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SIMULATOR STUDY OF FLIGHT CHARACTERISTICS OF A JET-FLAP STOL TRANSPORT AIRPLANE DURING APPROACH AND LANDING

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SUMMARY

A fixed-base simulator study was conducted to provide a preliminary determination of the low-speed handling qualities of a STOL transport configuration equipped with an external-flow jet flap and high-bypass-ratio turbofan engines. Real-time digital simuiation techniques were used. The computer was programed with equations of motion for six degrees of freedom and the aerodynamic inputs were based on measured wind-tunnel data. A visual display of a STOL airport was provided for simulation of the flare and touchdown characteristics. The primary piloting task was an instrument approach to a breakout at a 61-m (200-foot) ceiling, with a visual landing.

The results of the study indicated that satisfactory handling qualities could be obtained, but considerable stability augmentation was required. This was particularly true for the lateral-directional axes, where a pilot rating of 8 (unacceptable) was assigned to the basic (unaugmented) configuration because of unacceptable Dutch roll characteristics, poor turn coordination, and poor roll control. The use of autospeed control greatly simplified the piloting task and was considered by the pilots to be mandatory for satisfactory instrument approaches. With autospeed control engaged, the glide slope could easily be captured and tracked for descent angles as large as 7.5°. The results also showed that with the type and amount of stability augmentation used to produce satisfactory flying qualities, severe limitations on cross-wind landing performance may result.

INTRODUCTION

Over the past few years, interest has continuously increased in STOL (short takeoff and landing) airplanes which can operate out of small fields and yet retain high cruise performance. Since airplanes must have a high wing loading for efficient cruise performance, the future STOL airplane must have the capability of producing very high lift coefficients in order to take off and land within the desired field length.

Wind-tunnel tests have shown that one method of producing suitably high lift coefficients was the use of an external-flow jet-flap system (refs. 1 and 2). However, a STOL airplane based on this concept has aerodynamic characteristics which tend to cause handling-qualities problems. Furthermore, any STOL airplane that uses a power-augmented lift system operates in an environment of low dynamic pressure, which results in reduced aerodynamic damping. The present study was therefore conducted to determine the flight characteristics of a STOL transport configuration equipped with an external-flow jet flap in combination with high-bypass-ratio fan-jet engines. The investigation was conducted with a fixed-base simulator and a visual display of a STOL airport. Real-time digital simulation techniques were used. The computer was programed with equations of motion for six degrees of freedom and the aerodynamic coefficients were based on measured wind-tunnel data. The primary piloting task was an instrument approach to a breakout at a 61-m (200-foot) ceiling, with a visual landing.

The major objectives of the study were to determine: (1) the handling qualities of the subject jet-flap STOL airplane during the approach and landing, and the stability augmentation required to make the handling qualities satisfactory; (2) the advantages of auto-speed control; (3) the effects of approach angle; (4) the advantages of direct lift control (DLC); (5) the effects of turbulence and/or cross winds; and (6) the effects of including the changes in aerodynamics due to ground proximity on the pilot's ability to make satisfactory landings. The effects of "engine-out" during the landing approach were not simulated.

NOTATION

In order to facilitate international usage of data presented, dimensional quantities are presented in both the International System of Units (SI) and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

b — wing span, m (ft)

$C_{D,ge}$ — incremental drag coefficient due to ground effect

C_L — lift coefficient

$C_{L,ge}$ — incremental lift coefficient due to ground effect

C_l — rolling-moment coefficient

C_m — pitching-moment coefficient

$C_{m,ge}$ incremental pitching-moment coefficient due to ground effect

C_n yawing-moment coefficient

C_T thrust coefficient

C_X longitudinal-force coefficient

C_Y side-force coefficient

C_Z vertical-force coefficient

$\bar{c}$ mean aerodynamic chord, m (ft)

F_c force input to control column, N (lb)

g acceleration due to gravity, m/sec^2 (ft/sec^2)

I_X, I_Y, I_Z moments of inertia about X, Y, and Z body axes, respectively, kg-m^2 (slug-ft^2)

I_{XZ} product of inertia, kg-m^2 (slug-ft^2)

k ratio of commanded roll performance to applicable roll performance requirement, $\frac{(\varphi_t)_{command}}{(\varphi_t)_{requirement}}$

n normal acceleration, measured at the airplane center of gravity, g units

n/α steady-state normal acceleration change per unit change in angle of attack for an incremental elevator deflection at constant airspeed, $\frac{\text{g units}}{\text{rad}}$

