 as the host airplane. Also, the general form and functionality of the control laws for the proposed ACT system were to be validated. This simulation study was limited in scope and was not designed to demonstrate flight readiness of the 757 with the ACT system and relaxed static stability.

The study results can be considered in three categories: the airplane unaugmented, the airplane augmented with an Essential Pitch-Augmented Stability (PAS) System, and the airplane augmented with a Primary PAS System. Essential PAS is intended to provide minimum acceptable emergency handling qualities for an unstable airplane with very high reliability such that there is no requirement for acceptable unaugmented characteristics, whereas Primary PAS is intended to provide fully satisfactory handling qualities for the same flight conditions. For test purposes, the unaugmented airplane should also have controllable handling qualities at the nominal test conditions. Four Boeing experimental test pilots who had previous simulation experience with the unaugmented normal cg range characteristics of the 757 evaluated the airplane in terms of the revised Cooper-Harper Pilot Opinion Rating Scale (ref 1).

Two principal flight conditions were simulated in detail. Maximum weight landing approach and midweight high-altitude cruise were selected as being representative of normal flight test conditions. Other conditions were spot checked to verify that the results would be valid throughout the flight envelope. Ground stability and nose-wheel steering were not addressed in this study.

For unaugmented landing approach, Level 2 (acceptable, pilot rating < 6.5) handling qualities were attained at a cg of 57% mean aerodynamic chord (MAC) (6% aft of the neutral point). The Level 3 (unacceptable, pilot rating $= 9.5$) boundary could not be established because the required cg location was far aft of the trimmable cg range. For unaugmented cruise, Level 2 ratings were reported aft to 47% MAC (5% forward of the maneuver point). The Level 3 (unacceptable, pilot rating $= 9.5$) boundary is approached at cg locations of 55% to 60% MAC (or slightly aft of the maneuver point). Essential pitch-rate PAS provided pilot ratings that were very close to or within the Level 1 (good) boundaries. Primary PAS, although evaluated to a lesser extent than Essential PAS, yielded Level 1 pilot ratings in most cases. High-speed cruise stability rather than that of landing approach will determine the flight aft cg limit for the airplane.

The study results correlated reasonably well with several existing handling qualities criteria. The study results were also found to be comparable to those reported by both the Douglas Aircraft Company and the Lockheed-California Company for simulation investigations of transport configurations with roughly similar dimensional and mass characteristics.

The feasibility of flight testing an ACT system on a host 757 airplane has been demonstrated from the handling qualities point of view. The task of designing the software and hardware for the Test ACT System should proceed with flight demonstration as an objective.

2.0 INTRODUCTION

The main objective of the Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project was to assess the benefits associated with a major application of Active Controls Technology (ACT) to the design of a modern, subsonic, commercial transport. This project is one of several under the NASA Energy Efficient Transport (EET) Program. The IAAC Project has three major elements: design of an airplane configuration and a related current technology ACT system, examination of advanced technology implementation of ACT functions, and testing and evaluation of selected elements of the proposed ACT system. A detailed discussion of the IAAC Project Plan is presented in Reference 2.

A Test ACT System is currently being developed under the IAAC Project and will be built and subsequently evaluated in the laboratory and in flight. As part of that work, reduced stability levels and associated control laws were evaluated on a moving-base simulator with the Boeing 757 as the modeled airplane. Using the revised Cooper-Harper Pilot Opinion Rating Scale (ref 1), four experienced pilots (familiar with the 757) rated various 757 configurations for a range of flight conditions and cg locations. Two pitch-augmented stability (PAS) control law configurations were investigated: (1) a fixed-gain Essential PAS control law with pitch-rate feedback and (2) a variable-gain Primary PAS with pitch attitude hold and pitch-rate feedback.

The results reported herein include the simulation study results, how they correlate with existing handling qualities criteria, and also how they compare with results obtained by Douglas Aircraft Company (ref 3) and Lockheed-California Company (ref 4) for similar investigations.

The next step in the IAAC Project will be to design and build Test ACT System hardware and software and to prepare for evaluation of ACT functions by actual flight test.

2.1 OBJECTIVES

In support of Test ACT System development, the objectives of the piloted simulation task were to:

- Establish the cg range over which the unaugmented airplane is controllable
- Determine a simple augmentation configuration that would satisfy the requirements of Essential PAS; i.e., produce Level 2 (minimum acceptable) handling qualities for an unstable airplane
- Confirm the feasibility of obtaining Level 1 (good) handling qualities at extreme aft cg locations with the addition of Primary PAS
- Investigate alternative methods of integrating Essential and Primary augmentation systems
- Estimate authority requirements of selected configurations

2.2 APPROACH

This study used PAS concepts developed during the IAAC Wing Planform Study and Final Configuration Selection (refs 5 and 6) and modified for application to the Boeing 757 airplane. Performance and stability requirements as specified by the IAAC design requirements and objectives (DRO) (appendix A to ref 7) were used as guidelines. The simulation mathematical model was the 757 baseline under configuration control (i.e., all model changes required formal documentation) at the Boeing-Renton Flight Simulation Center.

Initially, the unaugmented airplane model was evaluated at progressively aft cg locations to determine minimum controllability limits. Essential PAS was then tested and modified as necessary to provide acceptable handling qualities throughout the proposed flight test envelope. In addition, Primary PAS was developed and evaluated for good handling qualities.

3.0 SYMBOLS AND ABBREVIATIONS

3.1 GENERAL ABBREVIATIONS

alt	altitude
ACEE	Aircraft Energy Efficiency (Program)
ACT	Active Controls Technology
$\bar{c}$	mean aerodynamic chord (same as MAC)
cg	center of gravity
CR	contractor report
CRT	cathode-ray tube
DOF	degree of freedom
DOT	Department of Transportation
DRO	design requirements and objectives
EET	Energy Efficient Transport
F_{COL}	column force
fig.	figure
g	acceleration due to gravity
h	altitude
IAAC	Integrated Application of Active Controls Technology to an Advanced Subsonic Transport Project
kn	knot
KEAS	knots equivalent airspeed
KP	pilot command gain
M	Mach number
MAC	mean aerodynamic chord (same as $\bar{c}$)
M-cab	multipurpose engineering simulator cab
n	normal load factor

n/α	normal acceleration per unit angle of attack
N	newton
PAS	pitch-augmented stability
q	dynamic pressure; perturbation value of pitch rate
Q	pitch rate
ref	reference
rms	root mean square
s	Laplace variable; second (same as sec)
SST	supersonic transport
SX	longitudinal distance from runway threshold (positive forward)
SY	lateral offset from runway centerline (positive right)
$t_{1/2X}$	time-to-half amplitude
t_{2X}	time-to-double amplitude
TE	trailing edge
T_{NET}	total thrust
u	incremental value of forward velocity
V	freestream velocity
$\ddot{z}$	vertical acceleration

3.2 SUBSCRIPTS

3.2.1 Subscripts Related to Velocity V or Mach Number M

D	dive
e	equivalent airspeed
MO	maximum operating
S	stall
T	true airspeed

3.2.2 General Subscripts

COL	column command
E	elevator
n	natural
p	phugoid
ref	reference
ss	steady state
SP	short period
STAB	stabilizer
u	longitudinal gust velocity
v	lateral gust velocity
w	vertical gust velocity

3.3 SYMBOLS

α	angle of attack
γ	flight path angle with horizon; glide slope deviation
δ	control deflection angle
Δ	change in quantity
ζ	damping ratio
θ	pitch attitude
σ	real part; root-mean-square gust velocity
ϕ	roll attitude
ψ	yaw attitude
ω	frequency

4.0 TEST FACILITY

4.1 GENERAL DESCRIPTION AND USER SERVICES

The piloted simulation tests were conducted in the multipurpose engineering simulator (M-cab) at the Boeing-Renton Flight Simulation Center (fig. 1). The M-cab shown in Figures 2, 3, and 4 is a three-degree-of-freedom (DOF) motion-based simulator with roll, pitch, and heave axes for movement and an electrohydraulic force feel system. The roll motion axis was not used for this study. The M-cab configuration uses a Model 737 cab, which was adapted for 757 and 767 simulation work. It also can be reconfigured to other multiple-throttle systems to simulate three- or four-engined airplanes.

The motion system includes cues for normal flight envelope ground rumble, touchdown, and engine-out for enhanced pilot recognition. Other features include "live" flight deck turbulence and pitch cues for takeoff rotation. Motion system dynamics and washouts have been tailored for realism within system limits.

The track-mounted, six-DOF television visual system provides a 43-deg field of view to captain and first-officer stations. The black and white television display system features a 3048m (10 000-ft) runway, 45.7m (150 ft) wide with ground shading and tree-like projections that provide sink rate cues to the pilot. The cathode-ray tube (CRT) image is projected through a beam-splitter, spherical mirror system. A masking feature is available to simulate a ceiling on takeoff or a breakout condition on landing approach.

The simulation, including the M-cab, is controlled with a multiprocessor Harris Series 200 computer system, where system refers to both hardware and software (ref 8). The following functions are supported simultaneously:

- Real-time simulation of Boeing airplanes with or without pilot in the loop
- Non-real-time simulations to evaluate various aircraft trim conditions and fixed situations
- Program development and data preparation via interactive terminals located both within the Boeing-Renton Flight Simulation Center and at remote Boeing locations
- Batch processing of simulation-related and general-purpose tasks
- Remote job entry to the Boeing Computer Services data center

The Harris Series 200 computer system consists of interrelated computer subsystems. Each subsystem consists of a Harris H800 central processing unit, 196 608 words of core memory, floating-point processor, virtual memory handling hardware, and various other internal central processor options to support the multiuser environment.

Available peripheral devices include a card reader, line printer, printer-plotter, nine-track magnetic tape, paper tape system, disk storage, and X-Y plotters.

