SIMULATOR STUDY OF THE LOW-SPEED HANDLING QUALITIES OF A SUPERSONIC CRUISE ARROW-WING TRANSPORT CONFIGURATION DURING APPROACH AND LANDING

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SUMMARY

A fixed-based simulator study was conducted to determine the low-speed flight characteristics of an advanced supersonic cruise transport having an arrow wing, a horizontal tail, and four dry turbojets with variable geometry turbines. The primary piloting task was the approach and landing.

The results of the study indicated that the statically unstable (longitudinally) subject configuration has unacceptable low-speed handling qualities with no augmentation. Therefore a hardened stability augmentation system (HSAS) will be required to achieve "acceptable" handling qualities should the normal operational stability and control augmentation system (SCAS) fail. In order to achieve "satisfactory" handling qualities, considerable augmentation was required. Although the SCAS developed in this study to achieve satisfactory handling qualities was complex, it is within current technology.

It was concluded from the results of this study that additional research is required to achieve improved lateral-directional static stability and satisfactory control power on the subject supersonic cruise transport configuration - particularly roll control power and reduced dihedral effect.

INTRODUCTION

During the National Supersonic Transport (SST) Program of the early 1960's, various aerodynamic research studies conducted at NASA Langley to develop an efficient supersonic cruise transport airplane resulted in the highly-swept, arrow-wing configuration designated the SCAT-15F. The SCAT-15F offered considerable promise for superior supersonic cruise performance; but unfortunately, such configurations designed for high-speed flight do not usually possess good low-speed handling characteristics. Some early wind-tunnel and piloted simulation studies (for examples see refs. 1 and 2) identified some of the low-speed handling problems of the SCAT-15F. Also, in 1968, the Boeing Company made an in-depth study of a supersonic cruise transport concept which was based on the NASA arrow-wing SCAT-15F configuration (see fig. 1), and the results are reported in reference 3. That airplane configuration promised good take-off and landing performance by utilizing a lifting canard and a small horizontal tail; the primary purpose of the canard was to trim the pitching moments due to the wing trailing-edge flap deflections. Although the use of a canard improved the trimmed lift-to-drag ratios, there was an associated reduction in airplane stability for similar center-of-gravity positions.

Since the early 1970's, the Langley Research Center has been conducting extensive wind-tunnel tests in support of the Supersonic Cruise Aircraft Research (SCAR) Program to improve the stability characteristics of the arrow-wing configuration at high angles of attack (low speeds) without a canard and with an aft mounted horizontal tail. The resulting improvements in longitudinal stability were achieved by careful attention to wing planform, leading-edge radius, leading-edge high-lift devices and locations, and trailing-edge flap location, size, and deflection. Utilizing these improved aerodynamic characteristics, performance calculations have shown that with 2 to 3 percent negative static margin, this configuration should produce lift-to-drag ratios as good as those of the stable concept with a forebody canard. However, the results of lateral-directional stability and control analyses in reference 4 indicated that the arrow-wing concept had several inherent deficiencies - especially in the high-lift landing approach configuration. Specifically, these were sluggish roll response and inadequate wings-level sideslip capability.

Since the aforementioned studies were made without a pilot in the loop and since the analyses of those studies compared the calculated dynamic stability characteristics of an advanced supersonic cruise airplane design with criteria developed for conventional airplanes, the subject simulation study was undertaken to investigate the low-speed, pilot-in-the-loop flight characteristics of an advanced, arrow-wing supersonic cruise transport airplane performing representative approach and landing tasks. The primary objective of this simulation study was to obtain sufficient information to provide guidance for future low-speed research requirements. Other major objectives of the present study were:

1. Evaluate the general handling qualities of the unaugmented airplane in the approach configuration and at the approach speed.

2. Develop the stability augmentation and flight control systems required to achieve satisfactory handling qualities (Normal Operational Augmentation) as well as acceptable handling qualities (Hard Augmentation).

3. Determine the control power required to meet the established criteria.

4. Evaluate the effects of various atmospheric conditions, including heavy turbulence, steady winds, and wind shear on the ability of the pilot to make a satisfactory approach and landing.

5. Attempt to determine if existing handling qualities criteria can be applied to statically unstable supersonic cruise transport airplanes.

SYMBOLS

Values are given in both SI and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

$\bar{c}_{ref}$	reference mean aerodynamic chord, m (ft)
g	acceleration due to gravity, meters/sec^2 (ft/sec^2)
I_X, I_Y, I_Z	moments of inertia about X, Y, and Z body axes, respectively, kilogram-meters^2 (slug-ft^2)
I_{XZ}	product of inertia, kilogram-meters^2 (slug-ft^2)
P_{SP}	period of longitudinal short period oscillation, sec
P_d	period of Dutch roll oscillation, sec
p, q	rolling and pitching angular velocities, respectively, deg/sec or rad/sec
S	wing area, meters^2 (ft^2)
S_{a_n}	static normal acceleration gust sensitivity, g/(m/sec) (g/(ft/sec))
s	Laplace operator
T	thrust, newtons (pounds force)
$t_{1/2}$	time to damp to one-half amplitude, sec
t_2	time to double amplitude, sec
V	airspeed, knots (ft/sec)
W	airplane weight, newtons (pounds force)
α	angle of attack, deg
β	angle of sideslip, deg
θ	pitch angle, deg
ϕ	roll angle, deg
ψ	heading angle, deg
δ_c	control-column deflection, positive for pull force, deg

δ_f	flap deflection, deg
δ_p	pedal travel, centimeters (inches)
δ_r	rudder deflection, deg
δ_a	aileron deflection, positive for right roll command, deg
δ_{af}	flaperon deflection, positive for right roll command, deg
δ_s	asymmetric deflection of spoilers for roll control, positive for right roll command, deg
δ_t	horizontal-tail deflection, positive when trailing edge is deflected down, deg
δ_w	wheel deflection, deg
ζ_d	Dutch roll damping ratio
ζ_{SP}	short period damping ratio
ζ_ϕ	damping ratio of numerator quadratic of ϕ/δ_a transfer function
ρ	air density, kilograms/meter^3 (slugs/ft^3)
τ_R	time constant of roll mode, sec
ω_d	undamped natural frequency of Dutch roll 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
L_α	lift per unit angle of attack per unit of momentum, per second
C_{L_α}	lift coefficient curve slope per unit angle of attack, per radian
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/radian
ψ_β	phase angle expressed as a lag for a cosine representation of the Dutch roll oscillation in sideslip, deg
$t_{\phi=30^\circ}$	time required to roll 30°, sec
p_1, p_2	rolling angular velocities at the first and second peaks of a roll rate oscillation, deg/sec or rad/sec

Subscripts:

c	commanded
ss	steady state
osc	oscillation
ave	average

Abbreviations:

HSAS	hardened stability augmentation system
IFR	instrument flight rules
ILS	instrument landing system
PR	pilot rating
SCAS	stability and control augmentation system

DESCRIPTION OF SIMULATED AIRPLANE

The airplane concept studied is a resized version of the configuration described in reference 4. It is a conventional fossil-fueled supersonic cruise transport incorporating four under-the-wing, single-spool, dry turbojets with variable geometry turbines. A three-view sketch of the simulated airplane is presented in figure 2; its geometric characteristics are given in table I; and the engine response characteristics used in the simulation are presented in figure 3.

The static aerodynamic data were estimated based on various low-speed wind-tunnel test results, e.g. references 5 and 6, and corrected for configuration differences. The control surfaces used for low-speed lateral control consisted of outboard ailerons, outboard spoiler slot and inverted spoiler slot deflectors, and inboard flaperons. The rigid lateral control data were estimated based on unpublished aileron control tests, and the flaperon, spoiler slot and inverted spoiler slot deflector data were taken from reference 3, and modified to account for the size and location of the subject airplane's control surfaces. A 40-percent chord, full-span rudder was used for low-speed directional control. The rigid rudder effectiveness data were estimated by using the method presented in reference 4. The reduction of lateral control effectiveness due to wing flexibility was estimated based on the data presented in reference 3; and the reduction of directional control effectiveness due to fuselage side-bending was based on unpublished data. The methods presented in reference 7 were used to estimate the aerodynamic effects of ground proximity.

The dynamic stability derivatives were estimated using a combination of the forced oscillation test data of reference 1 and the estimation techniques of reference 8.

The mass and dimensional characteristics, and the control-surface deflection and deflection rate limits are presented in table I.

DESCRIPTION OF SIMULATION EQUIPMENT

The fixed-base simulator had a transport-type cockpit which was equipped with conventional flight and engine-thrust controls and with a flight-instrument display representative of those found in current transport airplanes. (See fig. 4.) Instruments indicating angle of attack, sideslip, and flap angle were also provided. A conventional cross-pointer-type flight director instrument was used, but the command bars (cross pointers) were driven by the main computer program.

The simulator control forces were provided by a hydraulic servosystem and were functions of control displacement and rate. The control characteristics of the simulator are defined in table II. Real-time digital simulation techniques were used wherein a digital computer was programed with equations of motion for six degrees of freedom. The simulator did not incorporate cockpit motion.

A visual display of a hypothetical airport (fig. 5) was used in order to provide visual cues for the flare and landing. The display consisted of a closed-circuit television presentation, viewed through a collimating lens in the pilot's windshield, of the simulated approach to a 3505-meter (11,500 ft) runway. (See fig. 6.) Each flight was terminated at touchdown; the roll-out was not simulated.

TESTS AND PROCEDURES

The low-speed flight characteristics of the subject supersonic cruise transport airplane are presented and discussed in relation to pilot opinions and ratings (see table III for pilot rating system). Three research pilots participated in the simulation program and used standard flight-test procedures in the evaluation of the handling qualities. The primary piloting task was the approach and landing.