P period, sec

p,q,r rolling, pitching, and yawing angular velocities, respectively, rad/sec

T thrust, N (lb)

t time, sec

$t_{1/2}$ time to damp to one-half amplitude, sec

t_2 time to double amplitude, sec

t_R roll time constant, sec

V airspeed, knots

W airplane weight, N (lbf)

α angle of attack, deg or rad

β angle of sideslip, deg or rad

β_1 first peak angle of sideslip, deg or rad

$\Delta\beta_{max}$ maximum sideslip excursion at the airplane center of gravity, occurring within 2 seconds or one half-period of the Dutch roll, whichever is greater, for a step aileron command, deg or rad

γ flight-path angle, deg

δ_a combination of aileron and spoiler deflection, positive for right roll command, deg

δ_c control-column deflection, positive for pull force, deg

δ_e elevator deflection, positive for trailing-edge down, deg

δ_{f1} deflection of forward segment of trailing-edge flap, deg

δ_{f2} deflection of rearward segment of trailing-edge flap, deg

δ_p pedal travel, cm (in.)

δ_r rudder deflection, positive when trailing edge is deflected to left, deg

δ_t horizontal-tail deflection, positive when trailing edge is deflected down, deg

δ_w wheel deflection, deg

ζ damping ratio

ζ_d Dutch roll damping ratio

ζ_{sp} longitudinal short-period damping ratio

θ angle of pitch, deg or rad

φ angle of roll, deg or rad

φ_1 first peak angle of roll, deg or rad

φ_t roll-angle change in time t, deg

ψ angle of yaw or heading, deg or rad

ψ_β phase angle in a cosine representation of the Dutch roll component of sideslip, negative for a lag, deg

ω_d undamped natural frequency of Dutch roll mode, rad/sec

ω_{sp} longitudinal short-period undamped natural frequency, rad/sec

$C_{l_\beta} = \frac{\partial C_l}{\partial \beta}$ $C_{n_\beta} = \frac{\partial C_n}{\partial \beta}$ $C_{Y_\beta} = \frac{\partial C_Y}{\partial \beta}$

$C_{X_{\delta_{f2}}} = \frac{\partial C_X}{\partial \delta_{f2}}$ $C_{Z_{\delta_{f2}}} = \frac{\partial C_Z}{\partial \delta_{f2}}$ $C_{m_{\delta_{f2}}} = \frac{\partial C_m}{\partial \delta_{f2}}$

$C_{X_{\delta_e}} = \frac{\partial C_X}{\partial \delta_e}$ $C_{Z_{\delta_e}} = \frac{\partial C_Z}{\partial \delta_e}$ $C_{m_{\delta_e}} = \frac{\partial C_m}{\partial \delta_e}$

$C_{X_{\delta_t}} = \frac{\partial C_X}{\partial \delta_t}$ $C_{Z_{\delta_t}} = \frac{\partial C_Z}{\partial \delta_t}$ $C_{m_{\delta_t}} = \frac{\partial C_m}{\partial \delta_t}$

$C_{l_{\delta_r}} = \frac{\partial C_l}{\partial \delta_r}$ $C_{n_{\delta_r}} = \frac{\partial C_n}{\partial \delta_r}$ $C_{Y_{\delta_r}} = \frac{\partial C_Y}{\partial \delta_r}$

$$C_{l_{\delta_a}} = \frac{\partial C_l}{\partial \delta_a} \qquad C_{n_{\delta_a}} = \frac{\partial C_n}{\partial \delta_a} \qquad C_{Y_{\delta_a}} = \frac{\partial C_Y}{\partial \delta_a}$$

$$C_{l_p} = \frac{\partial C_l}{\partial \frac{pb}{2V}} \qquad C_{n_p} = \frac{\partial C_n}{\partial \frac{pb}{2V}} \qquad C_{Y_p} = \frac{\partial C_Y}{\partial \frac{pb}{2V}}$$

$$C_{l_r} = \frac{\partial C_l}{\partial \frac{rb}{2V}} \qquad C_{n_r} = \frac{\partial C_n}{\partial \frac{rb}{2V}} \qquad C_{Y_r} = \frac{\partial C_Y}{\partial \frac{rb}{2V}}$$

$$C_{m_q} = \frac{\partial C_m}{\partial \frac{q\bar{c}}{2V}} \qquad C_{n_{\dot{\beta}}} = \frac{\partial C_n}{\partial \frac{\dot{\beta} b}{2V}}$$

Subscripts:

max maximum

min minimum

Dots over symbols denote differentiation with respect to time.