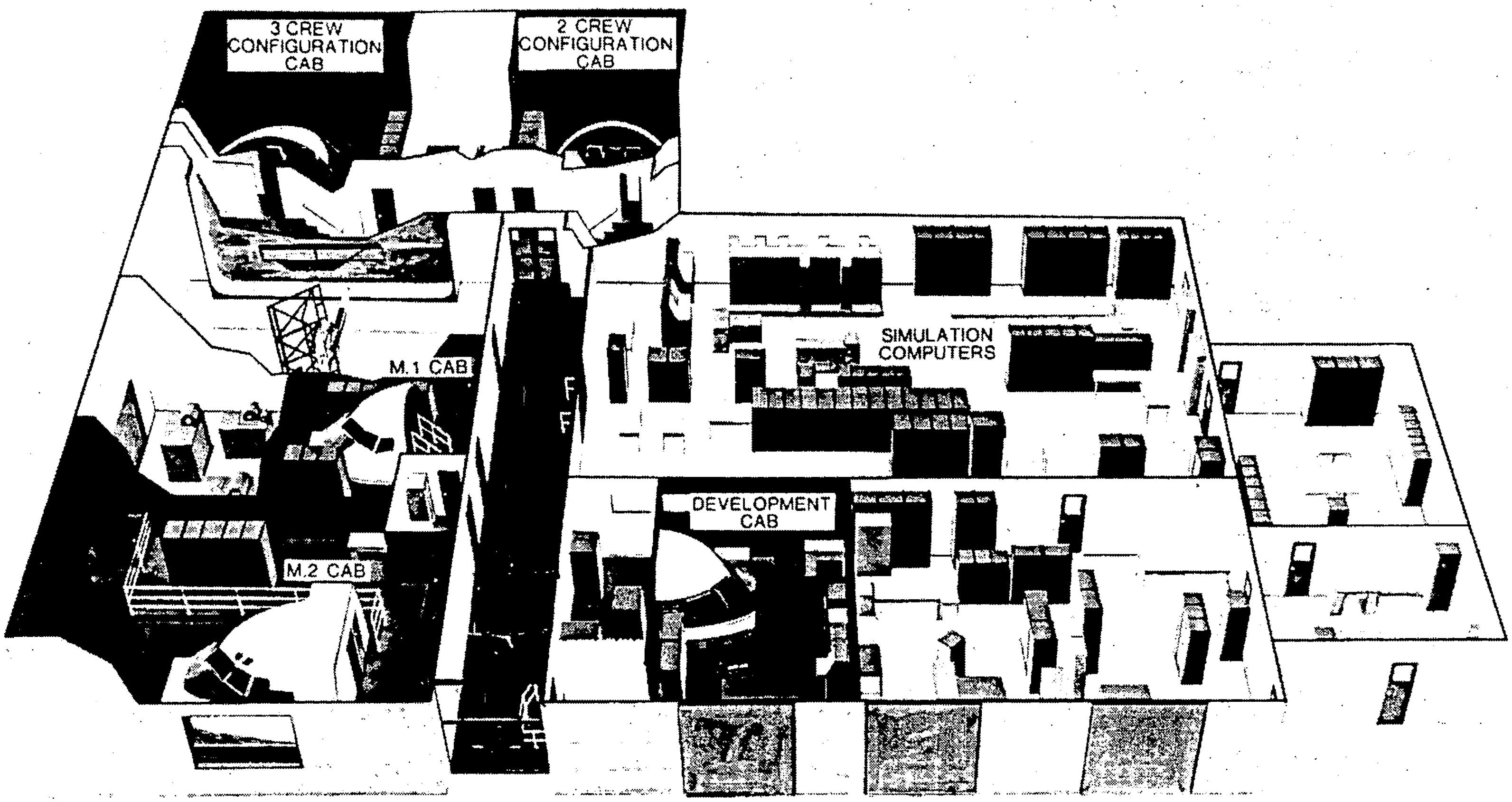

Figure 1. Boeing-Renton Flight Simulation Center

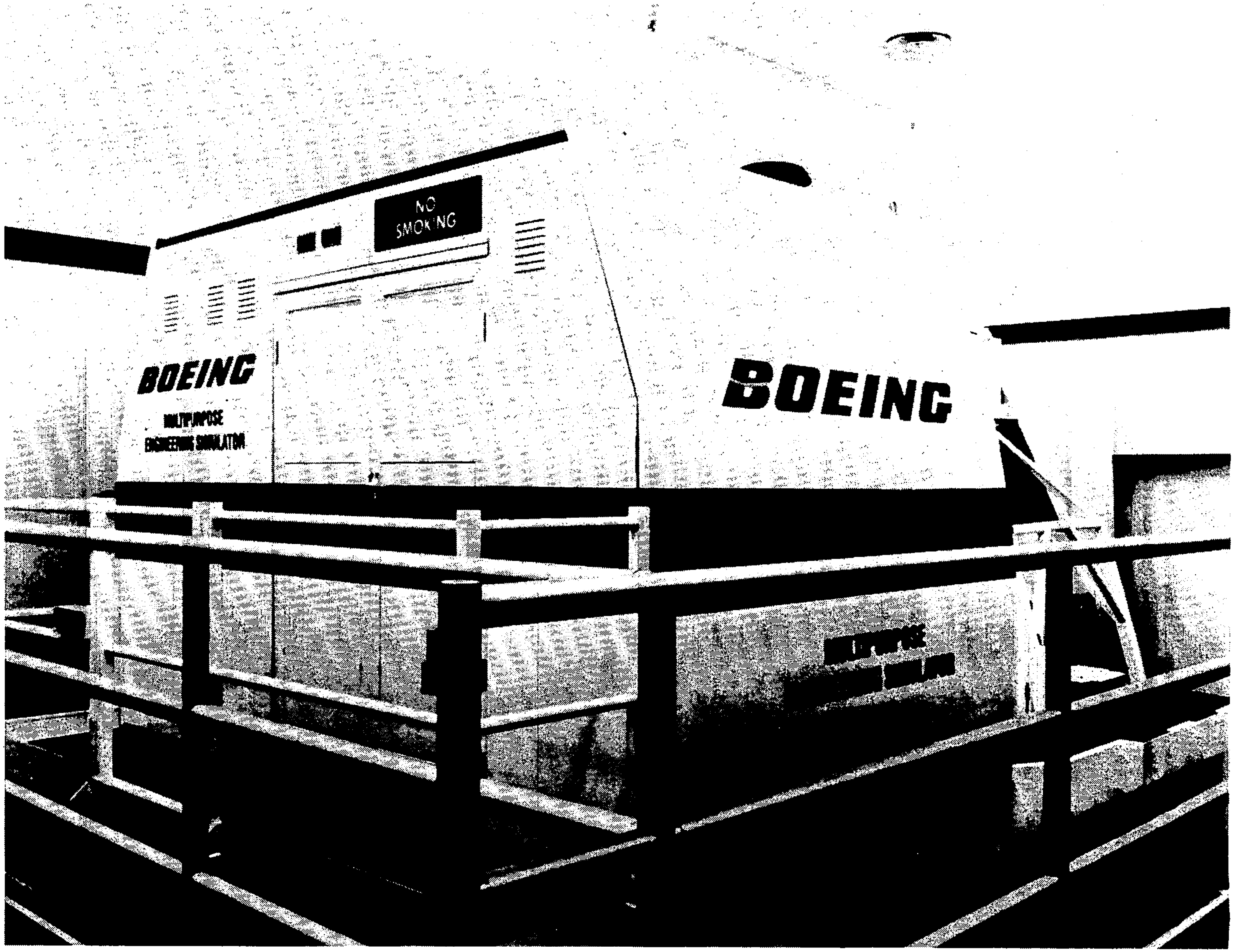

Figure 2. Boeing Multipurpose Engineering Simulator—Aft View

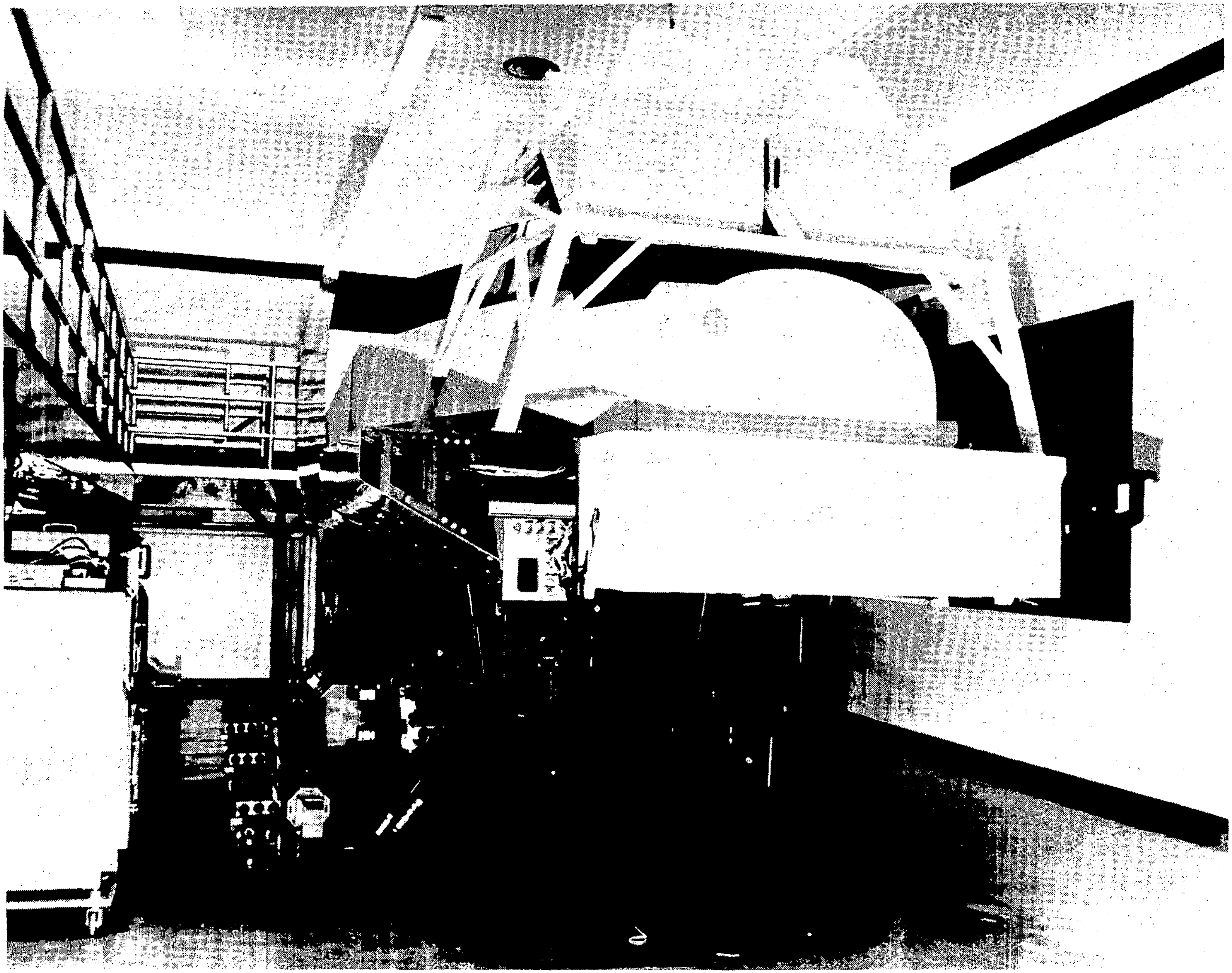

Figure 3. Boeing Multipurpose Engineering Simulator—Front View

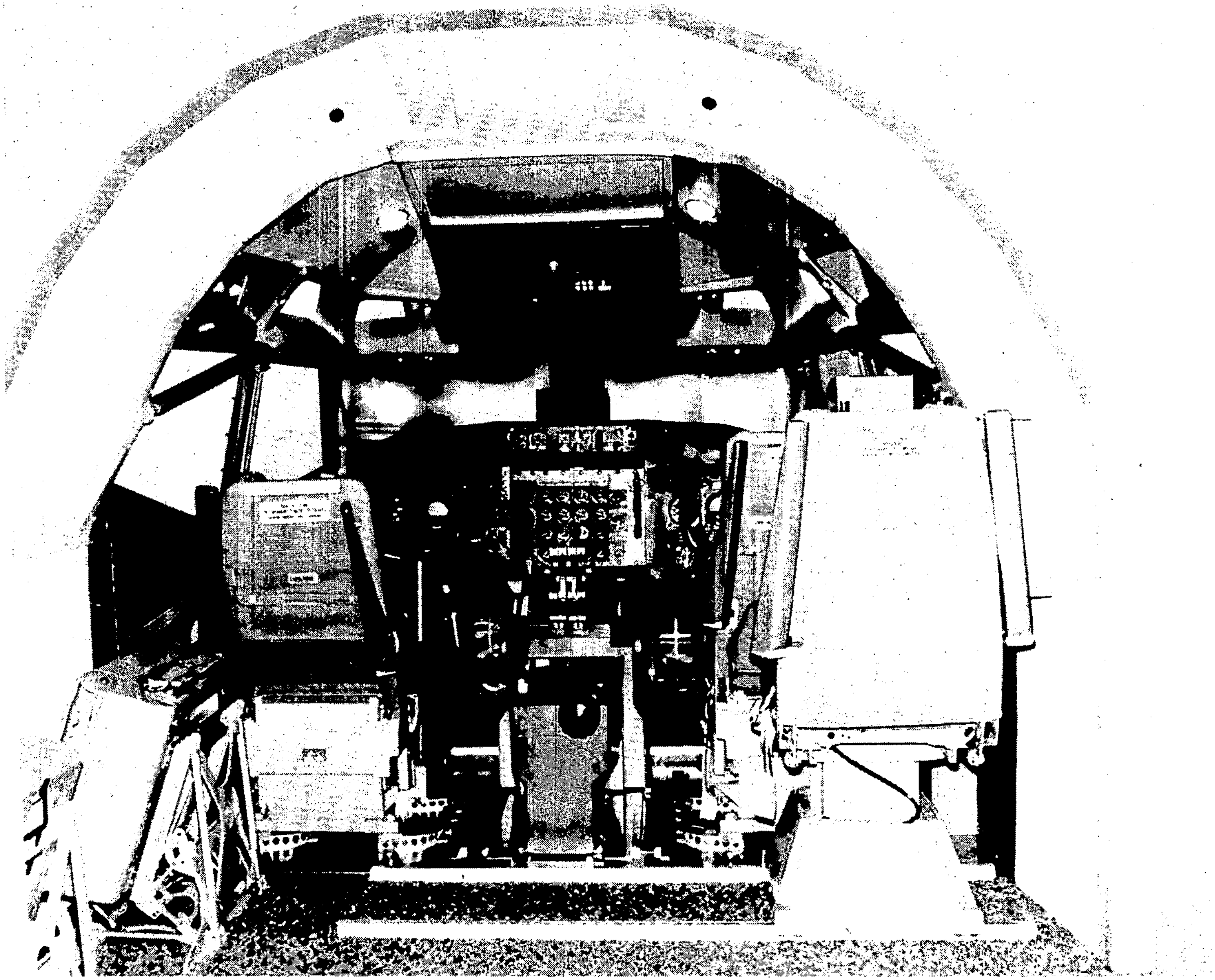

Figure 4. Boeing Multipurpose Engineering Simulator—Internal View

4.2 ATMOSPHERIC MODELS

The simulation uses "static" atmospheric data based on the U.S. Standard Atmosphere, 1962 (ref 9). For a nonstandard day, a specified temperature increment is input. A wind subroutine models airmass relative to the Earth and converts it to body axis components. Horizontal winds may be set either in north-south, east-west components or in magnitude and direction form. A vertical wind also can be used with either of the horizontal winds. Wind shears, as well as constant winds, may be simulated.

A gust model is available for all six DOFs. Individual levels of turbulence intensity are specified by the user. Table 1 lists recommended values for unidirectional clear air turbulence intensities. The medium turbulence level was used during the simulation task.

Table 1. Recommended Values for Unidirectional Clear Air Turbulence Intensities

Level	Intensity, m/s (ft/s) root mean square		
	σ_u	σ_v	σ_w
Light	0.76 (2.5)	0.76 (2.5)	0.38 (1.25)
Medium	1.52 (5.0)	1.52 (5.0)	0.76 (2.50)
Heavy	2.44 (8.0)	2.44 (8.0)	1.22 (4.00)

5.0 CONFIGURATIONS

5.1 UNAUGMENTED

The current Boeing 757 mathematical model, the airplane characteristics of which were based on preflight predictions, was the baseline reference for this study. An investigation of that model indicated that the data base was valid for the aft cg flight conditions that would be simulated. The 757 flight envelope shown in Figure 5 includes typical cruise and landing approach test conditions, where most of the evaluations were made. The V_{MO} and V_D test conditions represent typical flight envelope limits.

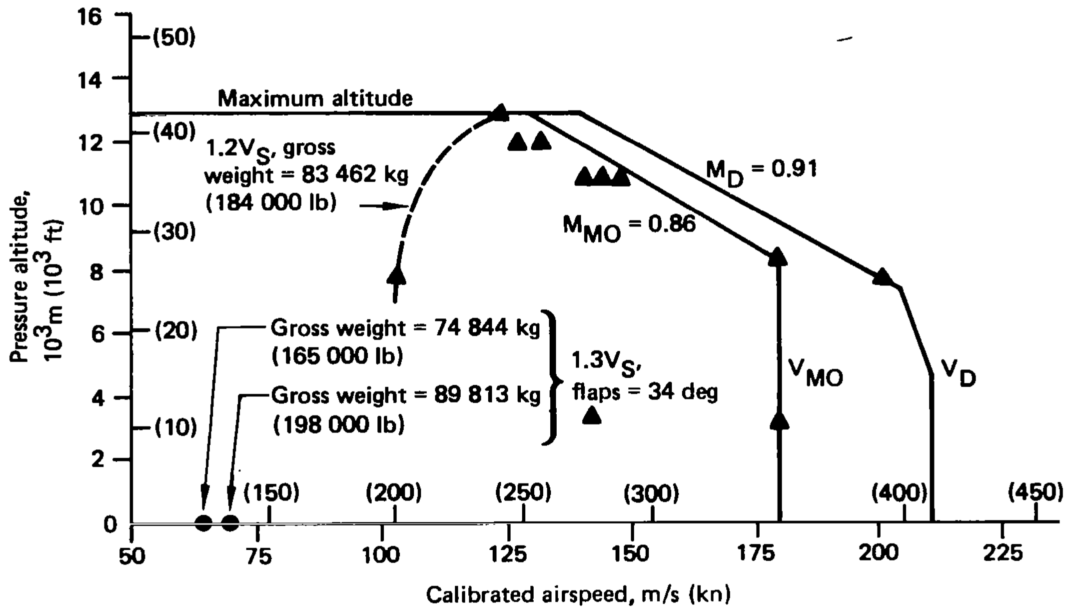

Figure 5. 757 Flight Envelope and Simulator Test Conditions

Prior to the simulation evaluation, stability analyses were performed for the test cases listed in Table 2. Stick-fixed neutral points and/or maneuver points were calculated for each test condition. The neutral point was defined as the cg location at which a speed change does not require a change in trim elevator position. Negative static margin (cg aft of the neutral point) indicates trim reversal. The maneuver point was defined as the cg at which the "elevator per g" goes to zero; i.e., a change in steady elevator deflection is not required for a corresponding change in load factor. At low speed and low altitude, the neutral point is usually more important to the pilot, in part due to the requirement for precise airspeed control and the otherwise demanding nature of the landing approach task. The maneuver point is usually well behind the cg range at low speed but tends to move forward as altitude increases. At high altitude and high speed, maneuvers involving load factor become more important and more critical than static stability; hence, maneuver margin and dynamic response are usually the critical longitudinal stability parameters at those conditions.

Table 2. 757 Simulation Test Flight Conditions

Condition	Weight		Gear	Flight path angle, γ	V_e		Mach No.	Altitude		Neutral point	Maneuver point
	kg	(lb)		deg	m/s	(KEAS)		m	(ft)	Percent MAC	Percent MAC
Landing conditions	89 813	(198 000)	Up	-3.0	69	(134)		305	(1 000)	48	65
	89 813	(198 000)*	Down	-3.0	69	(134)		305	(1 000)	50	62
	89 813	(198 000)	Down	0	69	(134)		305	(1 000)	49	62
	73 483	(162 000)	Down	-3.0	63	(123)		305	(1 000)	51	71
Cruise conditions	86 184	(190 000)	Up	0			0.80	10 668	(35 000)	41	52
	83 462	(184 000)*	Up	0			0.80	10 668	(35 000)	36	52
	83 462	(184 000)	Up	0			0.82	10 668	(35 000)	–	48
	83 462	(184 000)	Up	0			0.84	10 668	(35 000)	–	47
	83 462	(184 000)	Up	0			0.80	11 887	(39 000)	42	51
	74 844	(165 000)	Up	0			0.82	11 887	(39 000)	40	47
	83 462	(184 000)	Up	0			0.82	12 802	(42 000)	–	46
	83 462	(184 000)	Up	0			0.86	8 230	(27 000)	–	50
	83 462	(184 000)	Up	-4.9			0.91	7 620	(25 000)	–	58
	83 462	(184 000)	Up	0			0.63	3 050	(10 000)	39	55
	83 462	(184 000)	Up	0	100	(195)		7 620	(25 000)	44	51
Climb condition (maximum power)	74 844	(165 000)	Up	10.0	144	(280)		3 050	(10 000)	31	57

*Principal simulation test conditions.

The 757 pitch axis control model depicted in Figure 6 was modified for the unaugmented aft cg simulation study in only one area. At extreme aft cg locations, the positive (airplane nose down) electrical limits of the stabilizer (fig. 7) were relaxed. The added stabilizer authority enabled initial condition trim without elevator deflection other than the neutral shift as shown. The elevator neutral shift was arbitrarily maintained at a constant 5.5 deg for stabilizer positions greater than 4 deg. The standard stabilizer electrical limits are 3.8 deg for flaps-down low speed and 0.8 deg for flaps-up high speed.

5.2 ESSENTIAL PAS

For the PAS evaluation, the 757 flight control model was modified to represent a fly-by-wire interface from the column through Essential PAS to the control surface power control unit. The cable stretch and dead zone were removed. The hysteresis model relates primarily to the actuator control valve and was not changed, as shown in Figure 6. The force feel system was replaced by a column spring with stiffness of 4.54 kg/deg (10 lb/deg) and a breakout detent of 1.91 kg (4.2 lb). This was determined to be acceptable at both low and high speeds and met the stick force requirements of the IAAC DRO (appendix A to ref 7). The column-to-elevator sensitivity was set by a fixed gain at the input signal to Essential PAS. A piloted M-cab simulation session was used to refine and validate an acceptable augmented pitch control model.

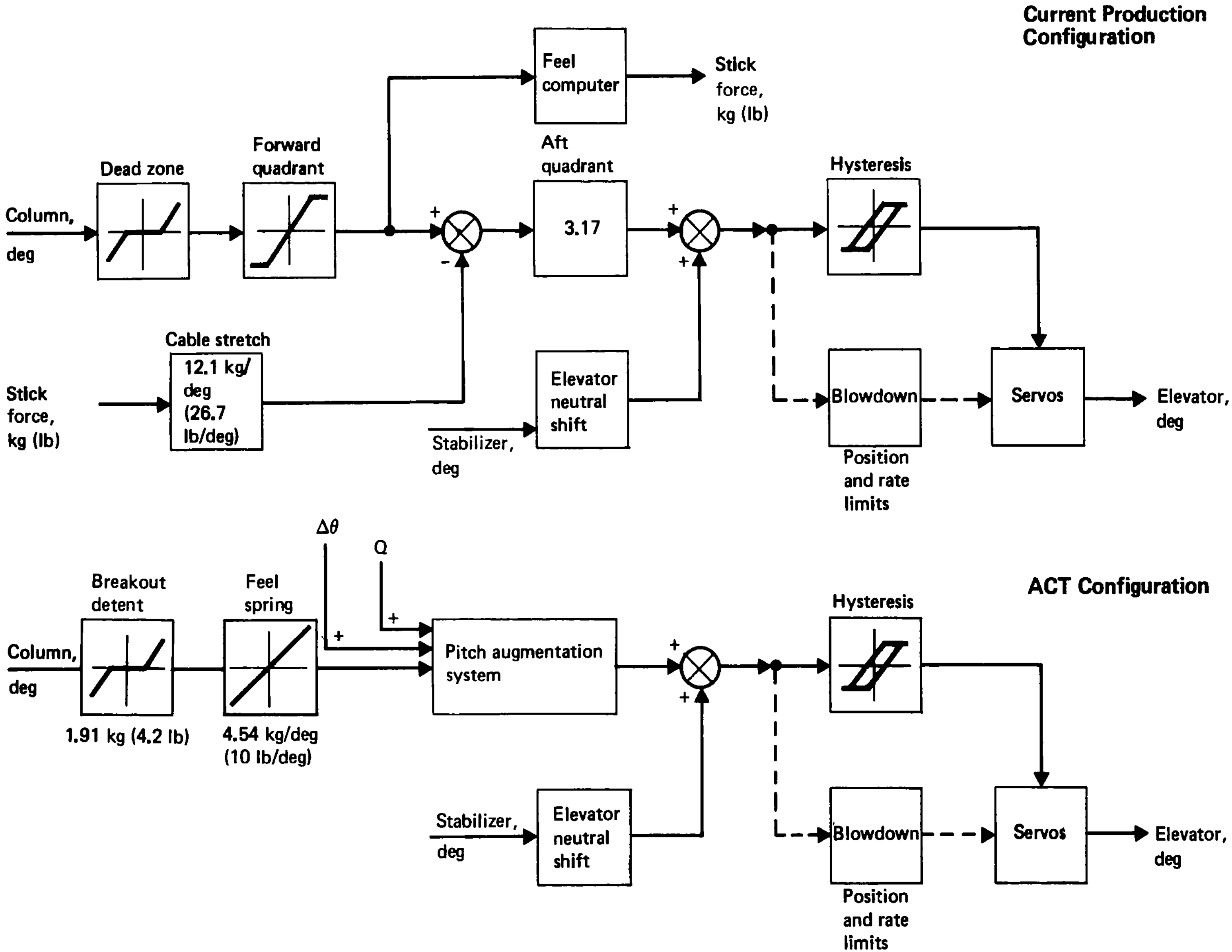

Figure 6. 757 Elevator Pitch Control Model

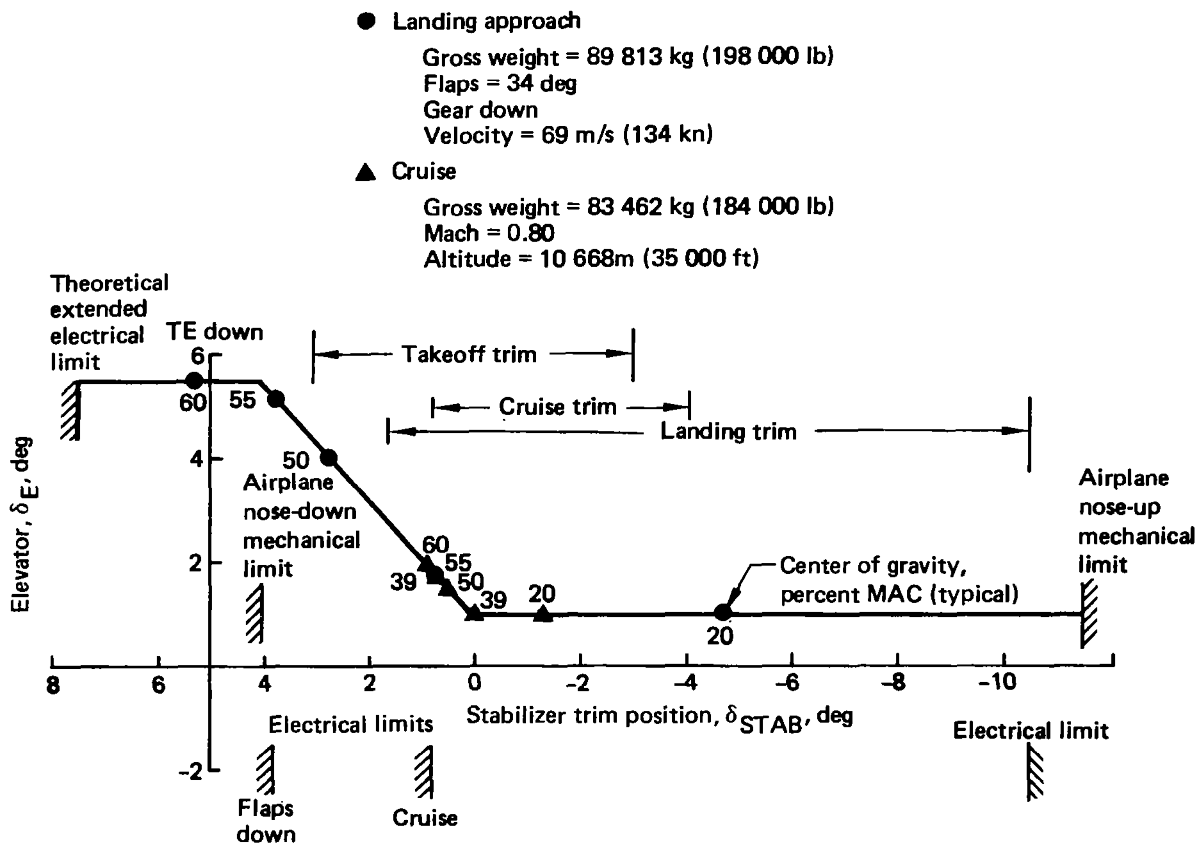

Figure 7. 757 Elevator Neutral Shift Program

Essential pitch-rate PAS (lower part of fig. 8) is required to provide acceptable (level 2) handling qualities over the full cg and weight range within the design envelope. The system must be of a sufficiently simple design to guarantee that a very low probability of failure ($<10^{-9}$ per flight hour) exists for safety of flight. Thus a sensitivity setting that was acceptable, although not necessarily optimum, at both high and low speeds was determined to allow a fixed-gain design. Pitch-rate feedback is the inner loop of the Primary PAS configuration.

5.3 PRIMARY PAS

Primary PAS is essentially a rate command, attitude hold system. Incremental pitch attitude was added to Essential PAS to provide good (level 1) handling qualities at both forward and aft cg limits. The attitude hold loop is designed to hold the pitch attitude prevailing after the control column is released. An "on ground" switch deactivated the loop during ground roll. Because the airplane held the reference attitude at stick force release, neither conventional "static stability" stick force gradients nor return to initial trim characteristics were experienced.