The ILS approach was initiated with the airplane in the power-approach condition (power for level flight) with a lateral offset from the localizer and at an altitude below the glideslope. The pilot's task was to capture the localizer and glideslope and to maintain them as closely as possible while under IFR conditions. At an altitude of 61 meters (200 ft) a visual display of the runway and surrounding area was displayed to the pilot, and from that altitude the pilot attempted to land the airplane visually (with limited reference to the flight director).

The various atmospheric conditions simulated included calm air, heavy turbulence, steady crosswinds, and various wind shears.

RESULTS AND DISCUSSION

The results of this study are discussed in terms of the previously stated objectives. Also, throughout the discussion, the pilot ratings listed for the various conditions will be an average of the ratings from all pilots who "flew" that particular condition.

The dynamic stability and response characteristics of the simulated supersonic cruise transport airplane for various levels of stability augmentation are presented in tables IV and V.

Basic Airplane (No Augmentation)

The pilot rating assigned to the longitudinal handling qualities of the unaugmented airplane was seven. As can be seen from table IV, the time to double amplitude (t_2) of the longitudinal aperiodic mode is 4.6 seconds, which might be expected to be unacceptable since the landing approach minimum-safe (PR = 6.5) criterion of reference 9 stated that a $t_2 < 6$ seconds would be unacceptable. A comparison of the pitch rate response of the unaugmented airplane to the desired response is presented in figure 7, and shows that the response to a column step input appears as an acceleration command instead of the desired rate command. Table V indicates that the airplane also has less than satisfactory pitch control power.

A pilot rating of seven was assigned to the unaugmented lateral-directional handling qualities. The major objections were: (1) unacceptably large adverse sideslip excursions in turns; (2) easily excited, lightly damped Dutch roll mode; (3) poor roll and heading control; and (4) sluggish roll response with low roll damping. The dynamic parameters shown in table IV indicate acceptable roll ($\tau_R < 3.0$) and Dutch roll characteristics ($\zeta_d \omega_d > 0.05$) according to reference 10. However, the pilots commented that more roll damping and Dutch roll damping were desirable. The primary factor that contributed to the poor pilot rating for the lateral-directional characteristics was the large adverse sideslip excursions experienced during rolling maneuvers. This characteristic is indicated in figure 8, and compared with the desired response for a lateral control step input. For a step input it is desirable to have: (1) a fast roll rate response that reaches a reasonably steady state value with a minimum of oscillations; (2) essentially zero sideslip produced by the roll control input; and (3) an immediate response in heading. However, it is obvious from figure 8 that for a lateral control step input on this unaugmented configuration, a large amount of adverse sideslip is experienced that washes out the roll rate ($\dot{\phi}$) in a short period of time and also causes an undesirable lag in the initiation of turn rate ($\dot{\psi}$). This large adverse sideslip characteristic, in combination with the low roll damping, required constant attention and considerable effort on the part of the pilot; even then, the lateral-directional control remained very poor.

It must be noted that although the longitudinal and lateral-directional handling qualities of this unaugmented supersonic cruise transport airplane were assigned a pilot rating of seven when evaluated individually, the combination of these resulted in a PR = 10 for all aspects of the airplane. Therefore, it is apparent that considerable stability and control augmentation will be required to achieve satisfactory handling qualities for the landing approach piloting task.

Normal Operational Stability and Control Augmentation System (SCAS)

Based on the results obtained for the unaugmented configuration the approach selected for design of the 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 obtained with this approach is shown in figure 9.

Longitudinally, a high gain pitch rate command/attitude hold system was chosen because: (1) stabilization of the unstable mode was achieved with the pitch attitude feedback; (2) the system provided good short-period characteristics and fast response to pilot inputs; and (3) the attitude hold feature minimized disturbances due to engine coupling effects and turbulence.

Laterally, a roll rate command/attitude hold system was employed to provide a fast roll mode and quick, uniform response to pilot inputs; the attitude hold feature resulted in a neutrally stable spiral mode while counteracting disturbances due to turbulence. Directionally, roll rate and roll attitude feedbacks were used to provide turn coordination and improved Dutch roll characteristics. A roll control to rudder interconnect was also included to reduce adverse sideslip and therefore minimize Dutch roll coupling during roll maneuvers (obtained $\omega_\phi/\omega_d \approx 1$).

An autothrottle was also used as part of the normal operational augmentation that maintained the selected airspeed during the approach and landing. Since the simulated engine dynamics produced very quick thrust response, the autothrottle generally maintained the desired airspeed within ±2 knots, and therefore reduced the pilot workload on the landing approach. Although this airplane is flown well up the "backside" of the thrust required curve at the approach speed of 153 knots $\left| \frac{\partial T/W}{\partial V} \approx -0.0023/\text{knot} \right.$, where normally the pilot would primarily use pitch attitude for airspeed control and thrust for glidepath control, the simulated quick, engine-thrust response allowed the use of thrust (manually or automatically) for airspeed control and thus enabled the pilot to use pitch attitude for glidepath control - which is a very natural, simple technique.

The longitudinal SCAS (fig. 9) provided 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. Figure 10 shows the improvement in pitch rate response provided by the SCAS, and it can be seen from table IV that the time to double amplitude (t_2) of the longitudinal aperiodic mode increased from 4.6 seconds with no augmentation to infinity with the SCAS configuration. With this augmentation system operative, the average pilot rating for the longitudinal handling qualities on the ILS approach was improved from seven with no augmentation to two.

Also shown in figure 9 is a block diagram of the lateral-directional SCAS. Laterally, a rate command system provided roll rate proportional to wheel position, and the directional system consisted of several turn coordination features. Table IV shows that the Dutch roll characteristics were improved considerably; (ω_ϕ/ω_d) was increased from 0.565 to 1.03, 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 0.066 rad/sec to 0.182 rad/sec. The improvement in the roll response and damping are indicated by the reduction of τ_R from 1.6 sec to 0.38 sec (table IV).

Figure 11 shows the improvement in the roll rate response provided by the SCAS; by elimination of the large adverse sideslip, the roll-rate reversal was eliminated and the heading response was immediate (no lag). The lateral SCAS also provided a desirable roll-attitude-hold feature which proved to be very beneficial, particularly during landing approaches made in simulated heavy turbulence. With this augmentation system operative, the average pilot rating for the lateral-directional handling qualities on the ILS approach was improved from seven with no augmentation to two with augmentation.

With the SCAS operative, the overall pilot rating of this simulated supersonic cruise transport airplane for the landing approach piloting task was two.

Hardened Stability Augmentation System (HSAS)

As discussed previously, the configuration had unacceptable low-speed handling qualities with no augmentation. Therefore, a hardened stability augmentation system (HSAS) will be required to achieve acceptable handling qualities should the normal operational augmentation (SCAS) fail. (The term "hardened" SAS implies sufficient redundancy to negate loss of this system.)

The HSAS design objective was to provide improved handling qualities so that acceptable pilot ratings ($PR \leq 6.5$) could be obtained for the approach and landing task, and that the system be kept as simple as possible to maximize reliability and ease of implementation. The HSAS design obtained using this approach is shown in figure 12. Longitudinally, a filtered pitch rate feedback signal acting through a relatively high gain was used to reduce the instability of the unstable mode and to enhance the short period characteristics. Laterally, a simple roll damper provided a faster roll mode and increased Dutch roll damping. Directionally, roll rate feedback was used to provide: (1) improved turn-entry coordination; (2) reduced Dutch roll coupling during roll maneuvers (increased (ω_ϕ/ω_d); and (3) further enhancement of the Dutch roll damping. Note that only two angular rate signals (pitch rate and roll rate) were required for the HSAS implementation so that sensor reliability problems and mechanization complexity would be minimized. The autothrottle was also considered to be part of the HSAS.

The average pilot rating assigned to the longitudinal handling qualities when the HSAS was operative was four. The primary objection was the less than desired pitch damping. Table IV shows that the short-period damping ratio (ζ_{SP}) for this configuration is 0.693, which would normally indicate adequate damping; however, the slowly divergent aperiodic mode (t_2 = 25.3 sec) superimposed on the short-period response caused the motions to appear to the pilot as being inadequately damped. It should be noted that reference 9 also indicated acceptable pilot ratings (PR $\leq$ 6.5) when t_2 was greater than 6 seconds. Figure 10 compares the pitch response to a column step for the unaugmented airplane, with SCAS operative, and with HSAS operative. The reason a higher gain was not implemented for the pitch rate damper, in order to satisfy the pilot's objection of low pitch damping, was that more damping would make the pitch axis unacceptably sluggish. It is obvious from figure 10 that the HSAS configuration is already very sluggish in pitch, compared to the SCAS configuration.

The average pilot rating assigned to the lateral-directional handling qualities with the HSAS operative was four. The primary objections were sluggish roll response and less than desired roll damping. Figure 11 shows a comparison of the roll response to a lateral control step input for the HSAS, SCAS, and unaugmented configurations.

Effects of Turbulence on Landing Apporach

Flight in rough air was evaluated by using a turbulence model based on the Dryden spectral form. The root-mean-square value of the longitudinal, lateral, and vertical gust-velocity components was 2.7 m/sec (9 ft/sec) and these values were described by the pilots as being representative of heavy turbulence.