Abbreviations:

DLC direct lift control

IFR instrument flight rules

ILS instrument landing system

PR pilot rating

SAS stability augmentation system

VFR visual flight rules

THE FIXED-BASE SIMULATOR

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. 1.) In addition, a direct-lift-control (DLC) thumb controller was mounted on the right horn of the control yoke.

(An instrument was installed in the display panel to indicate the direction and amount of DLC being commanded.) Instruments indicating angle of attack and sideslip were also provided. The simulator control forces were provided by a hydraulic servosystem and were functions of control displacement and rate. The control characteristics are defined in table I. Real-time digital simulation techniques were used wherein a digital computer was programed with the equations of motion for six degrees of freedom.

A visual display of a STOL airport was used in order to simulate the flare and landing. (Each flight was terminated at touchdown; the roll-out was not simulated.) A photograph of the airport model is presented in figure 2. The runway simulated was 914 m (3000 ft) long and 46 m (150 ft) wide. Although a 914 m (3000 ft) runway was used, each pilot was instructed to land within an area that was clearly marked on the runway. This target touchdown area was 137 m (450 ft) long and began 76 m (250 ft) from the approach end of the runway. It was assumed that if the pilot landed within the target area, he could easily turn off at the first runway exit, which meant that less than 610 m (2000 ft) of the runway would be used for the landing.

AIRPLANE CONFIGURATION SIMULATED

The airplane design used in this study was a four-engine subsonic jet transport with a high wing and high-bypass-ratio turbofan engines. It might be visualized as being similar to the models of references 1 and 2, since much of the aerodynamic data used in the simulation came from these sources.

The wing incorporated leading-edge flaps and double-slotted trailing-edge flaps which were set at $\delta_{f1}/\delta_{f2} = 25^{o}/50^{o}$ for the approach and landing conditions. The engines were mounted in such a manner that the jet exhaust impinged directly on the trailing-edge flap system. (See fig. 3.) The four engines were assumed to provide a total installed maximum thrust of 729 508 N (164 000 lbf), and the ratio of maximum thrust to airplane gross weight was taken as 0.60, which yielded a gross weight of 1 215 840 N (273 333 lbf). The engine thrust-response characteristics used are presented in figure 4. The airplane was equipped with a spoiler located on the wing and also with a small-chord spoiler located on the flap. (Both these spoilers were used in combination with ailerons for roll control during this study.) All the control surfaces (elevator, aileron, and rudder) were equipped with blowing.

The mass and dimensional characteristics of the simulated airplane are presented in table II, and the aerodynamic characteristics are presented in table III and figure 5. In general, the static aerodynamic characteristics were taken from references 1 and 2, and the dynamic derivatives were taken from reference 3, with the proper corrections applied for differences in configuration details and test conditions.

TESTS AND PROCEDURES

The low-speed flight characteristics of the subject STOL airplane are presented and discussed in relation to pilot opinions and ratings. (See table IV for pilot rating system.) In general, the test procedures were as follows:

1. Evaluate the flying qualities of the unaugmented airplane in level flight in the approach configuration and at the approach speed.

2. Determine stability augmentation required to make the handling qualities satisfactory.

3. Evaluate the effects of autospeed, DLC, approach angle, and cross winds on the pilot's ability to make satisfactory approaches and landings.

Two research pilots participated in the simulation program and used standard flight-test procedures in the evaluation of the handling qualities.

The ILS approach was initiated with the airplane in the power-approach condition (power for level flight) with a lateral offset from the localizer, at an altitude below the desired glide slope, and at a variable distance from the runway. (The distance from the runway and the altitude varied with glide-slope angle.) The initial flight conditions for this jet-flap STOL airplane were determined from the requirements for powered-lift flight used in the analysis of reference 4. Figure 6, which was constructed from the aerodynamic data of table III, indicated that the requirements were met at $\alpha = 0^{\circ}$ and $C_L = 4.7$ (V = 68.6 knots). The principal requirements were as follows: (1) 10° margin, or more, of angle of attack from the stall; (2) a speed of at least 1.2 times the minimum power-on level-flight speed; and (3) level-flight capability with three engines without change of speed or flap deflection. (Although flight with three engines was considered in determining the initial conditions, the effects of losing an engine during the landing approach were not evaluated by the pilots.) The glide-slope angle was varied from 3° to $7\frac{1}{2}^{\circ}$.