Drift from the selected attitude at column release is not expected to be a significant problem. The proposed additional integral feedback path shown in Figure 8 is intended to

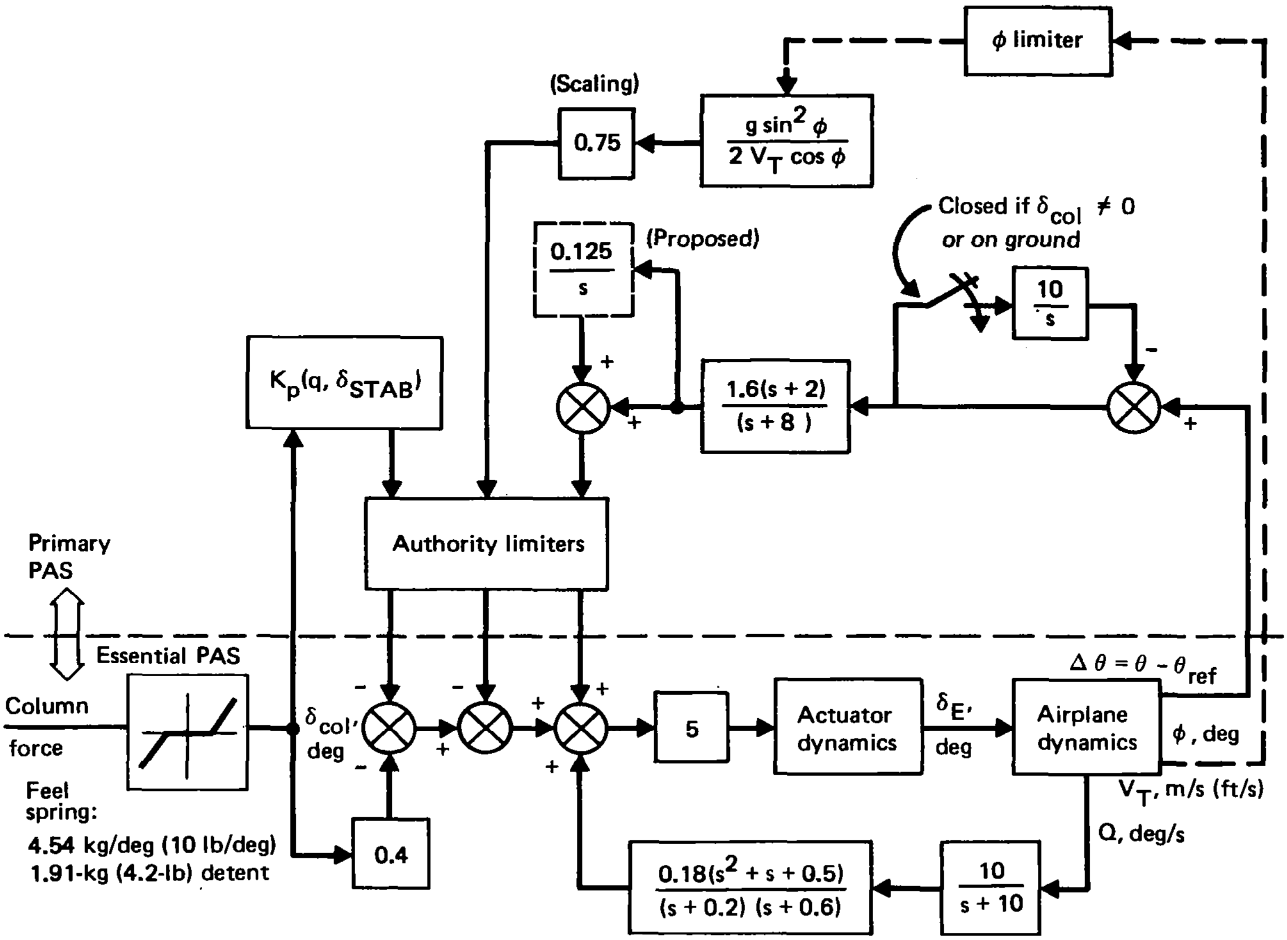

Figure 8. Pitch Axis Control Law for ACT Test

prevent such a tendency to drift, as discussed in Subsection 7.1. During turbulence encounters, a pilot will likely maintain hands-on control with the column out of detent most of the time, which would effectively disengage the attitude hold function.

Roll attitude compensation was added to the feel system by including the pitch-rate input required to maintain level turning flight. It was scaled to provide approximately the same stick-force-per-g characteristics in steady turning flight that the pilot would encounter in a wings-level pullup.

5.4 AUTHORITY LIMITATION

To achieve the required reliability, Essential PAS was assumed to be a multichannel "brickwall" analog system with full elevator authority. The Primary PAS inputs were assumed to be derived from a multichannel digital computer system. The digital system authority was restricted to provide protection against sudden generic multichannel hardovers. These limiters (fig. 8) would be implemented in hardware external to the digital calculations.

Authority limitations were not investigated in detail during the piloted simulations. Estimates of the elevator authority requirements of the attitude error and roll compensation loops were made by piloted maneuvers in both calm air and moderate turbulence. Indications were that the effectiveness of those loops could be retained with feedback commands limited to 4 deg. Roll attitude compensation was limited to a 30-deg bank signal for the level turn feel system compensation evaluations.

Additional authority may be required to vary the column-to-elevator sensitivity. If a fixed Essential System is assumed, the Primary PAS feedforward authority requirement was estimated to be approximately ±7 deg. By including a two-position gain switch in Essential PAS, a single Primary PAS hardware limiter for both feedforward and feedback signals with a value of ±4 deg is expected to be acceptable.

6.0 TEST TECHNIQUES

6.1 STABILITY AND CONTROL REQUIREMENTS

Handling qualities requirements for the simulation are based on the IAAC DRO (appendix A to ref 7). The simulation study was used to test the validity of the requirements for pitch-augmented configurations. Table 3 lists the basic longitudinal stability and control requirements. Frequency and time history criteria are discussed in Section 8.0.

Table 3. Longitudinal Stability and Control Requirements

Phugoid (low-frequency) damping*		
Level 1:	ζ_p	≥ 0.04
Level 2:	t_{2X}	≥ 12 sec
Level 3:	t_{2X}	≥ 6 sec
Short-period damping		
Level 1:	ζ_{SP}	≥ 0.35
Level 2:	ζ_{SP}	≥ 0.25
Level 3:	ζ_{SP}	≥ 0.15
Maneuvering stick forces		
Level 1:	13.6 to 18.1 kg/g (30 to 40 lb/g)	
Level 2:	9.1 to 22.7 kg/g (20 to 50 lb/g)	
Level 3:	4.5 to 36.3 kg/g (10 to 80 lb/g)	

*Phugoid combines with short period at aft cg to form third mode and aperiodic roots.

6.2 PILOT EVALUATIONS

The pilots were requested to perform a specific set of maneuvers at selected flight conditions and then provide a rating based on the revised Cooper-Harper Pilot Opinion Rating Scale (fig. 9 and ref 1). The pilots were also asked to comment on any specific deficiencies that they might identify. The pilots were not informed of either the cg location or the augmentation status to minimize the effect of their "learning curves" on the resultant ratings. Selection of both cg and augmentation status was randomized. At the beginning of each piloted session, the pilot was given a standard aft cg unaugmented 757 configuration for recalibration purposes.

The Cooper-Harper scale is frequently partitioned into three levels of handling qualities. Pilot ratings 1 through 3 correspond to Level 1 handling qualities; i.e., clearly adequate

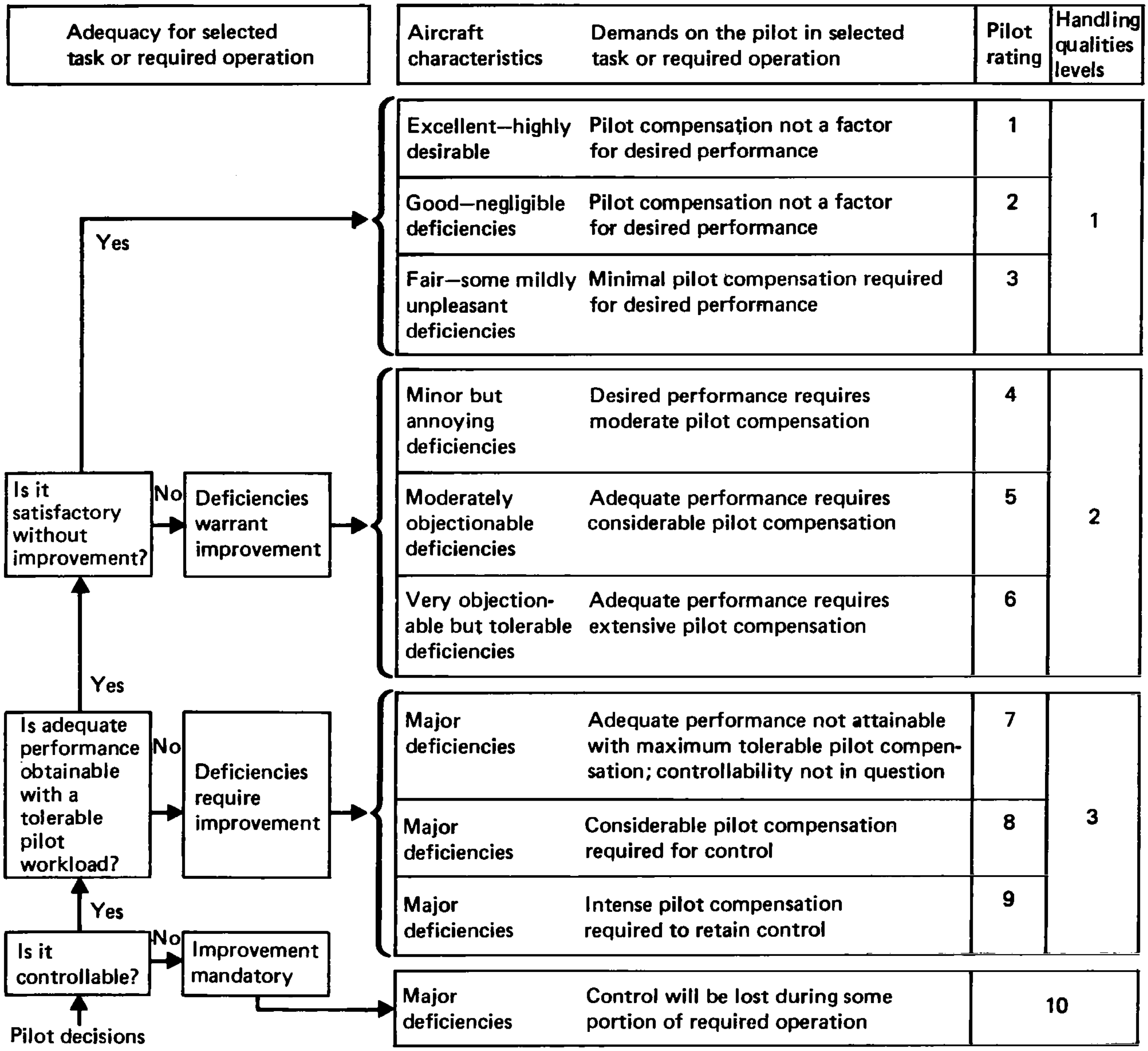

Figure 9. Cooper-Harper Pilot Opinion Rating Scale

for the mission or flight phase being evaluated. Pilot ratings 4 through 6 correspond to Level 2 handling qualities; i.e., adequate to accomplish the mission or flight phase but with objectionable deficiencies. Pilot ratings 7 through 9 correspond to Level 3 handling qualities; i.e., controllable but deficient for mission performance.

6.3 PILOT MANEUVERS

This simulation was evaluated by four pilots, not all of whom evaluated the entire set of test conditions. The plan was to have two pilots fly all the test conditions. However, because of the study schedule, simulator availability, and pilot scheduling conflicts, two additional pilots flew some of the test conditions. All pilots were Boeing experimental test pilots with current or recent flight test experience.

Table 4 lists the simulation maneuvers that the pilots were asked to perform. Originally, the approach initial condition was set at 12 192m (40 000 ft) back from the runway threshold and 610m (2000 ft) offset at 305m (1000-ft) altitude. However, after consultation with the pilots, those numbers were subsequently reduced by half, with negligible effect on pilot rating and with a significant reduction in time required to complete each task. The pilots were allowed to add other maneuvers such as windup turns if they deemed them necessary for a thorough evaluation.

Table 4. Pilot Simulation Maneuvers

Low-speed maneuvers
Approach and landing or go-around • Initial conditions • SX = -6096m (-20 000 ft), SY = 305m (1000 ft) • Alt = 152m (500 ft), γ = 0 deg, $V_e = 1.3V_S$ + 10.3 m/s (20 kn) • Gear up, flaps = 20 deg
Flight profile • 1.5 dots below glide slope—gear down[a] • 1.0 dot below glide slope— flaps = 30 deg, reduce to $1.3V_S$ • Glide slope capture • Approach on instruments at $1.3V_S$ • "Breakout" at 30.5m (100 ft) • Land or • Go-around at 15.2m (50 ft), full power, flaps = 20 deg • Gear up at positive rate of climb
With and without moderate turbulence and 10.3-m/s (20-kn) crosswind at 12.2m (40 ft) $(\sigma_u, \sigma_v, \sigma_w)$ = (1.52, 1.52, 0.76) (m/s) (rms) (5.0, 5.0, 2.5) (ft/s) (rms) Reference speeds 74 844 kg (165 000 lb) $1.3V_S$ = 63 m/s (123 kn) 89 813 kg (198 000 lb) $1.3V_S$ = 69 m/s (134 kn)

High-speed maneuvers[b]	
Still air	
• Roller coaster	$\Delta\ddot{z}$ = ±0.5g
• Altitude change	Δalt = ±91.4m (300 ft)
• Speed change	Δu = ±7.7 m/s (15 kn)
• Roll in/out	$\Delta\phi$ = 30 deg, $\Delta\psi$ = 15 deg
Turbulence (moderate)	
• Altitude change	Δalt = ±91.4m (300 ft)
• Roll in/out	$\Delta\phi$ = 30 deg, $\Delta\psi$ = 15 deg

[a]1.0 dot indicates approximately 0.35-deg deviation from glide slope.
[b]Initial conditions within the flaps-up flight envelope boundaries are applicable.

A limited number of test conditions were flown with moderate clear air turbulence to evaluate its effect on pilot rating. For the landing approach task, a lateral crosswind was also included that sheared to zero from a 12.2m (40-ft) altitude.

7.0 SIMULATION RESULTS

This simulation study was limited in scope and was not designed to demonstrate flight readiness of the 757 with relaxed static stability and augmentation. Instead, feasibility of the augmentation concepts was to be demonstrated. The results presented in this section show the trends in pilot rating as the cg moves aft for unaugmented, Essential PAS, and Primary PAS test conditions. The two principal flight conditions previously noted in Table 2 (maximum landing weight for landing approach and midweight high-altitude cruise) are discussed. Ratings for additional flight conditions and the ratings provided by the individual pilots are listed in Tables A-1 and A-2 of the appendix.

7.1 LANDING APPROACH

The pilot rating results for the landing approach task are presented in Figure 10 as a function of cg with the neutral point indicated. A scatter bandwidth of approximately two rating points exists for the unaugmented test conditions. The unaugmented rating points outside the scatter bands in Figure 10 are considered to be anomalies as discussed

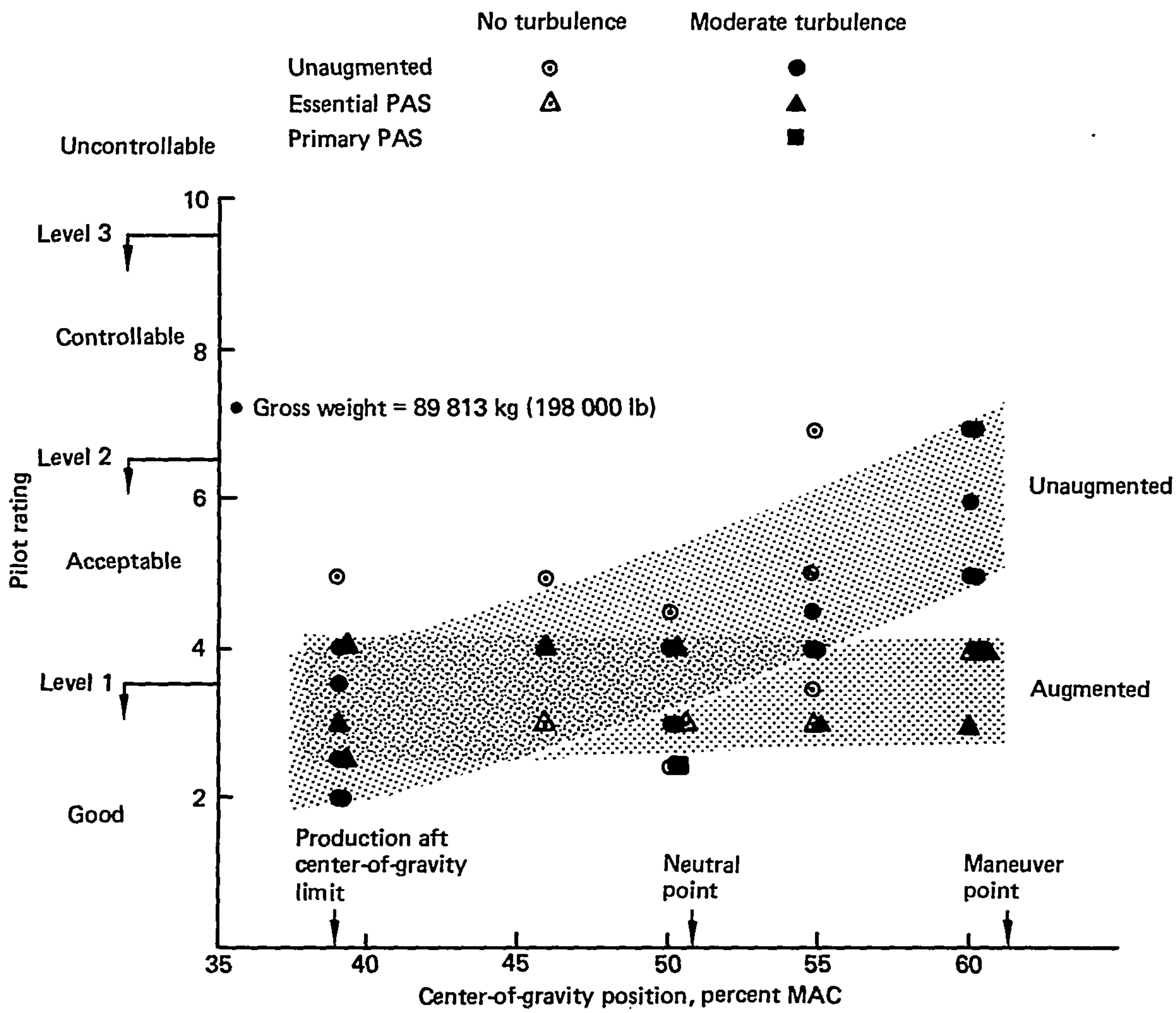

Figure 10. Effect of Center-of-Gravity Position on Pilot Rating—Landing Approach

in the appendix. If the upper boundary of that band is considered to define the requirements for service operation, it might be concluded that the unaugmented 757 can be landed with Level 2 (pilot rating $\leqslant 6.5$) handling qualities at cg locations about 6% aft of the neutral point. Ground handling in the landing roll was not investigated and would color this conclusion for the given airplane main gear location.

Moderate turbulence and a crosswind do not appear to seriously degrade the unaugmented ratings. The ratings of one pilot tended to be an average of one-half point higher due to turbulence effects. The effects of wind shears, downdrafts, and possibly "sidestep maneuvers" at 61m (200 ft) are probably significant but were not included in the simulation study.

Essential PAS yielded relatively constant ratings with the upper boundary of the scatter band just outside the Level 1 (pilot rating = 3.5) boundary. Thus, with this PAS design, the airplane could be flown safely at the aftmost cg tested (about 10% behind the neutral point). Principal adverse comments referred to high stick forces and low sensitivity during some flare maneuvers. The apparent cause of these comments is that because Essential PAS is to be, if possible, a fixed-gain system for simplicity and reliability, the gain that was set as required for high speed was low but still acceptable for landing approach. Primary PAS schedules gains for better handling qualities over the entire flight envelope.

Primary PAS feasibility was tested by only one pilot for a limited number of test conditions with moderate turbulence. The plan was to verify that the configuration would work and could be incorporated into the design of the flight control computer. Good results were reported for centers of gravity at 20% and 50% MAC, but slightly degraded ratings were given at 60% MAC. The reason given by the pilot for the degraded rating was a slight drift from the commanded attitude after column release. Preliminary analysis indicated that the drift could be prevented by adding a low-gain feedback signal proportional to the integral of pitch attitude error as was shown in Figure 8. The intent is to produce an elevator deflection equivalent to that required to maintain the selected attitude. This proposed additional feedback path was not evaluated by piloted simulation. However, analyses indicated that stability margins would not be compromised by this added feedback. Additional problems concerning Primary PAS would probably arise with more thorough evaluation.

The effect of moderate turbulence on the Essential PAS configurations was evaluated for only a few flight conditions. The incremental turbulence effects on pilot rating were similar to the results for the unaugmented test conditions. Primary PAS was evaluated with turbulence only.

Typical time histories of a pilot's control tasks and associated longitudinal airplane parameters for landing approach with moderate turbulence are presented in Figures 11, 12, and 13 for unaugmented stability, Essential PAS, and Primary PAS, respectively. The time histories for Essential PAS and Primary PAS are similar. For the latter, the pilot maintained hands-on control with the column out of detent most of the time, thus effectively disengaging the attitude hold function. The main effect of Primary PAS was to improve longitudinal feel characteristics through feedforward gain scheduling.