Static normal acceleration gust sensitivity can be defined as $S_{a_n} = \frac{C_{L_\alpha}\rho V}{2W/S}$; that is, the vertical response of an airplane to turbulence is directly proportional to the product of lift-curve slope and velocity, and is inversely proportional to the wing loading. Table VI presents a comparison of S_{a_n} for the subject supersonic cruise transport and a typical present-day subsonic jet transport during the landing approach. Note that the lower value of C_{L_α} for the subject supersonic transport is offset by the lower wing loading and slightly higher airspeed. Therefore, the two S_{a_n} values are nearly equal; the supersonic cruise transport actually showing a slightly lower value. From consideration of these points, the response of the subject supersonic cruise airplane to atmospheric turbulence would not be expected to be any worse than the response of present-day subsonic transport airplanes - neglecting flexibility differences.

The pilots commented that the pilot rating for the approach task on the subject supersonic cruise transport airplane was degraded by one rating when the landing approach was made in the simulated heavy turbulence since the ILS glideslope tracking task required considerable pilot effort - added pilot workload.

Crosswind Landings

Both steady crosswinds (up to 20 knots) and crosswinds with horizontal shear were simulated. The piloting technique used for making the approach and landing was the same for all crosswind conditions flown. The technique consisted of - crabbed approach, and at some nominal altitude, usually about 15 meters (50 ft), changing to a sideslipping, wing-down condition.

The requirements of reference 10 are that transport airplanes without crosswind landing gear be capable of landing in 90° crosswinds up to 30 knots, and that the lateral control used shall not exceed 75 percent of the control power available. Figure 13 indicates the amount of steady-state sideslip, bank angle, rudder deflection, and lateral control deflection required for sideslipping crosswind approaches at an airspeed of 153 knots (the nominal approach speed). It can be seen that 75 percent of available lateral control was required for a crosswind component of approximately 21 knots. It is, therefore, obvious that this supersonic cruise transport airplane could not be landed (with an adequate lateral control margin) in 90° crosswinds higher than approximately 20 knots. Also, from a piloting standpoint, the lateral-directional control coordination required for the transition from a crabbed-approach condition to a sideslipping, wing-down condition becomes increasingly difficult as the 90° crosswind increases above approximately 15 knots. It is, therefore, concluded from these ground-based, fixed-cockpit simulator results that the subject supersonic cruise transport airplane should be equipped with crosswind gear and/or provided with additional roll control power.

It should be mentioned that although the accuracy of the control coordination was the prime factor that affected the pilot's ability to make "precise" landings in high crosswinds, deficiencies of the visual presentation (lack of peripheral vision and adequate height cues) and possibly the lack of cockpit motion also affected the pilot's ability to make satisfactory landings in large crosswinds.

Dynamic Stability Requirements and Criteria

For several years the aircraft industry has been aware that many of the existing stability requirements of aircraft have become outdated because of the expansion of flight envelopes and the increases in airplane size. Although research is presently being conducted in an effort to remedy this situation, to date essentially no clearly defined stability requirements and criteria have been established for aircraft similar to that for the supersonic cruise transport. Therefore, in an effort to aid in the establishment of new stability requirements, the low-speed handling qualities parameters of the subject supersonic transport are compared with existing handling qualities criteria.

Two of the most widely used longitudinal handling qualities criteria are presented in figure 14. Figure 14(a) shows the short-period frequency requirements of reference 10, and as can be seen, this criterion agrees with the results obtained during the present simulation study. Figure 14(b) shows the Shomber-Gertsen longitudinal handling qualities criterion of reference 11. 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 by recognizing that the pilot's mode of control is not constant for all flight regimes, a criterion for satisfactory short-period characteristics was developed that correlates well with current airplane experience, and reasonably well with the results obtained during the present low-speed supersonic cruise transport simulation program. The low-speed pitch rate response criterion shown in figure 15, and reported in reference 12, was based on the Shomber-Gertsen criteria. As can be seen, there is excellent agreement of the results obtained during the present study and this low-speed pitch response criterion when the normal operational augmentation (SCAS) was operative. The constraints imposed upon the use of this criterion, however, negates its use for any of the other configurations evaluated during the present study. The pitch divergence criterion of reference 9, with a time-to-double pitch attitude of 6 seconds or greater for the most unstable root, was considered when the HSAS and unaugmented configurations were evaluated, and the subject simulation results agreed very well with the criterion.

The roll rate and bank angle oscillation limitations criteria of reference 10 are presented in figure 16. Figure 16(a) relates the phase angle of the Dutch roll component of sideslip (ψ_β) to the measure of the ratio of the oscillatory component of roll rate to the average component of roll rate $\frac{p_{osc}}{p_{ave}}$, and figure 16(b) relates the measure of the ratio of the oscillatory component of bank angle to the average component of bank angle $\frac{\phi_{osc}}{\phi_{ave}}$ with ψ_β. The conditions evaluated during the present simulation study are indicated in these plots, and it can be seen that these simulated characteristics agree, reasonably well, with the aforementioned criteria - particularly the fully augmented (SCAS) and unaugmented conditions.

Figure 17 presents a criterion for satisfactory roll-sideslip coupling characteristics. This criterion relates pilot rating to the roll coupling parameter ω_ϕ/ω_d, as presented in reference 13, and the conditions flown during the present simulation are indicated. It is seen that the results of this study agree very well with this criterion.

In general, it is concluded that the results of the present simulation study agree with the established handling qualities criteria used for comparison in this paper.

SUMMARY OF RESULTS

A fixed-base simulator program was conducted to determine the low-speed flight characteristics of an advanced supersonic cruise transport having an arrow wing, an aft mounted horizontal tail, and four dry turbojets with variable geometry turbines. The primary piloting task was the approach and landing. The results may be summarized as follows:

1. This statically unstable (longitudinally) supersonic cruise transport configuration has unacceptable low-speed handling qualities with no augmentation. Therefore, a hardened stability augmentation system (HSAS) will be required to achieve acceptable handling qualities should the normal operational stability and control augmentation system (SCAS) fail.

2. The longitudinal normal operational stability and control augmentation system, consisting of a high-gain pitch rate command/attitude hold system and an autothrottle, essentially eliminated the longitudinal control problems. The lateral-directional SCAS, consisting of a roll rate command/attitude hold system, and of roll rate (p), roll angle (ϕ), and roll control deflection (δ_w) feedback signals to the rudder, made the lateral-directional handling characteristics satisfactory. With these augmentation systems operative, the average pilot rating for the instrument approach task was 2.

3. The hardened stability augmentation system (HSAS), designed to provide "acceptable" handling qualities with maximum simplicity (for reliability and ease of implementation), consisted of a filtered pitch rate feedback signal to the longitudinal control surface for additional pitch damping, and a roll rate feedback signal to the roll control surfaces as well as to the rudder for additional roll damping and improved turn-entry coordination. With this HSAS operative, the average pilot rating for the instrument approach task was 4.

4. The available control power for all axes (roll, pitch, and yaw) was determined to be inadequate to meet existing handling qualities and crosswind requirements.

5. The response of the subject supersonic cruise transport airplane to atmospheric turbulence would not be expected to be any worse than the response of present-day subsonic transport airplanes - neglecting flexibility differences. However, the pilots commented that the pilot rating for the approach task on the subject supersonic cruise airplane was degraded by one rating when the landing approach was made in the simulated heavy turbulence since the glideslope tracking task required higher pilot workload.

6. In general, it is concluded that the results of the subject simulation study agree with the established handling qualities criteria used for comparison in this paper.

7. It is concluded that additional low-speed research is required to achieve satisfactory control power on this supersonic cruise transport configuration - particularly, roll control power.

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TABLE I.- MASS AND DIMENSIONAL CHARACTERISTICS OF SIMULATED SUPERSONIC CRUISE TRANSPORT AIRPLANE (LANDING WEIGHT)

Weight, N (lbf)	1,924,479 (432,640)
Reference wing area, m^2 (ft^2)	784.75 (8,447)
Wing span, m (ft)	38.66 (126.83)
Wing leading-edge sweep, deg	74.00/70.84/60.00
Reference mean aerodynamic chord, m (ft)	27.00 (88.59)
Center-of-gravity location, percent $\bar{c}_{ref}$	56
Static margin, percent	(-3.2)
I_X, kg-m^2 (slug-ft^2)	6,887,550 (5,080,000)
I_Y, kg-m^2 (slug-ft^2)	67,994,260 (50,150,000)
I_Z, kg-m^2 (slug-ft^2)	72,902,230 (53,770,000)
I_{XZ}, kg-m^2 (slug-ft^2)	-2,833,660 (-2,090,000)

Maximum control-surface deflections:

δ_t, deg	± 20
δ_f, deg	0 to 40
δ_a, deg	± 30
δ_{af}, deg	± 22.5
δ_s, deg	± 50
δ_r, deg	± 35