A conventional jet-transport type of flight director was provided for the pilot. Although neither the pitch nor the roll channel of the flight director was optimized for the simulated airplane, the pilots felt that the roll channel was particularly beneficial in that it minimized the localizer tracking task. The pilot's task was to capture the localizer and glide slope and to maintain them as closely as possible while under IFR conditions. At an altitude of 61 m (200 ft) a visual scene of the STOL runway and surrounding area was displayed to the pilot, and from that altitude the pilot attempted to land the airplane (VFR) on a prescribed area on the runway. In addition, a lateral-offset maneuver was sometimes used. That is, the localizer was offset 61 m (200 ft) from the runway center line, and at breakout the pilot had to maneuver the airplane to land on the runway (see fig. 7).

RESULTS AND DISCUSSION

The present study was conducted to provide a preliminary determination of the low-speed handling qualities of the simulated jet-flap STOL airplane. The results must be considered preliminary in the sense that not all characteristics of real systems were simulated. For example, during the present study the handling qualities of the basic airplane were improved by arbitrarily changing the values of various aerodynamic derivatives instead of attempting to develop realistic augmentation systems. Therefore, throughout the paper the configurations referred to as "unaugmented" and "augmented" correspond to the "basic" and "modified" configurations, respectively. For the most part, the handling qualities are discussed in relation to pilot ratings and opinions. In addition, the dynamic stability and response characteristics are compared with those of some other STOL airplanes (from ref. 5) in tables V and VI, and with existing handling qualities criteria.

No Stability Augmentation

The pilot rating assigned to the longitudinal handling qualities of the unaugmented configuration was 6, the major objections being sluggish initial pitch response and apparent low damping, as evidenced by some overshoot in pitch-attitude changes. The pilots also complained of poor speed-control characteristics. A pilot rating of 8 was assigned to the lateral-directional handling qualities, the major objections being unacceptable Dutch roll characteristics, poor turn coordination, and poor roll control.

Longitudinal characteristics.- The pilots felt that the static stick-fixed and stick-free longitudinal stability were adequate. The actual quantities involved at an airspeed of 69 knots (approach speed) were: $\delta_c/\Delta V \approx -0.185$ deg/knot and $F_c/\Delta V \approx -3.43$ N/knot (-0.77 lbf/knot).

The landing approaches made with this STOL airplane show the effects of being on the steep back side portion of the power-required curve where precise control of pitch attitude is needed for speed control and where thrust, which directly affects lift on this type of airplane, is used for controlling the glide path. The variation of thrust required with airspeed $\frac{\partial(T/W)}{\partial V}$ was approximately -0.015 per knot. Although this is a large amount of speed/thrust instability, it is not believed to be the factor that caused the pilots to rate the longitudinal characteristics of this airplane as unsatisfactory. As stated in reference 5, "Operating STOL aircraft on the back side of the drag-velocity curve has not posed the problem that has occurred with conventional aircraft where thrust cannot be used to rapidly develop normal acceleration." Instead, it is believed that the inability to control the pitch attitude precisely is the major reason for the degradation in the low-speed longitudinal handling qualities.

The dynamic stability characteristics of this configuration are presented in table VI. As can be seen, the short-period damping ratio $(\zeta_{sp} \approx 0.8)$ is more than adequate for most aircraft but the frequency $(\omega_{sp} \approx 0.8 \text{ rad/sec})$ is too low; the period of the short-period mode is almost one-half as long as the period of the phugoid mode. With the two periods so nearly equal, the first 2 or 3 seconds of the response to a pilot command is essentially the short-period response, while the remainder reflects the characteristics of the phugoid response. Therefore, the short-period portion of the response does not require attention, but the long-period portion requires additional damping. One series of comments made by the pilots was: "The phugoid is easy to excite. I can't make small, rapid pitch-attitude changes without exciting the phugoid. Actually, I am not sure whether I am exciting a short-period phugoid or a long-period, short-period oscillation. It is very easy to develop a PIO [pilot induced oscillation]."

Although the sluggish initial response and apparent low damping caused control problems during the approach, these problems were most evident during the landing flare, where the pilot was trying to arrive at a reasonably precise touchdown point with a reduced rate of descent and a proper landing attitude. The pilots felt that they tended to overcontrol during the flare, and occasionally rather severe cases of control pumping occurred. Even though pilot training may help to eliminate this type of oscillation, poor conditions such as turbulence or low visibility might produce dangerous situations during landings.