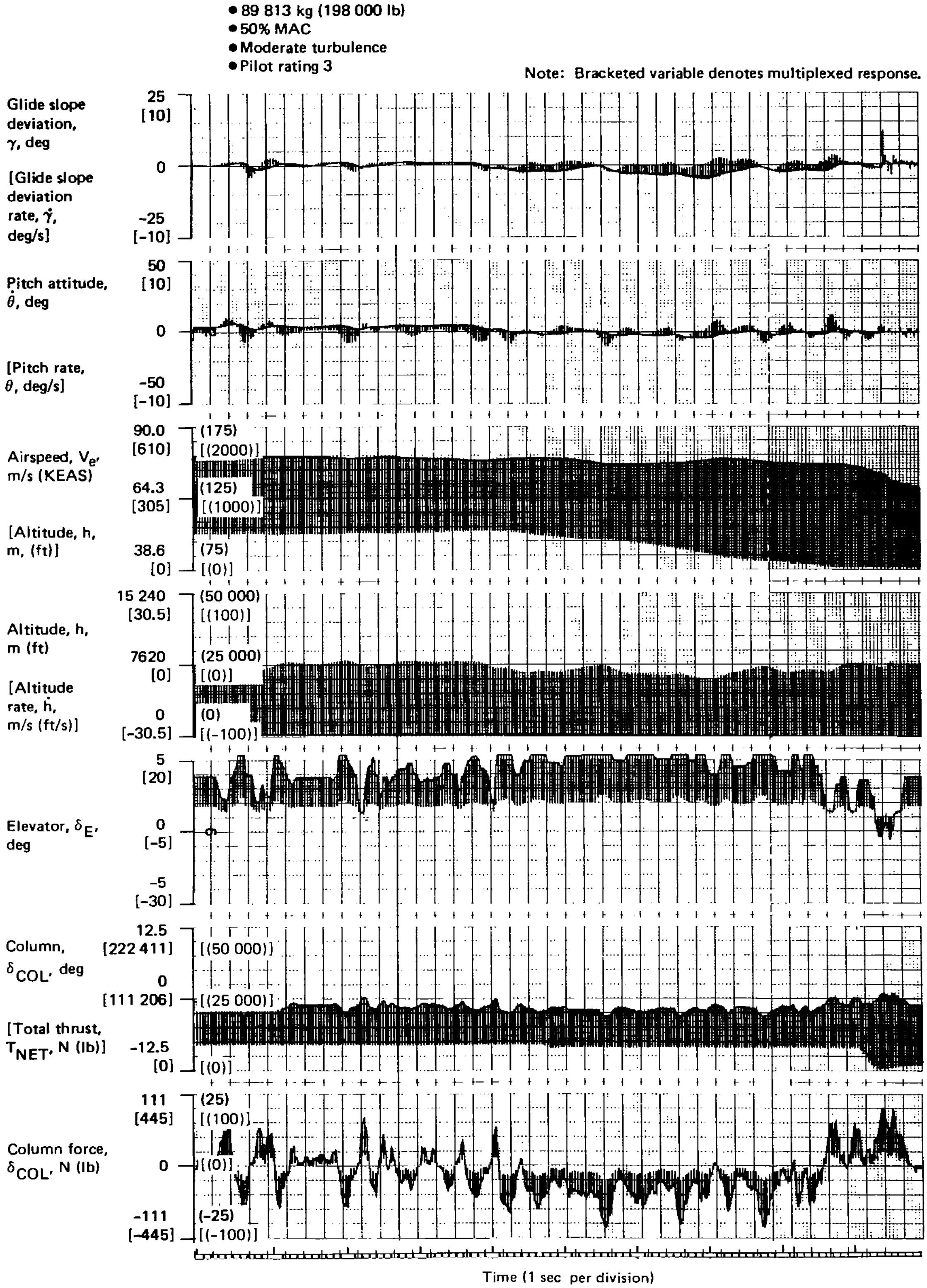

Figure 11. Unaugmented Landing Approach Time Histories

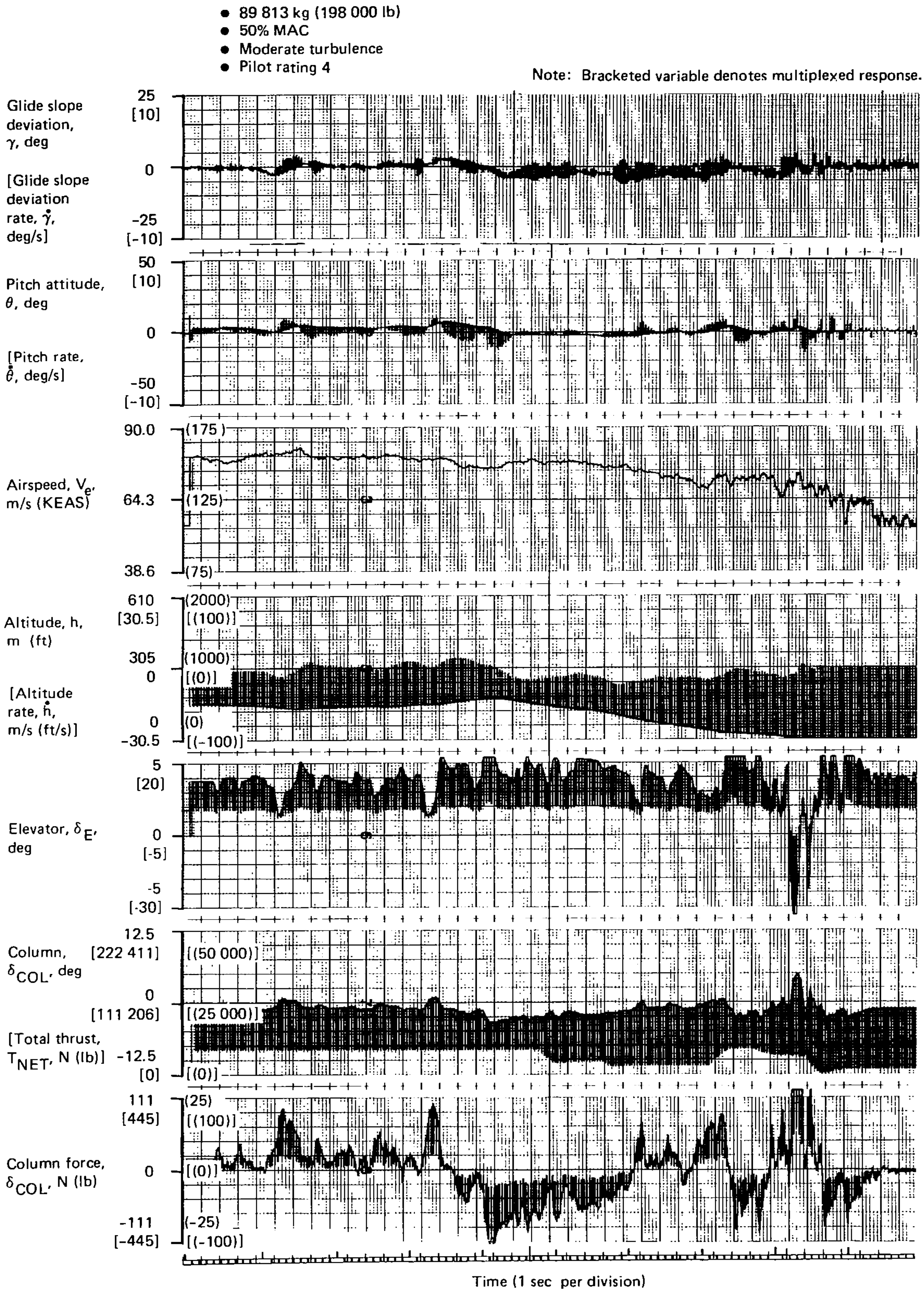

Figure 12. Essential Pitch-Augmented Stability Landing Approach Time Histories

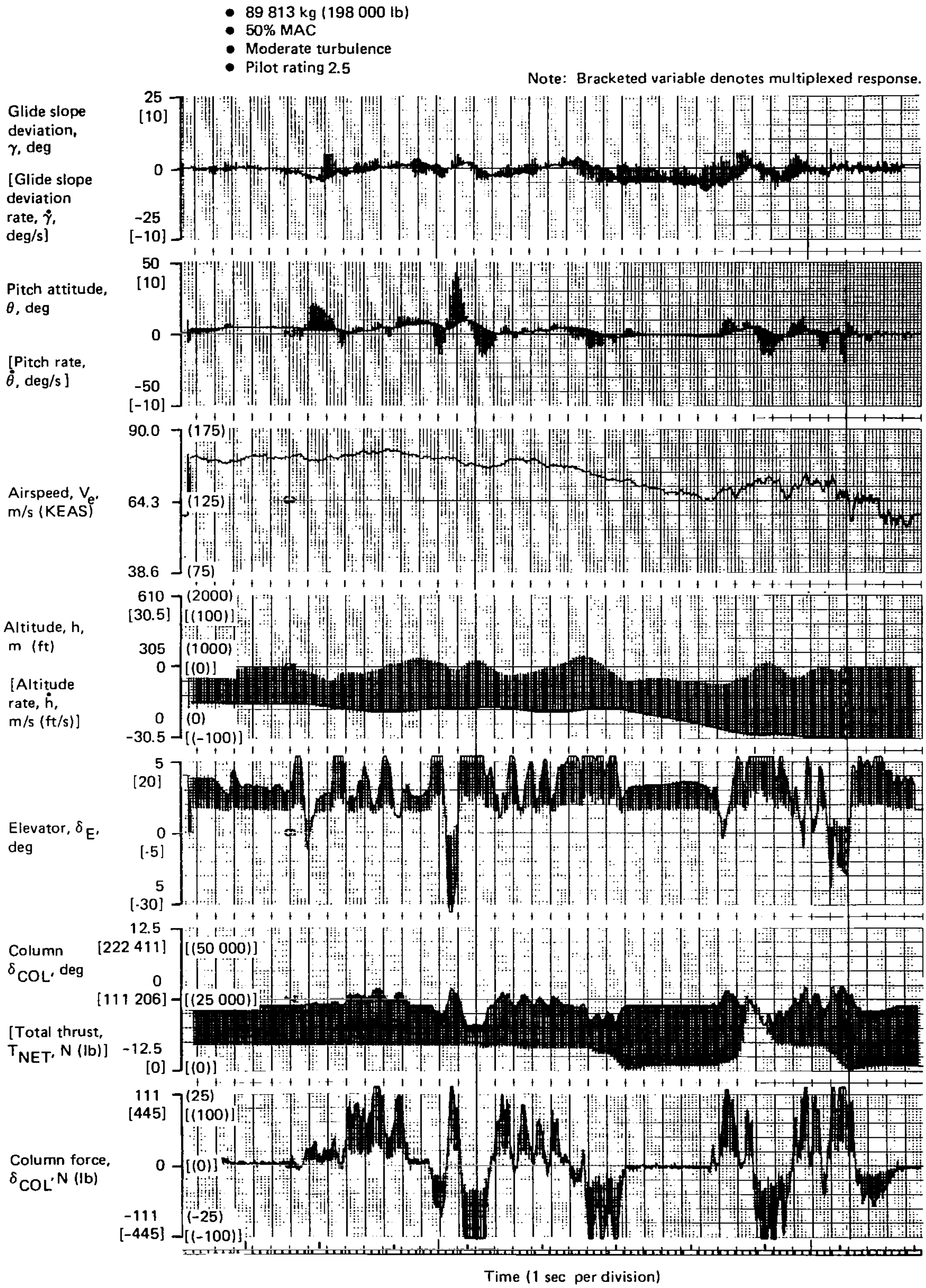

Figure 13. Primary Pitch-Augmented Stability Landing Approach Time Histories

7.2 HIGH-ALTITUDE CRUISE

The cruise results in Figure 14 show the maneuver point to be a more appropriate reference point for an aft cg limit than the neutral point. The upper boundary of the rating scatter band indicates that the unaugmented airplane can be flown with Level 2 (pilot rating $\leq$ 6.5) handling qualities for the cg at an aft limit of 47% MAC or 5% forward of the maneuver point. It should be noted that only one cruise condition was extensively evaluated and that other cruise conditions might result in less acceptable handling qualities ratings. The rating points outside the indicated rating scatter band were considered to be anomalies as discussed in the appendix. Moderate turbulence was found to have an insignificant effect on cruise condition handling qualities. After evaluating extreme aft cg unaugmented configurations, two of the pilots commented that control might be lost if large amplitude column inputs were made. Smaller amplitude and higher rate column inputs seemed to work better for those configurations.

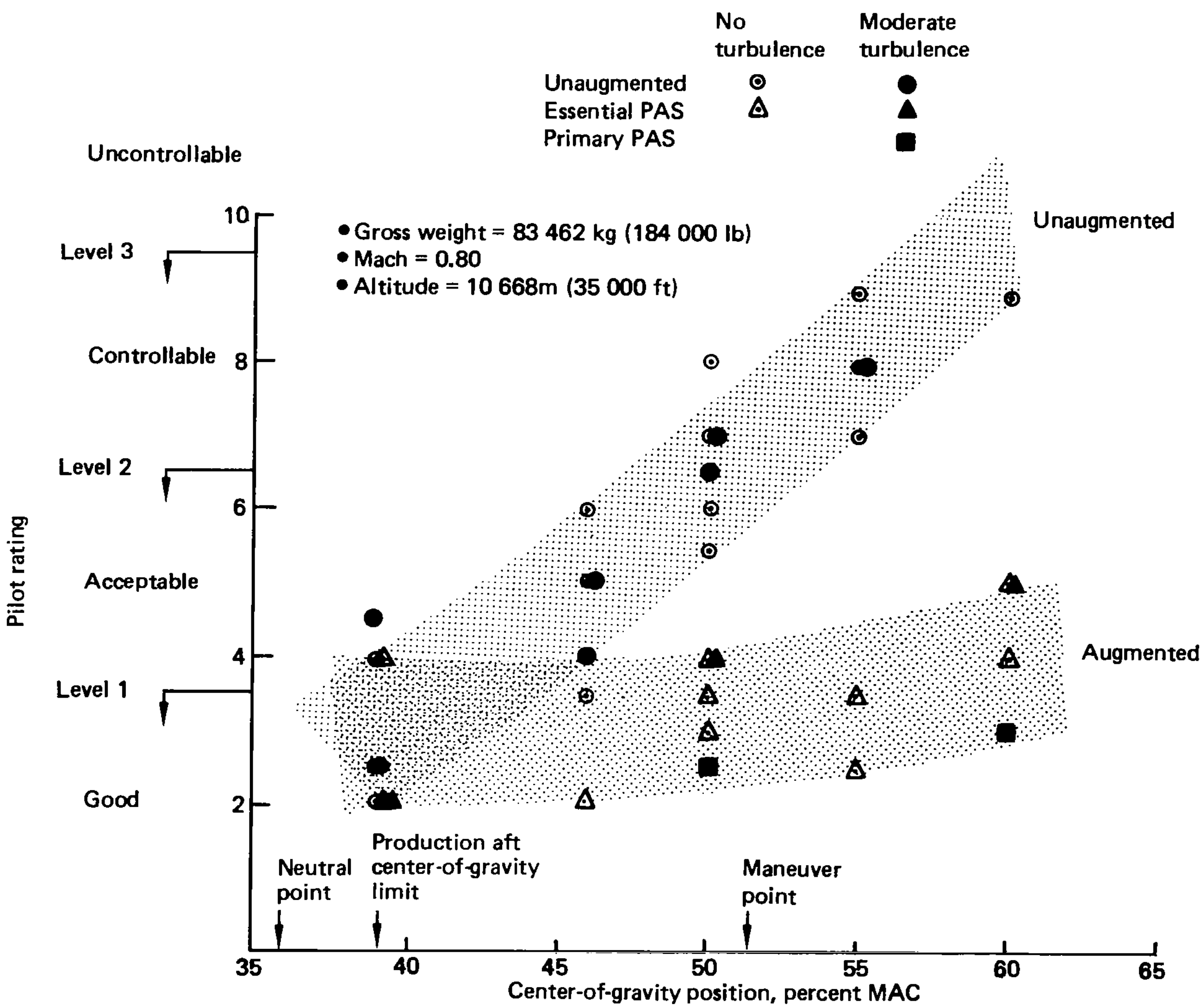

Figure 14. Effect of Center-of-Gravity Position on Pilot Rating—Cruise

The production 757 flight control system model was retained for the unaugmented study. Thus, the control forces and column sensitivities were not optimized for operation with centers of gravity aft of 39% MAC.

The neutral point in Figure 14 is shown located forward of 39% MAC. The neutral point locations noted herein are based on simulator results, which in turn are based on predicted preflight data (viz, analytical calculations and wind-tunnel data). Actual flight test data have indicated that the neutral point does not move forward of 39% MAC for any cruise condition. However, it does tend to move forward slightly for full-power climb conditions. A Mach trim system is provided to compensate stick force per knot for high-speed conditions that approach the neutral point. The Mach trim system was not included in the simulation model of the unaugmented airplane.

The upper boundary of the band of ratings for Essential PAS is very close to the Level 1 (pilot rating = 3.5) boundary but tends to degrade when the cg is aft of the unaugmented maneuver point. The feel forces were reported to be somewhat sensitive in the breakout area. The fixed gain was set slightly higher than optimum so that it could also be used for landing approach. Further optimization of the feel system for Essential PAS is indicated by those findings.

Primary PAS results for the three cruise test conditions (20% MAC rating listed in table A-2) were all within the Level 1 region. During this very limited testing of Primary PAS in cruise flight, no noticeable tendency to drift from the desired pitch attitude was observed when the column was released.

7.3 COMPARISON WITH OTHER TRANSPORT AIRPLANE SIMULATIONS

The results are comparable to those obtained by both the Douglas Aircraft Company and the Lockheed-California Company in simulation investigations of transport configurations with roughly similar dimensional and mass characteristics (refs 3 and 4). Figures 15 and 16 compare unaugmented data from References 3 and 4 and this investigation for the landing approach and cruise flight conditions. The agreement between the IAAC and Douglas results is remarkably close for the landing approach configuration, while the Lockheed results differ by one rating point at most in the vicinity of zero static margin. For the cruise configuration, agreement is not quite as good, but the maximum difference in the mean pilot ratings is a little more than one rating point.

These data appear to confirm reasonably well our assessment of minimum acceptable static margins for landing approach and possibly indicate that our assessment for cruise conditions is slightly conservative.

