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Ground-Based and In-Flight Simulator Studies of Flight Characteristics of a Twin-Fuselage Passenger Transport Airplane During Approach and Landing

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A portion of table II was found to be in error. Replace pages 15 and 17 with the enclosed corrected pages.

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TABLE II. AERODYNAMIC DATA USED IN SIMULATION OF TWIN-FUSELAGE AIRPLANE CONCEPT

α, deg	$C_{m_{\delta_h}}$, deg^{-1}	$\delta_f = 25°$			$\delta_f = 50°$		
		C_X	C_Z	C_m	C_X	C_Z	C_m
−8	−0.06422	−0.0316	0.1327	0.1130	−0.1575	−0.2152	−0.0430
−4	↓	−.0745	−.3265	−.0655	−.1870	−.6845	−.2215
0	↓	−.0675	−.7899	−.2143	−.1755	−1.1499	−.3703
4	↓	−.0250	−1.2558	−.2845	−.1348	−1.6204	−.4405
8	↓	.0420	−1.7328	−.3078	−.0665	−2.1025	−.4638
12	↓	.1472	−2.1090	−.3027	.0561	−2.4985	−.4587

α, deg	Numerical values at δ_e of—					
	0	±5°	±10°	±15°	±20°	±25°
	$C_{X_{\delta_e}}$, deg^{-1}					
−8	−0.00214	−0.00211	−0.00206	−0.00196	−0.00177	−0.00149
−4	−.00110	−.00108	−.00106	−.00101	−.00091	−.00077
0	−.00005	−.00005	−.00005	−.00005	−.00005	−.00005
4	.00100	.00098	.00096	.00091	.00081	.00067
8	.00204	.00201	.00196	.00186	.00167	.00139
12	.00307	.00303	.00296	.00280	.00252	.00210
	$C_{Z_{\delta_e}}$, deg^{-1}					
−8	−0.01484	−0.01465	−0.01432	−0.01356	−0.01222	−0.01022
−4	−.01496	−.01476	−.01443	−.01367	−.01232	−.01030
0	−.01500	−.01480	−.01447	−.01370	−.01235	−.01033
4	−.01496	−.01476	−.01443	−.01367	−.01232	−.01030
8	−.01486	−.01467	−.01434	−.01358	−.01224	−.01024
12	−.01468	−.01449	−.01416	−.01341	−.01209	−.01011
	$C_{m_{\delta_e}}$, deg^{-1}					
−8	−0.04460	−0.04400	−0.04303	−0.04073	−0.03672	−0.03071
−4	↓	↓	↓	↓	↓	↓
0	↓	↓	↓	↓	↓	↓
4	↓	↓	↓	↓	↓	↓
8	↓	↓	↓	↓	↓	↓
12	↓	↓	↓	↓	↓	↓

TABLE II. Concluded

α, deg	$\delta_f = 25°$			$\delta_f = 50°$		
	$C_{X_{\delta_s}}$, deg^{-1}	$C_{Z_{\delta_s}}$, deg^{-1}	$C_{m_{\delta_s}}$, deg^{-1}	$C_{X_{\delta_s}}$, deg^{-1}	$C_{Z_{\delta_s}}$, deg^{-1}	$C_{m_{\delta_s}}$, deg^{-1}
−8	0.00122	0.01265	0.00148	0.00325	0.02696	0.00302
−4	.00023	.01219	.00169	.00128	.02678	.00424
0	−.00066	.01167	.00192	−.00065	.02645	.00501
4	−.00146	.01121	.00207	−.00249	.02599	.00536
8	−.00213	.01028	.00222	−.00426	.02540	.00557
12	−.00266	.00917	.00231	−.00596	.02469	.00540
	C_{Y_p}, rad^{-1}	C_{l_p}, rad^{-1}	C_{n_p}, rad^{-1}	C_{Y_p}, rad^{-1}	C_{l_p}, rad^{-1}	C_{n_p}, rad^{-1}
−8	−0.0377	−0.5642	0.0872	0.0422	−0.5467	0.0546
−4	.0635	−.5649	.0157	.1438	−.5489	−.0084
0	.1753	−.5727	−.0518	.2558	−.5643	−.0427
4	.2644	−.5944	−.0477	.3420	−.5917	−.0423
8	.3594	−.6233	−.0947	.4356	−.6260	−.0960
12	.4327	−.6556	−.1490	.5088	−.6647	−.1554

α, deg	$\delta_f = 25°$			$\delta_f = 50°$		
	C_{Y_r}, rad^{-1}	C_{l_r}, rad^{-1}	C_{n_r}, rad^{-1}	C_{Y_r}, rad^{-1}	C_{l_r}, rad^{-1}	C_{n_r}, rad^{-1}
−8	0.6714	0.0983	−0.2383	0.7080	0.1873	−0.2893
−4	.6734	.1807	−.2421	.7163	.2736	−.2960
0	.6926	.2619	−.2491	.7423	.3582	−.3085
4	.7229	.3507	−.2547	.7789	.4496	−.3185
8	.7665	.4365	−.2667	.8286	.5405	−.3349
12	.8234	.4991	−.2788	.8919	.6097	−.3479

α, deg	$C_{Y_{\delta_r}}$, deg^{-1}	$C_{l_{\delta_r}}$, deg^{-1}	$C_{n_{\delta_r}}$, deg^{-1}	C_{m_q}, rad^{-1}	$C_{m_{\dot{\alpha}}}$, rad^{-1}
−8	−0.00536	0.00046	−0.00170	−33.505	−7.748
−4	↓	.00047	−.00170	↓	↓
0	↓	.00048	−.00170	↓	↓
4	↓	.00050	−.00169	↓	↓
8	↓	.00051	−.00168	↓	↓
12	↓	.00051	−.00168	↓	↓

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Summary

Six-degree-of-freedom ground-based and in-flight simulator studies were conducted to evaluate the low-speed flight characteristics of a twin-fuselage passenger transport airplane and to compare these characteristics with those of a large, single-fuselage (reference) transport configuration similar to the Lockheed C-5A airplane. The primary piloting task was the approach and landing task.

The results of this study indicated that the twin-fuselage transport concept had acceptable but unsatisfactory longitudinal and lateral-directional low-speed flight characteristics, and that stability and control augmentation would be required in order to improve the handling qualities.

The primary pilot objections to the unaugmented handling qualities were (1) low apparent pitch damping, (2) nonprecise attitude control due to large changes in pitch attitude caused by trailing-edge flap deflections, and (3) sluggish roll response.

Through the use of rate-command/attitude-hold augmentation in the pitch and roll axes, and the use of several turn coordination features, the handling qualities of the simulated transport were improved appreciably.

The in-flight test results showed excellent agreement with those of the six-degree-of-freedom ground-based simulator handling qualities tests.

As a result of the in-flight simulation study, a roll-control-induced normal-acceleration criterion was developed. This criterion states that the ratio of maximum incremental acceleration at the pilot station to the steady-state roll rate following a step lateral control input ($\Delta n_{z,p}/p_{\text{ss}}$, g unit/(deg/sec)) shall not be greater than 0.020, 0.048, and 0.069 for pilot rating levels 1 (satisfactory), 2 (acceptable but unsatisfactory), and 3 (unacceptable), respectively.

No problems were experienced because of engine failure for the simulated aircraft concept.

The handling qualities of the augmented twin-fuselage passenger transport airplane exhibited an improvement over the handling characteristics of the reference (single-fuselage) transport.

Introduction

Flying qualities simulation studies have been conducted recently at the NASA Langley Research Center on very large and/or unusually configured cargo transports. However, some of these concepts were seen to be impractical because of their present incompatibility with existing airport facilities. The present study concerns the flying qualities of a 250-passenger twin-fuselage transport. The aircraft is essentially two McDonnell-Douglas DC-9's joined together, but it has a gross weight less than twice that of the DC-9 and significantly improved seat-miles per gallon.

As previously stated in reference 1, the aircraft industry has for several years been aware that many of the existing stability and control requirements for aircraft are inappropriate because of the expansion of flight envelopes, the increase in airplane size, and the utilization of complex stability and control augmentation systems. Although research is presently being conducted in an effort to remedy this situation, to date essentially no clearly defined stability and control requirements and criteria have been established for very large conventional or unconventional transports. Therefore, in an effort to aid in the future establishment of new stability and control requirements, the low-speed handling qualities parameters of an unconventional, relatively large passenger transport are compared with some existing handling qualities criteria.

Piloted simulation studies offer a means of obtaining preliminary handling qualities evaluations of diverse airplane concepts and assessing the adequacy of current handling qualities requirements. A previous piloted simulation study of a large twin-fuselage design with augmented stability and control characteristics (ref. 1) compared the resulting handling qualities with those of a large single-fuselage transport configuration similar to the Lockheed C-5A airplane and assessed the adequacy of current handling qualities requirements. This paper will also utilize the "pseudo" C-5A as the reference configuration.

The primary objectives of this simulation study, which used both ground-based and in-flight simulators, were to evaluate the low-speed handling characteristics of a relatively large transport aircraft concept and to obtain adequate information to provide guidance for future research requirements. Other major objectives were as follows:

1. Compare the low-speed dynamic stability and control characteristics of the subject passenger transport with those of a large reference transport configuration. (The reference aircraft was similar to the C-5A.)
2. Develop the augmentation systems necessary to produce satisfactory handling qualities.
3. Evaluate the effects of pilot lateral offset and various atmospheric conditions on the ability of the pilot to make a satisfactory approach and landing.

Symbols and Abbreviations

Measurements and calculations were made in U.S. Customary Units, and all calculations are based on the aircraft body axes. Dots over symbols denote differentiation with respect to time.

a_n	normal acceleration, g units
a_y	lateral acceleration, g units
b	wing span, ft
C_{L_α}	lift-curve slope per unit angle of attack, per radian
C_l	rolling-moment coefficient
C_{l_β}	rolling-moment coefficient due to sideslip, per degree
C_m	pitching-moment coefficient
C_{m_α}	pitching-moment coefficient per unit angle of attack, per radian
C_n	yawing-moment coefficient
C_X	longitudinal-force coefficient
C_Y	side-force coefficient
C_Z	vertical-force coefficient
$\bar{c}$	mean aerodynamic chord, ft
g	acceleration due to gravity ($1g = 32.17$ ft/sec^2)
h	altitude, ft
I_X, I_Y, I_Z	moments of inertia about X, Y, and Z body axes, respectively, slug-ft^2
I_{XZ}	product of inertia, slug-ft^2
K_A	autothrottle gain, deg/knot
K_p	roll-rate gain, $\frac{\text{deg}}{\text{deg/sec}}$
$K_{p,c}$	commanded roll-rate gain, $\frac{\text{deg/sec}}{\text{deg}}$
$K_{p,I}$	roll-rate-integrator gain, deg/deg
$K_{p,Y}$	roll-rate gain in yaw axis, $\frac{\text{deg}}{\text{deg/sec}}$
K_q	pitch-rate gain, $\frac{\text{deg}}{\text{deg/sec}}$
$K_{q,c}$	commanded pitch-rate gain, $\frac{\text{deg/sec}}{\text{in.}}$
$K_{q,I}$	pitch-rate-integrator gain, $\frac{\text{deg/sec}}{\text{deg/sec}}$
K_V	autothrottle velocity gain, deg/deg
$K_{V,I}$	autothrottle velocity-integrator gain, per second
K_{WL}	wing-leveler gain, deg/deg
K_{δ_p}	rudder-to-pedal gearing, deg/in.
K_{δ_w}	aileron-to-wheel gearing, deg/deg
K_θ	pitch-attitude gain, deg/deg
$K_{\theta,A}$	autothrottle pitch-attitude gain, deg/deg
$K_{\theta,H}$	pitch-attitude-hold gain, $\frac{\text{deg/sec}}{\text{deg/sec}}$
$K_{\phi,2}$	roll-attitude-hold gain, deg/deg
$K_{\phi,R}$	roll-coordination gain, deg/deg
$K_{\phi,TC}$	roll-attitude-hold filter gain, per second
L_α	lift per unit angle of attack per unit momentum, $(\bar{q}S/mV)C_{L_\alpha}$, per second
m	airplane mass, slugs
$n_{y,p}$	lateral acceleration measured at pilot station, g units
$\Delta n_{z,p}$	incremental normal acceleration measured at pilot station, g units
n/α	steady-state normal-acceleration change per unit change in angle of attack for an incremental horizontal-tail deflection at constant airspeed, g units/rad
P	period, sec
P_d	period of Dutch roll oscillation, sec
P_{ph}	period of longitudinal phugoid oscillation, sec
P_{sp}	period of longitudinal short-period oscillation, sec
p, q, r	rolling, pitching, and yawing angular velocities, respectively, deg/sec or rad/sec
p_1, p_2	roll rates at first and second peaks, respectively, deg/sec or rad/sec
$\bar{q}$	dynamic pressure, lbf/ft^2
S	reference wing area, ft^2
s	Laplace operator
T	thrust, lbf
$T\theta_2$	numerator short-period time constant in pitch response to longitudinal control, sec
t_2	time required to double amplitude, sec

t_{s2}	time required for spiral mode to double amplitude, sec
$t_{\phi=30}$	time required to bank 30°, sec
t_1	time at intersection of pitch-rate-response maximum-slope tangent line and zero-amplitude line after control input (effective time delay), sec
t_2	time at intersection of pitch-rate-response maximum-slope tangent line and steady-state pitch-rate line after control input, sec
Δt	effective rise time parameter, $t_2 - t_1$, sec
V	indicated airspeed, knots or ft/sec
V_s	stall speed, knots
W	airplane weight, lbf
y_p	pilot lateral location from airplane centerline, ft
α	angle of attack, deg
β	angle of sideslip, deg
γ	flight-path angle, deg
Δ	increment
δ_a	ailerion deflection, positive for right roll command, deg
δ_c	column deflection, in.
δ_e	elevator deflection, deg
δ_f	trailing-edge flap deflection, deg
δ_h	horizontal-tail deflection, deg
δ_p	pedal deflection, in.
δ_r	rudder deflection, deg
δ_s	spoiler deflection, deg
δ_w	control wheel deflection, deg
ς	damping ratio
ς_d	Dutch roll mode damping ratio
ς_{ph}	longitudinal phugoid-mode damping ratio
ς_{sp}	longitudinal short-period-mode damping ratio
ς_ϕ	damping ratio of numerator quadratic ϕ/δ_a transfer function
η_b	position of bodies along wing as a fraction of semispan
θ	pitch attitude, deg
θ_o	initial trim (reference) pitch attitude, deg
$\Delta\dot{\theta}_1$	magnitude of first pitch-rate overshoot, deg/sec
$\Delta\dot{\theta}_2$	magnitude of first pitch-rate undershoot, deg/sec
$\Delta\dot{\theta}_2/\Delta\dot{\theta}_1$	transient peak ratio
κ	ratio of commanded roll performance to applicable roll performance requirement
$\tau_{p,\text{eff}}$	effective pitch time constant (time required to reach 63 percent of steady-state pitch rate following a step control input), sec
τ_R	roll mode time constant (from the characteristic equation of motion), sec
$\tau_{R,\text{eff}}$	effective roll mode time constant (time required to reach 63 percent of steady-state roll rate following a step control input), sec
ϕ	angle of roll, deg
ψ	heading angle, deg
ψ_β	phase angle expressed as a lag for a cosine representation of Dutch roll oscillation in sideslip, deg
ω	frequency, rad/sec
ω_d	undamped natural frequency of Dutch roll mode, rad/sec
ω_{ph}	undamped natural frequency of phugoid mode, rad/sec
ω_{sp}	longitudinal short-period undamped natural frequency, rad/sec
ω_ϕ	undamped natural frequency appearing in numerator quadratic of ϕ/δ_a transfer function, rad/sec

Subscripts:

app	approach
av	average
cw	crosswind
ge	ground effect
H	hold
ℓ	landing

max	maximum; for attitude responses, maximum control input was used
min	minimum
osc	oscillatory
RAH	roll-attitude-hold mode on
REF	reference
rms	root-mean-square
rs	roll spiral
ss	steady state
WL	wing-leveler mode on

Abbreviations:

ADI	attitude director indicator
CTOL	conventional takeoff and landing
DQ(PIL)	pilot-commanded pitch rate
DWN	down
IFR	instrument flight rules
ILS	instrument landing system
LDG	landing gear
PIO	pilot-induced oscillation
PLA	power lever angle
PR	pilot rating
RAH	roll-attitude-hold mode on
SAS	stability augmentation system
SCAS	stability and control augmentation system
TIFS	USAF-AFWAL Total In-Flight Simulator
VFR	visual flight rules
VMS	Langley Visual/Motion Simulator
WL	wing-leveler mode on

Description of Simulated Airplanes

Two distinctly different airplane concepts were simulated during the ground-based simulator study. Three-view sketches of the two concepts are presented in figures 1 and 2; the representative landing mass and dimensional characteristics as well as the control surface deflections and deflection rate limits for the aircraft are presented in table I. The aerodynamic data used in this study for the twin-fuselage configuration indicated in figure 1 are presented in table II, and the aerodynamic data used for the reference airplane configuration indicated in figure 2 are presented in table III of reference 1.

Twin-Fuselage Airplane

The twin-fuselage transport concept simulated in this study was developed to carry 250 passengers a distance of 2720 n.mi. at a Mach number of 0.75 and an initial cruise altitude of 37 000 ft. (See ref. 2.) The airplane, with the pilot location offset significantly from the roll axis (approximately 30 ft to the left of the center of gravity), was powered by two large turbofan engines, which provided a static takeoff thrust-to-weight ratio of 0.420. (Typical engine thrust response characteristics are indicated in fig. 3.) A three-view sketch of the airplane is presented in figure 1, and the simulated representative landing mass and dimensional characteristics are presented in table I(a).

Reference Airplane

A single-fuselage turbojet transport, similar to the C-5A airplane, was simulated during this study to provide a reference base from which various transport concepts could be evaluated. (See ref. 1.) Although the landing weight of the reference airplane was much greater than that of the twin-fuselage configuration, the reference airplane was used in this study because it has a very large roll moment of inertia, as does the twin-fuselage airplane. (As the separation distance of the two fuselages is increased, the roll moment of inertia of the airplane increases appreciably.) The reference airplane was powered by four turbojet engines providing a static takeoff thrust-to-weight ratio of 0.213. (Typical engine thrust response characteristics are indicated in fig. 3.) A three-view sketch of the airplane is presented in figure 2, and the simulated representative landing mass and dimensional characteristics are presented in table I(b).

Description of Simulation Equipment

Evaluations of the low-speed handling characteristics at approach and landing were made at Langley Research Center in the general-purpose cockpit of the Langley Visual/Motion Simulator (VMS). After the ground-based study, a brief in-flight simulation program was conducted in the USAF-AFWAL Total In-Flight Simulator (TIFS) airplane to provide (1) points of reference for interpretation of the ground-based simulator results, and (2) data on the effects of the vertical motion at the pilot station due to rolling maneuvers. The data on vertical motion obtained with the ground-based simulator were only marginally adequate because of the limited amplitude of the VMS motion cues.

Ground-Based Simulator

The VMS is a six-degree-of-freedom ground-based motion simulator (fig. 4(a)). For this study, the simulator had a transport-type cockpit equipped with conventional flight and engine-thrust controls as well as a flight-instrument display representative of those found in current transport airplanes. (See fig. 4(b).) Instruments that indicated angle of attack, angle of sideslip, and flap angle were also provided. A conventional cross-pointer-type flight-director instrument was used.

The control forces on the wheel, column, and rudder pedals were provided by a hydraulic system coupled with an analog computer. The system allows for the usual variable-feel characteristics of stiffness, damping, coulomb friction, breakout forces, detents, and inertia.

The airport-scene display used an "out-the-window" virtual-image system of the beam-splitter, reflective-mirror type. (See ref. 3.) A runway "model" was programmed which had a maximum width of 200 ft, a total length of 11 500 ft, roughness characteristics, and a slope from the center to the edge representing a runway crown. Only a dry runway was considered in this study.

The motion performance characteristics of the VMS system possess time lags of less than 60 msec. A nonstandard washout system, utilizing nonlinear coordinated adaptive motion, was used to present motion-cue commands to the motion base. (See ref. 4.)

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

In-Flight Simulator

The TIFS is a C-131 airplane with controllers for all six degrees of freedom and a separate fly-by-wire evaluation cockpit forward and below the normal C-131 cockpit. (See fig. 5.) When the airplane is flown from the evaluation cockpit, the pilot control commands are input to a model computer, which determines the aircraft motion commands to be reproduced. These are combined with the TIFS motion sensor signals in another portion of the onboard computer to provide TIFS controller commands. The simulated airplane motions are produced with maximum time lags of 50 to 150 msec in the frequency range of interest.

The evaluation cockpit instruments were mostly conventional and were positioned as shown in figure 6. In addition to the conventional instruments, displays of sideslip angle and angle of attack were provided. Airspeed error was displayed as a tape motion on the right side of the ADI. Aircraft position relative to the ILS glide slope was displayed (in feet) as a vertical bug motion on the right side of the ADI. A flight-director computer performing the same functions as the computer used in the ground-based simulator was modeled in the TIFS computer. This instrument was used in lieu of the conventional flight director on board the TIFS airplane to ensure that the flight director was compatible with the simulated twin-fuselage passenger transport dynamics.

Tests and Procedures

Three research pilots participated in the simulation program; two flew the ground-based simulator and two flew in the in-flight program. Each flew most types of simulated configurations and tasks, and each used standard flight-test procedures in the evaluation of the handling and ride qualities. The primary piloting task was the approach and landing task. The tests consisted of IFR and simulated VFR landing approaches for various configurations, with crosswinds, turbulence, wind shear, glide-slope and localizer offsets, and engine failure as added complicating factors. Crosswinds up to 30 knots, heavy turbulence, and wind shear of 8 knots per 100 feet (from 200 ft altitude to touchdown) were simulated. The ILS approach was initiated with the airplane in the power-approach condition (power for level flight) at an altitude below the glide slope, and on course but offset from the localizer. The pilot's task was to capture the localizer and glide slope and maintain them as closely as possible while under simulated IFR conditions. At an altitude of approximately 300 ft, the aircraft "broke out" of the simulated overcast, whereupon the pilot converted to VFR conditions and attempted to land the airplane visually (with limited reference to the flight instruments).

Using the aforementioned evaluation procedures, this study evaluated handling qualities by analysis of recorded aircraft motion time histories, calculation of various flying qualities parameters, and review of pilot comments on the flying qualities of the simulated twin-fuselage passenger transport and the effects of stability and control augmentation systems on these characteristics. The more significant results are reviewed in the following sections.

Results and Discussion

The results of this study are discussed in terms of the previously stated objectives. The flying quality evaluation scale is given in table III and the turbulence effect rating scale is given in table IV. The results discussed are those obtained during the landing phase with the ground-based simulation, unless specifically noted otherwise.

Unaugmented Airplane

The pilot ratings assigned to the longitudinal handling qualities of the unaugmented twin-fuselage passenger transport were 3.0 and 4.5 for pilots A and B, respectively. The primary objections were (1) low apparent pitch damping, and (2) large pitch-attitude excursions with changes in flap position.

A pilot rating of 4.0 was assigned by both pilots to the lateral-directional handling qualities of the unaugmented airplane, the major objection being the sluggish roll response.