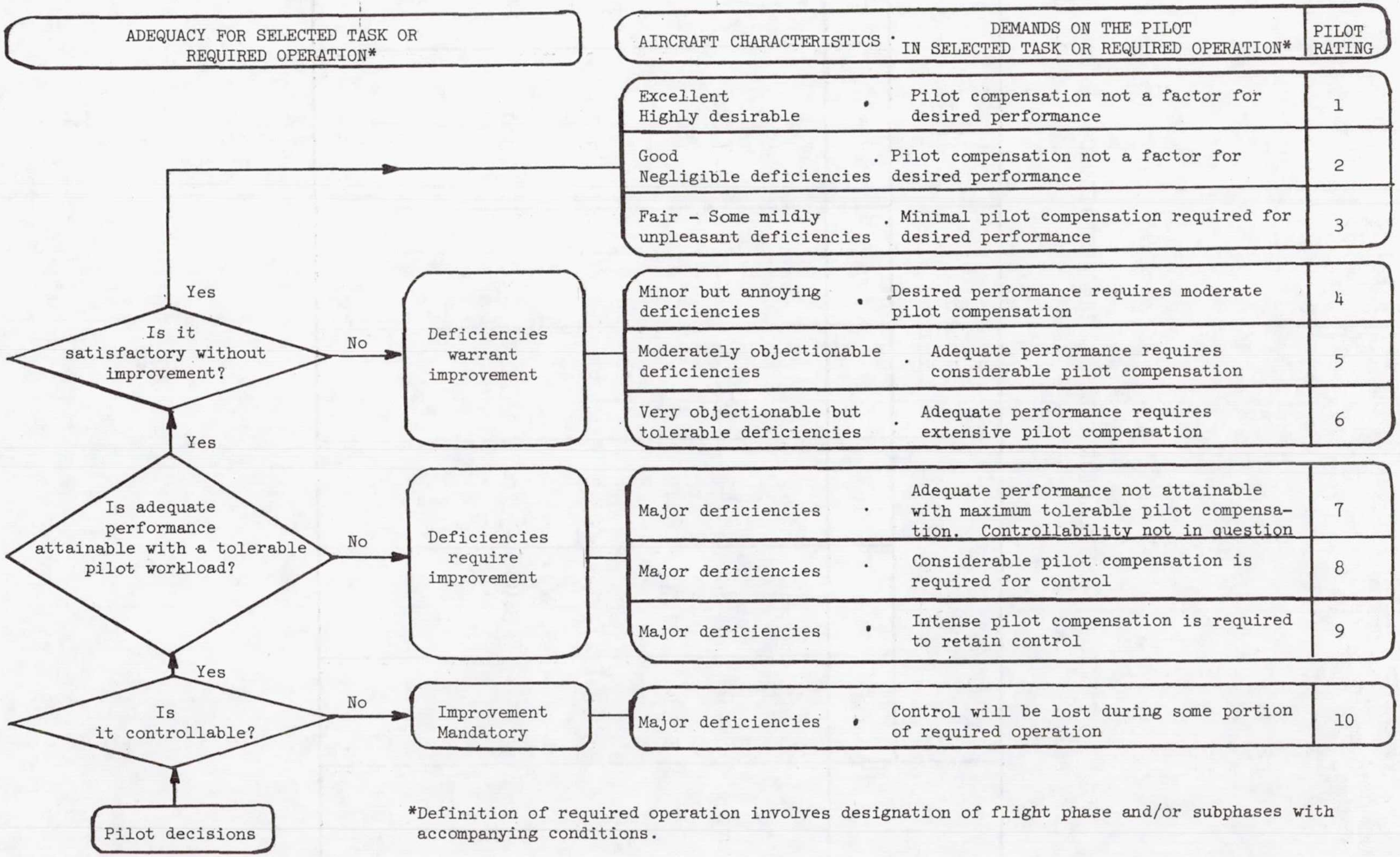
Maximum control-surface deflection rates:

$\dot{\delta}_t$, deg/sec	± 50
$\dot{\delta}_f$, deg/sec	± 10
$\dot{\delta}_a$, deg/sec	± 70
$\dot{\delta}_{af}$, deg/sec	± 40
$\dot{\delta}_s$, deg/sec	± 50
$\dot{\delta}_r$, deg/sec	± 50

TABLE II.- SIMULATOR CONTROL CHARACTERISTICS

Control	Maximum Travel In			Breakout Force		Force Gradient	
	deg	cm	in.	N	lbf	N/cm	lbf/in.
Column:							
Forward	14.0	16.43	6.47	15.5	3.5	17.5	10.0
Aft	18.0	21.34	8.40				
Wheel	±55.0	±16.48	±6.48	13.3	3.0	3.8	2.2
Pedal		±8.89	±3.50	15.3	3.5	70.0	40.0

TABLE III.- PILOT RATING SYSTEM



AIRCRAFT CHARACTERISTICS	DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION*	PILOT RATING
Excellent Highly desirable	Pilot compensation not a factor for desired performance	1
Good Negligible deficiencies	Pilot compensation not a factor for desired performance	2
Fair - Some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	3
Minor but annoying deficiencies	Desired performance requires moderate pilot compensation	4
Moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	5
Very objectionable but tolerable deficiencies	Adequate performance requires extensive pilot compensation	6
Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question	7
Major deficiencies	Considerable pilot compensation is required for control	8
Major deficiencies	Intense pilot compensation is required to retain control	9
Major deficiencies	Control will be lost during some portion of required operation	10

*Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

TABLE IV.- DYNAMIC STABILITY CHARACTERISTICS OF SIMULATED SUPERSONIC CRUISE TRANSPORT AIRPLANE

Augmentation / Parameters	None	HSAS*	SCAS*	Satisfactory criterion	Acceptable criterion
Short-period mode					
ω_{SP}, rad/sec	.154	.714	1.249	See figure 14	See figure 14
P_{SP}, sec	50.90	12.21	11.03	–	–
ζ_{SP}	.598	.693	.890	.35 to 1.30	.25 to 2.00
L_{α}/ω_{SP}	2.490	.537	.307	See figure 14	See figure 14
n/α, g units/rad	3.13	3.13	3.13	–	–
Long-period (aperiodic) mode					
t_2, sec	4.6	25.3	∞	–	> 6
Roll mode					
τ_R, sec	1.656	.545	.380	≤ 1.4	≤ 3.0
Spiral mode					
$t_{1/2}$, sec	21.2	18.6	∞	–	–
Dutch roll mode					
ω_d, rad/sec	.811	.480	.991	$> .4$	$> .4$
ζ_d	.081	.419	.184	$> .08$	$> .02$
$\zeta_d \omega_d$, rad/sec	.066	.201	.182	$> .15$	$> .05$
P_d, sec	7.77	14.42	6.45	–	–
ϕ/β	2.71	2.55	.88	–	–
Roll-control parameters					
ω_{ϕ}/ω_d	.565	.956	1.03	See figure 17	See figure 17
ζ_{ϕ}/ζ_d	3.12	.630	1.42	–	–

*Autothrottle on.

TABLE V.- CONTROL RESPONSE CHARACTERISTICS OF SIMULATED SUPERSONIC CRUISE TRANSPORT AIRPLANE

Parameter \ Augmentation	None	HSAS*	SCAS*	Satisfactory Criterion	Acceptable Criterion
Longitudinal					
$\ddot{\theta}_{max}$, rad/sec^2	$-.062^+$	$-.052^+$	$-.062^+$	$-.08$	-
$\dot{\theta}/\dot{\theta}_{ss}$	-	-	See fig. 15	See figure 15	-
Lateral					
$\ddot{\phi}_{max}$, rad/sec^2	.243	.203	.205	See figure 18	See figure 18
$\dot{\phi}_{max}$, deg/sec	16.84	9.54	20.86	-	See figure 18
p_2/p_1	$-.111$	.802	.896	$\geq .60$	$\geq .25$
p_{osc}/p_{ave}	1.299	.121	.007	See figure 16	See figure 16
ϕ_{osc}/ϕ_{ave}	1.042	.052	.052	See figure 16	See figure 16
$t_{\phi = 30^\circ}$, sec	2.66	3.88	2.65	≤ 2.5	≤ 3.2

* Autothrottle on.

[+] Minimum demonstrated speed of 125 knots. Note that at the design minimum demonstrated speed of 140 knots the criterion is satisfied.

TABLE VI.- COMPARISON OF SIMULATED SUPERSONIC CRUISE TRANSPORT AND TYPICAL SUBSONIC JET TRANSPORT GUST SENSITIVITY PARAMETERS

$$\left[S_{a_n} = \frac{C_{L_\alpha} \rho V}{2W/S} \right]$$

AIRPLANE	Weight, kN (lbf)	Wing Area, m^2 (ft^2)	W/S, kN/m^2 (lbf/ft^2)	C_{L_α}, RAD^{-1}	V, m/sec (ft/sec)	S_{a_n}, g/(m/sec) (g/(ft/sec))
Supersonic cruise transport	1924.5 (432640)	784.7 (8447)	2.5 (51.2)	2.06	78.8 (258.4)	0.056 (.017)
Subsonic jet transport	800.7 (180000)	256.2 (2758)	3.13 (65.3)	4.85	72.1 (236.5)	.069 (.021)

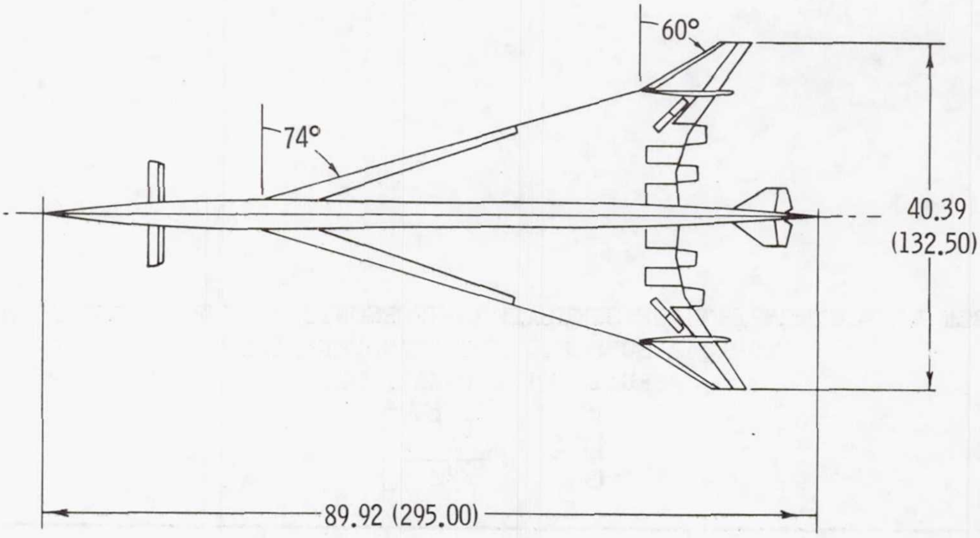


Figure 1.- Boeing model 969-336C based on NASA SCAT-15F configuration. All linear dimensions are in meters (feet).