Reference 6 states that the response of an airplane having low ω_{sp} is slow and sluggish, and that the pilot must overcontrol the airplane to obtain satisfactory pitch response. The reference also states that it is difficult for the pilot to judge the control input required to counter a response after overcontrolling the airplane to get it started. According to this reference, the pilot's ability to control the pitch attitude precisely is related to the magnitude of n/α as well as ω_{sp}. When the ratio $\frac{\omega_{sp}^2}{n/\alpha}$ falls below a critical value, the pilot resorts to a control technique which involves a pumping of the control in order to accomplish a precision task, such as the landing flare. This parameter has since been adopted by the military services for indicating the short-period frequency requirement (ref. 7) and is presented in figure 8. As can be seen in the figure, the subject unaugmented STOL airplane falls into the "unsatisfactory but acceptable" category, indicating that the pilots' assessment of the longitudinal handling qualities (PR = 6) agrees with this established criterion.

The pilots commented that the maximum control power was adequate but less than desired. The $\ddot{\theta}_{max}$ capability of the simulated airplane, which is 0.3 rad/sec^2, compares quite favorably with the control-power criterion presented in figure 9, in that for an airplane weighing approximately 1200 kN (270 000 lbf) the $\ddot{\theta}_{max}$ capability should be greater than 0.2 rad/sec^2 in order to be satisfactory $\left(PR \leqq 3\frac{1}{2}\right)$. It should also be noted, however, that another requirement (ref. 5) which should be met for satisfactory control power is the time to change pitch attitude by 10^o. Reference 5 states that this time $\left(t_{\Delta\theta=10^o}\right)$ should be less than 1.2 seconds, and as can be seen from table V the unaugmented STOL airplane has a $t_{\Delta\theta=10^o}$ of 1.7 seconds, which tends to support the pilots' assessment of the longitudinal response characteristics of this airplane as sluggish.

Lateral-directional characteristics.- As stated previously, the pilots assigned a pilot rating of 8 to the lateral-directional handling qualities of the unaugmented airplane. The pilots commented that the Dutch roll was very easy to excite and, once excited, was impossible to control. As can be seen from table VI, $\zeta_d\omega_d$ = 0.028 rad/sec, which corresponds to an unacceptable level of damping. (Ref. 7 states that a minimum value of $\zeta_d\omega_d$ = 0.05 rad/sec is required for "acceptable" damping.)

The pilots also stated that it was impossible to coordinate a turn with the rudder on the unaugmented airplane. This, of course, was because of the sideslip excursions that occurred for any roll-angle command. One criterion that has been used to indicate the amount of β that should allow satisfactory turn-entry characteristics is the ratio of β_1 to φ_1. Figure 10 presents pilot rating as a function of β_1/φ_1 (taken from ref. 8) and indicates the location of the subject STOL airplane $\left(\beta_1/\varphi_1 = 0.71\right)$. According to figure 10, in order for an airplane to have a satisfactory pilot rating the value of β_1/φ_1 should probably be less than 0.30. Reference 7 states, however, that the turn coordination is affected not only by the maximum change in sideslip occurring during a rudder-pedals-fixed rolling maneuver, $\Delta\beta_{max}$, but also by the phase angle of the Dutch roll component of sideslip, ψ_β. (The phase angle ψ_β is a measure of the sense of the initial sideslip response – whether adverse or proverse.) That is, the amount of $\Delta\beta_{max}$ that can be coordinated satisfactorily varies significantly with ψ_β. Figure 11 presents this criterion (taken from ref. 7) and indicates the location of the simulated STOL airplane. As can be seen, the pilots' assessment of the turn-coordination problem with the simulated airplane agrees with the criterion in that the sideslip characteristics were considered unacceptable.

The roll-control power was said to be adequate and the initial roll response satisfactory. (See fig. 12 and table V.) However, the longer term roll response was unacceptable because the unacceptable Dutch roll characteristics adversely affected the roll rate after a short period of time. An illustration of the roll response characteristics of this unaugmented STOL configuration is shown in figure 13, where the roll-rate response to an aileron step input is presented as a function of time. An undesirable oscillation in roll rate is evident. When the amplitude of this oscillation is compared with the maximum allowed (ref. 7), it is seen that the pilots' assessment of the roll response agrees with the criterion in that $\dot{\varphi}_{1(min)}/\dot{\varphi}_{1(max)} < 12$ percent, which corresponds to an unacceptable level, PR > $6\frac{1}{2}$. (Ref. 7 states that $\dot{\varphi}_{1(min)}/\dot{\varphi}_{1(max)}$ must be greater than 25 percent to be "acceptable" and greater than 60 percent to be "satisfactory.")