Longitudinal characteristics. The static longitudinal stability of the subject twin-fuselage transport airplane was considered by the pilots to be satisfactory. The aircraft was flown with a static margin of approximately 15 percent on the unstable side (back side) of the thrust-required curve. The variation in thrust required with velocity $\partial(T/W)/\partial V$ was approximately -0.00030 per knot, but speed control was not difficult.

The dynamic stability characteristics of this twin-fuselage configuration for the approach and landing flight conditions are indicated in table V(a). The short-period undamped natural frequency ω_{sp} and the damping ratio ς_{sp} of the simulated twin-fuselage transport are indicated in figure 7 along with the ω_{sp} and ς_{sp} for some present-day jet transports. As shown in table V(a), $\varsigma_{sp} = 0.704$, for the twin-fuselage transport, a value normally considered to be an indication of good pitch damping. However, as stated previously, the pilots commented that the damping in pitch appeared to be low for this configuration. (For comparison, table V(b) shows the dynamic stability characteristics of the reference airplane.)

Figure 8 presents two of the most widely used longitudinal handling qualities criteria. Figure 8(a) shows the short-period frequency requirement of reference 5 and figure 8(b) shows the Shomber-Gertsen longitudinal handling qualities criterion of reference 6. The reference 6 criterion relates the ability of the pilot to change flight path (using normal acceleration) to the factor L_α. By using this parameter and recognizing that the pilot's control technique is not constant for all flight regimes, a criterion for satisfactory low-speed short-period characteristics was developed (ref. 6) which correlates well with current airplane experience as well as with the results obtained during the present twin-fuselage transport simulation program. It can be seen from figure 8 that the low magnitude of ω_{sp} prevents the twin-fuselage configuration from falling within the satisfactory regions.

Although the pilots did not comment adversely on the pitch response characteristics to a column input, figure 9 indicates that the initial pitch-rate response, calculated from two-degree-of-freedom equations of motion with airspeed constrained, is slightly sluggish. The reference 7 criterion dictates that the pitch-rate rise time parameter Δt of the simulated twin-fuselage configuration must be less than 0.87 sec for satisfactory response (level 1) and less than 2.81 sec for acceptable response (level 2). As noted in table VI and figure 9, the pitch-rate rise time parameter during landing for the unugmented twin-fuselage transport (table VI(a)) was 1.92 sec, which predicts acceptable, but not satisfactory, pitch-rate response characteristics. Therefore, stability and control augmentation would be required to achieve satisfactory handling qualities for the approach and landing piloting tasks. The pitch control power was rated acceptable insofar as the longitudinal control power requirements for the approach and landing tasks were concerned. This is in agreement with the control power requirements criterion of reference 8, as shown in figure 10. Also note from table VI(b) that the pitch-rate rise time parameter for the reference aircraft was acceptable, but not satisfactory, when compared with the reference 7 criterion.

Lateral-directional characteristics. As stated previously, the pilots assigned a rating of 4.0 to the lateral-directional handling qualities of the unaugmented airplane. The primary factor that contributed to the pilot rating of acceptable but not satisfactory was the sluggish roll response. Table VI(a) indicates that it takes approximately 2.9 sec to bank 30° on this unaugmented airplane in the landing configuration; however, the requirement of reference 5 is $t_{\phi=30} \leq 2.5$ sec for satisfactory handling qualities. Desirable lateral-directional handling characteristics following a step wheel input require (1) a rapid roll-rate response that reaches a reasonably steady-state value with a minimum of oscillation, (2) essentially zero sideslip, and (3) an immediate response in heading. It is evident from figure 11 that the lateral-directional response to a step wheel input is good, with an immediate heading response, and a low level of adverse sideslip.

The dynamic stability characteristics of this twin-fuselage configuration for the approach and landing flight conditions are indicated in table V(a). The roll and spiral mode characteristics are satisfactory, as is the Dutch roll mode.

Augmented Airplane

Based on the results obtained for the unaugmented configuration, the objective for the design of the stability and control augmentation system (SCAS) was that the system should provide satisfactory handling qualities (PR $\leq$ 3.5) at all flight conditions evaluated during the study. A block diagram of the SCAS design is shown in figure 12. The selected gains for the pitch, roll, and yaw axes SCAS are indicated in figures 12(a), 12(b), and 12(c), respectively.

It may be noted from table V(a) that a coupled roll-spiral mode is present for the augmented configurations. This mode was determined by analyses of the linear quasi-static lateral-dynamic characteristic equations, including the stability and control augmentation systems, but was not detected by the pilots while flying the ground-based simulator.

Longitudinally, a high-gain pitch-rate command/attitude-hold system was chosen because (1) the system provided good short-period characteristics and rapid response to pilot inputs and (2) the attitude-hold feature minimized disturbances due to turbulence or variations in flaps and/or thrust.

Laterally, a roll-rate command/attitude-hold system was employed in an attempt to provide a rapid roll mode and quick uniform response to pilot inputs. The attitude-hold feature resulted in a desirable neutrally stable spiral mode while counteracting disturbances due to turbulence. In addition, a wings-leveler feature was provided which automatically leveled the wings ($\phi = 0$) whenever the bank angle was less than 2° and the wheel was centered. This feature relieved the pilot of the task of "hunting" for zero bank angle and was particularly useful when rolling out of a turn to a desired heading. (See fig. 12(b) for a diagram of the lateral control system.)

Directionally, roll-rate and roll-attitude feedbacks were used to provide good turn coordination and increased Dutch roll damping. (See fig. 12(c).)

An autothrottle that maintained the selected airspeed throughout the landing approach was also used as part of the normal operational augmentation. (See fig. 13 for a block diagram of the autothrottle design.) Since the simulated engine dynamics (e.g., fig. 3) produced very good thrust response, the autothrottle generally maintained the desired airspeed within ±3 knots and considerably reduced the pilot workload on the landing approach.

Longitudinal characteristics. The longitudinal SCAS (fig. 12(a)) provided a pitch rate proportional to column deflection and produced the desired characteristics of rapid, well-damped responses to pilot inputs, as well as inherent attitude stability.

The improvement in pitch-rate response provided by the SCAS is illustrated in figure 14. As can be seen, the SCAS improved the pitch-rate response of the twin-fuselage transport appreciably; the pitch time constant was decreased by approximately 86 percent ($\tau_{p,\text{eff}}$ decreased from 2.62 to 0.36 sec) and the steady-state pitch rate commanded by a given column input was decreased to the more desirable rate of 1.2 deg/sec, which was the level desired by the evaluation pilots. With the augmentation system operative, the pilot rating for the longitudinal handling qualities during the ILS approach was improved from 3.0 and 4.5 for pilots A and B, respectively, to 2.0 for both pilots.

Figure 15 compares the longitudinal handling characteristics of the augmented twin-fuselage and reference transports with the short-period handling qualities criteria of references 5 and 6. As can be seen, the twin-fuselage configuration conforms quite well to both criteria; in both cases the augmented configuration is within the satisfactory region.

Figure 16 (ref. 9) represents the proposed requirements for short-term pitch response to pitch controller for airplanes during Category C flight phase (approach and landing) and indicates the relative performance of simulations of large transports, twin-fuselage transports, and the reference transport. These results indicate satisfactory dynamic stability characteristics for the augmented transports.

The low-speed pitch-rate response criterion shown in figure 17 and reported in reference 10 was based on the Shomber-Gertsen criterion of reference 6. Indications are that the twin-fuselage configuration meets the pitch-rate response requirements of this criterion. (Note, however, that the simulated reference airplane does not fully meet this criterion.) When the pitch-rate response of the augmented twin-fuselage configuration is compared with the criterion of reference 7, the predicted characteristics were also at satisfactory levels for effective time delay, transient peak ratio, and the rise time parameter (fig. 18 and table VI(a)).

Lateral-directional characteristics. A block diagram of the lateral-directional SCAS is presented in figure 12. Laterally, a rate command system provided roll rate proportional to wheel position (fig. 12(b)), and the directional system consisted of two turn coordination features (fig. 12(c)).

Table V(a) shows that the Dutch roll characteristics of the twin-fuselage transport during landing were improved with augmentation; ω_ϕ/ω_d was increased from 0.961 to 0.996 (which indicates that the Dutch roll oscillation should be much less easily excited for roll control inputs), and the damping parameter $\zeta_d\omega_d$ was increased from 0.175 to

0.230 rad/sec. Note, however, that the effective roll mode time constant remains essentially unchanged.

Figure 19 shows the improvement in the roll-rate response of the twin-fuselage transport provided by the SCAS. With the adverse sideslip minimized, the roll rate attained for a given wheel deflection increased appreciably, and the heading response was immediate (no lag). A comparison of the lateral-directional response to a step wheel input for the augmented twin-fuselage airplane and the augmented reference airplane indicates that the twin-fuselage configuration had the more desirable characteristics.

With the SCAS operative, the pilot rating for the lateral-directional handling qualities on the ILS approach in calm air was improved from 4.0 to 2.0.

The roll-rate response characteristics presented in tables V(a) and VI(a) indicate that (1) the effective time delay would be expected to be at a satisfactory level since $t_1 < 0.283$ sec, (2) the roll mode time constant would be expected to be at a satisfactory level since $\tau_R < 1.4$ sec, and (3) the time required to bank 30° would be expected to be at an acceptable level since $2.5 \leq t_{\phi=30} \leq 4$ sec. As stated previously, the roll response of the augmented configuration was rated as satisfactory.

Turbulence effects. Flight in rough air was evaluated with a turbulence model based on the Dryden spectral form. The root-mean-square value of the longitudinal, lateral, and vertical gust-velocity components was 6 ft/sec. This value was described by the pilots as being representative of heavy turbulence.

For the twin-fuselage transport simulated, the pilots commented that the rating for the approach task on the augmented transports was degraded by 1½ when the landing approach was made in the simulated heavy turbulence because of the significantly increased workload required to maintain ILS tracking. Utilizing the turbulence effect rating scale (table IV), both pilots assigned a rating of D to the subject transport.

Engine failure. During the subject study, attempts were made to simulate the go-around capabilities as well as continued approaches and landings after one engine failed. No problems were experienced either when attempting to continue the approach to land or when attempting to perform a go-around.

Evaluation of Roll Performance Requirements

The roll requirements of reference 5 for class III (large, heavy, low-to-medium-maneuverability airplanes) the airplane class applied to the configuration simulated in the present study because of its large passenger payload, even though it was lighter than many class III aircraft—are as follows for satisfactory performance:

1. The roll mode time constant τ_R shall be no greater than 1.4 sec.
2. The yaw and roll control power shall be adequate to develop at least 10° of sideslip in the power-approach flight condition with not more than 75 percent of the available roll control power.
3. It shall be possible to land with normal pilot skill and technique in 90° crosswinds of velocities up to 30 knots.
4. The time required to bank the airplane 30° shall not exceed 2.5 sec.

As can be seen from table V(a), the roll-mode time constant τ_R was less than 1.4 sec for the augmented transport concept. This level met the requirement of reference 5 for satisfactory performance. Note, however, that the reference transport had larger roll-mode time constants than those specified for satisfactory performance (table V(b)).

Figure 20 indicates the crosswind trim capability of the twin-fuselage transport concept. It can be seen that (1) the yaw and roll control power is adequate to develop more than 10° sideslip with 75 percent of the roll control power available, and (2) the roll and yaw control power is sufficient to trim the aircraft in 90° crosswinds of velocities up to approximately 27 knots. Therefore, the roll control power is essentially sufficient to meet both of these reference 5 requirements.

In addition to these requirements, reference 5 dictates that the time required to bank the airplane 30° shall not exceed 2.5 sec. As can be seen from table VI, all simulated augmented configurations exceed that requirement. However, the pilots rated the lateral-directional handling qualities of the twin-fuselage transport as satisfactory. Also, when performing simulated landing approaches in 90° crosswinds, the pilots rated the subject transport satisfactory in crosswinds up to approximately 22 knots and acceptable in crosswinds up to approximately 29 knots. (See fig. 21.)

Comparison of Ground-Based and In-Flight Results

As stated previously, upon completion of the ground-based simulator tests, a brief in-flight simulation program was conducted in order to provide (1) points of reference for interpretation of the ground-based simulator results and (2) data on the effects of the "vertical" motion at the pilot station due to rolling maneuvers, which was only marginally adequate with the limited-amplitude motion cues of the VMS. The handling qualities assessments made on the ground-based simulator were substantiated during the in-flight simulator tests. Although the in-flight tests were more realistic (for example, the motions were realistic and the scene out of the window was the real world), these factors did not significantly affect the pilots' opinions of the handling characteristics of the simulated airplane up to and including touchdown. Both pilots rated the lateral-directional handling qualities of the twin-fuselage configuration, with tasks that included 200-ft lateral runway offsets and 15-knot crosswinds, as satisfactory. Average pilot ratings during approach of 2.3 and 3.0 for pilots A and C, respectively, and an overall average pilot rating that included touchdown of 2.7 for pilot A, were obtained from in-flight simulation testing. These ratings are compared with average PR's of 2.5 and 2.6 for pilots A and B, respectively, for the ground-based simulation tests.

In addition to the in-flight comparison tests noted above, a brief investigation was conducted to ascertain the effects of pilot lateral offset and variation of airplane effective roll-mode time constant. The additional experimental variables were pilot lateral offsets of 0 and −50 ft and effective roll-mode time constants of 0.6 and 2.3 sec. Note that the baseline pilot offset position was −30 ft, and the effective roll-mode time constant of the augmented twin-fuselage configuration was approximately 1.1 sec.

The in-flight experimental data presented in reference 11 indicated significant scatter, especially for a pilot lateral offset of −50 ft with an effective roll-mode time constant of 0.6 sec. Averaging each pilots' rating minimized the scatter, and hence aided in the analysis of the data. Weingarten (ref. 11) postulated that the normal acceleration experienced by the pilot during rolling maneuvers may be the characteristic that causes handling problems when the pilot is laterally offset from the airplane center of gravity. He suggested that a measure of this effect can be expressed by $\Delta n_{z,p}/p_{\mathrm{ss}}$, the ratio of the maximum incremental normal acceleration experienced at the pilot station to the steady-state roll rate following a step lateral control input. This is similar to the lateral acceleration parameter $n_{y,p}/p_{\max}$ developed during the program reported in reference 12 and presented in reference 7.

The relationship between $\Delta n_{z,p}/p_{\mathrm{ss}}$ (established for each configuration from step control response time histories and tabulated in table VII) and average pilot rating is presented in figure 22 for both evaluation pilots for the conditions of approach only and approach to touchdown. A review of the pilots' comments (ref. 11) made it possible to identify those tasks that resulted in PIO's. The symbols representing these tasks are marked with a flag in figure 22. These data indicate that the pilot ratings degraded as the value of the parameter $\Delta n_{z,p}/p_{\mathrm{ss}}$ increased (an indication of poorer handling and ride qualities) and that the handling qualities were also a strong function of the altitude change effects that caused the PIO's. This figure suggests that based on incremental normal acceleration experienced at the pilot station alone, a potential roll-control-induced normal-acceleration criterion would state that the ratio of maximum incremental acceleration at the pilot station to steady-state roll rate following a step lateral control input should not exceed the values indicated in figure 22 and shown in the following table:

Level	$\Delta n_{z,p}/p_{\mathrm{ss}}$, g units/(deg/sec)
1	0.020
2	.048
3	.069

Figure 23 shows the change in pilot rating at each lateral pilot location for the various effective roll-mode time constants evaluated. The shaded areas were determined from the envelope of non-PIO data from figure 22. It was assumed that the pilot ratings at zero lateral pilot offset were identical for all values of τ_R. Between the two pilots there was a variation in pilot rating of approximately 1 with the pilot located on the axis of symmetry and approximately 3/4 for the other pilot locations. The shaded parts of this figure indicate that the pilots downgraded the handling qualities as the pilot station moved farther from the aircraft center of gravity. The amount of change in pilot rating was a function of effective roll-mode time constant. This figure implies that to maintain satisfactory flying qualities on a twin-fuselage airplane configuration, the fuselage separation distance should be no greater than approximately 60 ft. (That is, the maximum allowable lateral pilot location from the airplane center of gravity would be no greater than approximately 30 ft.)

If it is assumed that the ratio of $n_{y,p}/p_{\max}$ (ref. 7) to $\Delta n_{z,p}/p_{\mathrm{ss}}$ (developed in this study) is equivalent to the ratio $(a_y)_{\mathrm{rms}}/(\Delta a_n)_{\mathrm{rms}}$ for the twin-fuselage configurations presented as figure 24 (fig. 26 in ref. 1), then it would be expected that an acceptable value of $\Delta n_{z,p}/p_{\mathrm{ss}}$ would be as follows:

$$\frac{n_{y,p}/p_{\max}}{(a_y)_{\mathrm{rms}}/(\Delta a_n)_{\mathrm{rms}}} = \Delta n_{z,p}/p_{\mathrm{ss}}$$

For example, for level 2, $n_{y,p}/p_{\max} = 0.035$ g units/(deg/sec) (ref. 7) and $(a_y)_{\text{rms}}/(\Delta a_n)_{\text{rms}} = 0.265$ (fig. 24). Thus $\Delta n_{z,p}/p_{\text{ss}} = 0.132$ g units/(deg/sec). Figure 24 also presents the suggested acceptable ride qualities boundaries for CTOL jet transport aircraft from reference 13. The fact that the calculated "acceptable" value of $\Delta n_{z,p}/p_{\text{ss}}$ is 2.75 times larger than that indicated in figure 22 suggests that all pilot ratings were influenced by the altitude change effects caused by lateral control inputs, even when no PIO's resulted.

Dynamic Stability Requirements and Criteria

As previously stated, the aircraft industry has for several years been aware that many of the existing aircraft stability and control requirements are inappropriate because of the expansion of flight envelopes, the increase in airplane size, and the utilization of complex stability and control augmentation systems. Therefore, in an effort to aid in the future establishment of new stability requirements, the low-speed handling qualities parameters of an unconventional, relatively large, passenger transport are compared with some existing handling qualities criteria. These results add to the data base developed in references 1, 7, 12, and 14.

Two of the most widely used longitudinal handling qualities criteria are presented in figure 15. Figure 15(a) shows the short-period frequency requirements of reference 5, and as stated previously, the results predicted by the criterion agree with the results obtained during the present simulation studies. Figure 15(b) shows the Shomber-Gertsen longitudinal handling qualities criterion of reference 6; this criterion relates the ability of the pilot to change flight path with normal acceleration to the factor L_α. By using this parameter and recognizing that the pilot's control technique is not constant for all flight regimes, a criterion for satisfactory low-speed short-period characteristics was developed (ref. 6) that correlates well with current airplane experience and is consistent with the results of the present simulation study of the twin-fuselage transport airplane.

Ashkenas (ref. 15) observed that the criterion $\omega_{sp}T\theta_2$ of reference 9 (presented in fig. 16) provided a slightly better short-period frequency requirement than did the criterion of reference 5 (presented in fig. 15). Physically, $\omega_{sp}T\theta_2$ represents the separation in phase between aircraft responses in path and pitch attitude. Figure 16 (ref. 9) gives the proposed requirements for short-term pitch response to pitch controller for airplanes during Category C flight phase, and also presents the results of past and present studies. These results indicate satisfactory dynamic stability characteristics for the noted augmented transports and is consistent with the results of the present simulation study of the twin-fuselage transport airplane.

The low-speed pitch-rate response criterion presented in figure 17, and reported in reference 10 was based on the Shomber-Gertsen criterion of reference 6. There is excellent agreement between the results obtained during the present study and the low-speed pitch response criterion. In terms of effective time delay, rise time parameter, and transient peak ratio, as defined in reference 7, the twin-fuselage transport exhibits level 1 (satisfactory) characteristics. (See fig. 18.)

The roll-acceleration capability criterion for transport aircraft is presented in figure 25 and reported in reference 16. The twin-fuselage passenger transport is indicated to have acceptable characteristics, an evaluation not consistent with the satisfactory ratings given by the pilots during the ground-based and in-flight simulation tests.

The roll-rate capability criterion for transport aircraft is presented in figure 26 and reported in reference 17. The twin-fuselage transport configuration is indicated to have acceptable characteristics. This evaluation could be interpreted to be consistent with the satisfactory ratings given by the pilots during the ground-based and in-flight simulation tests because the reference 17 criterion only delineates between acceptable and unacceptable handling characteristics.

The bank-angle oscillation, roll-rate oscillation, and sideslip excursion limitations criteria of reference 5 are presented in figure 27. They relate the phase angle of the Dutch roll component of sideslip (ψ_β) to the measure of the ratio of the oscillating component to the average component of bank angle and roll rate, and also to the maximum sideslip excursion. The twin-fuselage transport configuration is shown to have satisfactory characteristics, an evaluation consistent with the ratings given by the pilots during the ground-based and in-flight simulation tests. (Note that $\phi_{\text{osc}}/\phi_{\text{av}}$ is not indicated in fig. 27(a) for the reference transport because of the airplane's strong spiral stability.)

In general, the results of the present simulation study agree reasonably well with the handling qualities criteria used for comparison in this paper, with the exception of the roll-acceleration capability criterion of reference 16. It may also be noted that the augmented twin-fuselage transport configuration exhibited improved handling characteristics relative to the reference transport, and that the pilots considered the reference transport to have good handling characteristics.

Concluding Remarks

Six-degree-of-freedom ground-based and in-flight simulator studies have been conducted to evaluate the low-speed flight characteristics of a twin-fuselage passenger transport airplane and to compare these characteristics with those of a large, single-fuselage (reference) transport configuration similar to the C-5A airplane. The primary piloting task was the approach and landing task. This paper has attempted to summarize the results of these studies, which support the following major conclusions.

The pilot ratings assigned to the longitudinal handling qualities of the unaugmented twin-fuselage airplane were 3.0 and 4.5 for pilots A and B, respectively, the primary objections being (1) low apparent pitch damping and (2) unusually large pitch-attitude excursions associated with changes in flaps.

A pilot rating of 4.0 was assigned by both pilots to the lateral-directional handling qualities of the unaugmented airplane, the major objection being the sluggish roll response. The longitudinal stability and control augmentation system developed for this twin-fuselage transport airplane consisted of a high-gain pitch-rate command/attitude-hold system and an autothrottle. The augmentation system provided good short-period characteristics and rapid response to pilot inputs, and the attitude-hold feature minimized disturbances caused by turbulence or variations in flaps and/or thrust. With this augmentation system operative, the pilot ratings for the longitudinal handling qualities on the instrument approach improved from 3.0 (satisfactory) and 4.5 (acceptable but unsatisfactory) for pilots A and B, respectively, to 2 for both pilots.

Laterally, a roll-rate command/attitude-hold augmentation system was employed in an attempt to provide a rapid roll mode and quick uniform response to pilot inputs. The attitude-hold feature resulted in a desirable neutrally stable spiral mode while counteracting disturbances caused by turbulence. Directionally, roll-rate and roll-attitude feedbacks were used to provide turn coordination and improved Dutch roll characteristics. With this augmentation system operative, the pilot rating for the lateral-directional handling qualities on the instrument approach in calm air was improved from an average pilot rating of 4.0 (acceptable but unsatisfactory) to a 2.0 (satisfactory) for both evaluation pilots.

These handling qualities assessments determined on the ground-based simulator were substantiated during the in-flight simulator tests.