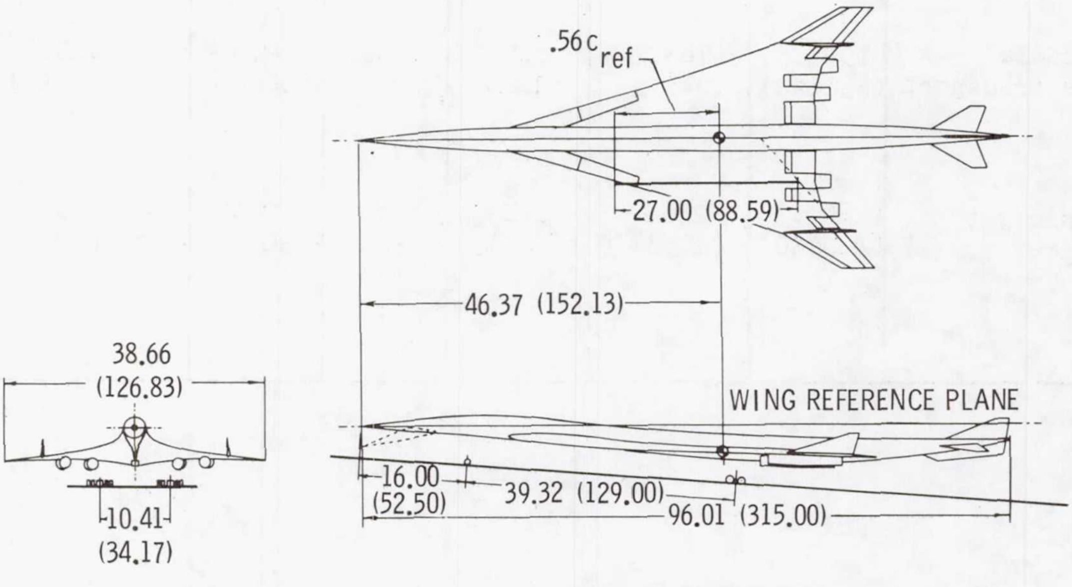


Figure 2.- Three-view sketch of simulated airplane. All dimensions are in meters (feet).

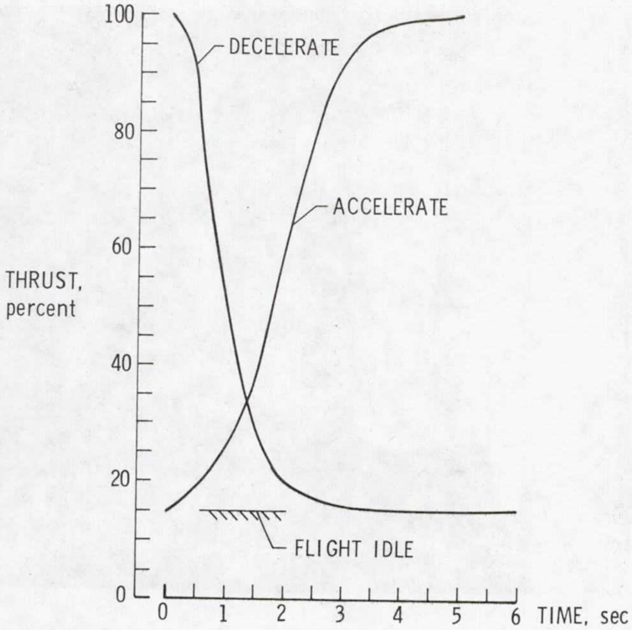


Figure 3.- Simulated engine response characteristics.

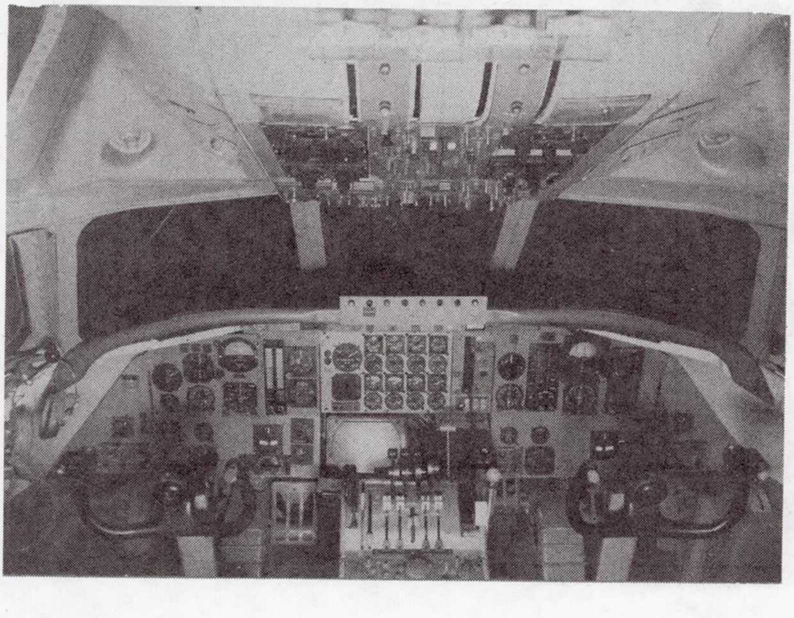


Figure 4.- Simulator cockpit and instrument display.

Figure 5.- Photograph of landing scene equipment and airport model.

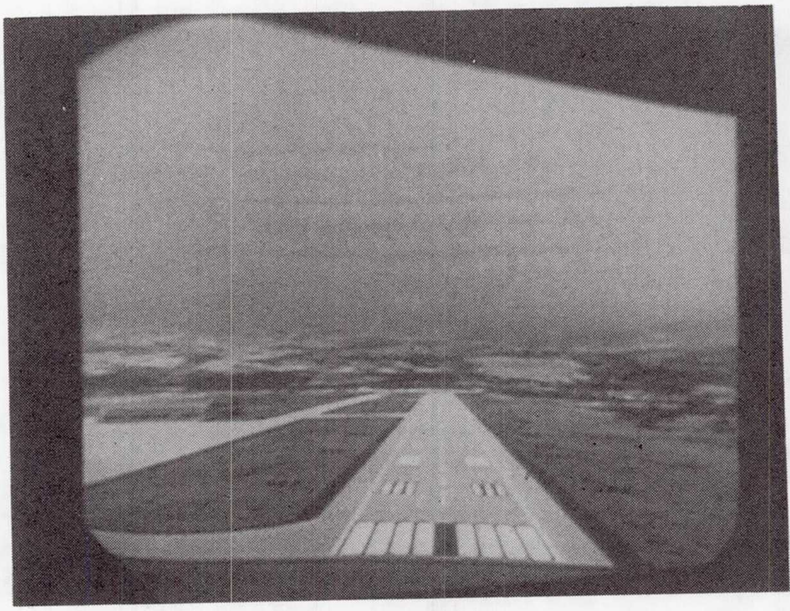


Figure 6.- View of runway as seen by pilot prior to touchdown.

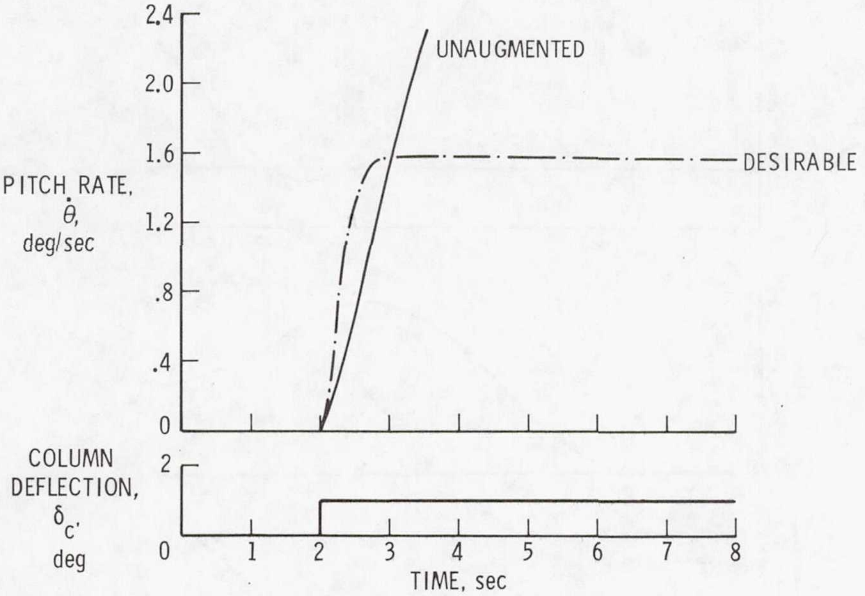


Figure 7.- Comparison of desirable pitch rate response characteristics with those of unaugmented airplane.