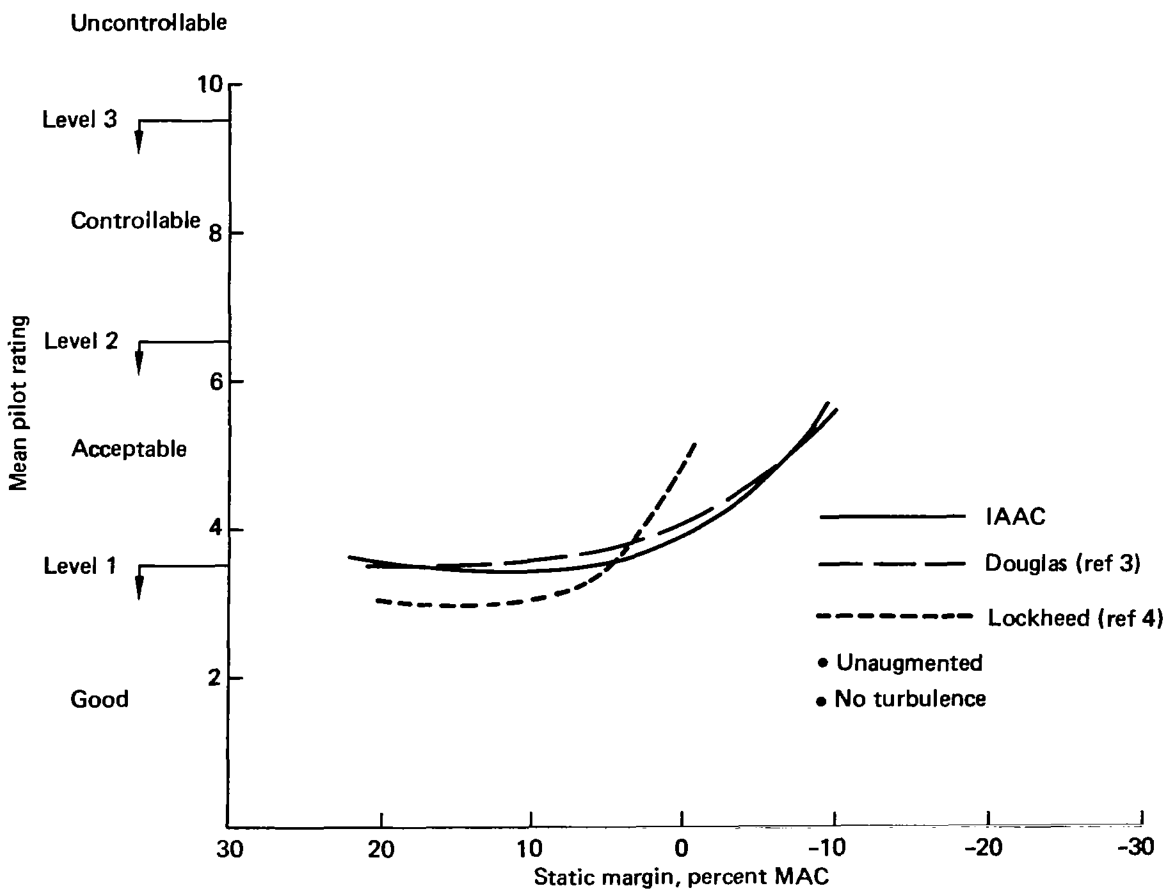

Figure 15. Effect of Longitudinal Stability on Mean Pilot Rating—Landing Approach

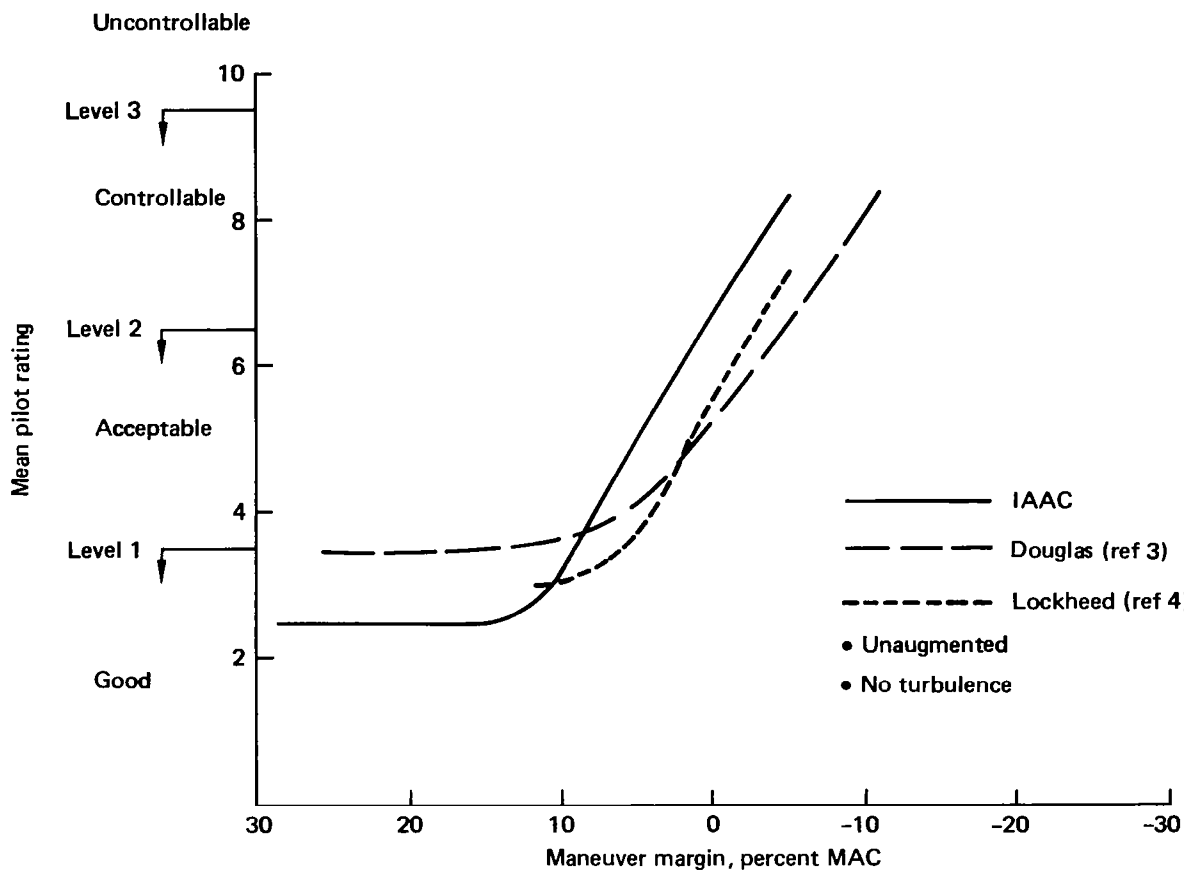

Figure 16. Effect of Longitudinal Stability on Mean Pilot Rating—Cruise

8.0 ANALYSIS

Existing handling qualities criteria were used to correlate the ratings obtained from the simulation study and to provide predicted handling qualities levels for comparison.

8.1 TIME-TO-DOUBLE AMPLITUDE

Pilot ratings are frequently compared with the time-to-double or time-to-half amplitudes associated with low-frequency dynamics. The time-to-double amplitude can be measured experimentally, but that method was not attempted during this study. Instead, analytical values associated with the flight conditions simulated were used.

Figure 17 plots the times to double of the least stable low-frequency root as a function of cg position. Simulated conditions, both without and with augmentation, are included. The unaugmented cruise condition is definitely much less stable than the unaugmented landing approach case at the same aft cg condition. Previous studies have concluded conservatively that 6 sec or greater time-to-double amplitude is necessary for minimum acceptable handling qualities. Table 3 specifies t_{2X} = 6 sec as the Level 3 minimum. For unaugmented cruise in Figure 17, t_{2X} = 6 sec corresponds to a cg location at approximately 51% MAC.

The landing approach pilot ratings as a function of t_{2X} and $t_{1/2X}$ in Figure 18 show a definite trend of improved handling qualities with increasing stability, as was expected. The scatter bandwidth of two to four rating points also indicates that other factors such as column forces and sensitivities should be considered if this criterion is to be used in the prediction process. The cruise results in Figure 19 also exhibit a scatter bandwidth, but of two or fewer rating points. The more demanding and exacting nature of the landing approach task compared with that of cruise is a probable explanation.

8.2 SUPERSONIC TRANSPORT PITCH-RATE RESPONSE CRITERIA

The unaugmented pitch-rate time response criteria for Level 1 handling qualities, proposed for the U.S. supersonic transport (SST) program described in Reference 10, were applied to the simulation test conditions. The low-speed criterion boundary for n/α = 3.98 is superimposed on the normalized responses for the unaugmented landing approach test conditions (n/α = 3.6) in Figure 20. The aft cg locations for responses near the Level 1 boundary correspond closely with the piloted simulation results presented in Subsection 7.1. At farther aft centers of gravity, ratings worse than Level 1 may result from the sluggish response shown or from airplane characteristics not related to the time response.

The high-speed cruise criterion was applied in Figure 21. The criterion n/α = 16.54 was considered sufficiently close to that of the cruise test condition n/α = 18 for that Level 1 boundary to be applicable. The cg for a Level 1 rating is very close to the production aft cg limit of 39% MAC, agreeing reasonably well with the simulation results in Figure 14. The response at 50% MAC appears very sluggish and definitely worse than Level 1 as the simulation ratings indicated.

The same criterion boundaries were applied to responses augmented by Essential PAS (figs. 22 and 23). The responses slightly exceed the Level 1 boundary in some regions,

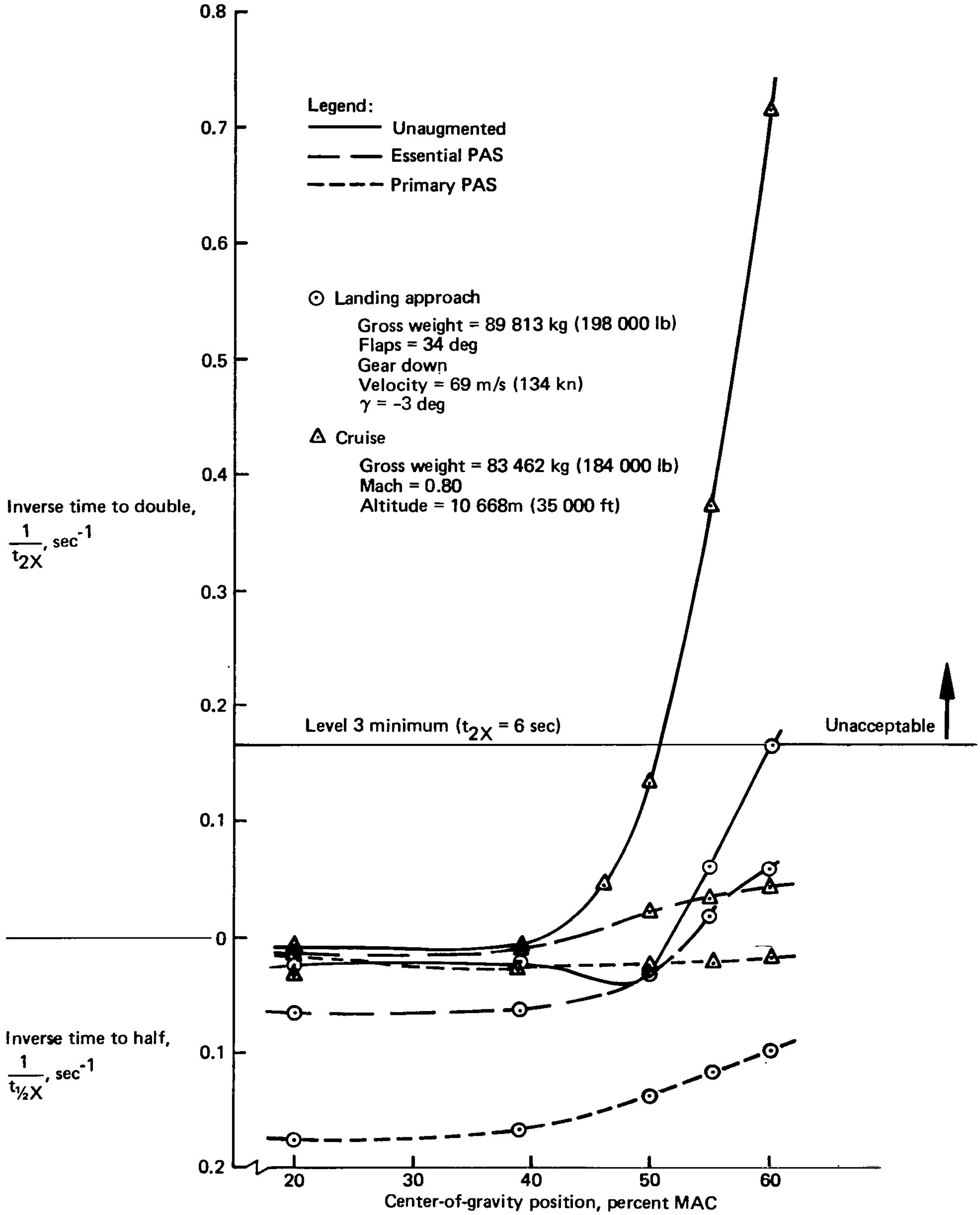

Figure 17. Effect of Center-of-Gravity Position on Time-to-Double Amplitude

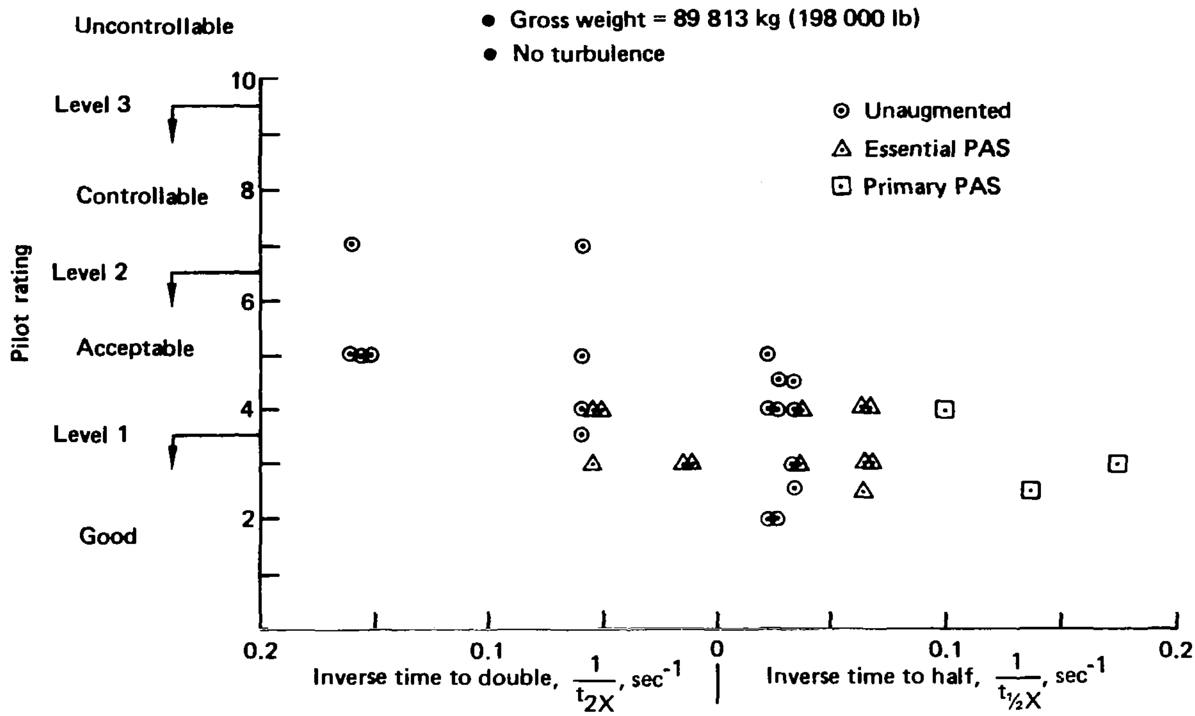

Figure 18. Effect of Time-to-Double Amplitude on Pilot Rating—Landing Approach

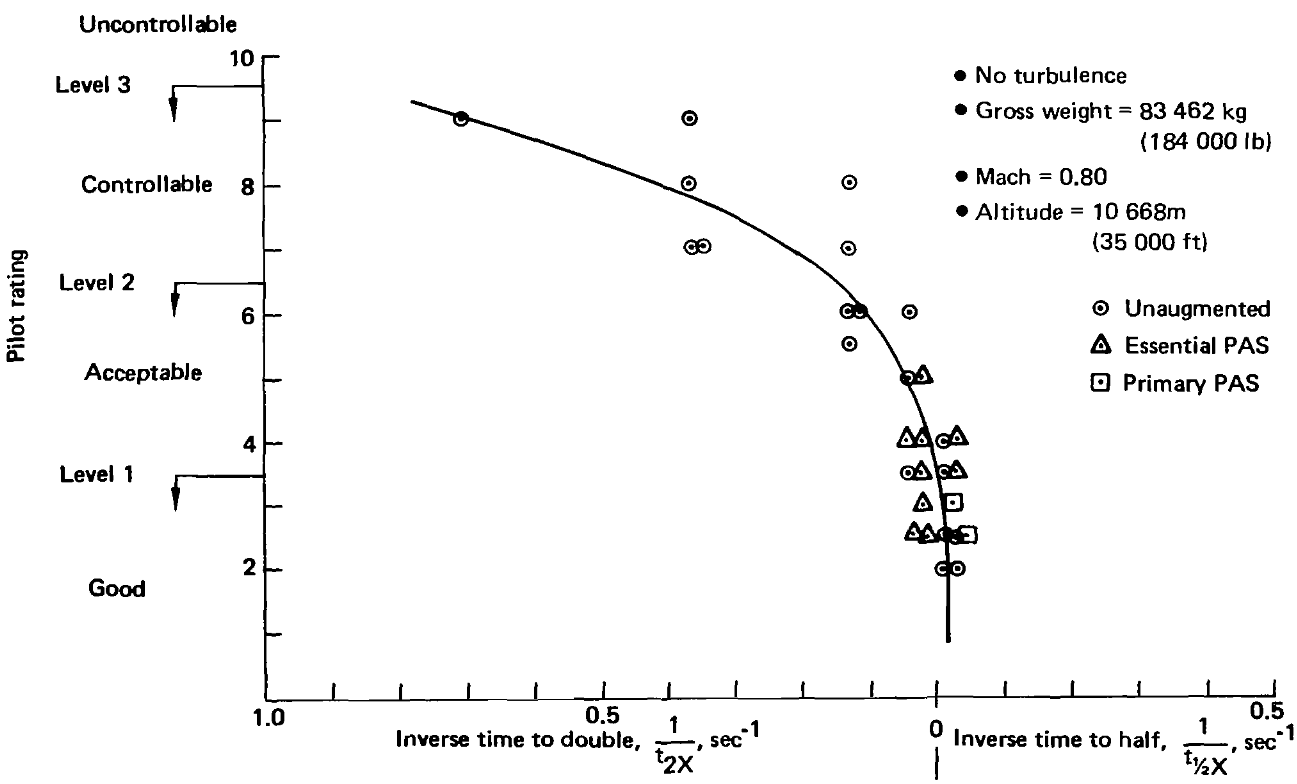

Figure 19. Effect of Time-to-Double Amplitude on Pilot Rating—Cruise

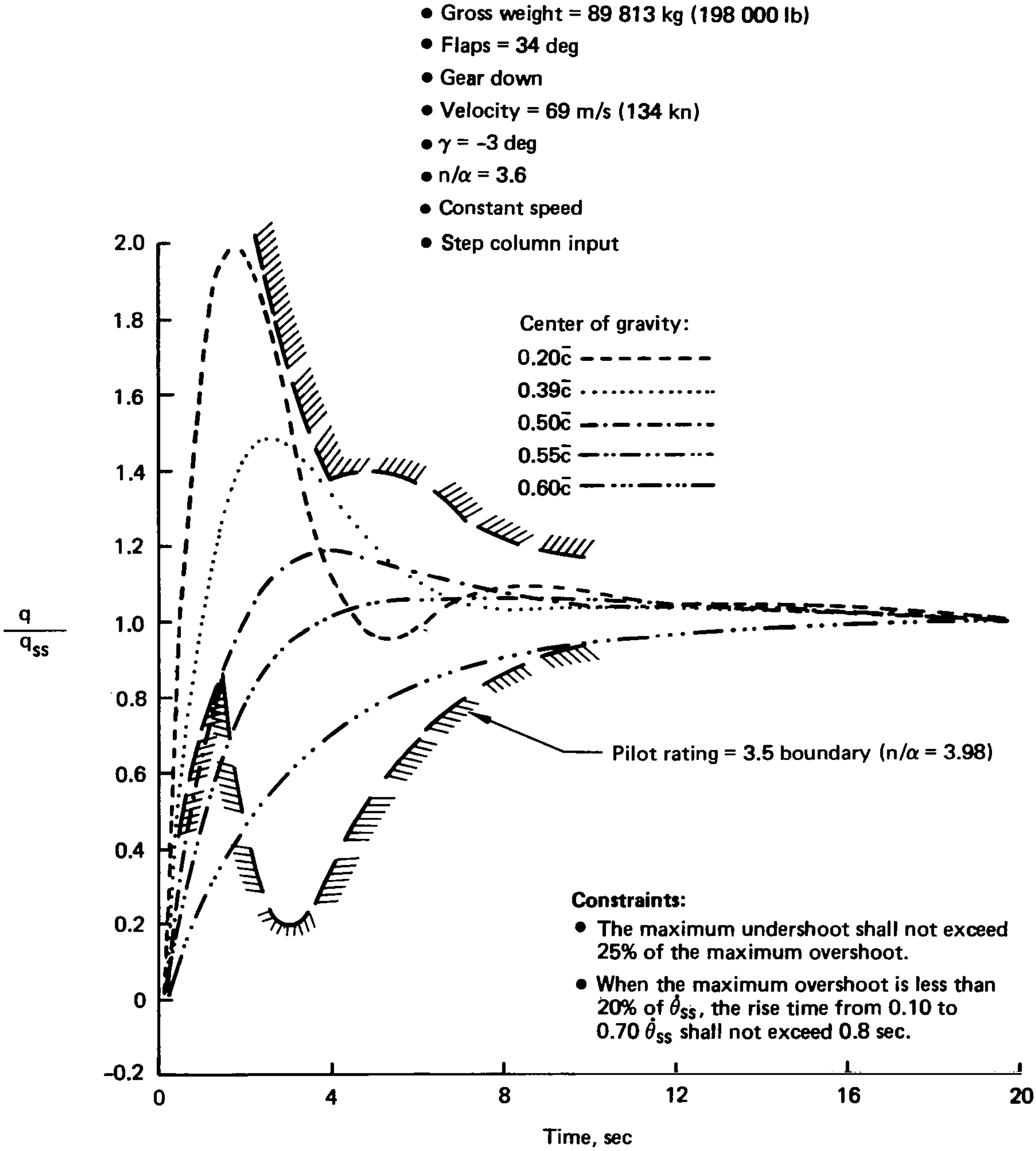

Figure 20. Unaugmented Pitch-Rate Response Compared With SST Criteria—Landing Approach