The pilots commented that the pilot rating for the instrument approach on the augmented twin-fuselage concept was degraded by 1 1/2 when the landing approach was made in simulated heavy turbulence because of the increased workload required to maintain glide slope and localizer tracking. The twin-fuselage airplane was assigned a rating of D (moderate deterioration of task performance) from the turbulence effect rating scale.

When simulated landing approaches were performed in 90° crosswinds, the pilots felt that they could perform satisfactory landings on the twin-fuselage airplane in crosswinds up to 22 knots (pilot ratings less than 3.5) and could perform acceptable landings in crosswinds as high as approximately 29 knots (pilot ratings less than 6.5).

The go-around capabilities as well as continued approaches and landings were simulated after one engine failed. No handling problems were experienced while performing either task.

Because the pilots are located a significant distance from the roll axis on the simulated twin-fuselage configurations studied, relatively high levels of normal acceleration can be generated during certain phases of flight. As a result of the in-flight simulation study, a roll-control-induced normal-acceleration criterion was developed. This criterion states that the ratio of maximum incremental acceleration at the pilot station to steady-state roll rate following a step lateral control input ($\Delta n_{z,p}/p_{ss}$, g units/(deg/sec)) shall not be greater than 0.020, 0.048, and 0.069 for levels 1, 2, and 3, respectively. However, evidence also indicated that the pilot ratings were probably influenced by the altitude change effects at the cockpit caused by lateral control input. Pilot ratings also decreased as the pilot station moved farther from the aircraft center of gravity. From these results it was determined that on a twin-fuselage airplane configuration, the fuselage separation distance should be no greater than approximately 60 ft, to yield a maximum lateral pilot location from the airplane center of gravity of approximately 30 ft.

In general, it was concluded that the results of the present simulation study agree reasonably well with the handling qualities criteria used for comparison in this paper, with the exception of the roll-acceleration capability requirement. It was also noted that the augmented twin-fuselage concept exhibits improved handling characteristics over those of the reference (single-body) transport. These experimental results further extend the low-speed data base being developed at the Langley Research Center so that handling qualities and ride qualities criteria can be formulated for highly augmented and/or unusually configured aircraft of the future.

References

1. Grantham, William D.; Deal, Perry L.; Keyser, Gerald L., Jr.; and Smith, Paul M.: *Simulator Study of Flight Characteristics of a Large Twin-Fuselage Cargo Transport Airplane During Approach and Landing.* NASA TP-2183, 1983.
2. Houbolt, John C.: Why Twin-Fuselage Aircraft? *Astronaut. & Aeronaut.*, vol. 20, no. 4, Apr. 1982, pp. 26–35.
3. Rollins, John D.: *Description and Performance of the Langley Visual Landing Display System.* NASA TM-78742, 1978.
4. Martin, D. J., Jr.: *A Digital Program for Motion Washout on Langley's Six-Degree-of-Freedom Motion Simulator.* NASA CR-145219, 1977.
5. *Military Specification—Flying Qualities of Piloted Airplanes.* MIL-F-8785C, Nov. 5, 1980. (Supersedes MIL-F-8785B, Aug. 7, 1969.)
6. Shomber, H. A.; and Gertsen, W. M.: Longitudinal Handling Qualities Criteria: An Evaluation. AIAA Paper No. 65-780, Nov. 1965.
7. Chalk, C. R.: *Recommendations for SCR Flying Qualities Design Criteria.* NASA CR-159236, 1980.
8. Stability and Control, Flight Control, Hydraulic Systems and Related Structures Criteria. Doc. No. D6-6800-5, Boeing Co., Jan. 1970.
9. Hoh, Roger H.; Mitchell, David G.; Ashkenas, Irving L.; Klein, Richard H.; Heffley, Robert K.; and Hodgkinson, John: *Proposed MIL Standard and Handbook—Flying Qualities of Air Vehicles. Volume II: Proposed MIL Handbook.* AFWAL-TR-82-3081, Vol. II, Nov. 1982. (Available from DTIC as AD A123 726.)
10. Sudderth, Robert W.; Bohn, Jeff G.; Caniff, Martin A.; and Bennett, Gregory R.: *Development of Longitudinal Handling Qualities Criteria for Large Advanced Supersonic Aircraft.* NASA CR-137635, 1975.
11. Weingarten, Norman C.: *An In-Flight Investigation of a Twin Fuselage Configuration in Approach and Landing.* NASA CR-172366, 1984.
12. Grantham, William D.; Nguyen, Luat T.; Deal, Perry L.; Neubauer, M. J., Jr.; Smith, Paul M.; and Gregory, Frederick D.: *Ground-Based and In-Flight Simulator Studies of Low-Speed Handling Characteristics of Two Supersonic Cruise Transport Concepts.* NASA TP-1240, 1978.
13. Stephens, David G.: Developments in Ride Quality Criteria. *Noise Contr. Eng.*, vol. 12, no. 1, Jan.-Feb. 1979, pp. 6–14.
14. Grantham, William D.; Smith, Paul M.; Deal, Perry L.; and Neely, William R., Jr.: *Simulator Study of Flight Characteristics of Several Large, Dissimilar, Cargo Transport Airplanes During Approach and Landing.* NASA TP-2357, 1984.
15. Ashkenas, I. L: Summary and Interpretation of Recent Longitudinal Flying Qualities Results. AIAA Paper No. 69-898, Aug. 1969.
16. Chalk, C. R.; Neal, T. P.; Harris, T. M.; Pritchard, F. E.; and Woodcock, R. J.: *Background Information and User Guide for MIL-F-8785B(ASG), "Military Specification—Flying Qualities of Piloted Airplanes."* AFFDL-TR-69-72, U.S. Air Force, Aug. 1969. (Available from DTIC as AD 860 856.)
17. Aerospace Recommended Practice: Design Objectives for Flying Qualities of Civil Transport Aircraft. ARP 842B, Soc. Automot., Eng., Aug. 1, 1964. Revised Nov. 30, 1970.

TABLE I. MASS AND DIMENSIONAL CHARACTERISTICS OF SIMULATED TRANSPORT AIRPLANES

(a) Twin-fuselage transport

Weight, lbf:	
Takeoff	241 300
Landing	193 000
Reference wing area, ft^2	2147
Wing span, ft	157.00
Wing leading-edge sweep, deg	23.5
Reference mean aerodynamic chord, ft	15.074
Center-of-gravity location, percent $\bar{c}$	62
Static margin, percent	15.38
I_X, slug-ft^2	4 003 900
I_Y, slug-ft^2	5 408 550
I_Z, slug-ft^2	9 181 470
I_{XZ}, slug-ft^2	223 410
Maximum control surface deflections:	
δ_f, deg (approach/landing)	25/50
δ_h, deg	1 to −10
δ_e, deg	15 to −25
δ_a, deg	±15
δ_s, deg	0 to 60
δ_r, deg	±35
Maximum control surface deflection rates:	
$\dot{\delta}_f$, deg/sec	+223, −2.00
$\dot{\delta}_h$, deg/sec	±0.333
$\dot{\delta}_e$, deg/sec	±25
$\dot{\delta}_a$, deg/sec	±15
$\dot{\delta}_s$, deg/sec	±60
$\dot{\delta}_r$, deg/sec	±35
Horizontal tail:	
Gross horizontal-tail area, ft^2	500
Mean aerodynamic chord, ft	9.09
Distance from center of gravity to horizontal tail $0.25\bar{c}$, ft	54.50
Vertical tail:	
Exposed vertical-tail area, ft^2	365
Mean aerodynamic chord, ft	12.08
Distance from center of gravity to vertical tail $0.25\bar{c}$, ft	50.34
Engines:	
Lateral distance from center of gravity to engine centerline, ft	15.64
Vertical distance from center of gravity to engine centerline, ft	−0.79

TABLE I. Concluded

(b) Reference transport

Weight, lbf:	
Takeoff	769 000
Landing	579 000
Reference wing area, ft^2	6200
Wing span, ft	219.20
Wing leading-edge sweep, deg	28
Reference mean aerodynamic chord, ft	30.93
Center-of-gravity location, percent $\bar{c}$	35
Static margin, percent	10.77
I_X, slug-ft^2	34 900 000
I_Y, slug-ft^2	40 400 000
I_Z, slug-ft^2	60 100 000
I_{XZ}, slug-ft^2	60 600
Maximum control surface deflections:	
δ_f, deg (approach/landing)	25/50
δ_h, deg	2 to −16.5
δ_e, deg	15 to −25
δ_a, deg	±40
δ_s, deg	0 to 60
δ_r, deg	±35
Maximum control surface deflection rates:	
$\dot{\delta}_f$, deg/sec	+15
$\dot{\delta}_h$, deg/sec	±0.5
$\dot{\delta}_e$, deg/sec	±25
$\dot{\delta}_a$, deg/sec	±40
$\dot{\delta}_s$, deg/sec	±60
$\dot{\delta}_r$, deg/sec	±35
Horizontal tail:	
Gross horizontal-tail area, ft^2	965.82
Mean aerodynamic chord, ft	15.29
Distance from center of gravity to horizontal tail $0.25\bar{c}$, ft	125.87
Vertical tail:	
Exposed vertical-tail area, ft^2	961.07
Mean aerodynamic chord, ft	27.95
Distance from center of gravity to vertical tail $0.25\bar{c}$, ft	110.15
Engines:	
Lateral distance from center of gravity to outboard engine centerline, ft	61.9
Lateral distance from center of gravity to inboard engine centerline, ft	39.8
Vertical distance from center of gravity to outboard engine centerline, ft	5.4
Vertical distance from center of gravity to inboard engine centerline, ft	3.4

TABLE II. AERODYNAMIC DATA USED IN SIMULATION OF TWIN-FUSELAGE AIRPLANE CONCEPT

α, deg	$C_{m_{\delta_h}}$, deg^{-1}	$\delta_f = 25^\circ$			$\delta_f = 50^\circ$		
		C_X	C_Z	C_m	C_X	C_Z	C_m
−8	−0.08208	−0.0293	0.1526	0.4580	−0.1549	−0.1933	0.3020
−4		−.0741	−.3136	.0460	−.1864	−.6686	−.1100
0		−.0680	−.7860	−.3160	−.1760	−1.1470	−.4720
4		−.0249	−1.2628	−.6130	−.1349	−1.6264	−.7690
8		.0420	−1.7360	−.8560	−.0660	−2.1098	−1.0120
12	↓	.1486	−2.1183	−1.0270	.0577	−2.5078	−1.1830

α, deg	Numerical values at δ_e of—					
	0	±5°	±10°	±15°	±20°	±25°
	$C_{X_{\delta_e}}$, deg^{-1}					
−8	−0.00214	−0.00211	−0.00206	−0.00196	−0.00177	−0.00149
−4	−.00110	−.00108	−.00106	−.00101	−.00091	−.00077
0	−.00005	−.00005	−.00005	−.00005	−.00005	−.00005
4	.00100	.00098	.00096	.00091	.00081	.00067
8	.00204	.00201	.00196	.00186	.00167	.00139
12	.00307	.00303	.00296	.00280	.00252	.00210
	$C_{Z_{\delta_e}}$, deg^{-1}					
−8	−0.01484	−0.01465	−0.01432	−0.01356	−0.01222	−0.01022
−4	−.01496	−.01476	−.01443	−.01367	−.01232	−.01030
0	−.01500	−.01480	−.01447	−.01370	−.01235	−.01033
4	−.01496	−.01476	−.01443	−.01367	−.01232	−.01030
8	−.01486	−.01467	−.01434	−.01358	−.01224	−.01024
12	−.01468	−.01449	−.01416	−.01341	−.01209	−.01011
	$C_{m_{\delta_e}}$, deg^{-1}					
−8	−0.05700	−0.05624	−0.05499	−0.05206	−0.04693	−0.03925
−4						
0						
4						
8						
12	↓	↓	↓	↓	↓	↓

TABLE II. Continued

α, deg	Numerical values at h/b of—									
	0.075	0.10	0.15	0.20	0.25	0.30	0.40	0.50	0.60	0.80	1.00
	$C_{X_{ge}}$										
−8	−0.0314	−0.0182	−0.0121	−0.0084	−0.0060	−0.0046	−0.0023	−0.0011	−0.0003	−0.0001	0
−4	.0028	.0061	.0055	.0048	.0040	.0034	.0025	.0018	.0013	.0003	
0	.0469	.0408	.0313	.0246	.0195	.0157	.0104	.0067	.0042	.0011	
4	.0990	.0842	.0644	.0503	.0398	.0320	.0210	.0134	.0084	.0022	
8	.1546	.1339	.1027	.0805	.0640	.0514	.0339	.0219	.0137	.0036	
12	.1904	.1713	.1330	.1049	.0830	.0675	.0451	.0295	.0186	.0048	
	$C_{Z_{ge}}$										
−8	−0.2349	−0.1398	−0.0941	−0.0658	−0.0480	−0.0365	−0.0193	−0.0089	−0.0031	−0.0009	0
−4	−.1977	−.1179	−.0794	−.0556	−.0406	−.0309	−.0164	−.0077	−.0027	−.0008	
0	−.1490	−.0887	−.0596	−.0417	−.0304	−.0231	−.0122	−.0057	−.0019	−.0006	
4	−.0853	−.0490	−.0324	−.0223	−.0160	−.0120	−.0061	−.0026	−.0006	−.0002	
8	.0086	.0110	.0092	.0076	.0063	.0052	.0036	.0026	.0017	.0005	
12	.1468	.0996	.0708	.0521	.0396	.0309	.0183	.0103	.0053	.0014	
	$C_{m_{ge}}$										
−8	0.0708	0.0421	0.0283	0.0198	0.0144	0.0110	0.0058	0.0027	0.0009	0.0003	0
−4	.0306	.0182	.0122	.0086	.0062	.0047	.0025	.0012	.0004	.0001	
0	.0072	.0043	.0029	.0020	.0015	.0011	.0006	.0003	.0001	0	
4	−.0072	−.0043	−.0029	−.0020	−.0015	−.0011	−.0006	−.0003	−.0001	0	
8	−.0153	−.0091	−.0061	−.0043	−.0031	−.0024	−.0013	−.0006	−.0002	−.0001	
12	−.0181	−.0108	−.0072	−.0051	−.0037	−.0028	−.0015	−.0007	−.0002	−.0001	

α, deg	$\delta_f = 25°$			$\delta_f = 50°$		
	$C_{Y_{\delta_a}}$, deg^{-1}	$C_{l_{\delta_a}}$, deg^{-1}	$C_{n_{\delta_a}}$, deg^{-1}	$C_{Y_{\delta_a}}$, deg^{-1}	$C_{l_{\delta_a}}$, deg^{-1}	$C_{n_{\delta_a}}$, deg^{-1}
−8	0	0.00151	−0.00001	0	0.00151	0.00003
−4		.00150	.00009		.00150	.00011
0		.00149	.00014		.00149	.00018
4		.00148	.00021		.00148	.00025
8		.00147	.00029		.00146	.00033
12		.00145	.00035		.00144	.00039
	C_{Y_β}, deg^{-1}	C_{l_β}, deg^{-1}	C_{n_β}, deg^{-1}	C_{Y_β}, deg^{-1}	C_{l_β}, deg^{-1}	C_{n_β}, deg^{-1}
−8	−0.02852	−0.00184	0.00243	−0.03136	−0.00197	0.00338
−4		−.00196	.00267		−.00216	.00361
0		−.00204	.00290		−.00230	.00382
4		−.00233	.00307		−.00264	.00397
8		−.00256	.00320		−.00295	.00407
12		−.00272	.00328		−.00317	.00412

TABLE II. Concluded

α, deg	$\delta_f = 25^\circ$			$\delta_f = 50^\circ$		
	$C_{X_{\delta_s}}$, deg^{-1}	$C_{Z_{\delta_s}}$, deg^{-1}	$C_{m_{\delta_s}}$, deg^{-1}	$C_{X_{\delta_s}}$, deg^{-1}	$C_{Z_{\delta_s}}$, deg^{-1}	$C_{m_{\delta_s}}$, deg^{-1}
−8	0.00122	0.01265	0.00148	0.00325	0.02696	0.00302
−4	.00023	.01219	.00169	.00128	.02678	.00424
0	−.00066	.01167	.00192	−.00065	.02645	.00501
4	−.00146	.01121	.00207	−.00249	.02599	.00536
8	−.00213	.01028	.00222	−.00426	.02540	.00557
12	−.00266	.00917	.00231	−.00596	.02469	.00540
	C_{Y_p}, rad^{-1}	C_{l_p}, rad^{-1}	C_{n_p}, rad^{-1}	C_{Y_p}, rad^{-1}	C_{l_p}, rad^{-1}	C_{n_p}, rad^{-1}
−8	−0.0377	−0.5642	0.0872	0.0422	−0.5467	0.0546
−4	.0635	−.5649	.0157	.1438	−.5489	−.0084
0	.1753	−.5727	−.0518	.2558	−.5643	−.0427
4	.2644	−.5944	−.0477	.3420	−.5917	−.0423
8	.3594	−.6233	−.0947	.4356	−.6260	−.0960
12	.4327	−.6556	−.1490	.5088	−.6647	−.1554

α, deg	$\delta_f = 25^\circ$			$\delta_f = 50^\circ$		
	C_{Y_r}, rad^{-1}	C_{l_r}, rad^{-1}	C_{n_r}, rad^{-1}	C_{Y_r}, rad^{-1}	C_{l_r}, rad^{-1}	C_{n_r}, rad^{-1}
−8	0.6714	0.0983	−0.2383	0.7080	0.1873	−0.2893
−4	.6734	.1807	−.2421	.7163	.2736	−.2960
0	.6926	.2619	−.2491	.7423	.3582	−.3085
4	.7229	.3507	−.2547	.7789	.4496	−.3185
8	.7665	.4365	−.2667	.8286	.5405	−.3349
12	.8234	.4991	−.2788	.8919	.6097	−.3479

α, deg	$C_{Y_{\delta_r}}$, deg^{-1}	$C_{l_{\delta_r}}$, deg^{-1}	$C_{n_{\delta_r}}$, deg^{-1}	C_{m_q}, rad^{-1}	$C_{m_{\dot\alpha}}$, rad^{-1}
−8	−0.00536	0.00046	−0.00170	−41.882	−12.664
−4		.00047	−.00170		
0		.00048	−.00170		
4		.00050	−.00169		
8		.00051	−.00168		
12		.00051	−.00168		

TABLE III. FLYING QUALITIES EVALUATION SCALE

				PR	
CONTROLLABLE Capable of being controlled or managed in context of mission, with available pilot attention.	ACCEPTABLE May have deficiencies which warrant improvement, but adequate for mission. Pilot compensation, if required to achieve acceptable performance, is feasible.	SATISFACTORY Meets all requirements and expectations; good enough without improvement. Clearly adequate for mission.	Excellent, highly desirable.	1	Level 1
			Good, pleasant, well behaved.	2	
			Fair. Some mildly unpleasant characteristics. Good enough for mission without improvement.	3	3.5
		UNSATISFACTORY Reluctantly acceptable. Deficiencies which warrant improvement. Performance adequate for mission with feasible pilot compensation.	Some minor but annoying deficiencies. Improvement is requested. Effect on performance is easily compensated by pilot.	4	Level 2
			Moderately objectionable deficiencies. Improvement is needed. Reasonable performance requires considerable pilot compensation.	5	
			Very objectionable deficiencies. Major improvements are needed. Requires best available pilot compensation to achieve acceptable performance.	6	6.5
	UNACCEPTABLE Deficiencies which require improvement. Inadequate performance for mission even with maximum feasible pilot compensation.		Major deficiencies which require improvement for acceptance. Controllable. Performance inadequate for mission, or pilot compensation required for minimum acceptable performance in mission is too high.	7	Level 3
			Controllable with difficulty. Requires substantial pilot skill and attention to retain control and continue mission.	8	
			Marginally controllable in mission. Requires maximum available pilot skill and attention to retain control.	9	9.0
UNCONTROLLABLE Control will be lost during some portion of mission.			Uncontrollable in mission.	10	

TABLE IV. TURBULENCE EFFECT RATING SCALE

Increase of pilot effort with turbulence	Deterioration of task performance with turbulence	Rating
No significant increase	No significant deterioration	A
More effort required	No significant deterioration	B
	Minor	C
	Moderate	D
Best efforts required	Moderate	E
	Major (but evaluation tasks can still be accomplished)	F
	Large (some tasks cannot be performed)	G
Unable to perform tasks		H

TABLE V. DYNAMIC STABILITY CHARACTERISTICS OF SIMULATED LARGE SUBSONIC TRANSPORT AIRPLANES IN APPROACH AND LANDING FLIGHT CONDITIONS

(a) Twin-fuselage cargo transport

Parameter	$V_{app}/\delta_f = 142/25$		$V_{\ell}/\delta_f = 132/50$		Satisfactory criterion	Acceptable criterion
	Unaugmented	SCAS (a)	Unaugmented	SCAS (a)		
Short-period mode						
ω_{sp}, rad/sec	0.641	3.010	0.770	2.684	See figs. 8(a), 15(a)	See figs. 8(a), 15(a)
P_{sp}, sec	22.68	3.28	11.49	3.24		
ζ_{sp}	0.902	0.771	0.704	0.691	0.35 to 1.30	0.25 to 2.00
L_α/ω_{sp}	0.972	0.207	0.753	0.216	See figs. 8(b), 15(b)	See figs. 8(b), 15(b)
n/α, g units/rad	5.00	5.00	4.32	4.32	See figs. 8(a), 15(a)	See figs. 8(a), 15(a)
Longitudinal (aperiodic) mode						
t_2, sec						> 6
Long-period mode						
ω_{ph}, rad/sec	0.101	0.259	0.146	0.262		
P_{ph}, sec	62.20		43.12			
ζ_{ph}	0.061	1.383	0.036	1.222	≥ 0.04	≥ 0
Roll-spiral mode						
τ_R or $\tau_{R,\mathrm{eff}}$, sec	0.93	[b]1.07	0.99	[b]1.13	≤ 1.4	≤ 3.0
t_{s2}, sec	20.96		16.14		≥ 12	≥ 8
ω_{rs}, rad/sec		2.788		2.753		
ζ_{rs}		0.284		0.264		
$\zeta_{rs}\omega_{rs}$, rad/sec		0.793		0.726	≥ 0.5	≥ 0.3
P_{rs}, sec		2.35		2.37		
Dutch roll mode						
ω_d, rad/sec	0.763	0.738	0.792	0.771	≥ 0.4	≥ 0.4
ζ_d	0.221	0.284	0.221	0.299	≥ 0.08	≥ 0.02
$\zeta_d\omega_d$, rad/sec	0.169	0.210	0.175	0.230	≥ 0.10	≥ 0.05
P_d, sec	8.44	8.87	8.14	8.54		
ϕ/β	0.948	0.177	1.024	0.188		
Roll control parameters						
ω_ϕ/ω_d	0.963	0.997	0.961	0.996	0.80 to 1.15	0.65 to 1.35
ζ_ϕ/ζ_d	1.264	1.007	1.326	0.994		

[a]Autothrottle on.
[b]Value of $\tau_{R,\mathrm{eff}}$.