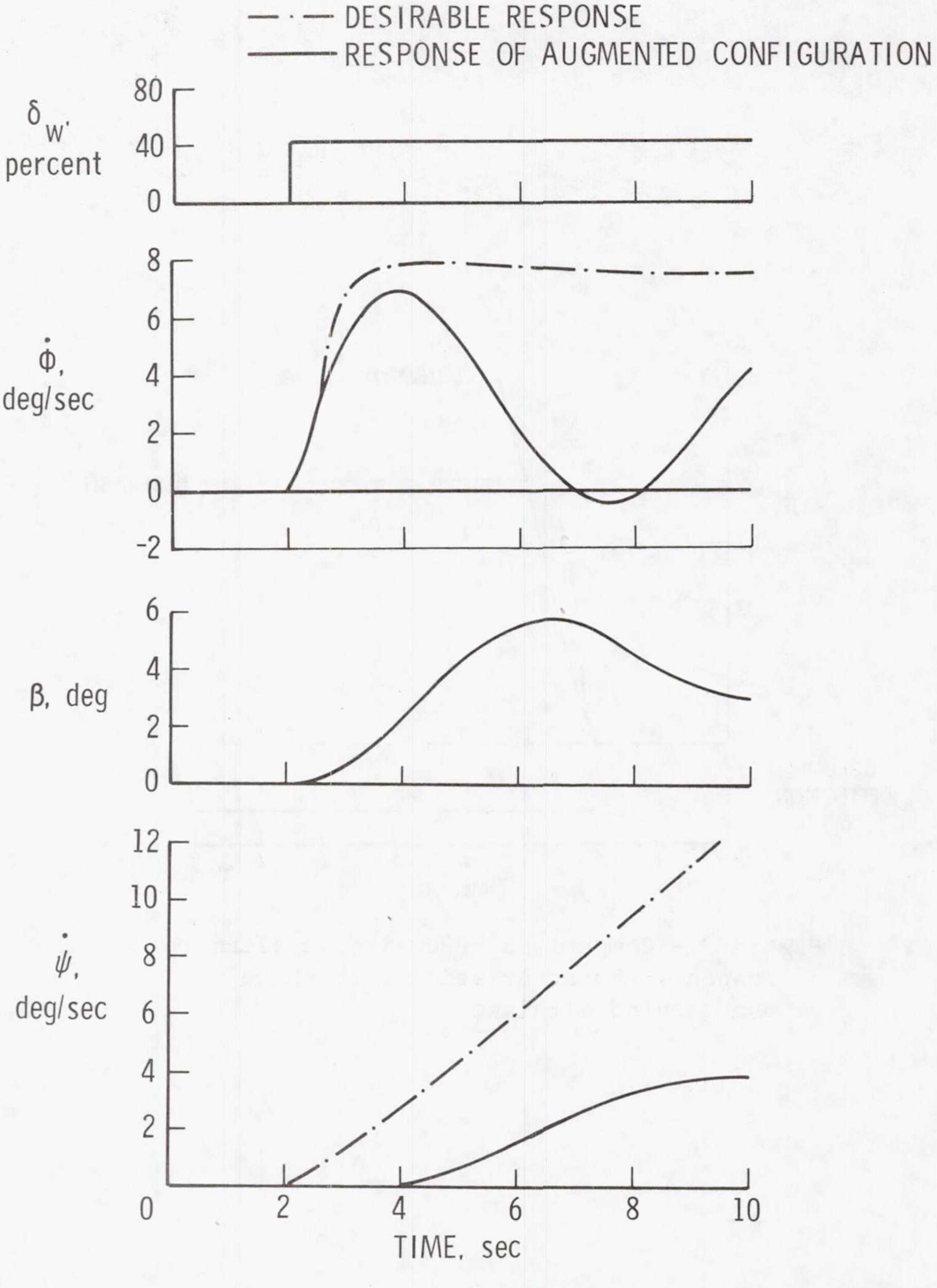


Figure 8.- Comparison of desirable lateral-directional response characteristics with those obtained for unaugmented configuration.

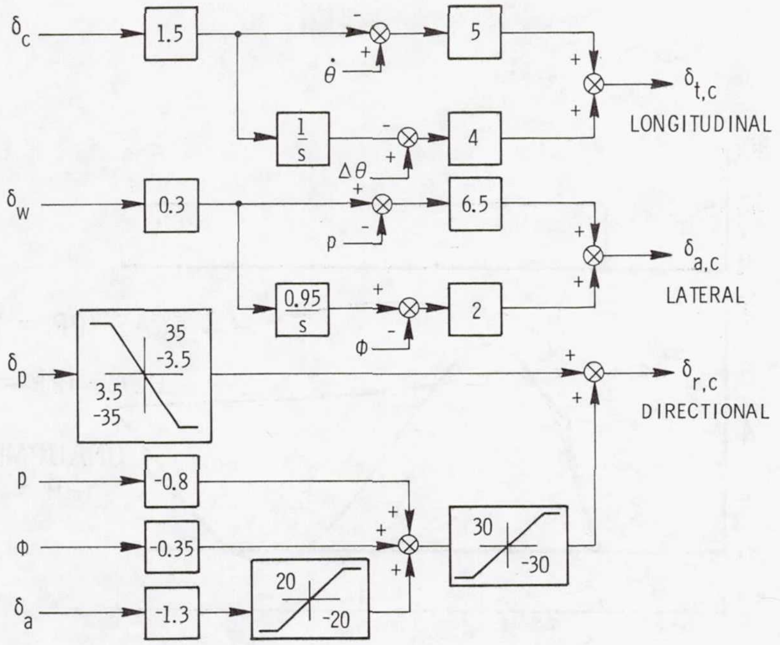


Figure 9.- Normal operating stability and control augmentation system (SCAS).

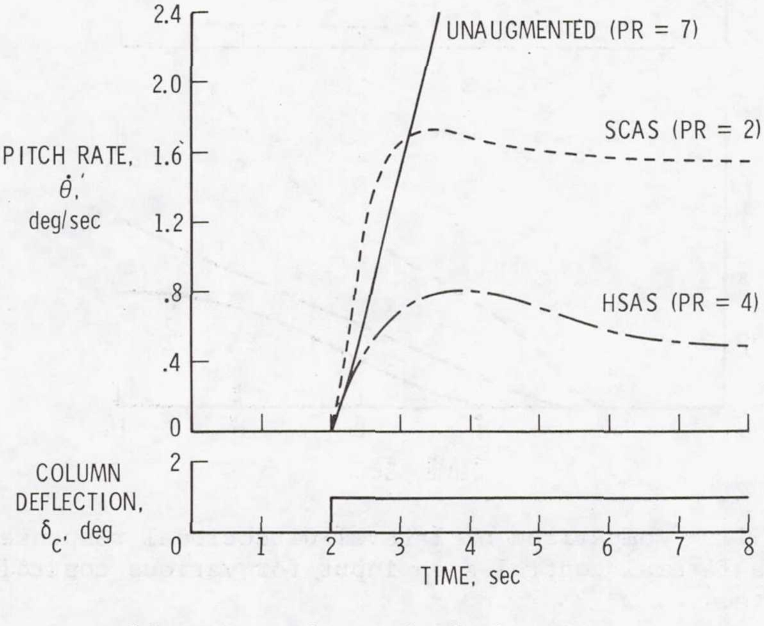


Figure 10.- Comparison of pitch rate response characteristics for various control systems.

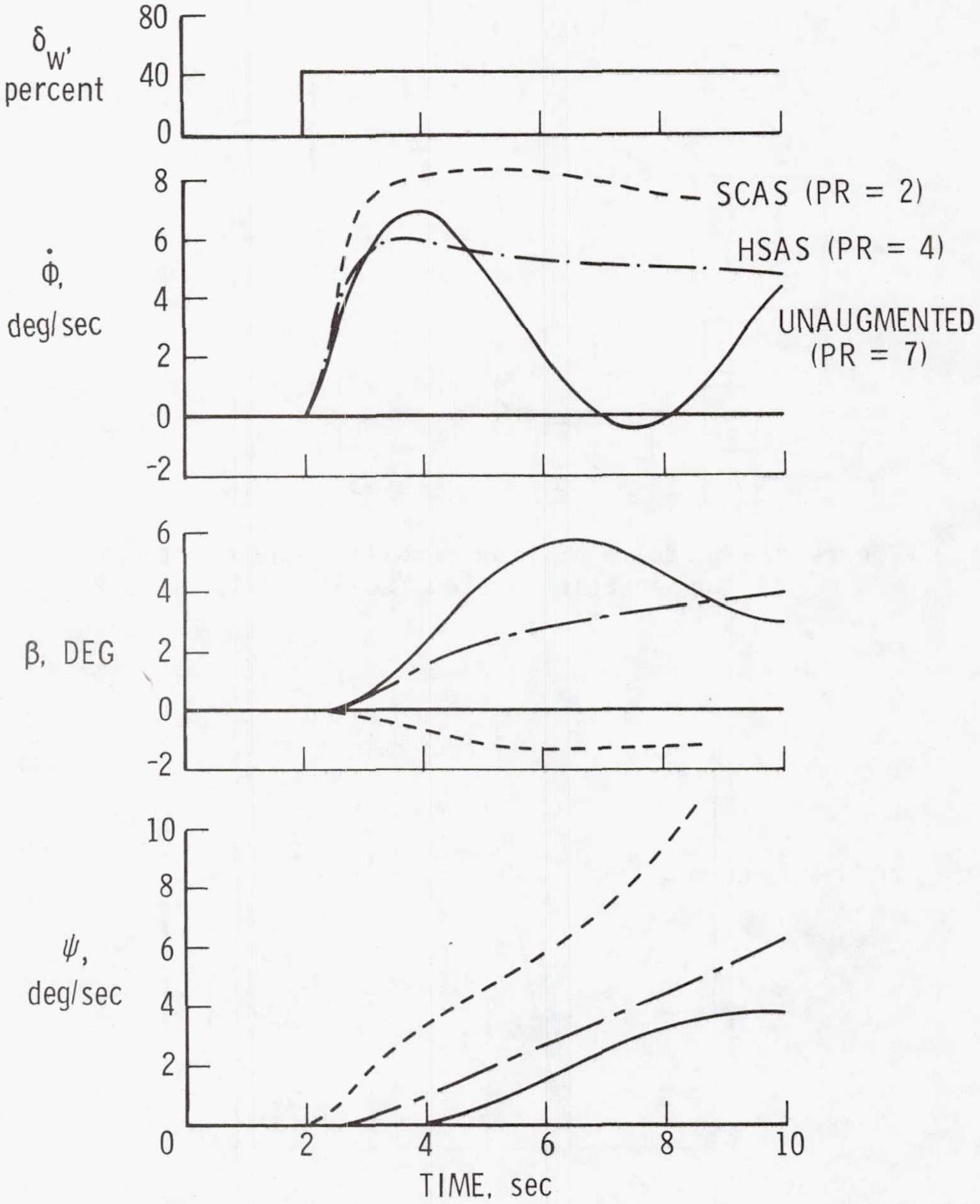


Figure 11.- Comparison of lateral-directional response to a lateral control step input for various control systems.