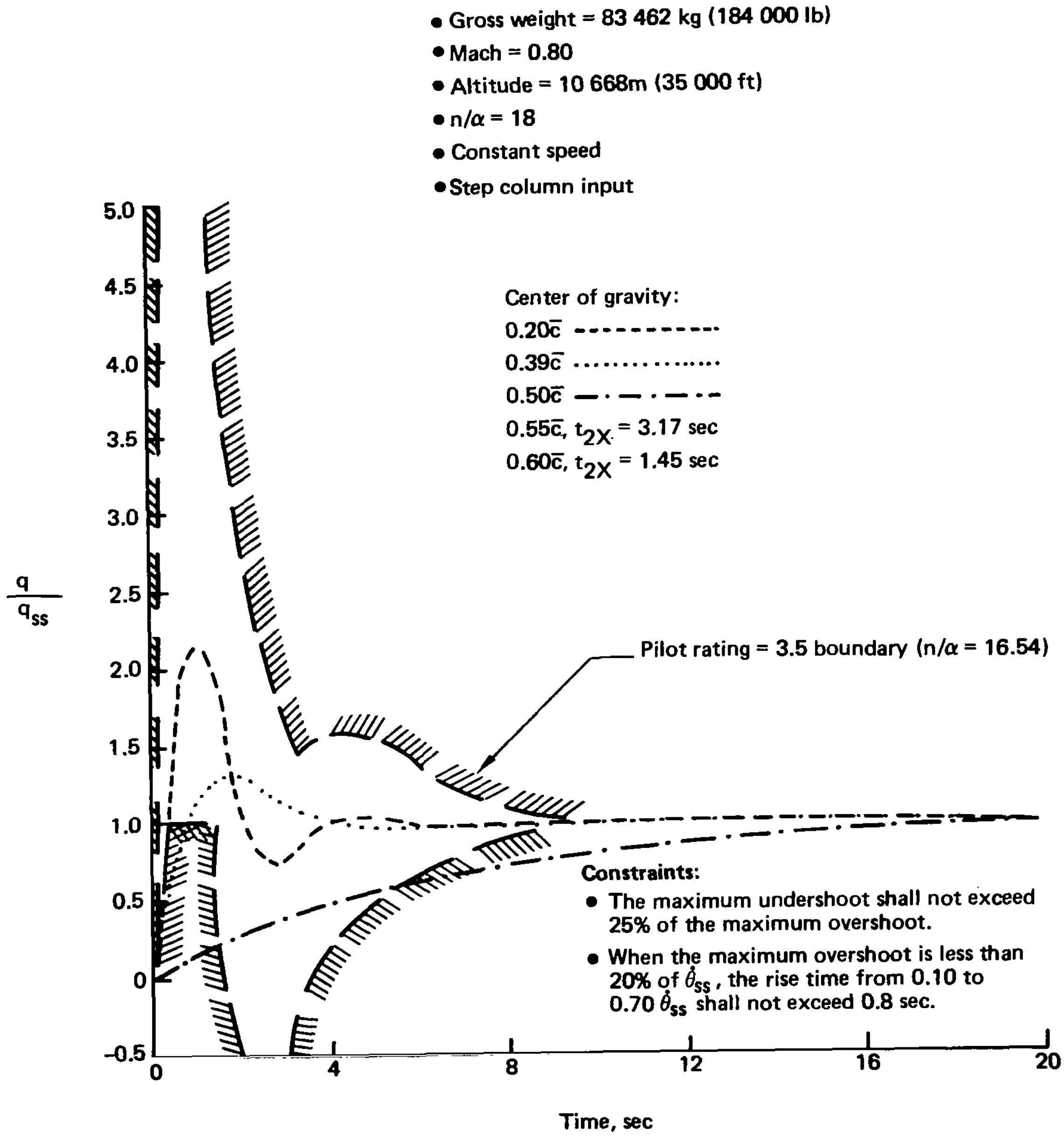

Figure 21. Unaugmented Pitch-Rate Response Compared With SST Criteria—Cruise

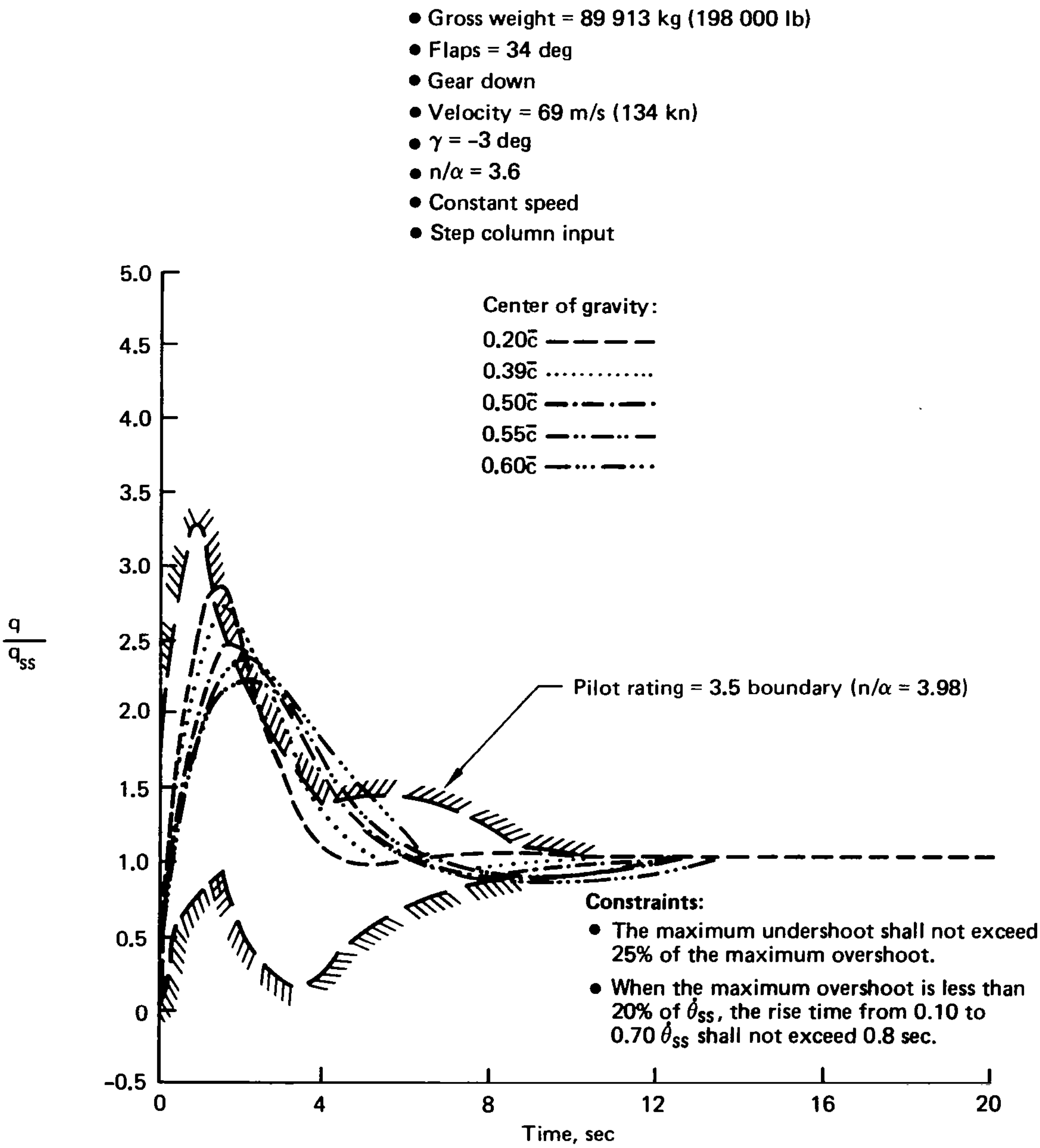

Figure 22. Essential Pitch-Augmented Stability Pitch-Rate Response Compared With SST Criteria—Landing Approach

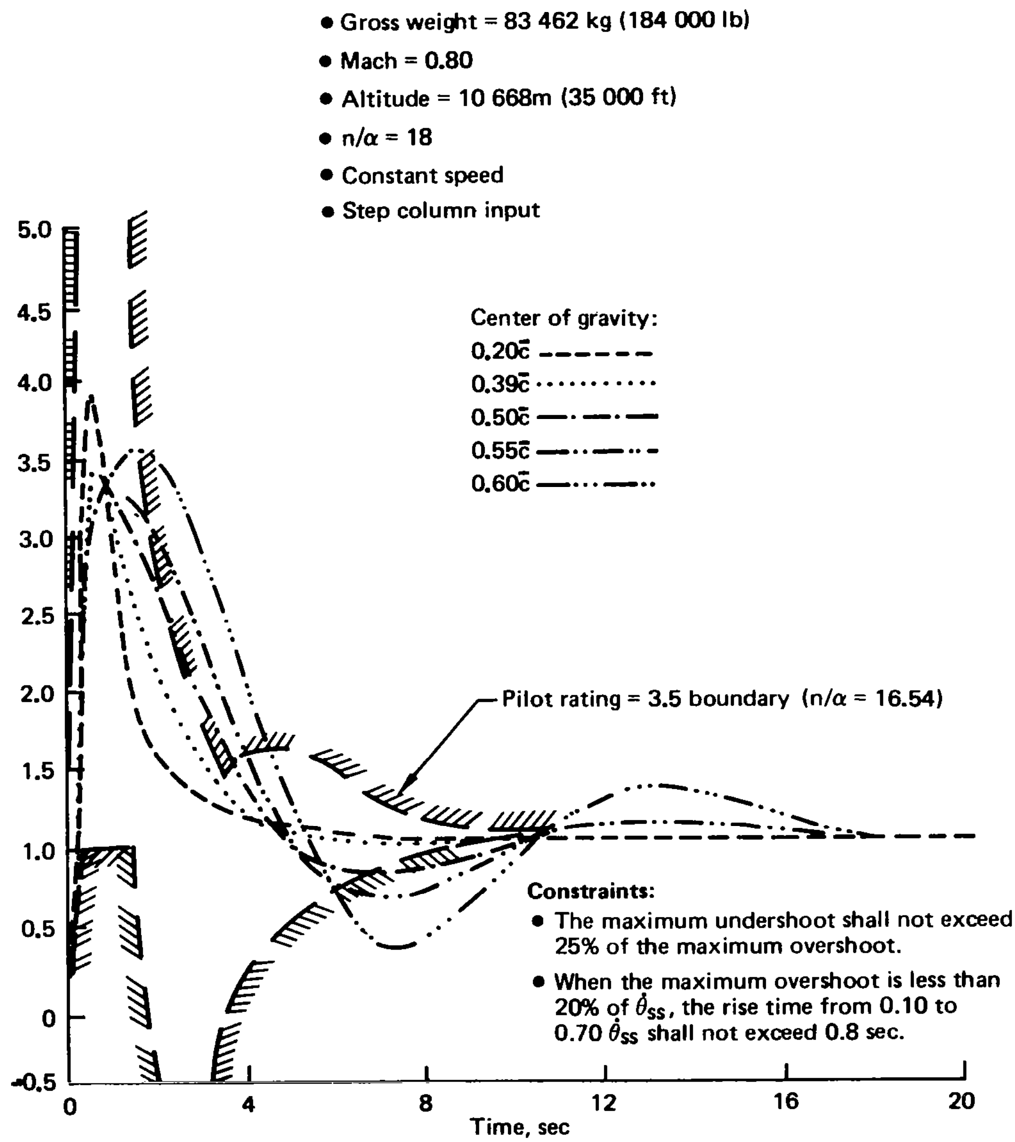

Figure 23. Essential Pitch-Augmented Stability Pitch-Rate Response Compared With SST Criteria—Cruise

again comparing favorably with the piloted results. The relatively long-duration overshoots that result from the fixed-gain architecture of Essential PAS appear to be the predominant cause for the response amplitudes outside that boundary.

Because Essential PAS is the inner loop of Primary PAS, the initial response of the Primary PAS System is similar to that of Essential PAS, except for feedforward sensitivity changes. However, the nonlinear characteristics of the attitude hold loop (e.g., no attitude feedback with column out of detent) should be noted in this comparison.

8.3 MILITARY SHORT-PERIOD REQUIREMENTS

At sufficiently aft cg locations, the short period is not distinct, as found in a classical analysis, but combines with the phugoid to form a third mode (ref 11). A second-order approximation is necessary before the MIL-F-8785C (ref 12) short-period frequency requirements can be applied as shown in Figures 24 and 25.

In general, the predicted levels of handling qualities agree very well with the piloted ratings from the study of the unaugmented 757. The degradation of the cruise ratings as the cg is moved progressively aft appears to be due, in good part, to low-frequency sluggish responses to pilot inputs.

The limited amount of data from this study does indicate that the lower boundary frequency for Level 3 may be too high and should be less than that for Level 2. The unaugmented landing approach test configuration at 60% MAC and that for cruise at 50% MAC were given pilot ratings well within the Level 3 handling qualities region while the response parameters of those test conditions are shown to be located beyond the Level 3 boundaries of Figures 24 and 25.

The large overshoots caused by Essential PAS made it difficult to estimate second-order frequencies as required for application to this criterion. The approximation procedure appears to require further development for application to the higher order Essential PAS responses.

8.4 ROOT LOCUS WITH CENTER-OF-GRAVITY VARIATIONS

Longitudinal root loci for unaugmented, Essential PAS, and Primary PAS configurations are presented in Figures 26 through 31 as a function of cg location. All low-frequency roots are plotted. The evolution of the third mode is evident, especially for the unaugmented cruise condition. Eigenvector modal data for the unaugmented test conditions and for the augmented cases at 50% MAC are tabulated in the appendix.

The military short-period frequency requirements (ref 12) are included with the IAAC DRO low-frequency requirements (appendix A to ref 7). Although the military frequency requirements are based on short-period approximations at constant airspeed, good agreement with the study results was found for the normal production cg locations at 20% and 39% MAC. At farther aft cg locations and for the augmented configurations, those short-period frequency boundaries tend to agree to a lesser extent or not at all. In general, the low-frequency root locations indicate a good correlation between the IAAC criteria and the simulation results.

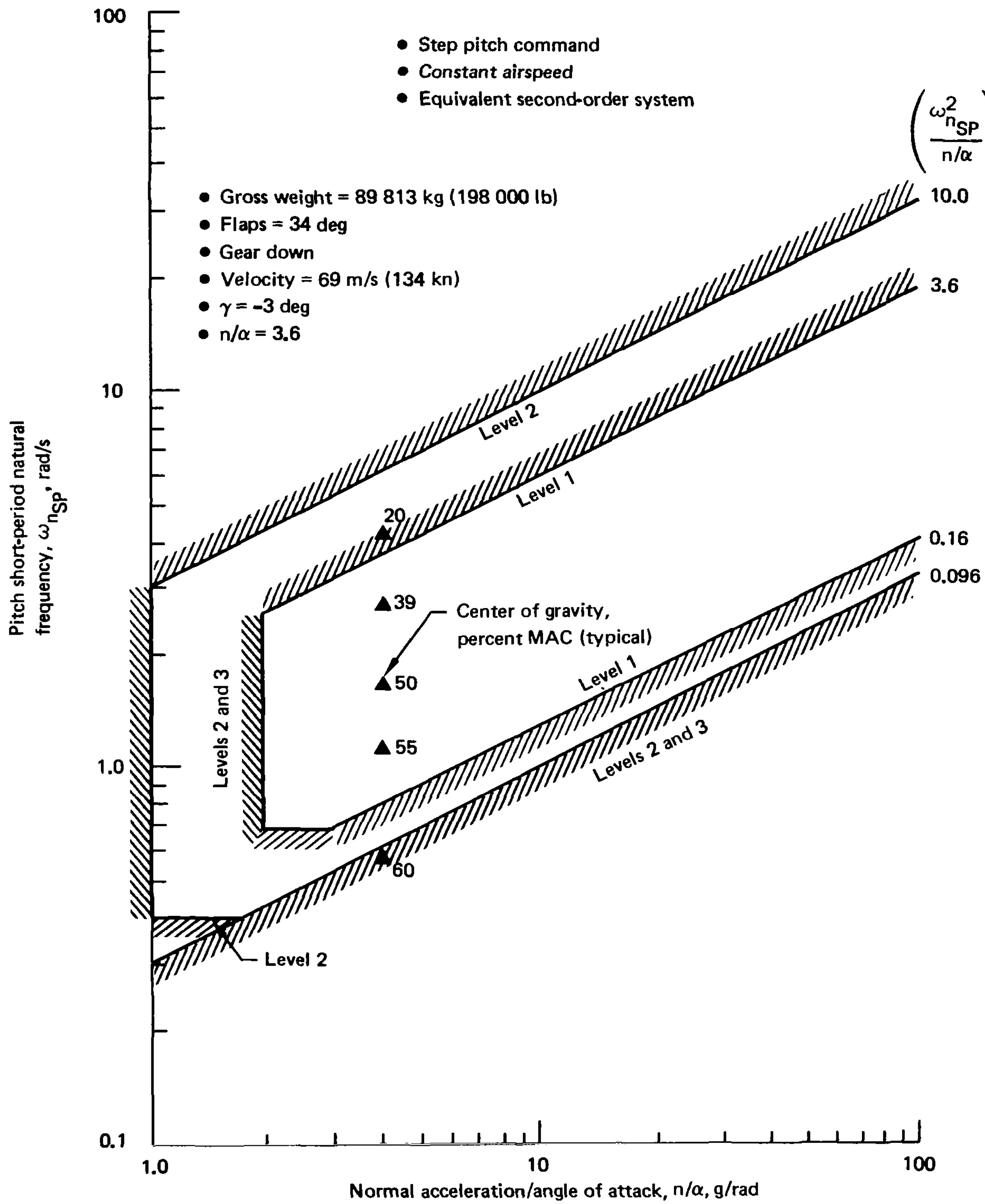

Figure 24. MIL-F-8785C Short-Period Frequency Requirements Compared With Unaugmented 757 Short-Period Frequencies—Landing Approach

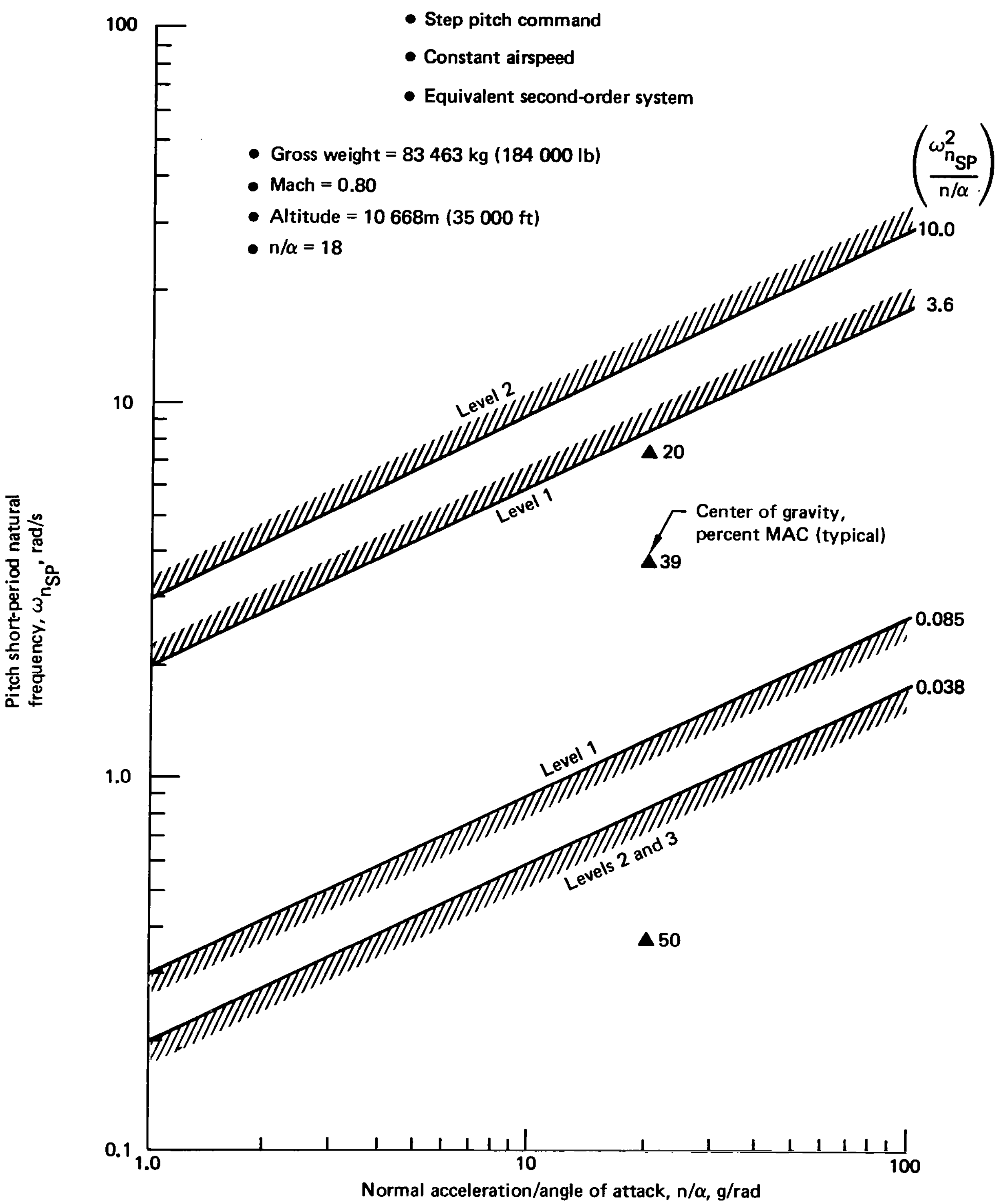

Figure 25. MIL-F-8785C Short-Period Frequency Requirements Compared With Unaugmented 757 Short-Period Frequencies—Cruise