TABLE V. Concluded

(b) Reference transport

Parameter	$V_{app}/\delta_f = 135/25$ Unaugmented	SAS (a)	$V_\ell/\delta_f = 128/40$ Unaugmented	SAS (a)	Satisfactory criterion	Acceptable criterion
Short-period mode						
ω_{sp}, rad/sec	0.675	0.754	0.645	0.706	See figs. 8(a), 15(a)	See figs. 8(a), 15(a)
P_{sp}, sec	18.80	23.79	19.73	25.99		
ζ_{sp}	0.869	0.937	0.870	0.940	0.35 to 1.30	0.25 to 2.00
L_α/ω_{sp}	0.829	0.742	0.823	0.752	See figs. 8(b), 15(b)	See figs. 8(b), 15(b)
n/α, g units/rad	3.96	3.96	3.56	3.56	See figs. 8(a), 15(a)	See figs. 8(a), 15(a)
Longitudinal (aperiodic) mode						
t_2, sec		[b] -35.69		[b] -35.82		> 6
Long-period mode						
ω_{ph}, rad/sec	0.122		0.129			
P_{ph}, sec	51.39		48.72			
ζ_{ph}	0.045		0.072		≥ 0.04	≥ 0
Roll-spiral mode						
τ_R, sec	1.75	2.31	1.79	3.35	≤ 1.4	≤ 3.0
t_{s2}, sec	10.75	[b] -28.20	10.37	[b] -3.41	≥ 12	≥ 8
ω_{rs}, rad/sec						
ζ_{rs}						
$\zeta_{rs}\omega_{rs}$, rad/sec					≥ 0.5	≥ 0.3
P_{rs}, sec						
Dutch roll mode						
ω_d, rad/sec	0.579	0.432	0.553	0.395	≥ 0.4	≥ 0.4
ζ_d	0.135	0.544	0.125	0.445	≥ 0.08	≥ 0.02
$\zeta_d\omega_d$, rad/sec	0.078	0.235	0.069	0.176	≥ 0.10	≥ 0.05
P_d, sec	10.95	17.33	11.44	17.77		
ϕ/β	1.053	0.850	1.187	0.861		
Roll control parameters						
ω_ϕ/ω_d	0.824	1.148	0.857	1.243	0.80 to 1.15	0.65 to 1.35
ζ_ϕ/ζ_d	1.951	0.818	2.332	1.022		

[a] Autothrottle on.
[b] Minus sign signifies time to half amplitude.

TABLE VI. CONTROL RESPONSE CHARACTERISTICS OF SIMULATED LARGE SUBSONIC CRUISE TRANSPORT AIRPLANES

(a) Twin-fuselage cargo transport

Parameter	$V_{app}/\delta_f = 142/65$		$V_\ell/\delta_f = 132/50$		Satisfactory criterion	Acceptable criterion
	Unaugmented	SCAS (a)	Unaugmented	SCAS (a)		
Longitudinal						
$\ddot{\theta}_{max}$, rad/sec^2	[b] – 0.111	[b] – 0.142	[b] – 0.097	[b] – 0.124	[b] – 0.142	[b] – 0.091
$\dot{\theta}/\dot{\theta}_{ss}$					See fig. 17[c]	
$\Delta a_n/\ddot{\theta}$, $\frac{g \text{ units}}{\text{deg/sec}^2}$						See fig. 10[c]
t_1, sec	0.05	0.01	0.05	0.01	$\leq$ 0.200	$\leq$ 0.283
Δt, sec	2.20	0.47	1.92	0.54	[c]0.039 to 0.872	[c]0.014 to 2.811
$\Delta\dot{\theta}_2/\Delta\dot{\theta}_1$	0	0.037	0	0.059	$\leq$ 0.30	$\leq$ 0.60
Lateral						
$\ddot{\phi}_{max}$, rad/sec^2	0.151	0.148	0.184	0.181	See fig. 25	See fig. 25
$\dot{\phi}_{max}$, deg/sec	14.84	16.82	18.70	20.67		See fig. 26
p_2/p_1	0.785	1.000	0.996	1.000	$\geq$ 0.60	$\geq$ 0.25
ϕ_{osc}/ϕ_{av}	0.019	0.007	0.018	0.008	See fig. 27(a)	See fig. 27(a)
$t_{\phi=30}$, sec	3.28	3.24	[c]2.93	2.92	$\leq$ 2.5	$\leq$ 4.0
t_1, sec	0.01	0.04	0.01	0.04	$\leq$ 0.283	$\leq$ 0.400
Δt, sec	1.30	1.41	1.42	1.54		

[a]Autothrottle on.
[b]Minimum demonstrated speed = $1.06V_s$.
[c]Landing configuration.

(b) Reference transport

Parameter	$V_{app}/\delta_f = 135/25$		$V_\ell/\delta_f = 128/40$		Satisfactory criterion	Acceptable criterion
	Unaugmented	SAS (a)	Unaugmented	SAS (a)		
Longitudinal						
$\ddot{\theta}_{max}$, rad/sec^2	[b] – 0.051	[b] – 0.051	[b] – 0.046	[b] – 0.046	[b] – 0.055	[b] – 0.035
$\dot{\theta}/\dot{\theta}_{ss}$					See fig. 17[c]	
$\Delta a_n/\ddot{\theta}$, $\frac{g \text{ units}}{\text{deg/sec}^2}$						See fig. 10[c]
t_1, sec	0.05	0.03	0.05	0.03	$\leq$ 0.200	$\leq$ 0.283
Δt, sec	1.58	1.42	1.71	1.35	[c]0.041 to 0.901	[c]0.014 to 2.905
$\Delta\dot{\theta}_2/\Delta\dot{\theta}_1$	0	0.14	0	0.18	$\leq$ 0.30	$\leq$ 0.60
Lateral						
$\ddot{\phi}_{max}$, rad/sec^2	0.121	0.120	0.155	0.153	See fig. 25	See fig. 25
$\dot{\phi}_{max}$, deg/sec	15.56	17.25	20.86	22.52		See fig. 26
p_2/p_1	0.865	0.854	0.930	0.918	$\geq$ 0.60	$\geq$ 0.25
ϕ_{osc}/ϕ_{av}					See fig. 27(a)	See fig. 27(a)
$t_{\phi=30}$, sec	3.6	3.6	3.1	3.1	$\leq$ 2.5	$\leq$ 4.0
t_1, sec	0.15	0.15	0.16	0.16	$\leq$ 0.283	$\leq$ 0.400
Δt, sec		2.90		2.51		

[a]Autothrottle on.
[b]Minimum demonstrated speed = $1.06V_s$.
[c]Landing configuration.

TABLE VII. NORMAL ACCELERATION AT PILOT STATION PER STEADY-STATE ROLL RATE

y_p, ft	τ_R, sec	$\Delta n_{z,p}$, g units	p_{ss}, deg/sec	$\Delta n_{z,p}/p_{ss}$, g units/(deg/sec)
0	0.6	0	3.83	0
−30	.6	.073	3.83	.019
−50	.6	.126	3.83	.033
0	1.1	0	4.46	0
−30	1.1	.049	4.46	.011
−50	1.1	.086	4.46	.020
0	2.3	0	6.59	0
−30	2.3	.041	6.59	.006
−50	2.3	.070	6.59	.011

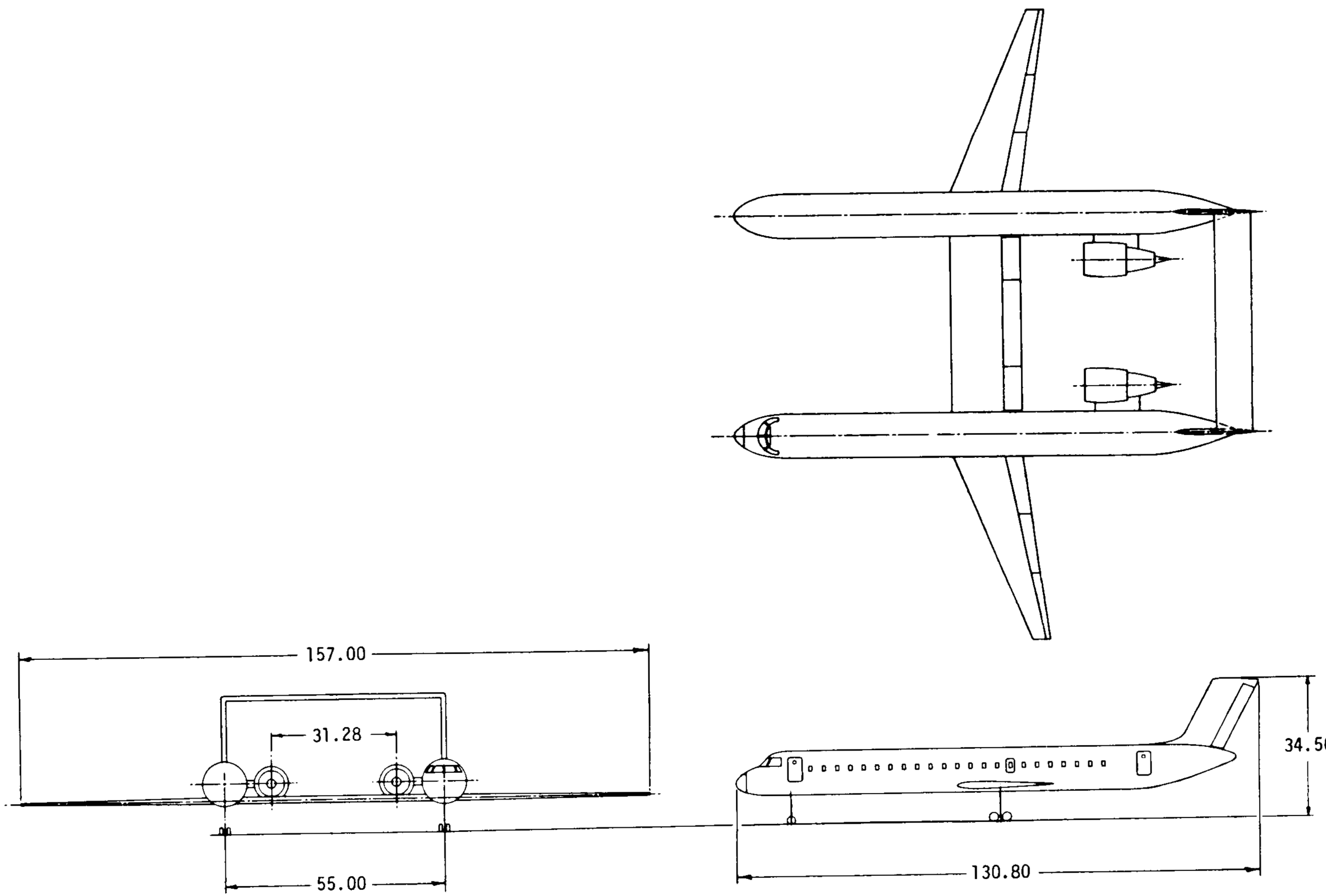


Figure 1. Three-view sketch of simulated twin-fuselage transport. All linear dimensions in feet.

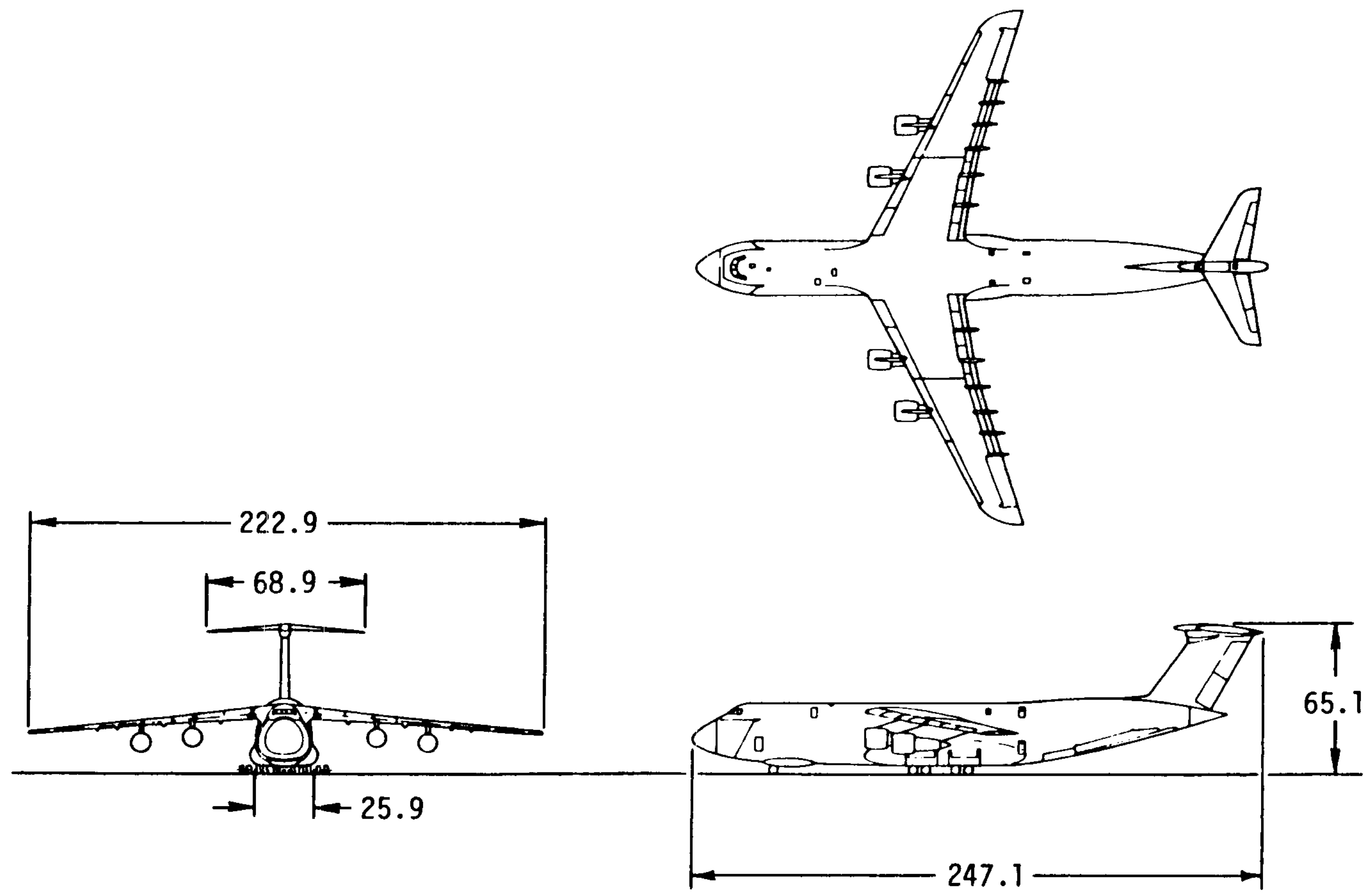


Figure 2. Three-view sketch of simulated reference transport. All linear dimensions in feet. (From ref. 1.)

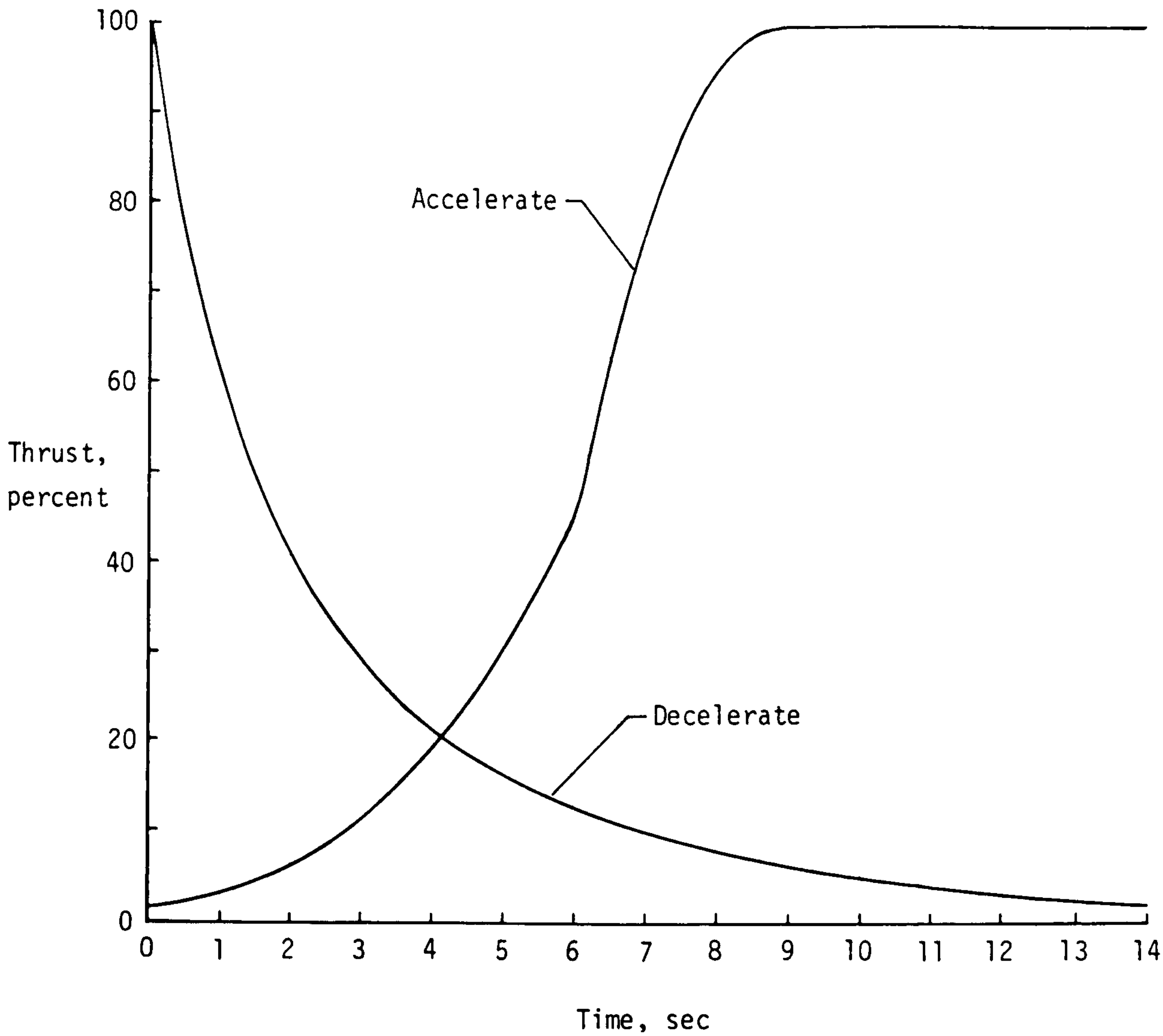
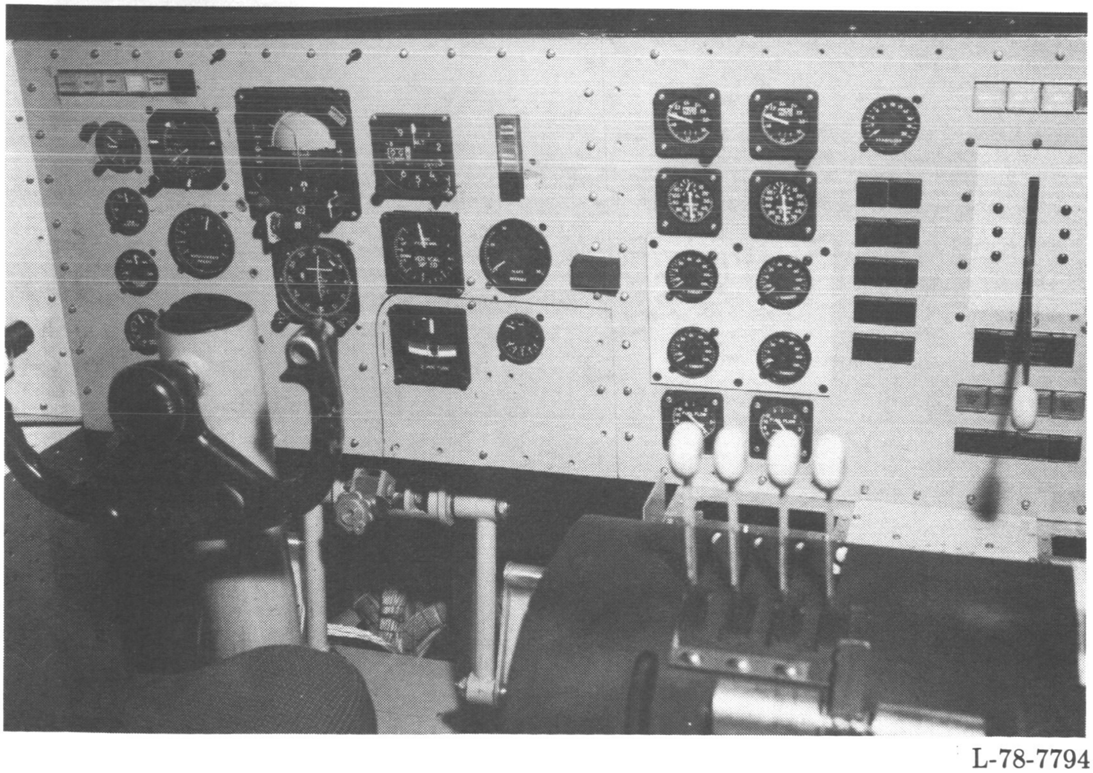


Figure 3. Typical engine thrust response characteristics used in simulations. (From ref. 1.)

L-75-7570

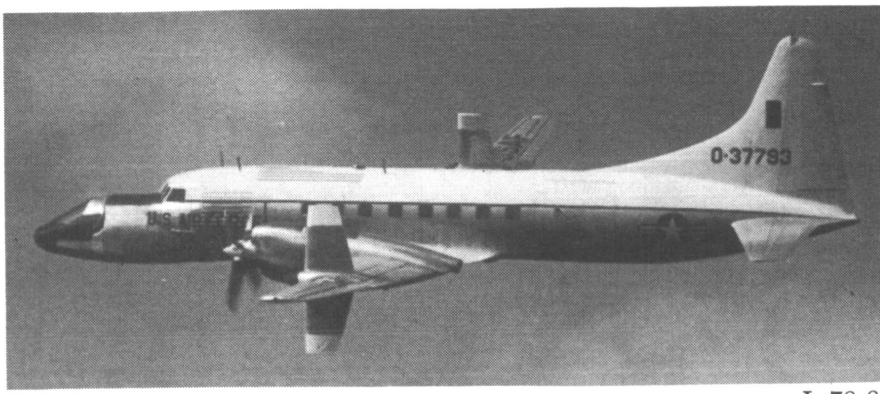
(a) Langley Visual/Motion Simulator.