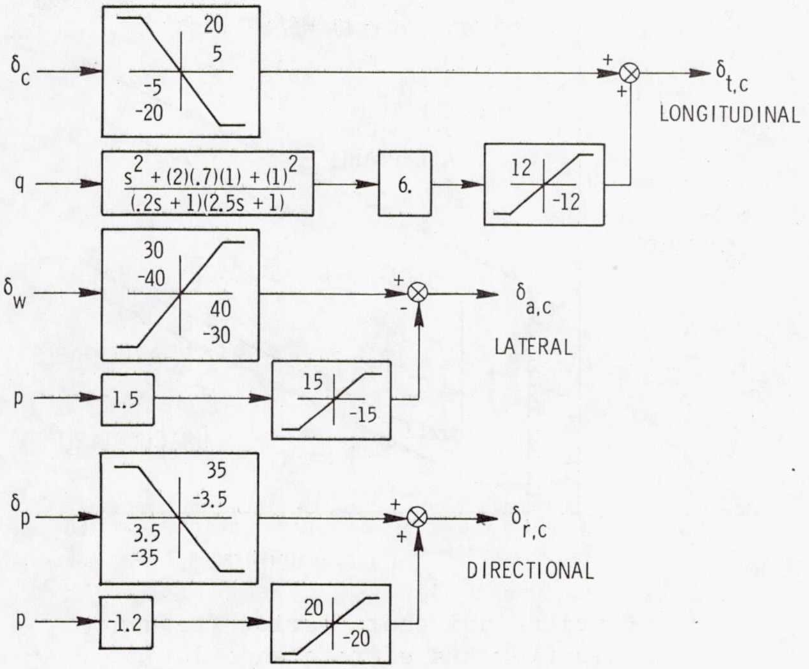


Figure 12.- Hardened stability augmentation system (HSAS).

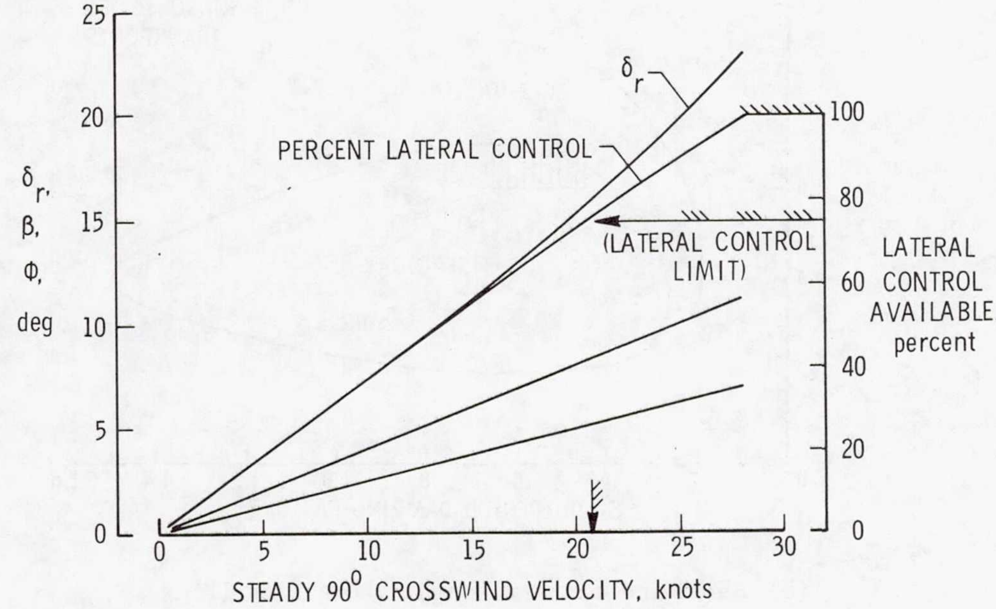
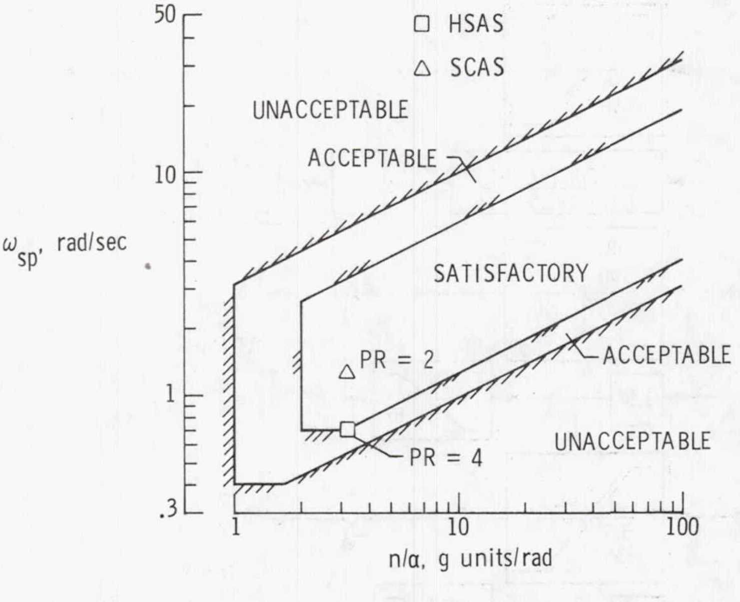
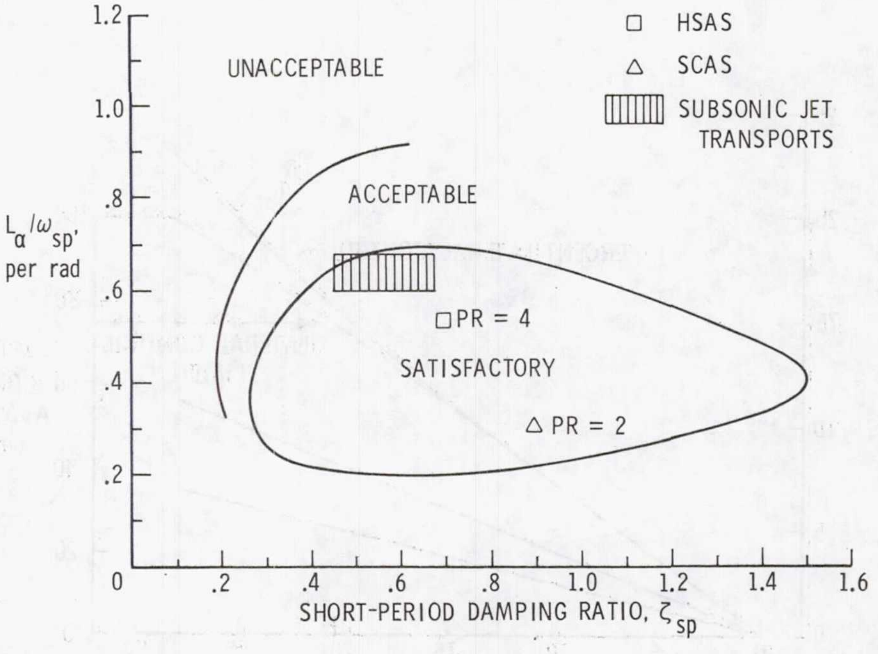


Figure 13.- Indication of crosswind trim capability ($\psi = 0^\circ$).



(a) Longitudinal short-period frequency requirements of reference 10.



(b) Shomber-Gertsen longitudinal handling qualities of reference 11.

Figure 14.- Longitudinal handling qualities criteria.