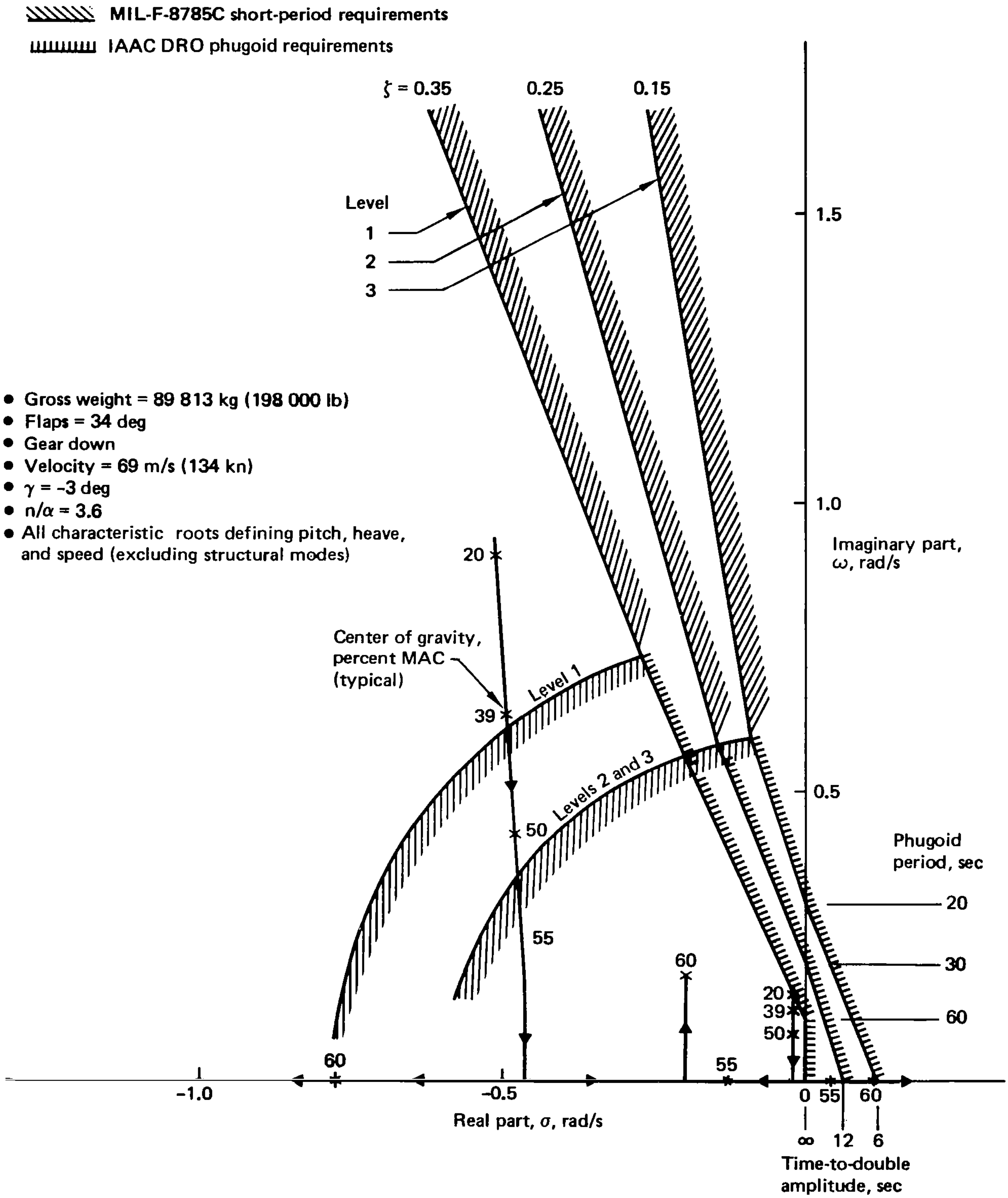

Figure 26. Variation of Longitudinal Roots With Center of Gravity, Unaugmented—Landing Approach

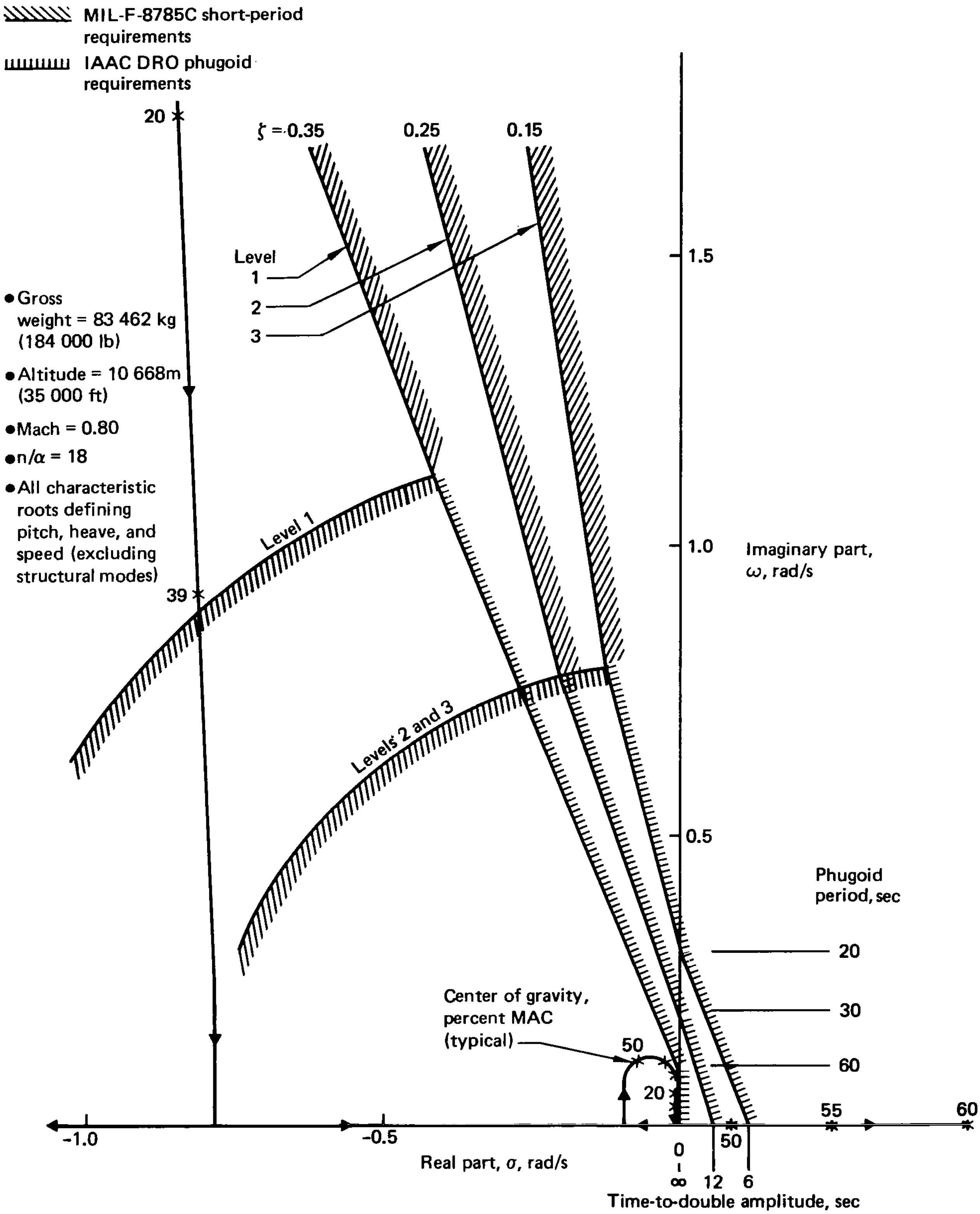

Figure 27. Variation of Longitudinal Roots With Center of Gravity, Unaugmented—Cruise

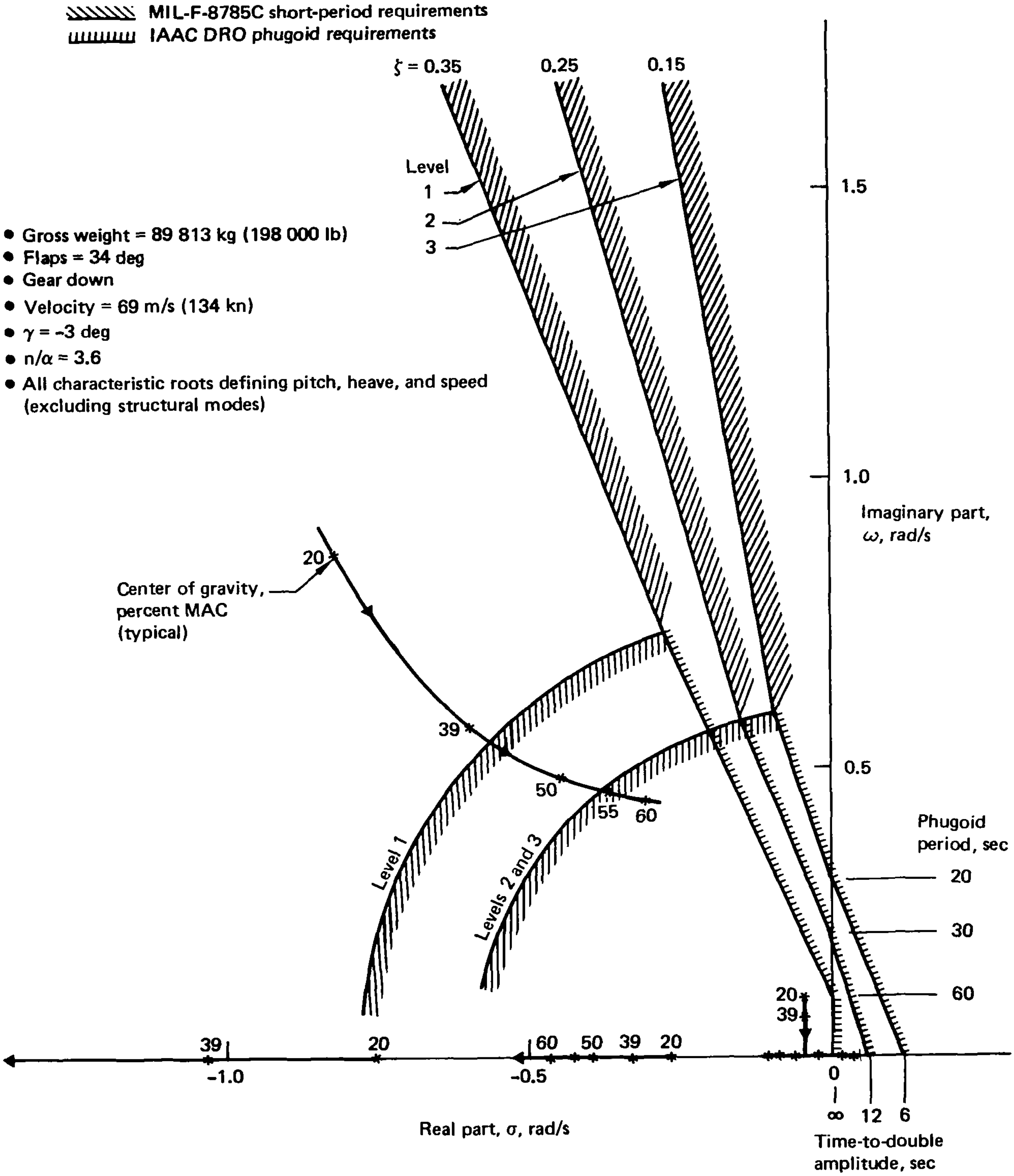

Figure 28. Variation of Longitudinal Roots With Center of Gravity, Essential Pitch-Augmented Stability—Landing Approach

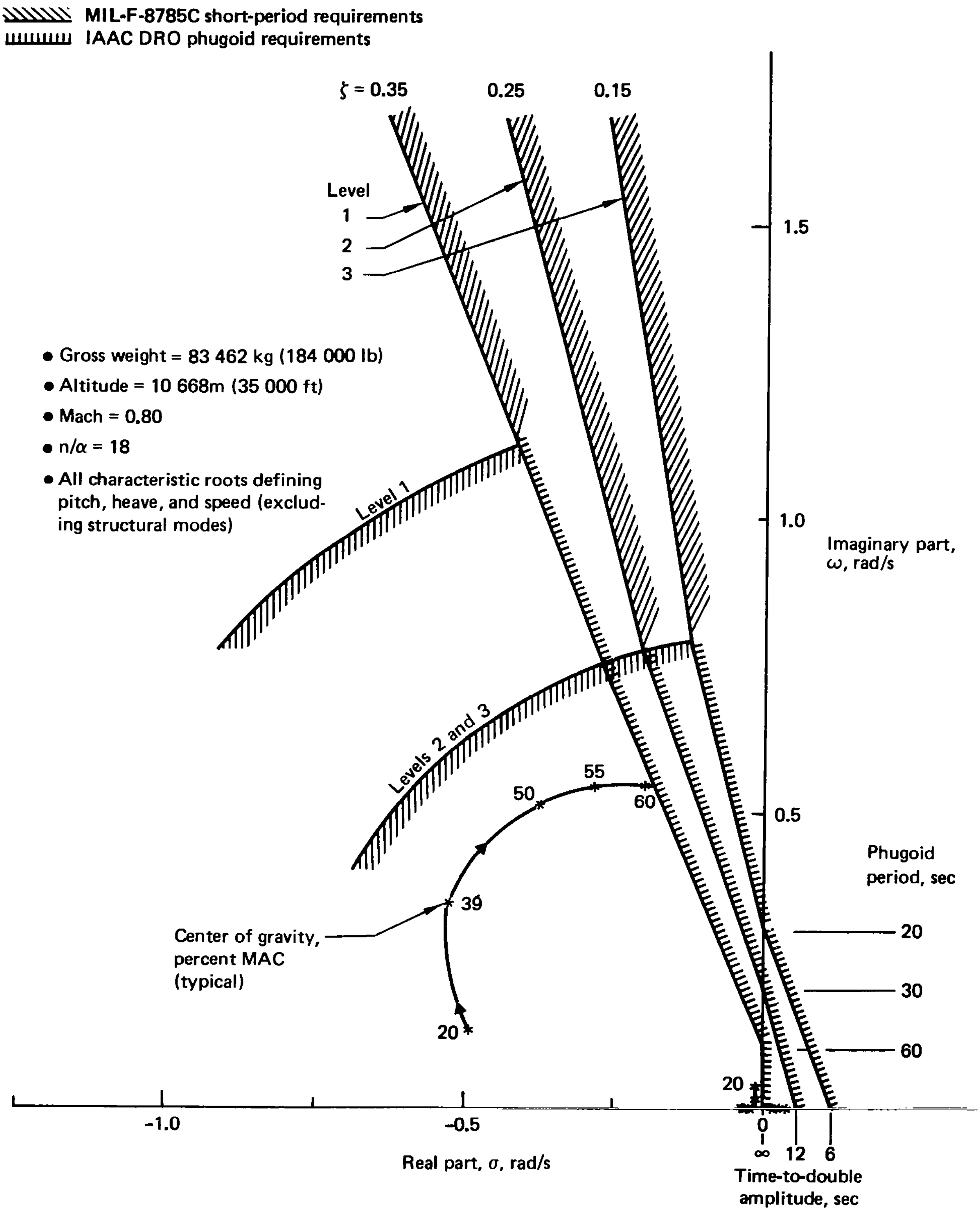

Figure 29. Variation of Longitudinal Roots With Center of Gravity, Essential Pitch-Augmented Stability—Cruise

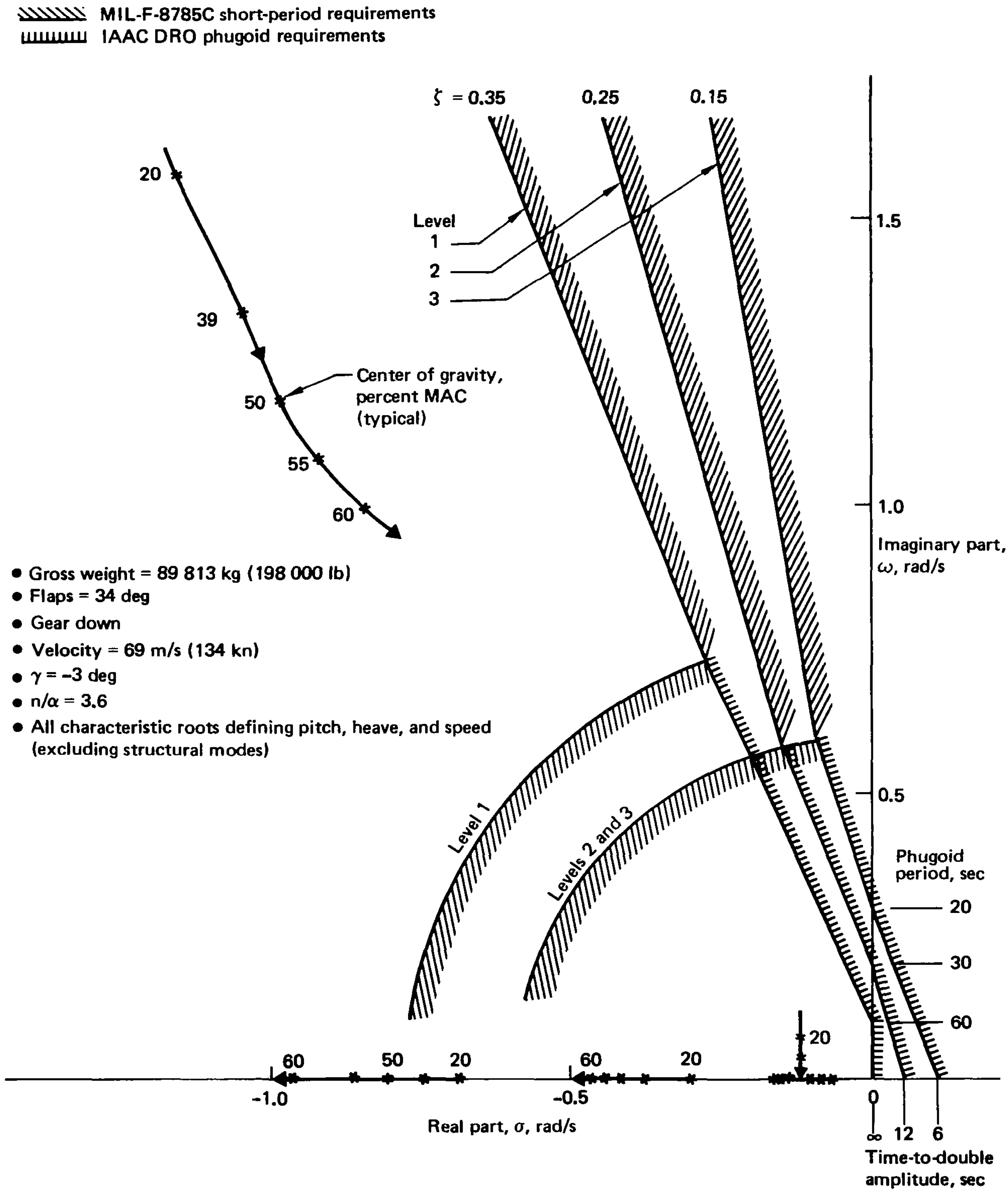

Figure 30. Variation of Longitudinal Roots With Center of Gravity, Primary Pitch-Augmented Stability—Landing Approach