L-78-7794

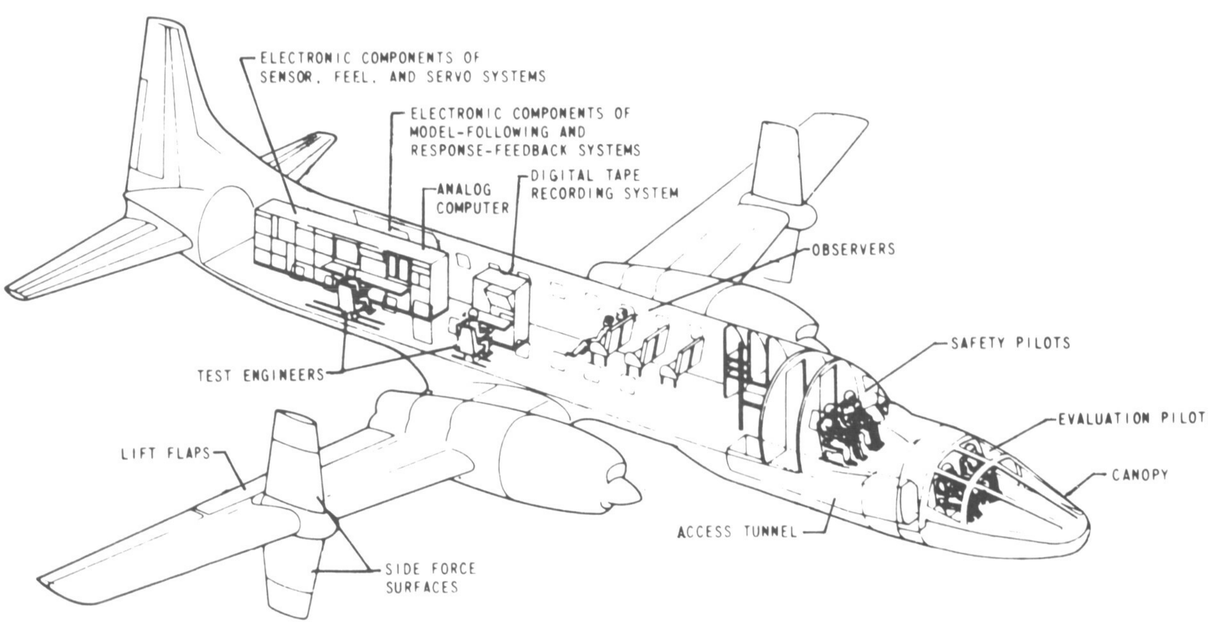
(b) VMS instrument panel.

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



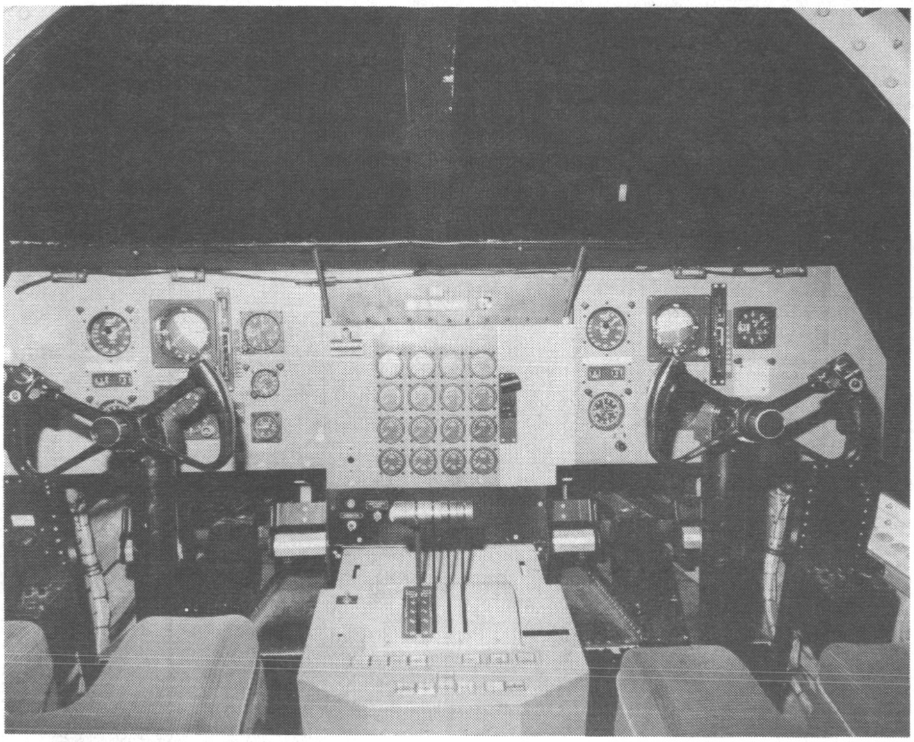
L-78-81

(a) TIFS airplane.

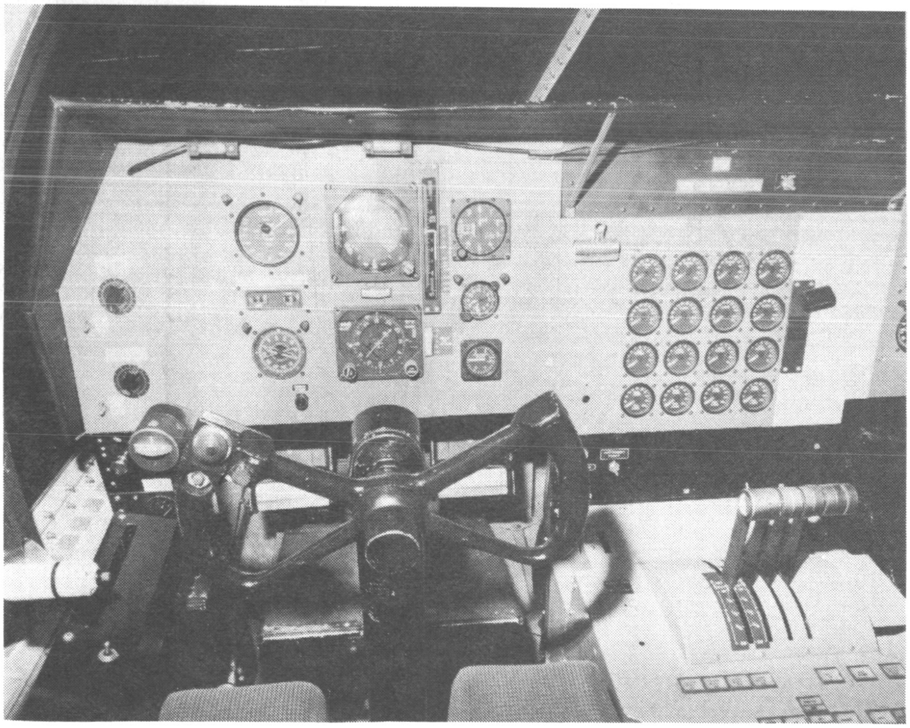


(b) Layout of TIFS.

Figure 5. Photograph and layout diagram of USAF/AFWAL Total In-Flight Simulator (TIFS). (From ref. 1.)



(a) Overall view of TIFS cockpit.



(b) TIFS cockpit and instrument display.

L-78-82

Figure 6. TIFS cockpit and instrument display.

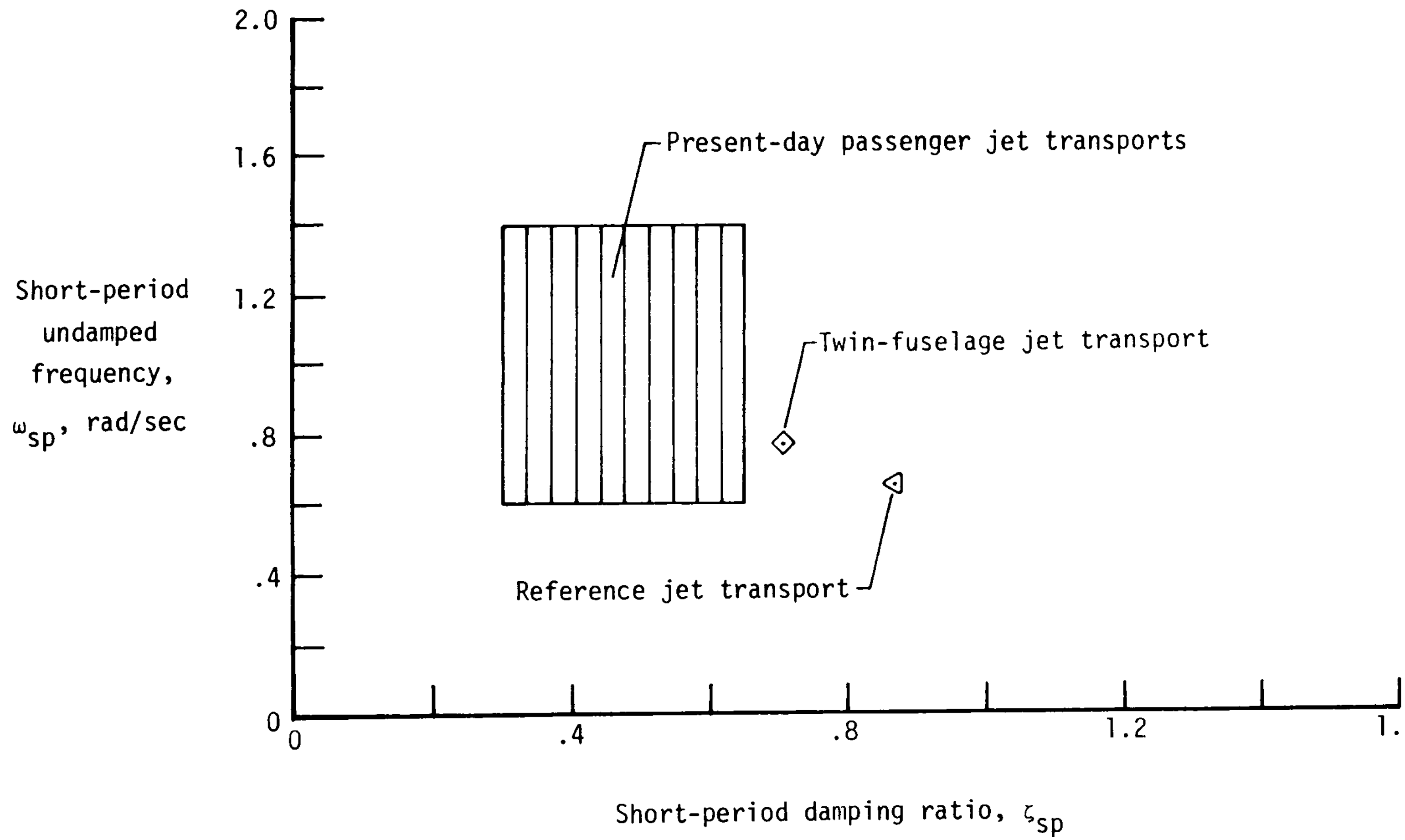
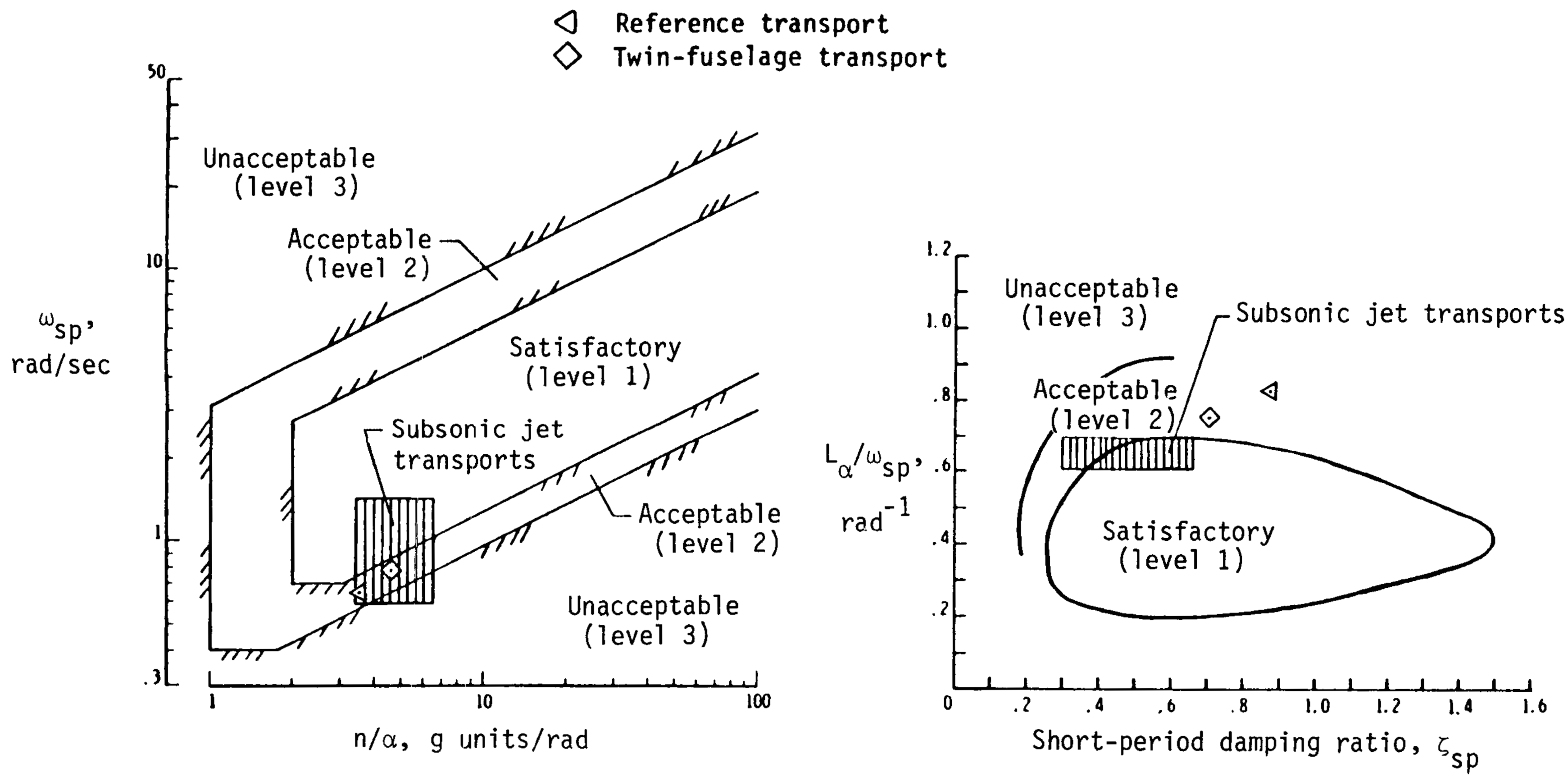


Figure 7. Short-period frequency and damping ratios for unaugmented twin-fuselage and reference jet transport configurations and some present-day passenger jet transports.



(a) Criterion from reference 5.

(b) Criterion from reference 6.

Figure 8. Longitudinal handling characteristics of simulated unaugmented twin-fuselage passenger transport and reference transport relative to two longitudinal handling qualities criteria.

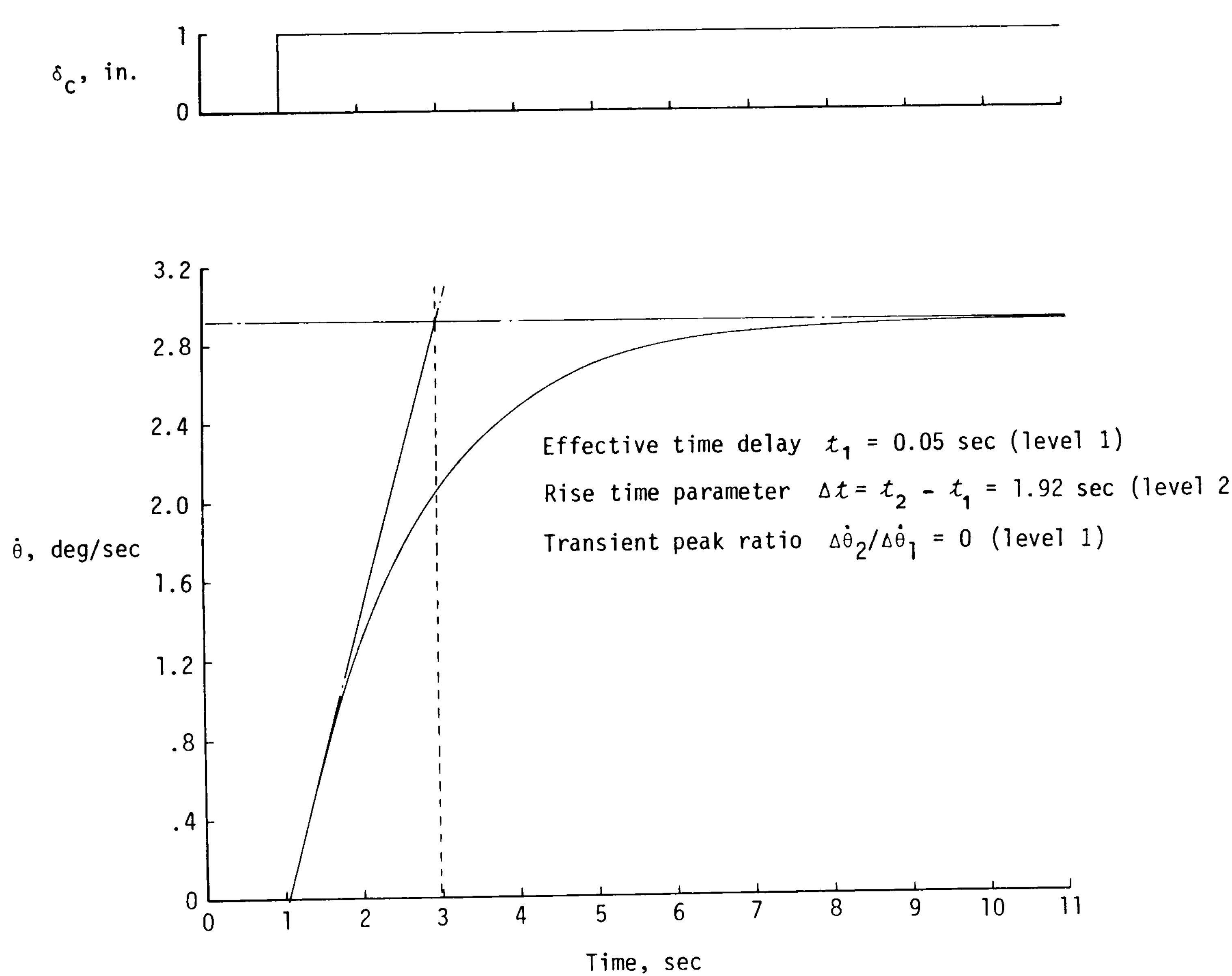


Figure 9. Pitch-rate response to step column input on unaugmented twin-fuselage passenger transport. (Criteria from ref. 7.) $\gamma = 0; h = 2000$ ft; LDG = DWN; $\delta_f = 50°$; Indicated airspeed = 132.0 knots (constant).

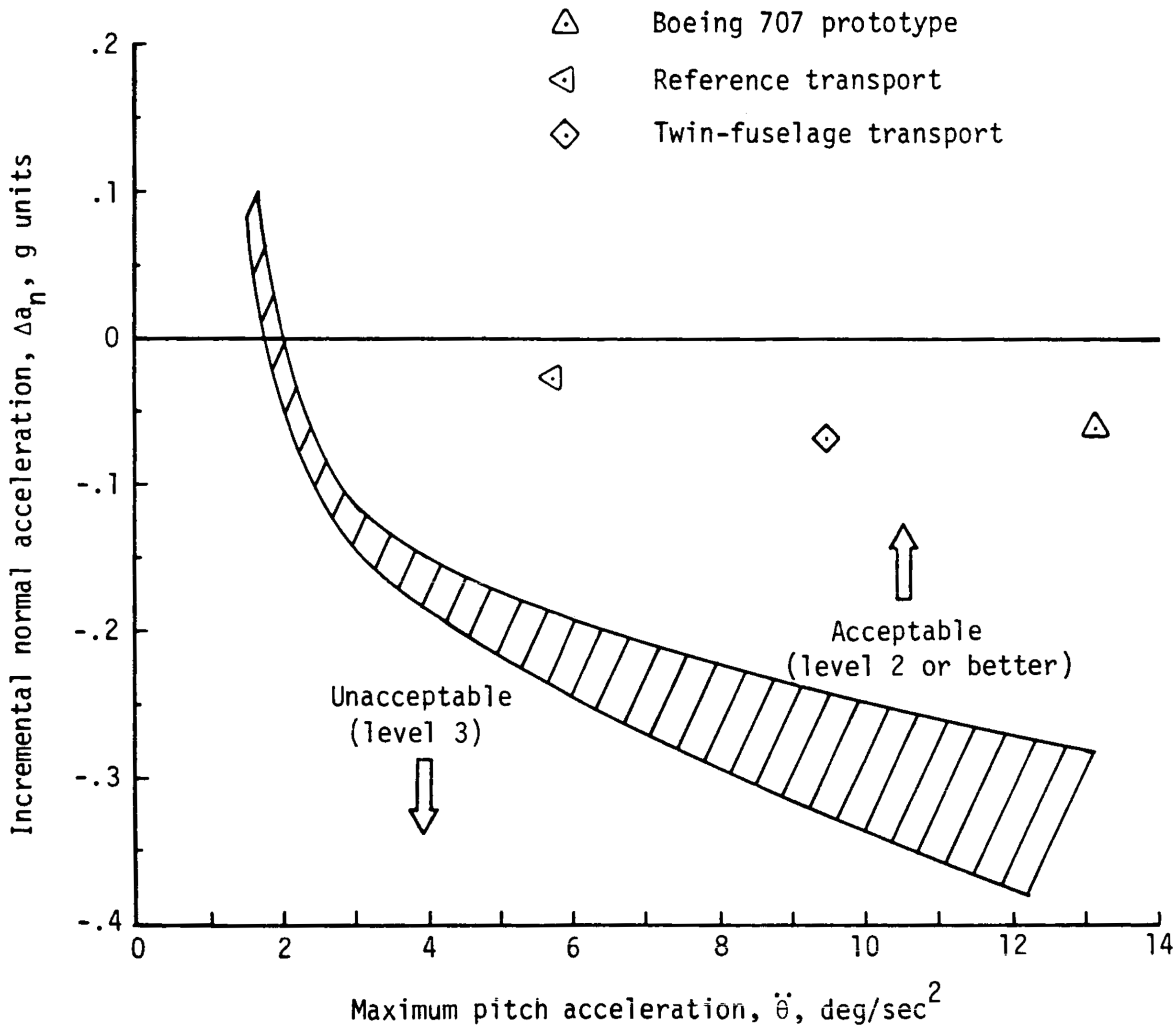


Figure 10. Longitudinal control characteristics of simulated transport concepts relative to control requirements of refernce 8 and control characteristics of Boeing 707 prototype.