Stability Augmentation On

Some aerodynamic derivatives were varied in an attempt to make the low-speed flight characteristics of this jet-flap STOL airplane satisfactory. The damping-in-pitch parameter C_{m_q} was increased from -42 per radian to -126 per radian, and the elevator control-effectiveness parameter $C_{m_{\delta_e}}$ was increased from -2.56 per radian to -3.84 per radian. The pilot rating assigned to the longitudinal handling qualities of this augmented configuration was $3\frac{1}{2}$, with the pilots commenting that the initial pitch response was still less than desired.

In order to make the lateral-directional handling qualities satisfactory, the following changes were required:

1. The directional-stability parameter C_{n_β} was increased by a factor of 2.

2. A $\dot{\beta}$ damper was added that was equivalent to increasing $C_{n_{\dot{\beta}}}$ from 0 to 1.03 per radian.

3. The damping-in-roll derivative C_{l_p} was increased by a factor of 1.75.

4. The roll-control-effectiveness parameter $C_{l_{\delta_a}}$ was increased by a factor of 1.5.

5. A pitch decoupler was used that involved driving the horizontal tail as a function of roll angle.

With these modified lateral-directional parameters the pilot rating of the lateral-directional handling qualities was $3\frac{1}{2}$, and the pilots commented that the sideslip excursions for turn entries were still unsatisfactory, but acceptable. The subsequent discussion is concerned with various effects of the stability augmentation.

<u>Longitudinal characteristics</u>.- The increased values of C_{m_q} and $C_{m_{\delta_e}}$ changed the pilot rating from 6 to $3\frac{1}{2}$. As can be seen from figure 8, the pilot rating of this augmented configuration agrees with the $\frac{\omega_{sp}^2}{n/\alpha}$ criterion of reference 7 in that a satisfactory rating was assigned to the longitudinal handling qualities. As stated previously, however, the pilots still complained that the initial pitch response was less than desired. This

factor can probably best be seen from table V where it is shown that $t_{\Delta\theta=10^o}$ is about 0.6 second longer than the criterion offered as being satisfactory in reference 5. It should be mentioned that one method of improving the initial pitch response is to use some sort of pitch-quickening technique, such as a first-order lead compensator. Such a system would, in effect, increase the short-period natural frequency of the airplane by increasing the elevator-to-column gain δ_e/δ_c for an initial transient time period. This pitch-quickening technique was evaluated briefly during the present simulation program, and the pilot indicated that the longitudinal handling characteristics would be improved with such a lead network. (With the pitch-quickening system installed, the pilot rating of the augmented airplane was improved from $PR = 3\frac{1}{2}$ to $PR = 2\frac{1}{2}$ to 3.)

Lateral-directional characteristics.- The pilot rating of the lateral-directional handling qualities was improved from 8 to $3\frac{1}{2}$ by the stability augmentation. From table VI it can be seen that the Dutch roll damping $\zeta_d\omega_d$ has been increased from 0.028 rad/sec to 0.454 rad/sec. (Ref. 7 states that a minimum value of $\zeta_d\omega_d = 0.15$ rad/sec is required for "satisfactory" damping.) Also, figure 10 shows that the parameter β_1/φ_1 has been decreased from 0.71 to 0.21 and thereby indicates that the sideslip excursion in a turn entry is within satisfactory limits. However, the criterion of reference 7 for the maximum sideslip allowed during turning maneuvers is not totally in agreement with the pilots' assessment of this STOL configuration in that this augmented configuration falls into the "acceptable but unsatisfactory" region of the criterion (fig. 11) and yet was assigned a pilot rating corresponding to "marginally satisfactory." It must be noted, however, that although the pilots assigned a rating of 3.5 to the lateral-directional characteristics of this configuration, they qualified this 3.5 rating with the comment that "the sideslip excursions during turn entries are still unsatisfactory, but acceptable." With this qualification, it is felt that the rating agrees with the criterion of reference 7.

The lateral response characteristics were said to be satisfactory. As shown in figure 13, $\dot{\varphi}_{1,min}/\dot{\varphi}_{1,max}$ for this augmented configuration is 96 percent, compared with less than 12 percent for the unaugmented configuration. (Ref. 7 states that a value of $\dot{\varphi}_{1,min}/\dot{\varphi}_{1,max} \geqq 60$ percent is required for satisfactory roll response characteristics.)

It should be mentioned that although the changes made in the derivatives may seem large, they are not large at all compared with changes that have been made in some previous STOL handling qualities studies, or in relation to the amount of control-surface deflection that would be required to generate these effective derivatives – in particular, C_{n_β} and $C_{n_{\ddot{\beta}}}$. For example, the type of lateral-directional augmentation used on the STOL configuration identified in table V as NC-130 (Mod.), whose results are reported in references 5 and 9, was much the same as that required and used in the present study.