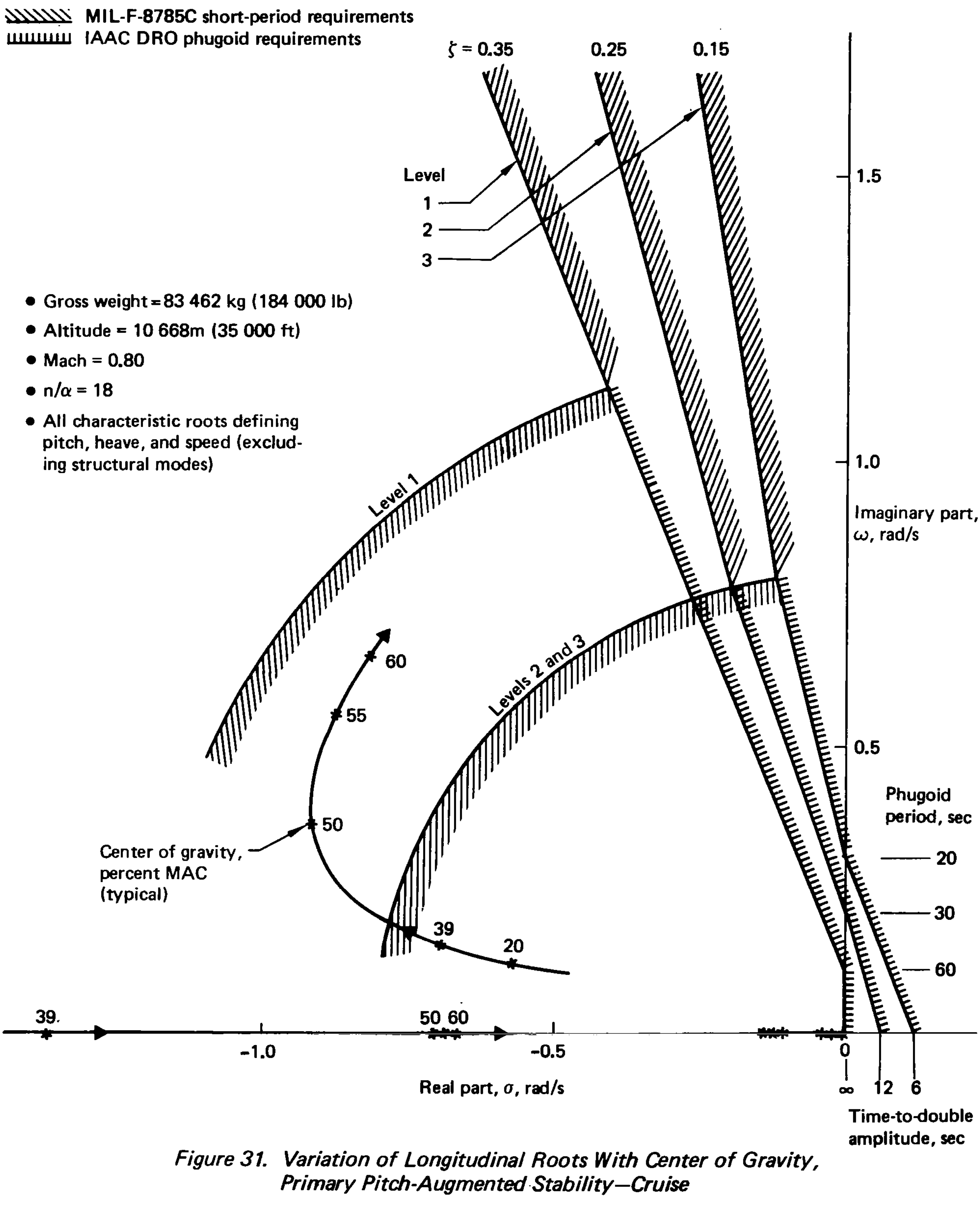

Figure 31. Variation of Longitudinal Roots With Center of Gravity, Primary Pitch-Augmented Stability—Cruise

9.0 CONCLUDING REMARKS AND RECOMMENDATIONS

The principal objective of the IAAC Project was to assess the effects of the integrated application of ACT to a medium-range, subsonic transport airplane. The Boeing 757 is being evaluated as the vehicle for flight test of an ACT system. A piloted simulation of an ACT-configured Boeing 757 whose flight characteristics were based on preflight predictions is reported herein. The primary goals were to establish cg limits that would ensure adequate handling qualities for safe continued flight and landing with the augmentation failed and reversion made to a mechanical control system with production control characteristics during an actual flight test. Also, the general form and functionality of the control laws for the proposed ACT system were to be validated.

9.1 CONCLUDING REMARKS

The piloted simulation study demonstrated that the appropriate handling qualities necessary for flight demonstration tests can be attained for extreme aft cg locations with the augmentation systems described herein. Actual flight readiness testing would entail a study of significantly greater scope.

Two principal flight conditions were simulated in detail. Other conditions were spot checked to verify that the results would be valid throughout the flight envelope. Midweight high-altitude cruise and maximum weight landing approach were selected as being representative of normal flight test conditions. For unaugmented landing approach, Level 2 handling qualities were attained at 57% MAC (6% aft of neutral point). The Level 3 (pilot rating = 9.5) boundary was not established because the required cg location was aft of the trimmable cg range. For unaugmented cruise, Level 2 ratings were reported aft to 47% MAC (5% forward of the maneuver point). The Level 3 boundary is approached at cg locations slightly aft of the maneuver point. Essential PAS provided pilot ratings that were very close to or within the Level 1 boundaries. Primary PAS, although evaluated to a lesser extent than Essential PAS, yielded Level 1 (good) pilot ratings in most cases.

A time-to-double amplitude criterion of $t_{2X} \geqslant 6$ sec related to the low-frequency dynamics roughly corresponds to a cg location of 51% MAC for the principal cruise test condition. With a flight control system optimized for cg locations aft of the production 39% MAC limit, Level 2 (pilot rating $\leqslant$ 6.5) handling qualities could probably be attained for centers of gravity aft to about 50% MAC for the principal cruise test condition. Also, as is evident, the high-speed cruise conditions rather than landing approach flight conditions will determine the aft cg limit for this airplane. Nose-wheel steering control on the runway in the takeoff or landing mode has not been considered in this study. During an actual flight test, inflight reballasting to position the cg within the standard 757 loading range would be necessary prior to landing.

The study results correlate well with several existing handling qualities criteria. The study results were also found to be comparable to those obtained by both the Douglas Aircraft Company and the Lockheed-California Company in simulation investigations of transport configurations with roughly similar dimensional and mass characteristics.

9.2 RECOMMENDATIONS

The ACT study development should be continued according to the IAAC Project Plan (ref 2).

10.0 REFERENCES

1. Cooper, G. E., and R. P. Harper. The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. NASA TN D-5153, April 1969.

2. Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport—Project Plan. NASA CR-3305, Boeing Commercial Airplane Company, February 1981.

3. Development of a Low-Risk Augmentation System for an Energy-Efficient Transport Having Relaxed Static Stability. NASA CR-159166, Douglas Aircraft Company, December 1979.

4. Accelerated Development and Flight Evaluation of Active Controls Concepts for Subsonic Transport Aircraft—Volume II—Aft CG Simulation and Analysis. NASA CR-159098, Lockheed-California Company, September 1979.

5. Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project—Wing Planform Study and Final Configuration Selection, Final Report. NASA CR-165630, Boeing Commercial Airplane Company, June 1981.

6. Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project—Wing Planform Study and Final Configuration Selection, Summary Report. NASA CR-3468, Boeing Commercial Airplane Company, October 1981.

7. Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project—Initial ACT Configuration Design Study, Final Report. NASA CR-159249, Boeing Commercial Airplane Company, July 1980.

8. Renton Flight Simulation Center User Manual. BCS-G0914, Boeing Computer Services, August 1979.

9. U. S. Standard Atmosphere, 1962. Prepared under sponsorship of NASA, U. S. Air Force, and U. S. Weather Bureau, Washington, D. C., December 1962.

10. Sudderth, R. W., et al. Development of Longitudinal Handling Qualities Criteria for Large Advanced Supersonic Aircraft. Boeing Commercial Airplane Company, NASA CR-137635, March 1975.

11. Etkin, B. Dynamics of Flight. John Wiley & Sons, Inc., November 1966.

12. Flying Qualities of Piloted Airplanes. MIL-F-8785C, November 1980.

APPENDIX: PILOT RATINGS AND AIRPLANE MODAL CHARACTERISTICS

Individual pilot ratings for all flight conditions tested are listed in Tables A-1 and A-2. Flight conditions other than the primary landing approach and midweight cruise cases are included. Multiple ratings for the same test conditions usually were made during different test sessions. In most cases, the multiple ratings were within one rating point of each other. However, several unaugmented calm air test conditions flown by pilot B for landing approach (table A-1) were given ratings that varied by as much as three points. The lower of those ratings for each test condition appears to be more realistic when compared with the same condition flown with moderate turbulence. The higher (worse) ratings were provided during test sessions that emphasized augmented airplane characteristics. The unaugmented conditions were flown for comparison, and the pilot may have overemphasized the degraded handling qualities of the unaugmented airplane.

Mode shapes (eigenvectors) were computed from state models of the primary simulation flight conditions and are presented in Tables A-3 and A-4. The relative phase angles and magnitudes of response are shown for the longitudinal motion states.

Table A-1. Pilot Simulation Ratings—Landing Approach

Weight, kg (lb)	Initial altitude, m (ft)	$1.3V_S$, m/s (kn)	Center of gravity, percent MAC	t_{2X}[a]		Cooper-Harper pilot rating											
						Pilot A			Pilot B					Pilot C			
						Unaugmented			Unaugmented			Essential PAS	Primary PAS	Unaugmented		Essential PAS	
						Moderate turbulence											
				Land	G/A	Off	On	On[b]	Off	On	On[b]	On	On	Off	On	Off	On
89 813 (198 000)	152.4 (500)	69 (134)	20	–	–				4.0			4.0,4.0	3.0	4.5		3.0	
			39	–	–	2.0	2.0	2.0	2.0,5.0	3.5	2.5	4.0,3.0		4.0		2.5	
			46	–	–				5.0			4.0,4.0		5.0		3.0	
			50	–	7.7	3.0	3.0	3.0	2.5,4.0	3.0	3.0	4.0,4.0	2.5	4.5		3.0	
			55	16.9	4.0	4.0	4.0	4.0	3.5,7.0	4.0	4.5	3.0		5.0		3.0	
			60	6.2	3.2	5.0	5.0	7.0	5.0,7.0	6.0	5.0	4.0,3.0	4.0	5.0		4.0	
74 844 (165 000)		63.3 (123)	20	–	–				3.0			4.0		4.0		3.5	
			39	–	–				4.0					3.5		3.0	
			46	–	8.4									5.0	7.0	4.5	6.0
			50	–	4.3	3.0	3.0		5.0,4.0	6.0		4.0		4.0		3.0	
			55	28.1	3.5	4.0		5.0	5.0,6.0		6.0	3.0		4.0		3.5	
			60	7.3	3.0									4.5		4.0	

[a]For unstable low-frequency pole.

[b]Full-power go-around.

Table A-2. Pilot Simulation Ratings—Flaps Up

Weight, kg (lb)	Altitude, m (ft)	M/V_e	Center of gravity, percent MAC	t_{2X},* sec	Cooper-Harper pilot rating											
					Pilot A			Pilot B					Pilot C		Pilot D	
					Unaugmented		Essential PAS	Unaugmented		Essential PAS		Primary PAS	Unaugmented	Essential PAS	Unaugmented	Essential PAS
					Moderate turbulence											
					Off	On	Off	Off	On	Off	On	On	Off	Off	Off	Off
83 462 (184 000)	10 668 (35 000)	0.80	20	—	3.5		4.0	2.0		3.0, 3.0		2.5			2.0	2.0
			39	—	2.5	2.5	4.0	2.0, 4.0	4.5	2.0	2.0				2.0	2.0
			46	23.5	3.5	4.0		5.0, 6.0	5.0	2.0						
			50	7.6	6.0, 5.5	6.5	3.5	7.0, 8.0	7.0	4.0, 4.0	4.0	2.5		4.0	6.0	3.0
			55	2.7	9.0		3.5	7.0, 8.0	8.0	2.5					7.0	2.5
			60	1.4				9.0		4.0, 5.0	5.0	3.0				
		0.84	20	—				4.0		2.0						
			50	7.4				7.0		4.0						
	8 230	0.86	25	—				3.0		2.0						
	(27 000)		50	4.5				8.0		3.0						
	7 620	0.91	25	—				3.0		2.0						
	(25 000)		50	18.7				8.0		4.0						
		100 m/s 195 KEAS	25	—				2.5		3.0						
			50	6.6				7.0		2.0						
	12 802	0.82	25	—				5.0		2.0						
	(42 000)		50	2.9				7.0		4.0						
	3 048 (10 000)	0.63	50	8.5				7.0		4.0						
74 844 (165 000)	11 887 (39 000)	0.82	50	3.9				8.0		2.5						

*For unstable low-frequency pole.

Table A-3. Landing Approach Modal Data

PAS	Center of gravity, percent MAC	Real root	Imaginary root	ω_n, rad/s	Damping ratio, ζ	Mode shapes							
						Incremental velocity, u		Angle of attack, α		Attitude, θ		Pitch rate, q	
						Real	Imaginary	Real	Imaginary	Real	Imaginary	Real	Imaginary
Off	20	-0.0169	±0.155	0.156	0.108	1.0	0	-0.0185	∓0.0057	-0.0546	∓0.2787	0.0441	∓0.0038
		-0.518	±0.904	1.04	0.497	-0.1009	∓0.0251	1.0	0	0.763	∓0.4346	-0.0024	±0.9149
	39	-0.0153	±0.123	0.124	0.124	1.0	0	-0.0525	∓0.0017	-0.0733	∓0.2167	0.0277	∓0.0057
		-0.494	±0.621	0.794	0.622	-0.0099	∓0.2194	1.0	0	0.5886	∓0.5032	0.0220	±0.6142
	50	-0.0227	±0.0718	0.0753	0.301	1.0	0	-0.0906	±0.0048	-0.0835	∓0.1223	0.0107	∓0.0032
		-0.485	±0.415	0.638	0.759	-0.1191	∓0.4731	1.0	0	0.3742	∓0.4884	0.0215	±0.3922
Essential	50	-0.0247	0	0.0247	1.0	1.0	0	-0.1098	0	-0.0922	0	0.0023	0
		-0.0597	0	0.0597	1.0	1.0	0	-0.1177	0	-0.0363	0	0.0022	0
		-0.401	0	0.401	1.0	1.0	0	-0.7422	0	0.0607	0	-0.0243	0
		-0.440	±0.485	0.655	0.672	0.0266	∓0.4282	1.0	0	0.4435	∓0.5606	0.0766	±0.4619
Primary	50	-0.0095	0	0.0095	1.0	1.0	0	-0.1357	0	0.0138	0	-0.0013	0
		-0.131	0	0.131	1.0	1.0	0	-0.1645	0	0.0567	0	-0.0074	0
		-0.419	0	0.419	1.0	1.0	0	-0.8039	0	0.0379	0	-0.0159	0
		-0.809	0	0.809	1.0	-0.4213	0	1.0	0	0.4128	0	-0.3337	0
		-0.985	±1.18	1.54	0.640	0.0432	∓0.0024	-0.3042	∓0.0230	-0.2498	±0.0755	0.1567	∓0.3699
Off	55	0.0409	0	0.0409	-1.0	1.0	0	-0.1191	0	-0.2102	0	-0.0086	0
		-0.127	0	0.127	1.0	1.0	0	-0.1608	0	0.0529	0	-0.0067	0
		-0.467	±0.242	0.526	0.888	-0.4988	∓0.6188	1.0	0	0.1562	∓0.3676	0.0159	±0.2094
	60	0.111	0	0.111	-1.0	1.0	0	-0.1587	0	-0.3531	0	-0.0391	0
		-0.197	±0.183	0.269	0.732	1.0	0	-0.0892	±0.2772	0.244	∓0.1311	-0.0240	±0.0704
		-0.744	0	0.744	1.0	-0.4432	0	1.0	0	0.3546	0	-0.2638	0

Gross weight = 89 813 kg (198 000 lb), velocity = 69 m/s (134 kn), γ = -3 deg, gear down, flaps = 34 deg

Table A-4. Cruise Modal Data

PAS	Center of gravity, percent MAC	Real root	Imaginary root	ω_n, rad/s	Damping ratio, ζ	Mode shapes							
						Incremental velocity, u		Angle of attack, α		Attitude, θ		Pitch rate, q	
						Real	Imaginary	Real	Imaginary	Real	Imaginary	Real	Imaginary
Off	20	-0.0067	$\pm$0.060	0.0604	0.111	1.0	0	-0.0076	0	-0.0194	$\mp$0.1066	0.0065	$\mp$0.00045
	↓	-0.844	$\pm$1.74	1.94	0.436	0.0743	$\pm$0.1716	-0.0242	$\mp$0.5688	-0.2249	$\mp$0.4647	1.0	0
	39	-0.0061	$\pm$0.0388	0.0393	0.155	1.0	0	-0.0125	$\pm$0.00021	-0.0192	$\mp$0.0687	0.0028	$\mp$0.00033
	↓	-0.812	$\pm$0.921	1.23	0.662	0.0755	$\pm$0.1396	-0.5278	$\mp$0.6677	-0.6222	$\mp$0.1504	0.6438	$\mp$0.4507
	50	0.0915	0	0.0915	-1.0	1.0	0	-0.036	0	-0.1991	0	-0.0182	0
		-0.118	$\pm$0.111	0.162	0.729	1.0	0	-0.0122	$\pm$0.0657	0.1835	$\mp$0.1694	-0.0029	$\pm$0.0403
	↓	-1.46	0	1.46	1.0	-0.3571	0	1.0	0	0.4886	0	-0.7150	0
Essential	50	0.0147	0	0.0147	-1.0	1.0	0	-0.0167	0	-0.0582	0	-0.00086	0
		-0.0314	0	0.0314	1.0	1.0	0	-0.0176	0	0.0230	0	-0.0007	0
		-0.375	$\pm$0.512	0.635	0.591	0.5334	$\pm$0.1482	0.1649	$\pm$0.9102	0.9161	$\pm$0.0883	-0.3892	$\pm$0.4362
	↓	-0.718	0	0.718	1.0	-0.7162	0	1.0	0	-0.0465	0	0.0334	0
Primary	50	-0.0172	0	0.0172	1.0	1.0	0	-0.0163	0	-0.0017	0	0.00003	0
		-0.143	0	0.143	1.0	1.0	0	-0.0667	0	0.200	0	-0.0287	0
		-0.704	0	0.704	1.0	-0.7384	0	1.0	0	-0.0664	0	0.0468	0
	↓	-0.920	$\pm$0.429	1.01	0.906	-0.3432	$\mp$0.1604	1.0	0	0.3219	$\mp$0.3159	-0.1605	$\pm$0.4286
Off	55	-0.0231	$\pm$0.108	0.110	0.209	1.0	0	0.0121	$\pm$0.0075	0.0218	$\mp$0.1909	0.0201	$\pm$0.0068
		0.254	0	0.254	-1.0	1.0	0	-0.1378	0	-0.4957	0	-0.1261	0
	↓	-1.8	0	1.8	1.0	-0.326	0	1.0	0	0.586	0	-1.057	0
	60	-0.0105	$\pm$0.089	0.090	0.117	1.0	0	0.0029	$\pm$0.0015	-0.0035	$\mp$0.1583	0.0141	$\pm$0.0013
		0.488	0	0.488	-1.0	-0.867	0	0.3128	0	0.7679	0	0.3750	0
	↓	-2.05	0	2.05	1.0	-0.3119	0	1.0	0	0.6369	0	-1.308	0

Gross weight = 83 462 kg (184 000 lb), altitude = 10 668m (35 000 ft), Mach = 0.80

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16. Abstract

This report describes the results of a piloted simulation study of longitudinal handling qualities of an airplane with relaxed static stability. This task was performed under the Integrated Application of Active Controls (IAAC) Technology Project within the NASA Energy Efficient Transport Program. A representative medium-range transport airplane, the Boeing Model 757, was simulated. Evaluations were made of the unaugmented airplane and of the airplane with an Essential Pitch-Augmented Stability (PAS) System and with a Primary PAS System at various center-of-gravity (cg) conditions. Level 2 pilot ratings were attained with cg locations aft to about 57% mean aerodynamic chord (MAC) or 6% aft of the neutral point for unaugmented landing approach. For Mach = 0.80, unaugmented cruise Level 2 ratings were attained to 47% MAC or 5% forward of the maneuver point. The augmented airplane model provided handling qualities close to or within the Level 1 boundary at all cg locations for both Essential and Primary PAS. Analyses of the test conditions when compared with existing handling qualities criteria based on classical unaugmented airplane characteristics agreed well with the pilot ratings. The unaugmented results are comparable to those reported by both the Douglas Aircraft Company and Lockheed-California Company from simulation investigations of transport configurations with roughly similar dimensional and mass characteristics.

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