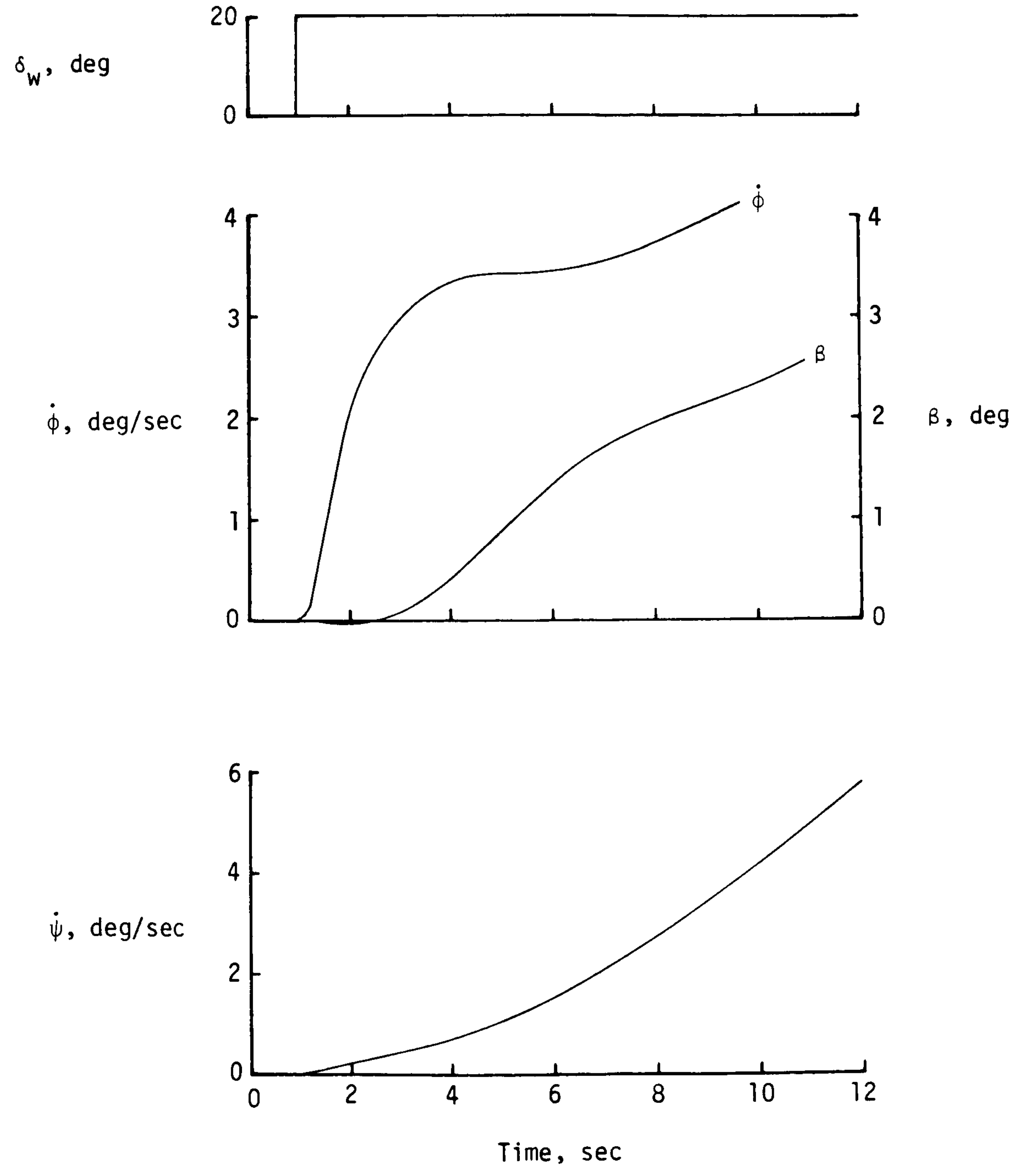
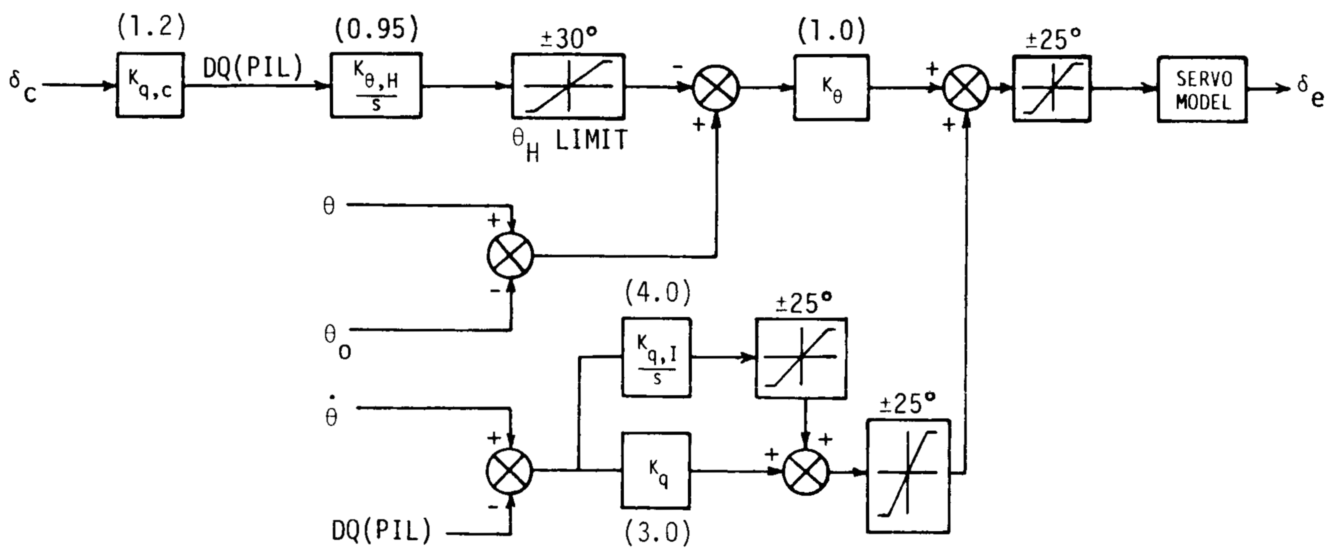
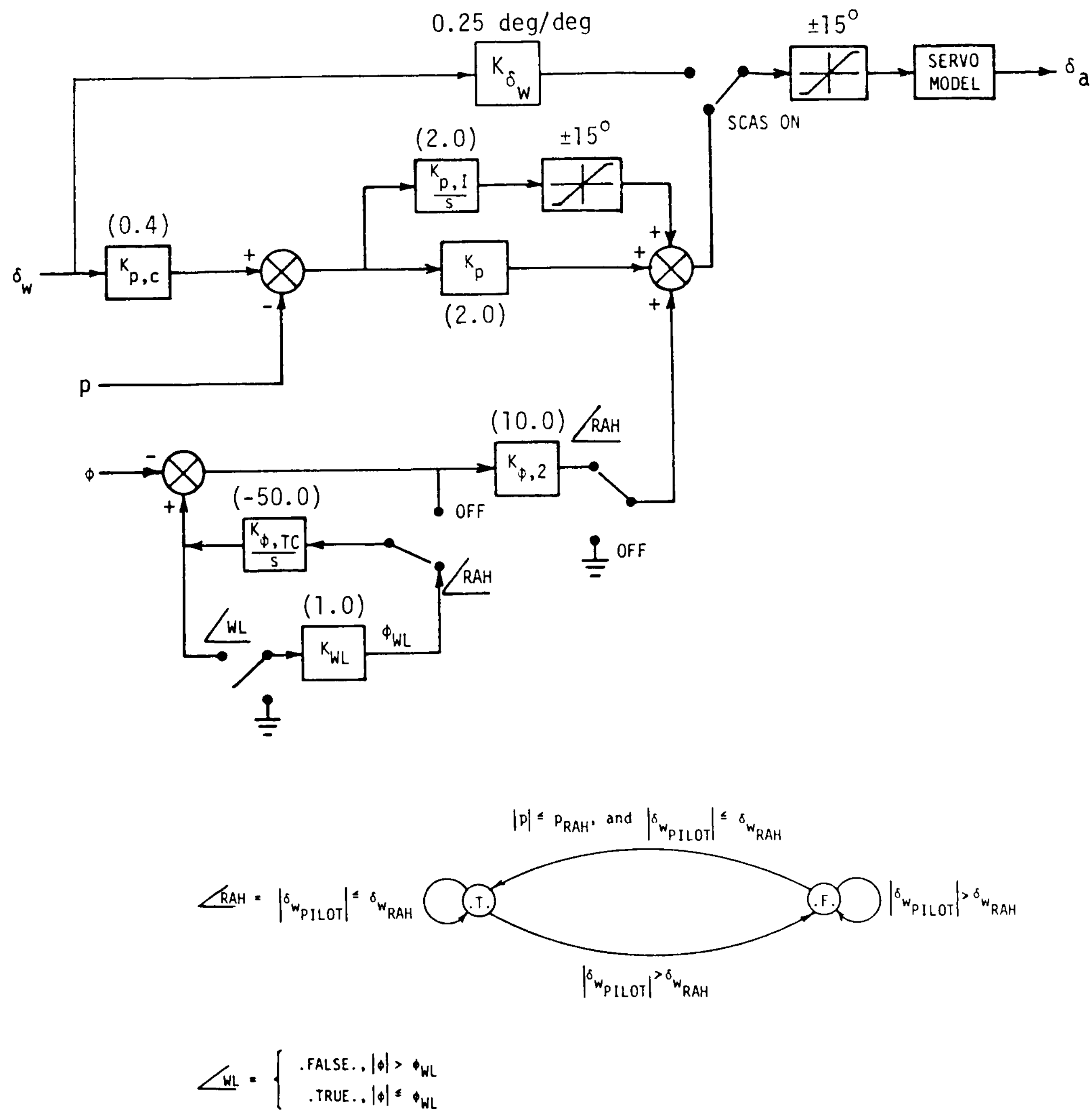


Figure 11. Lateral-directional response to a step wheel input on unaugmented twin-fuselage transport airplane.



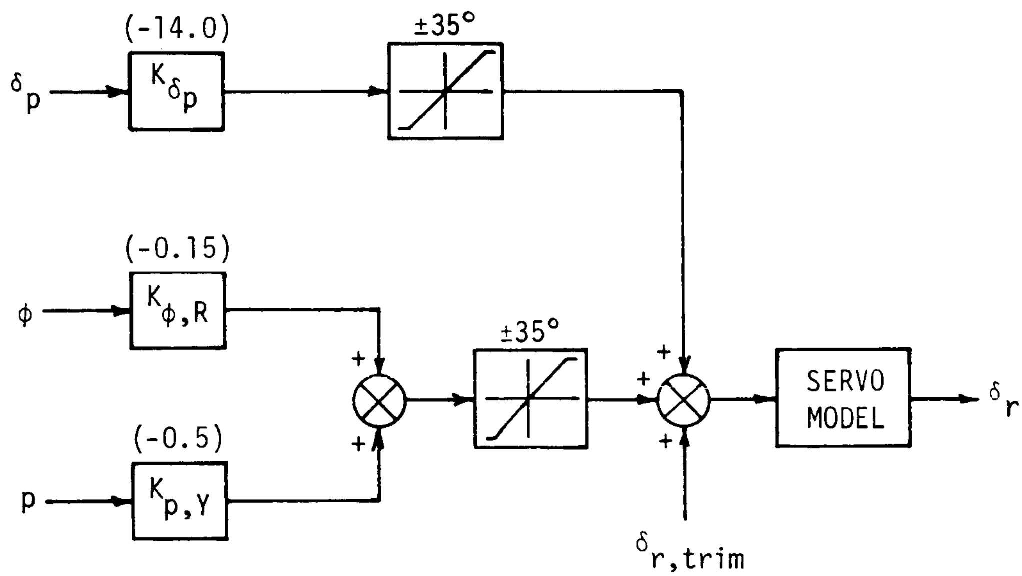
(a) Longitudinal (pitch) control system.

Figure 12. Normal operational stability and control augmentation system (SCAS). SCAS gains are indicated in parentheses.



(b) Lateral (roll) control system and switching logic.

Figure 12. Continued.



(c) Directional (yaw) control system.

Figure 12. Concluded.

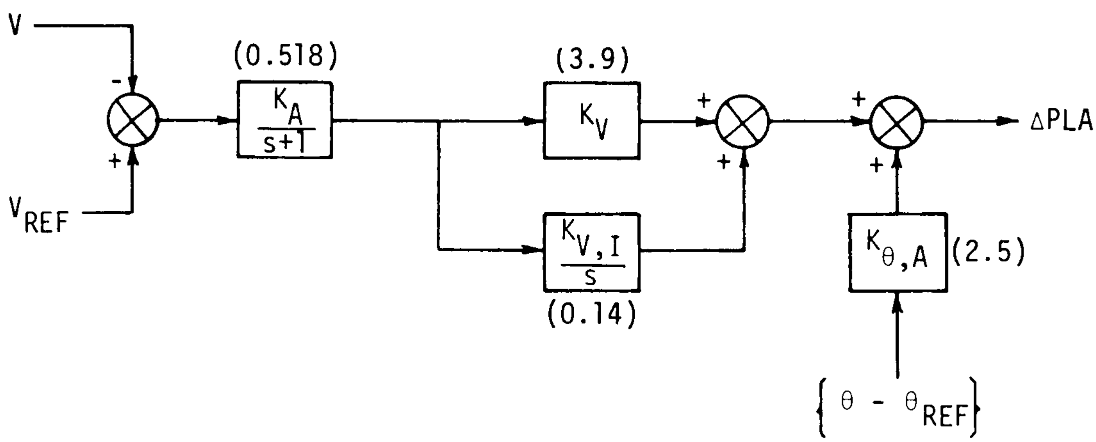


Figure 13. Block diagram of autothrottle for twin-fuselage configuration. Gains are indicated in parentheses.

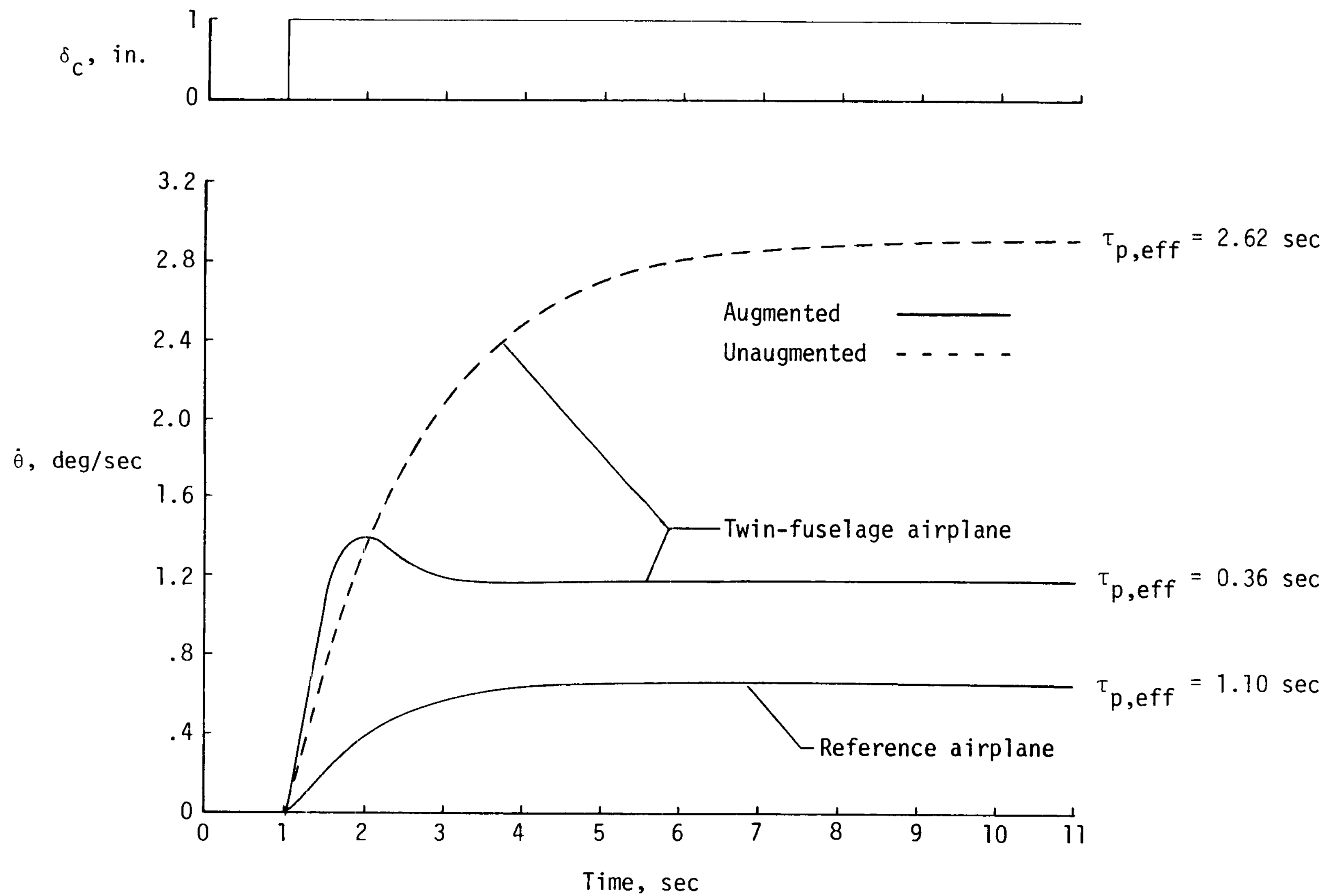
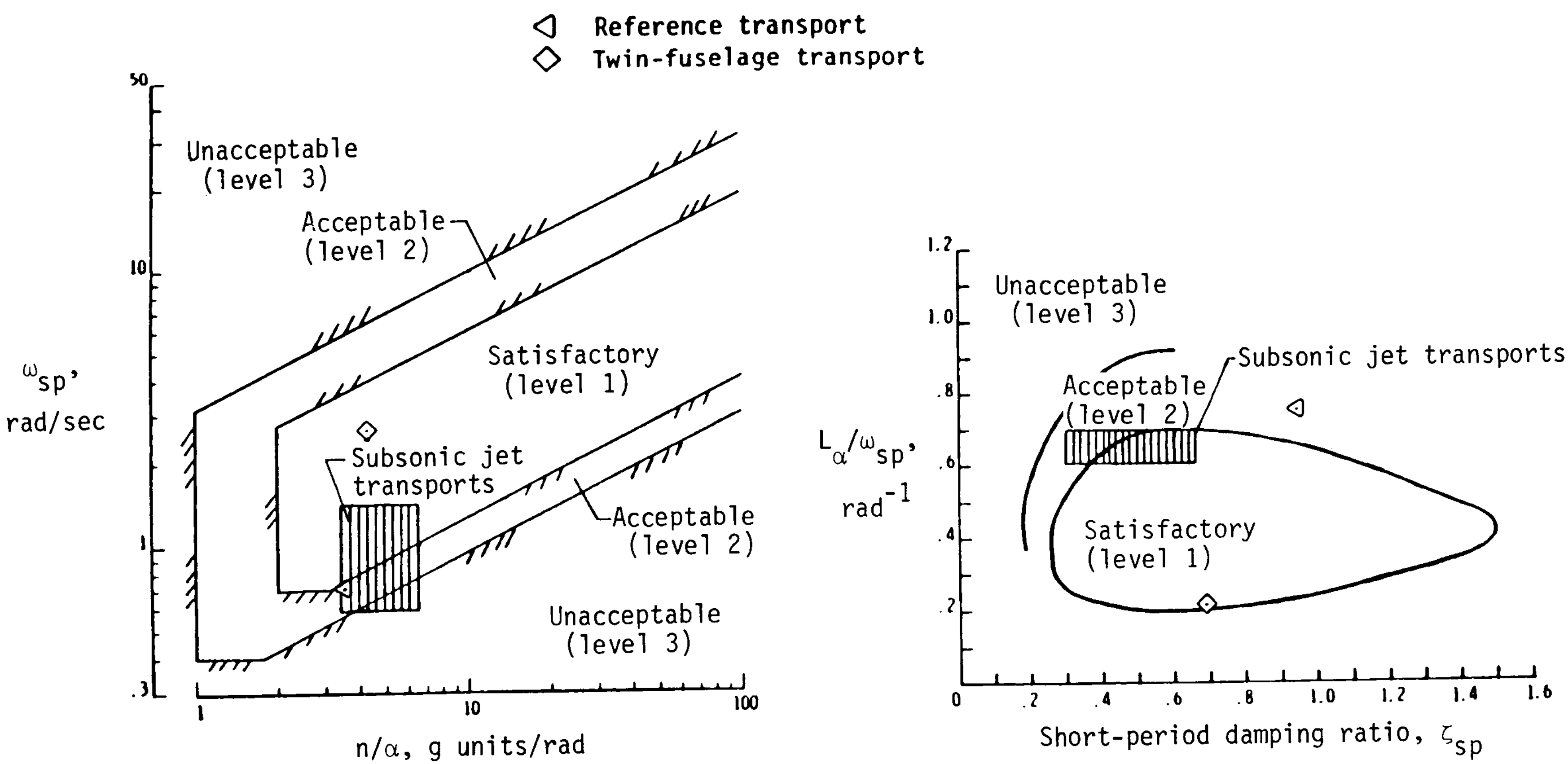


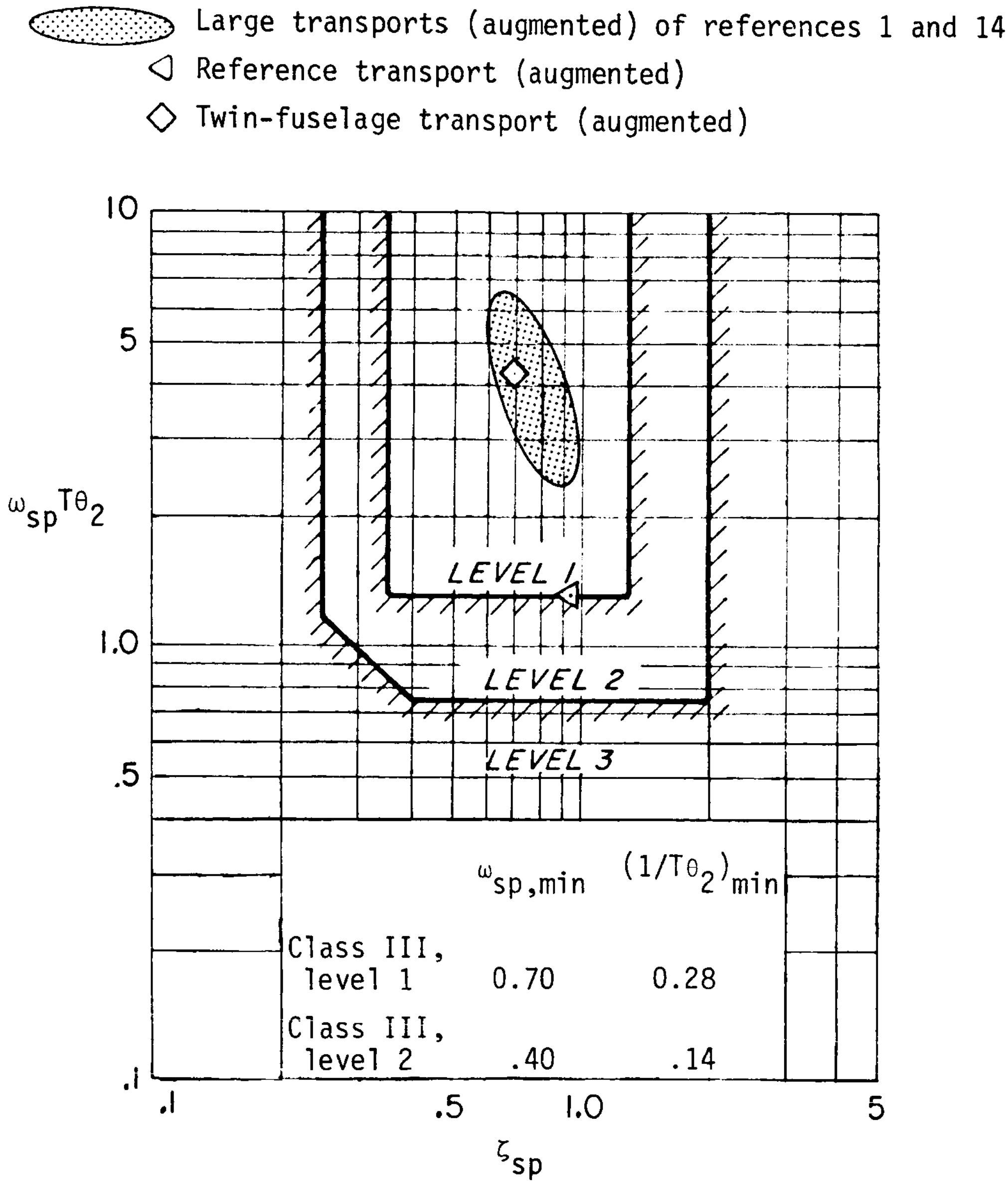
Figure 14. Pitch-rate response of simulated reference and augmented and unaugmented twin-fuselage transports.