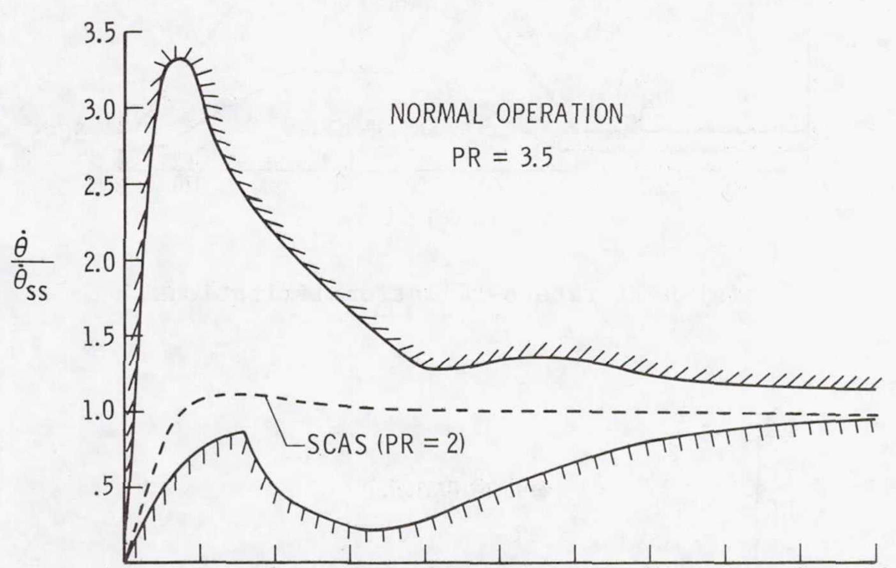
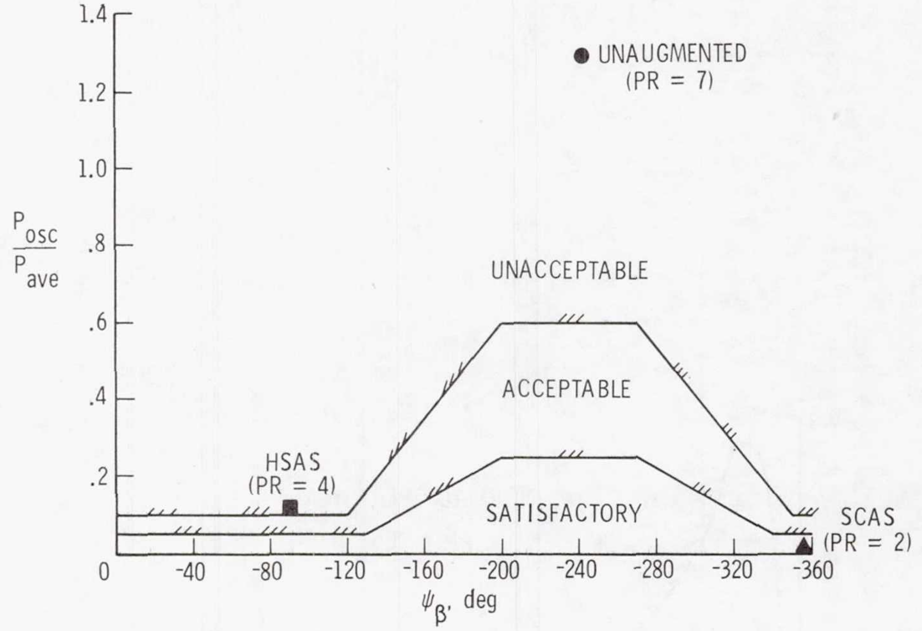
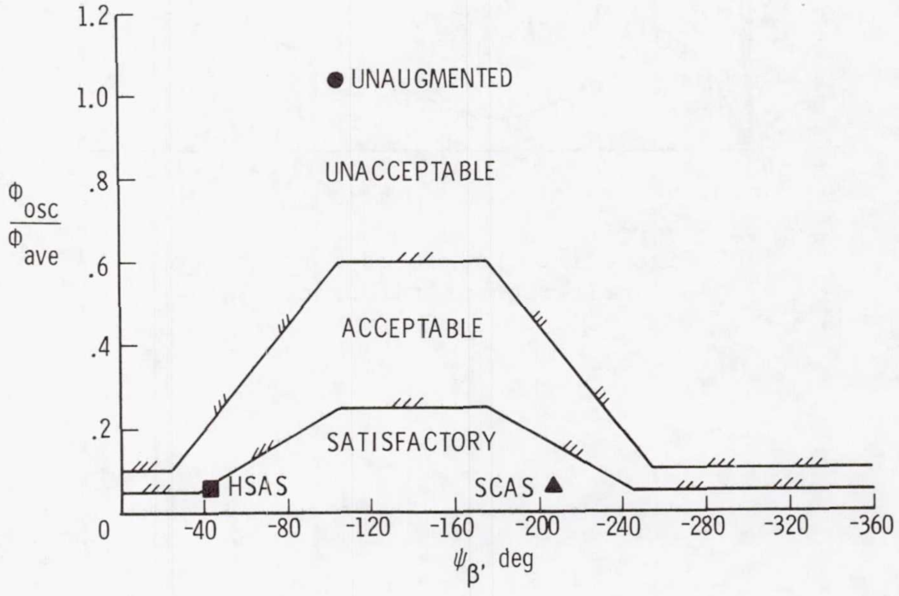


Figure 15.- Low-speed rate response criterion of reference 12.



(a) Roll rate oscillation limitations.



(b) Bank angle oscillation limitations.

Figure 16.- Lateral-directional handling qualities criteria of reference 10.

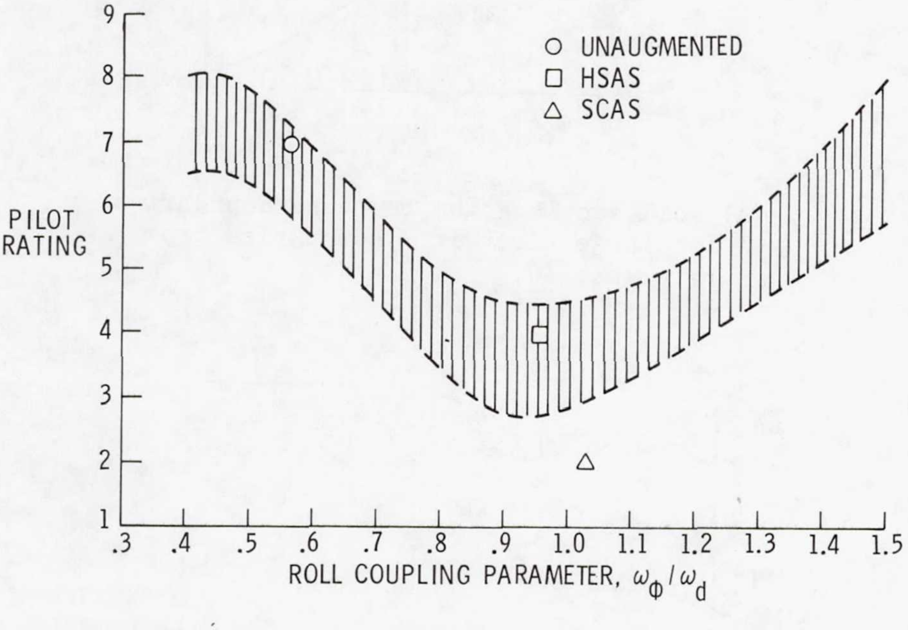
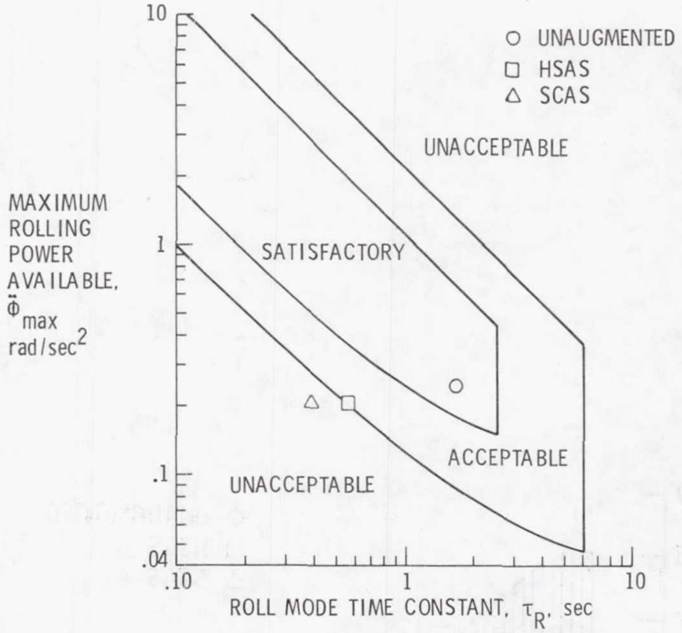
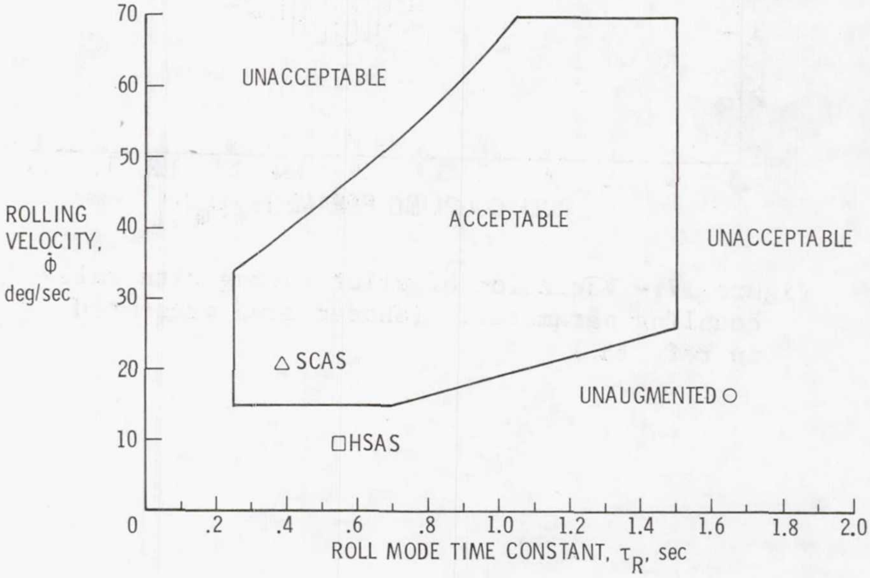


Figure 17.- Variation of pilot rating with roll coupling parameter. (Shaded area presented in ref. 13.)



(a) Roll acceleration response boundaries for large aircraft. Boundaries from reference 10.



(b) Roll rate response criterion for transport aircraft. Boundaries from reference 14.

Figure 18.- Lateral response criteria.