Figure 14 presents the gains used for the SAS in the study reported in reference 9, and also shows the location of the simulated STOL airplane of the present study. As can be seen, the value of C_{n_β}, as well as the gain $\Delta\delta_r/\Delta\beta$ required to generate C_{n_β}, was lower for the augmentation used in this study than for that of reference 9. Also, the value of $C_{n_{\dot{\beta}}}$ required for this study was less, though the gain $\Delta\delta_r/\Delta\dot{\beta}$ was the same. Both these studies agree that the $\dot{\beta}$ damper is of significant importance even after a sufficient value of C_{n_β} has been attained. Figure 15 indicates the relative effects of C_{n_β} (directional stability) and $C_{n_{\dot{\beta}}}$ ($\dot{\beta}$ damping) on pilot opinion that were determined during the STOL handling-qualities study of reference 9. Data for the unaugmented and augmented configurations simulated during the present study are located in figure 15 and agree with reference 9 as to the type and amount of augmentation required to make the handling qualities of these STOL airplanes satisfactory.

Automatic Speed Control

The autospeed system used during the evaluation of the subject jet-flap STOL airplane consisted of driving the second segment of the double-slotted flap as a function of change in airspeed $\left(\text{that is, } \delta_{f2}/\Delta V\right)$. Since the ideal system would be a "pure" drag device, for a practical configuration it would be necessary to balance the variations in pitching moment and lift caused by δ_{f2}. The pitching moments produced by deflection of the flap from its null position $(\delta_{f2} = 50^\circ)$ were balanced with an elevator-flap interconnect $\left(\text{that is, } \delta_e/\delta_{f2}\right)$. Although not mechanized in the present study, the variations in lift with δ_{f2} could probably be balanced with a spoiler-flap interconnect. (In the present exploratory study the variations of lift with δ_{f2} were arbitrarily set at zero.) With the simulated autospeed system $\left(\delta_{f2}/\Delta V = 10^\circ/\text{knot},\ \delta_e/\delta_{f2} = -0.0045, \text{ and } \Delta C_L/\delta_{f2} = 0\right)$, the airspeed variation was generally less than ±2 knots during the landing approach.

The pilots that participated in the simulation program stated that automatic speed control was mandatory for satisfactory landing approaches with the simulated STOL airplane. As stated previously, this airplane is flown well up the back side of the thrust-required curve $\left(\frac{\partial(T/W)}{\partial V} \approx -0.015 \text{ per knot}\right)$ during the landing approach, and therefore the rate of sink is controlled primarily with thrust (throttles) and airspeed is controlled primarily by precise control of pitch attitude (column). The pilots commented that it would take "a lot of learning" to coordinate the thrust and pitch attitude of this airplane. One pilot stated: "The addition of autospeed control allows me to fly an ILS approach much more precisely and with a 50-percent improvement in overall workload. Without autospeed, I have a hard time correlating θ, V, and thrust."

Effects of Approach Angle

Although most of the simulated landing approaches were made with a glide-slope angle of 3°, the approach angle was varied during the program. (Glide-slope angles of $4\frac{1}{2}^\circ$, 6°, and $7\frac{1}{2}^\circ$ were also simulated.) Since no attempt was made to mechanize a two-segment approach, the approaches made for glide slopes larger than 3° were generally terminated at an altitude of 61 m (200 ft).

Autospeed off.- The pilots commented that they could fly 3°, $4\frac{1}{2}^\circ$, and 6° glide slopes if they were given a sufficient amount of time to stabilize on the glide slope. Once the glide slope was intercepted, an unusual amount of time was required to stabilize the rate of descent and airspeed, and the higher the approach angle the longer the time required for stabilization. The rate of sink and airspeed could not be stabilized when the approach angle was $7\frac{1}{2}^\circ$. This result was not unexpected because, as can be seen from figure 6, for the flap deflection used and $\gamma = -7.5^\circ$, a reduction in thrust ($T/W \approx 0.2$) and an increase in angle of attack ($\alpha \approx 9^\circ$) are required that puts the airplane essentially at the stall angle of attack ($\alpha \approx 10^\circ$) for this low power setting. Even if the angle-of-attack margin required for safety is disregarded, the airplane could not be flown at an approach angle greater than approximately 6°; and if the required 10° angle-of-attack margin is considered, an approach angle of approximately 5° is the maximum. (See fig. 6.)