(a) Criterion from reference 5.

(b) Criterion from reference 6.

Figure 15. Longitudinal handling characteristics of simulated augmented twin-fuselage passenger transport and augmented reference transport relative to two longitudinal handling qualities criteria.



	$\omega_{sp,min}$	$(1/T_{\theta_2})_{min}$
Class III, level 1	0.70	0.28
Class III, level 2	.40	.14

Figure 16. Proposed Category C flight phase requirements for short-term pitch response to pitch controller. Boundaries from reference 9.

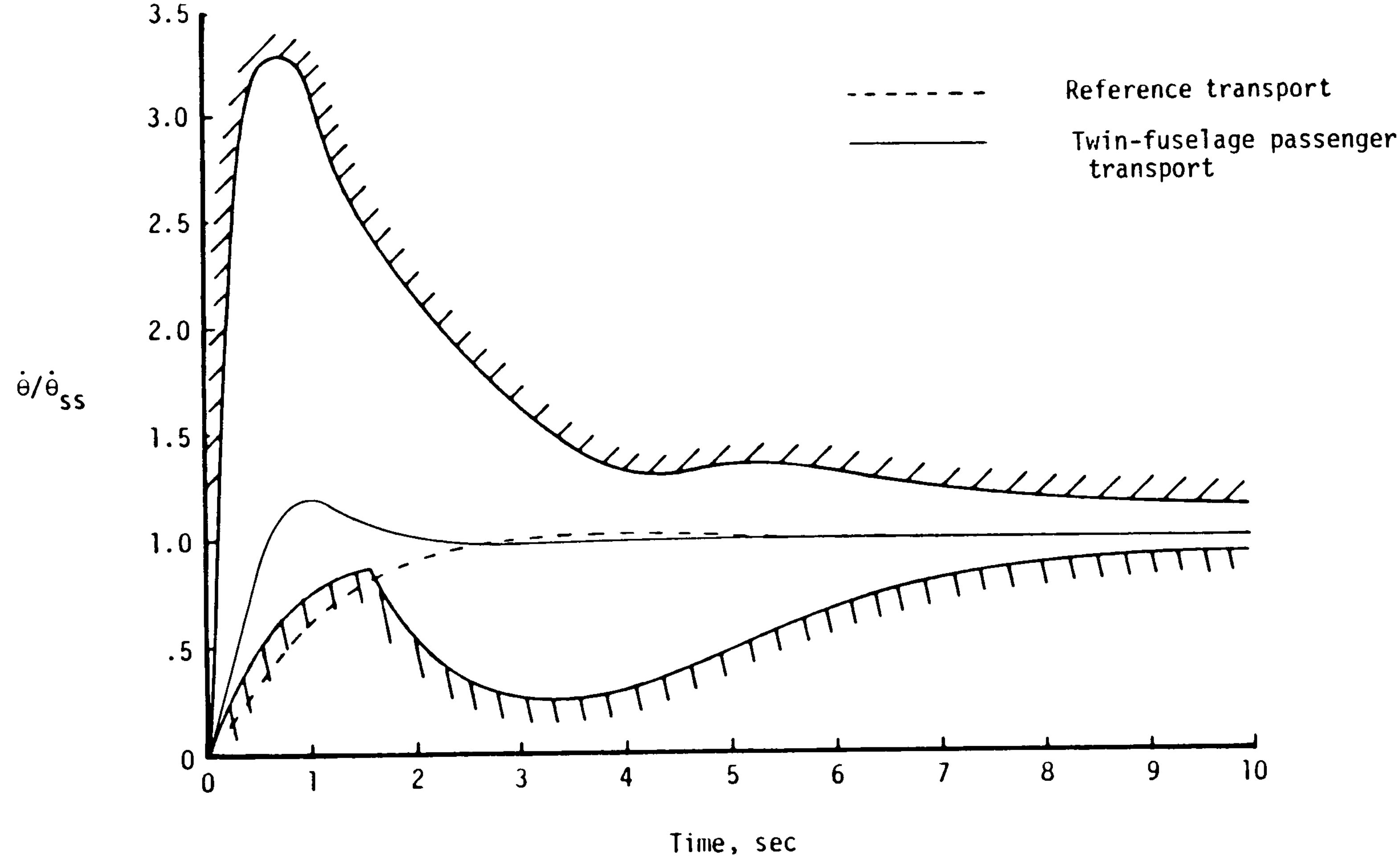


Figure 17. Low-speed pitch-rate response criterion of reference 10. Boundaries for normal flight operations (PR $\leq$ 3.5).

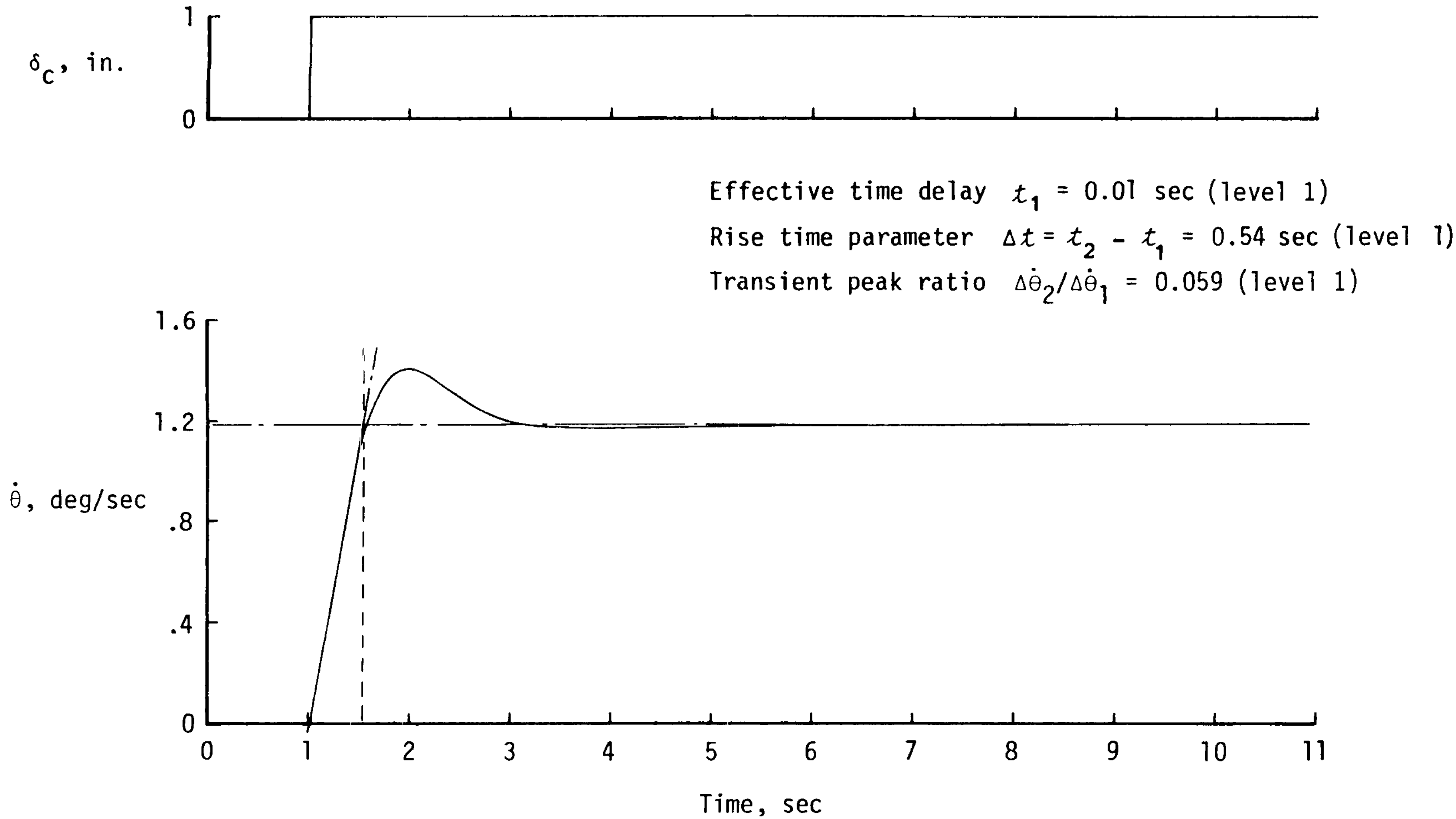


Figure 18. Pitch-rate response to column step input on augmented twin-fuselage passenger transport in landing configuration. Criteria from reference 7.

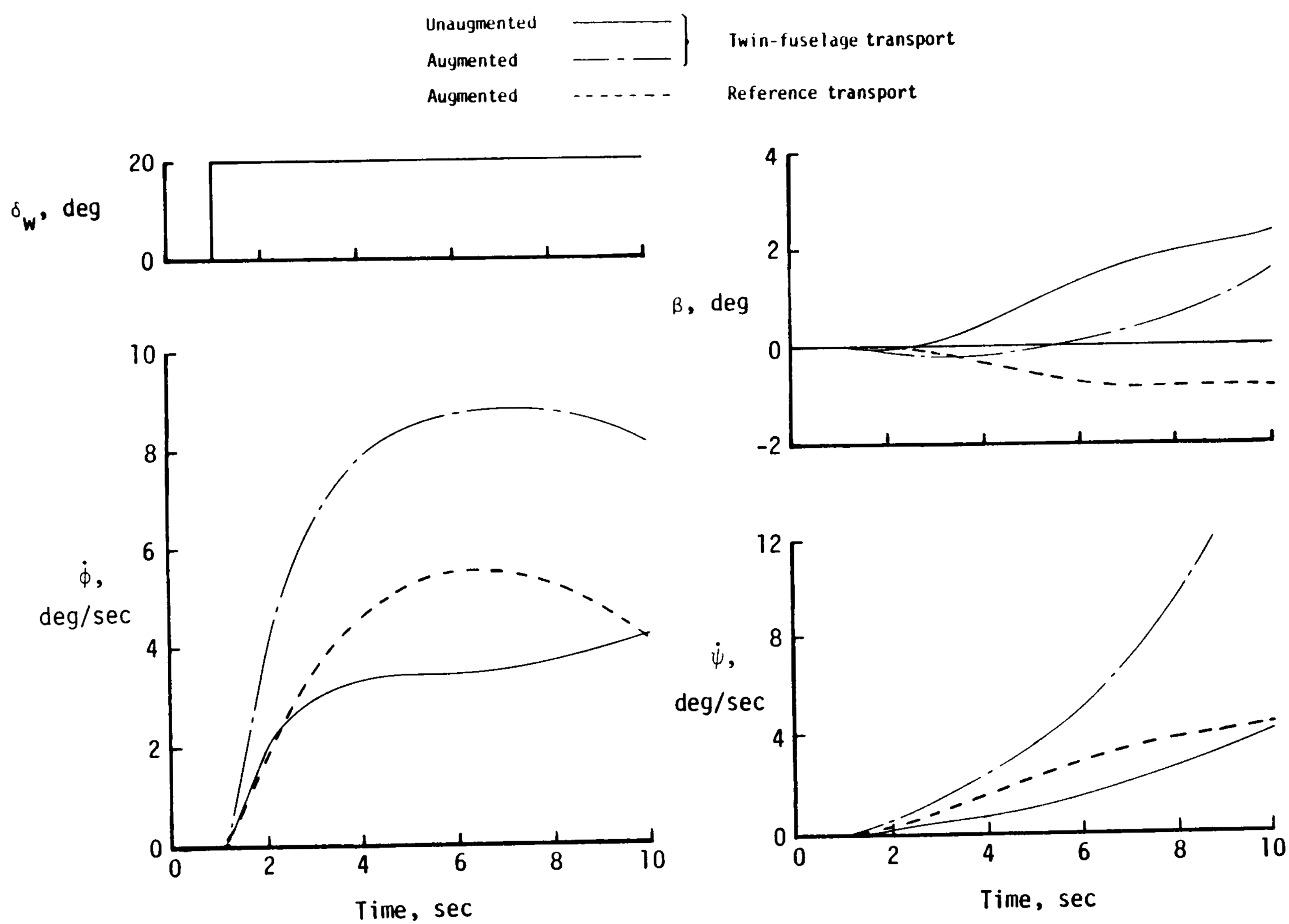


Figure 19. Lateral-directional response to step wheel input on unaugmented and augmented twin-fuselage airplane and simulated augmented reference airplane.

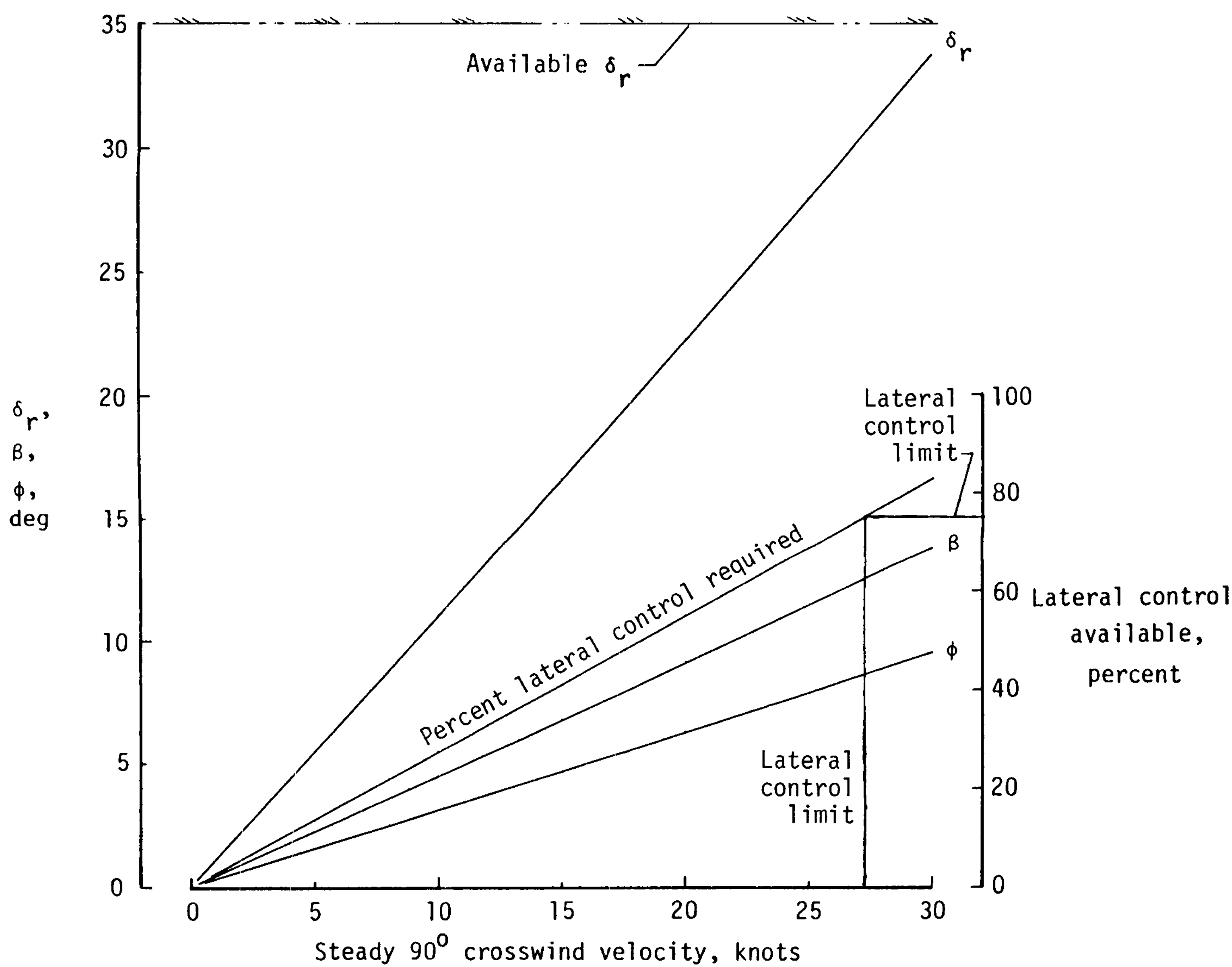


Figure 20. Crosswind trim capability of simulated twin-fuselage passenger transport concept.

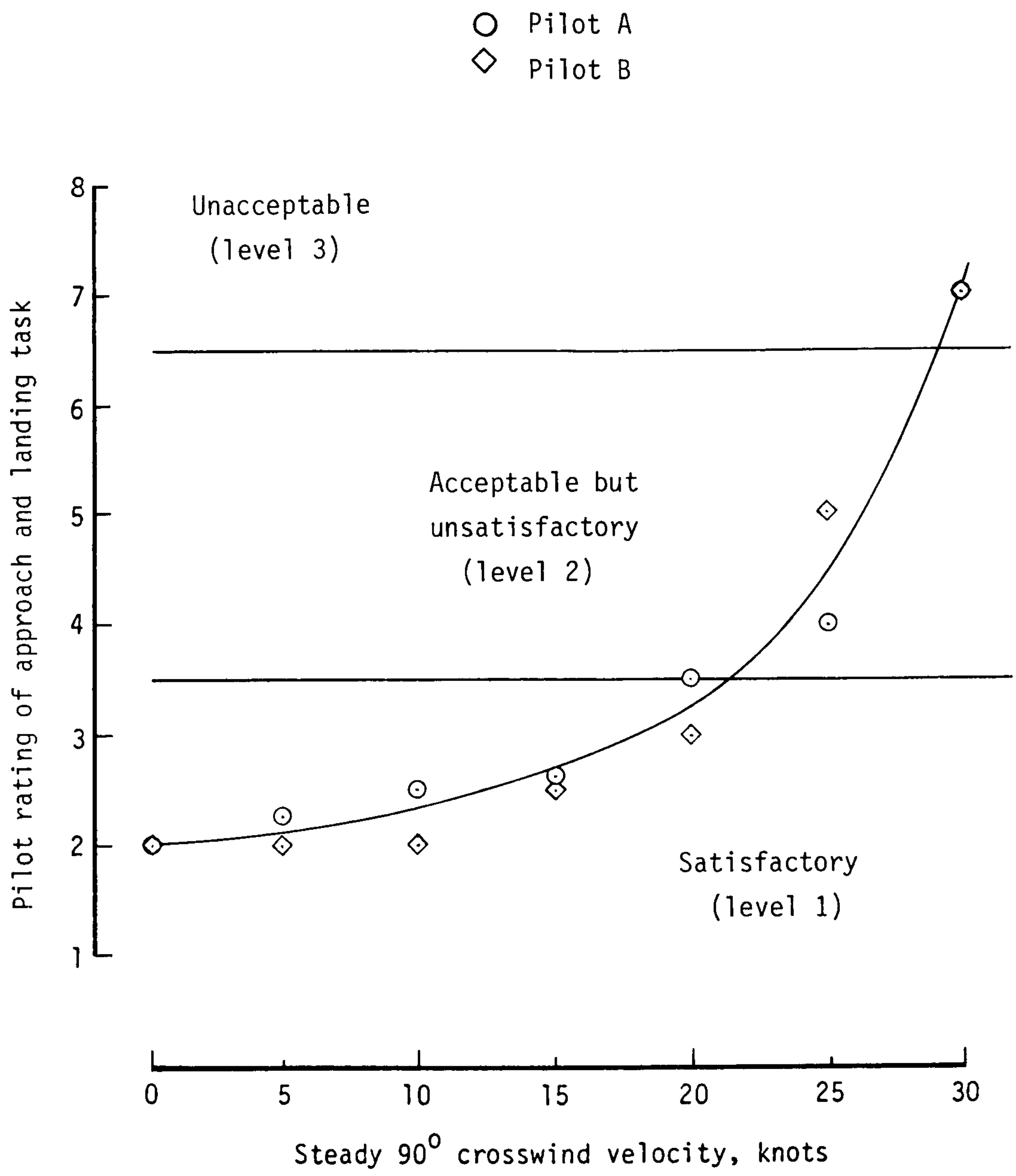


Figure 21. Pilot ratings of handling qualities for approach and landing task in 90°crosswinds.

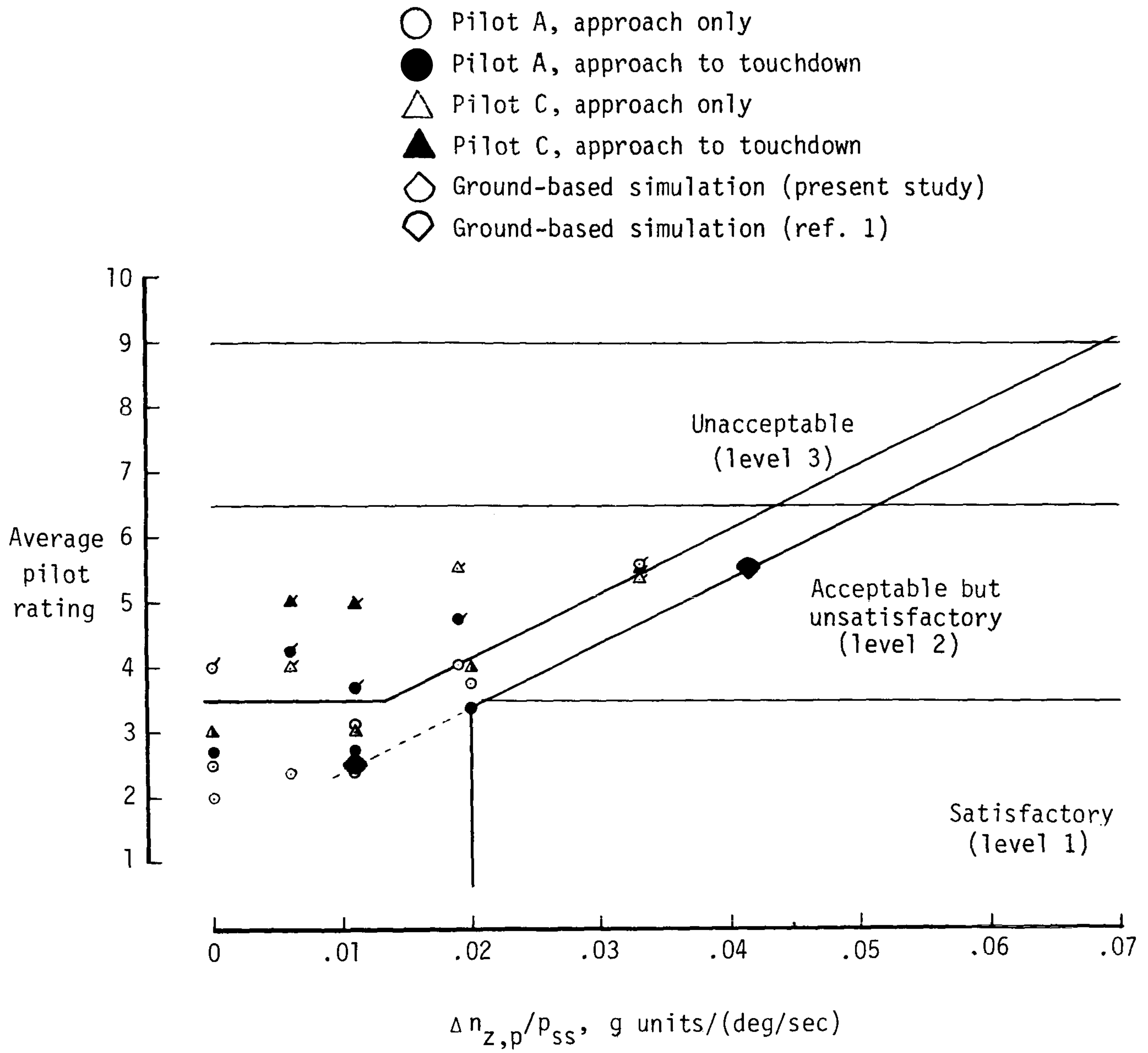


Figure 22. Average pilot rating relative to $\Delta n_{z,p}/p_{ss}$ for approach only and approach to touchdown based on in-flight simulation of twin-fuselage transport. $V_{cw} = 15$ knots; Lateral runway offset = 200 ft. Flagged symbols indicate PIO's (noticeable altitude changes due to roll control inputs). In-flight data from reference 11.

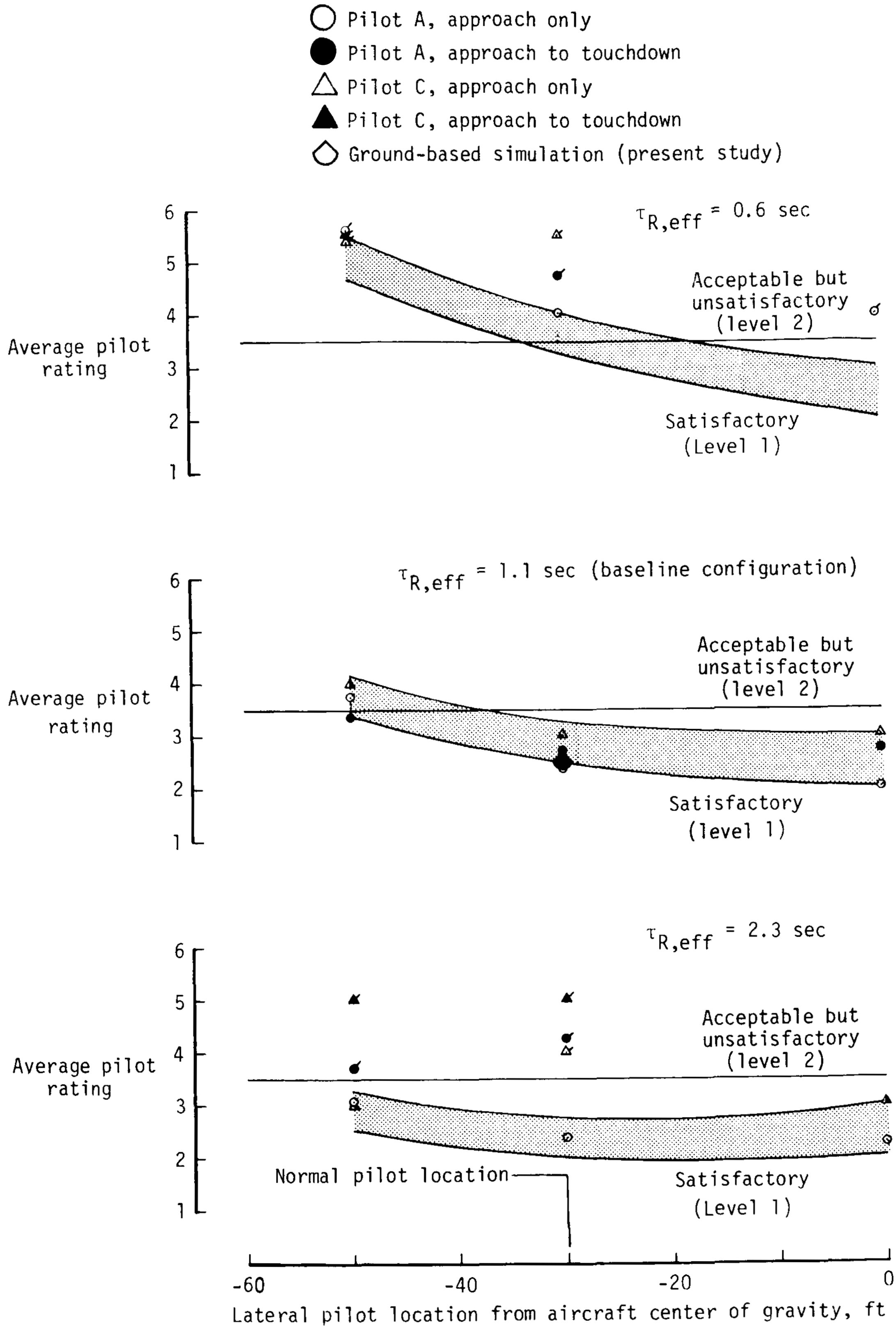


Figure 23. Effect of pilot location and effective roll mode time constant on pilot rating during approach and landing. Shaded areas based on test data containing predominantly normal acceleration cues.

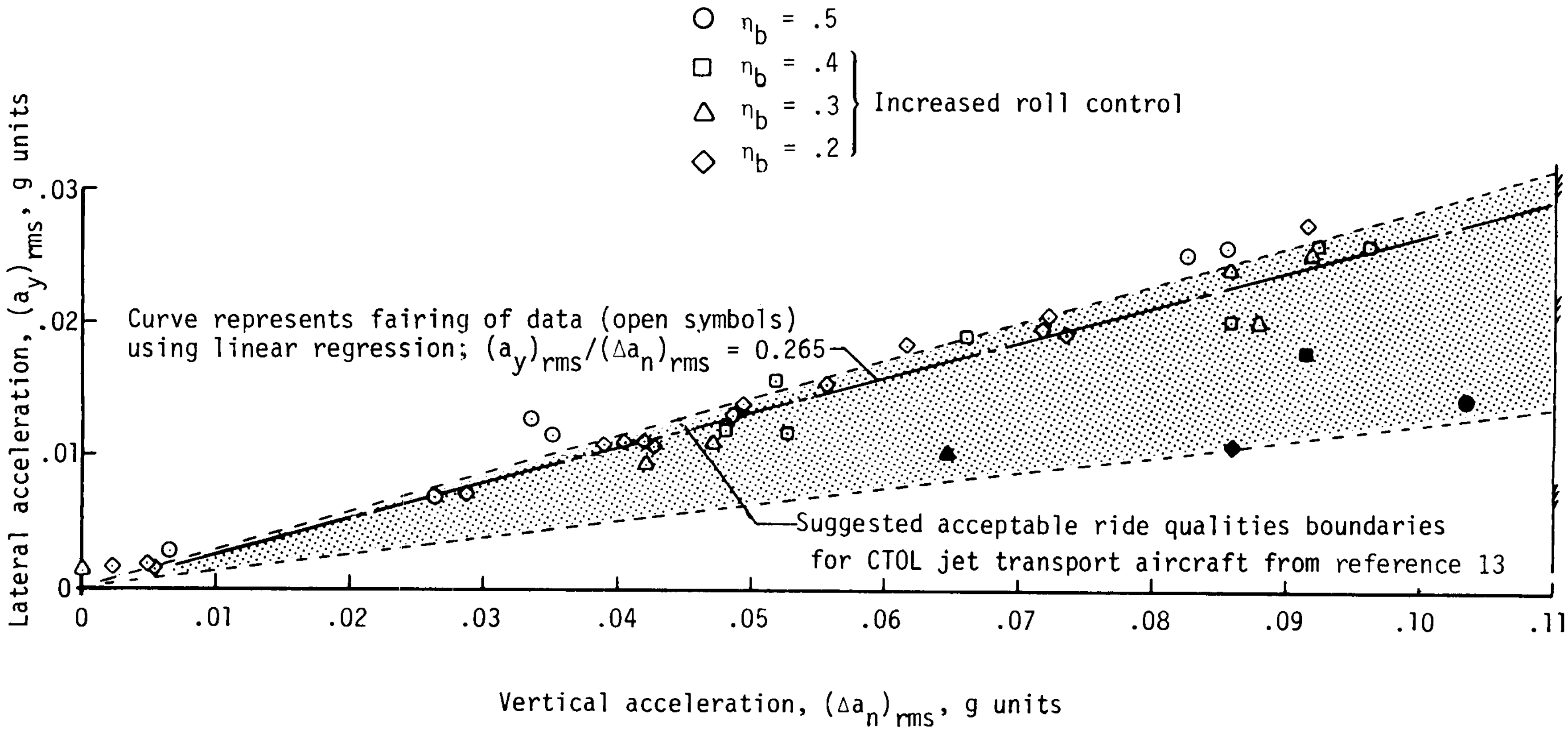


Figure 24. Acceleration responses measured at pilot station during landing task on various twin-fuselage configurations. Open symbols represent landing task in crosswinds or shear with 300-ft ceiling and 200-ft offset from runway centerline. Solid symbols represent landing task in heavy turbulence with 300-ft ceiling and no offset from runway centerline. (From ref. 1.)

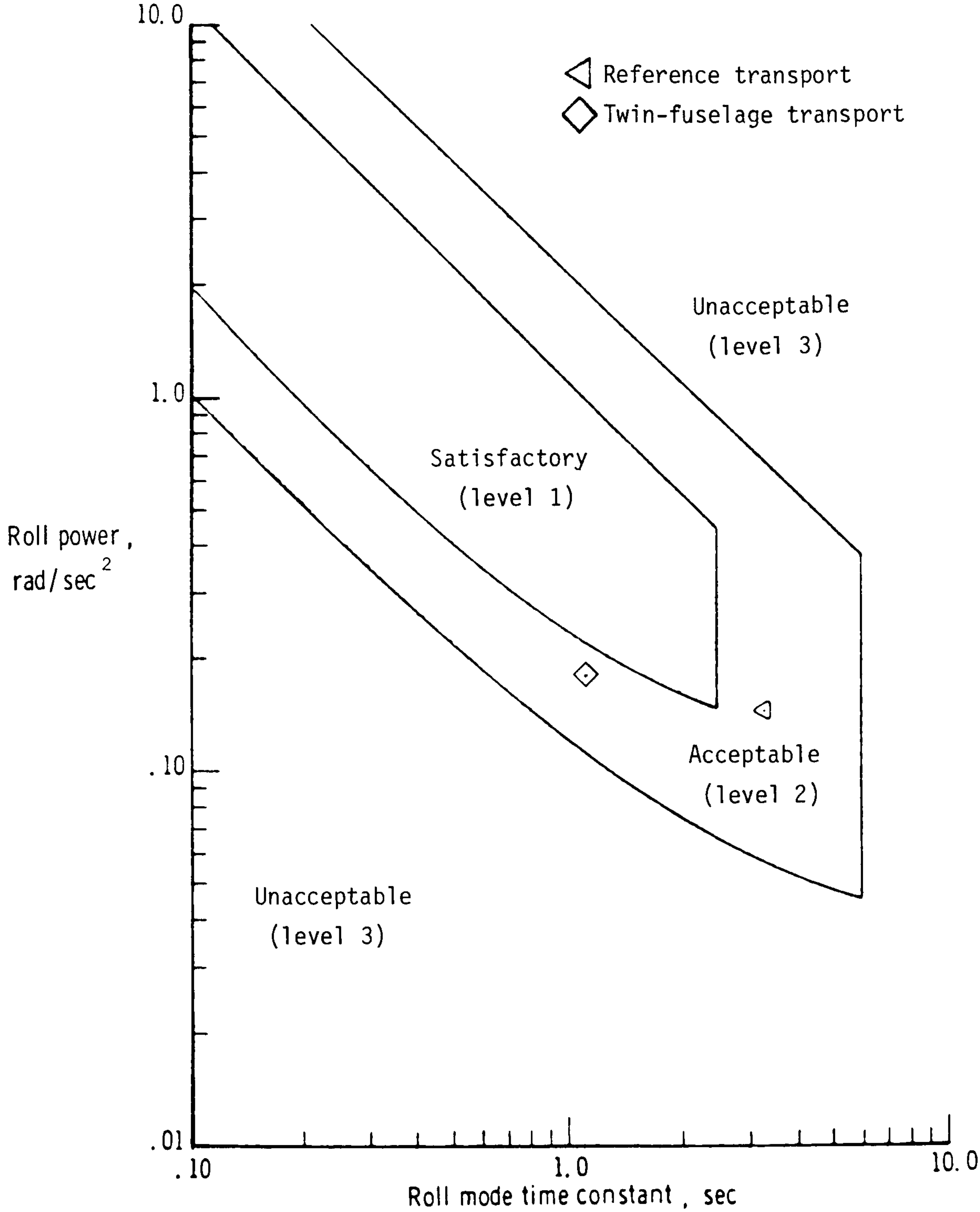


Figure 25. Roll acceleration response boundaries for large aircraft. Boundaries from reference 16.

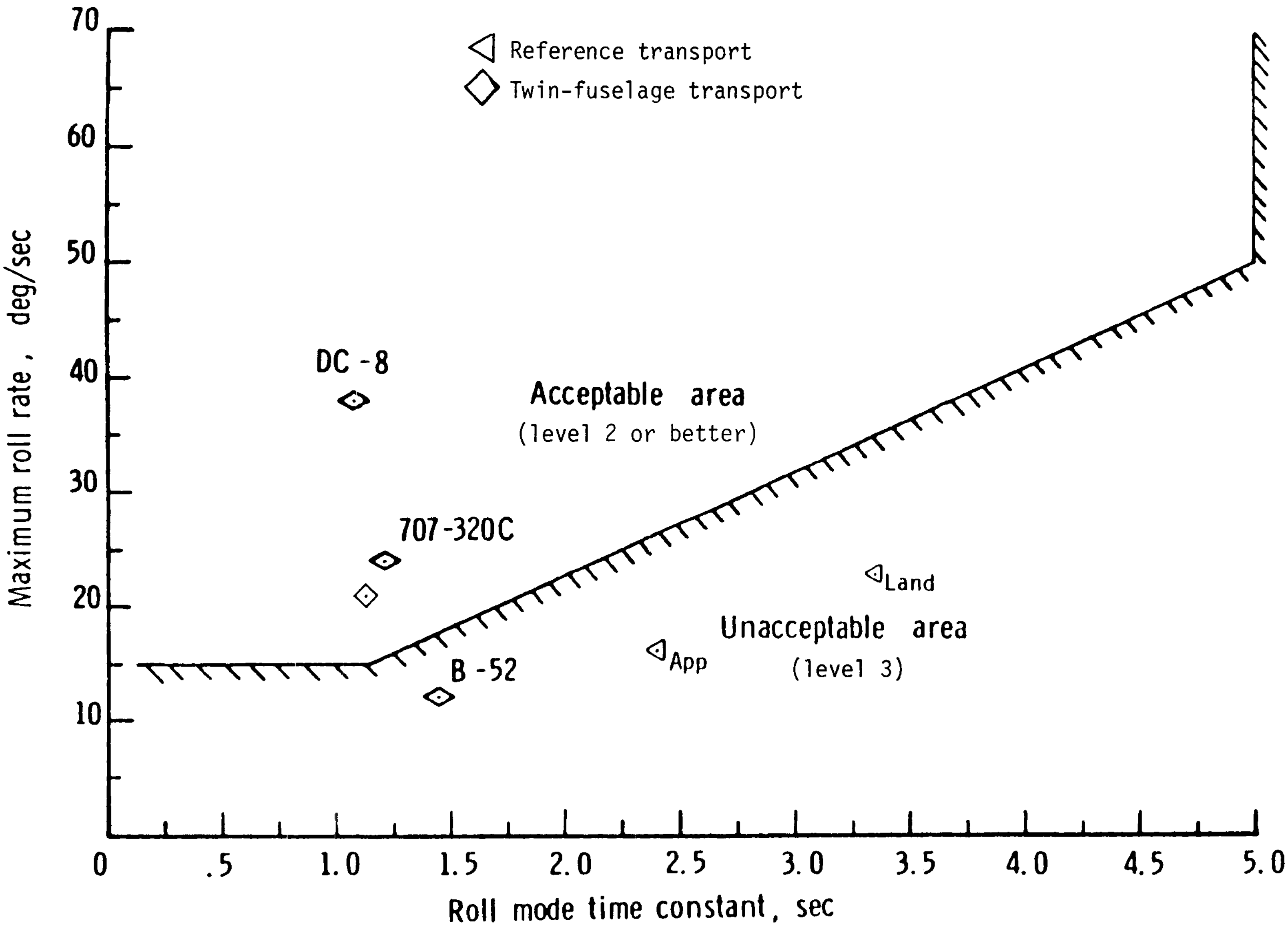
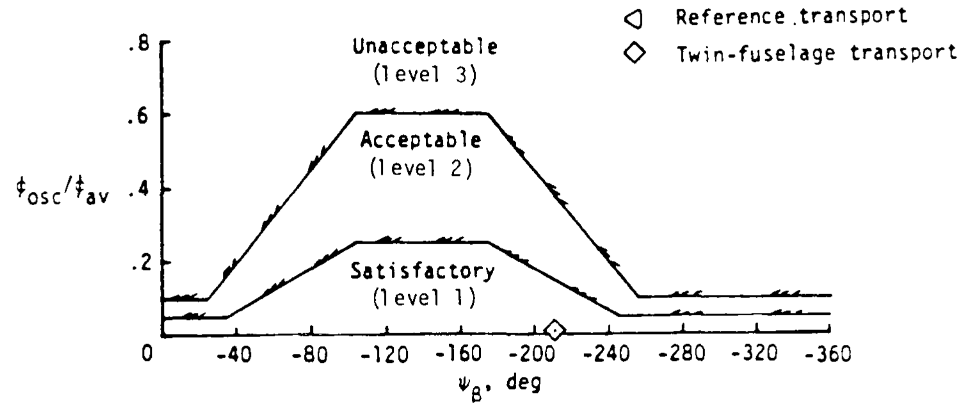
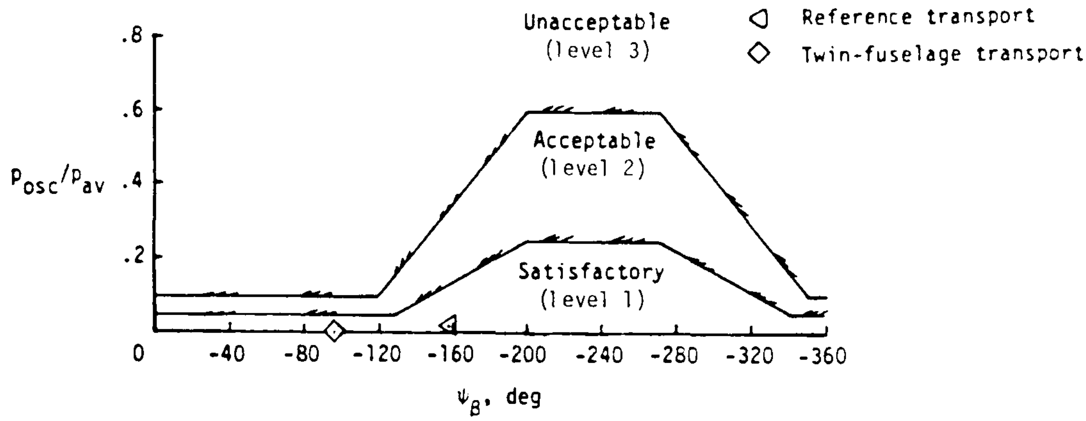


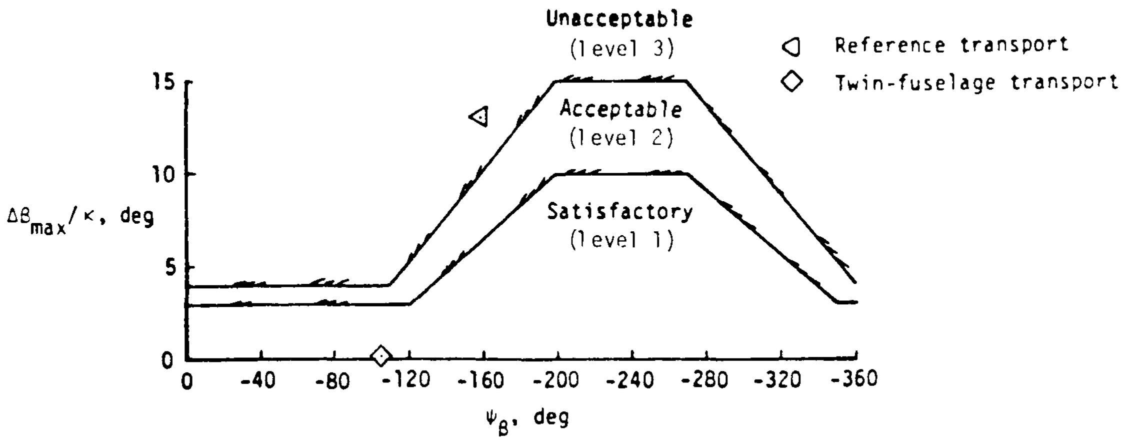
Figure 26. Roll-rate capability criterion for transport aircraft. Boundaries from reference 17.



(a) Bank-angle oscillation limitations.



(b) Roll-rate oscillation limitations.



(c) Sideslip excursion limitations.

Figure 27. Bank-angle oscillation, roll-rate oscillation, and sideslip excursion limitations of reference 5. Final approach; SCAS on.

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16. Abstract

Six-degree-of-freedom ground-based and in-flight simulator studies were conducted to evaluate the low-speed flight characteristics of a twin-fuselage passenger transport airplane and to compare these characteristics with those of a large, single-fuselage (reference) transport configuration similar to the Lockheed C-5A airplane. The primary piloting task was the approach and landing task. The results of this study indicated that the twin-fuselage transport concept had acceptable but unsatisfactory longitudinal and lateral-directional low-speed flight characteristics, and that stability and control augmentation would be required in order to improve the handling qualities. Through the use of rate-command/attitude-hold augmentation in the pitch and roll axes, and the use of several turn coordination features, the handling qualities of the simulated transport were improved appreciably. The in-flight test results showed excellent agreement with those of the six-degree-of-freedom ground-based simulator handling qualities tests. As a result of the in-flight simulation study, a roll-control-induced normal-acceleration criterion was developed. This criterion states that the ratio of maximum incremental acceleration at the pilot station to the steady-state roll rate following a step lateral control input ($\Delta n_{z,p}/p_{ss}$, g unit/(deg/sec)) shall not be greater than 0.020, 0.048, and 0.069 for pilot rating levels 1 (satisfactory), 2 (acceptable but unsatisfactory), and 3 (unsatisfactory), respectively. The handling qualities of the augmented twin-fuselage passenger transport airplane exhibited an improvement over the handling characteristics of the reference (single-fuselage) transport.

17. Key Words (Suggested by Authors(s))
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