Autospeed on.- With the automatic speed-control system used in this program, the pilots could easily capture the glide slope for any of the approach angles used ($\gamma = -3^\circ$ to -7.5°). When this autospeed controller is used, no change in thrust and very little change in α is required to fly approach angles as large as 7.5°. Essentially, $\gamma = \theta$ with autospeed on, and therefore the pilot is relieved of maintaining the angle-of-attack safety margin and of having to control θ for airspeed and thrust for γ.

Direct Lift Control

Two types of direct lift control (DLC) were evaluated during the present study, with the thumb controller shown in figure 1(b) used as a vernier control for lift, and thus for flight-path tracking. The first scheme consisted of deflecting the spoilers to a null position of 30° and modulating their deflection for DLC, while the second scheme consisted of using thrust modulation for DLC. The automatic speed control system was used in conjunction with both DLC schemes.

Symmetrical spoiler deflection for DLC.- With the spoilers deflected 30° in order to use them for DLC, the approach speed had to be increased from 69 knots to 78 knots in order to maintain the same speed margin from the stalling speed. The use of this DLC scheme (Δn capability of approximately $\pm 0.2g$) improved the pilot's ability to make quick and precise corrections to the glide slope and therefore to make smoother touchdowns – that is, touchdowns at a lower rate of sink. However, this DLC scheme had some detrimental effects. The most obvious, of course, is the higher approach speed (9 knots); secondly, the thrust required for level flight (thrust is maintained throughout the approach when autospeed is used) is unusually high – about 94 percent of maximum – which would be undesirable because of the fuel expended and the engine noise level. In addition, although the use of this DLC scheme allowed the pilot to make a smoother flare and touchdown, the touchdown spot on the runway varied considerably more than when only the column was used for the flare.

Thrust modulation for DLC.- When thrust modulation was used for DLC, the pilots commented that this technique for controlling the glide path was better than using the column at altitudes greater than 61 m (200 ft). (Although the normal-acceleration capability of this DLC scheme was very low, the pilots liked this technique of controlling γ during the approach in that it gave them a vernier control of thrust.) However, for altitudes less than 61 m (200 ft), where quick and precise changes in flight path are required, the response of the engines was too slow for the DLC to be of appreciable assistance in precise control of the glide path.

Effects of Turbulence

Flight in both smooth air and rough air was evaluated during the present simulation program. The rough air was simulated by introducing noise with a Gaussian noise generator, the peak gusts being ±6 knots along all axes. The pilots commented that the effects of turbulence were most noticeable as small attitude variations, and these resulted in an increased pilot workload as attempts were made to smooth the ride. Such attempts occasionally led to overcontrol, and the ride, in general, would probably be considered unacceptable – even with the stability-augmentation system operative.

Effects of Cross Winds

Effective utilization of STOL airplanes will probably require operations in any wind velocities in which conventional airplanes would operate – possibly as high as 30 knots, and from practically any direction. Because of the low flight speeds of STOL airplanes in the take-off and landing operations, the effects on these operations of even moderate wind velocities and variability can be large. Probably the most important aspect of wind, insofar as terminal operations are concerned, is the sensitivity of the STOL airplane to the cross-wind component – that is, the wind component perpendicular to the flight path. For example, if the airplane is approaching for a landing at an along-track speed of 69 knots with a cross-wind component of only 15 knots, a severe heading change of approximately 12° would have to be made very precisely just before touchdown.

When landing approaches were made with the subject STOL airplane, cross winds up to 90° at 30 knots did not impose any undue hardships or problems in tracking the localizer (crab angle up to 26°). The only problem associated with cross winds was the inability to correct the heading for the landing, and this was limited by the directional control available; the SAS was too tight for this maneuver. As can be seen from table V, the SAS decreases $\ddot{\psi}_{max}$ from 0.17 rad/sec^2 to 0.11 rad/sec^2; also, figure 16 indicates that this decrease in yaw-acceleration capability changes the level from one that is normally considered to be satisfactory to one that is unsatisfactory. Table V also shows that with the SAS on, $t_{\Delta\psi=15^{\circ}} = 3.0$ sec, which is about 36 percent longer than the maximum time allowed for satisfactory operation (ref. 5), whereas with the SAS off, $t_{\Delta\psi=15^{\circ}} = 2.0$ sec, which is about 9 percent faster than the requirement. It therefore appears that in order to land in cross winds greater than approximately 10 knots, the airplane would require more rudder power or a "command" control system instead of a simple SAS.

It should be mentioned that although the maximum yaw-acceleration capability was the prime factor that affected the pilot's ability to correct the heading for landing in cross winds, deficiencies of the visual presentation of the runway also affected the pilot's ability to judge when and where to make the heading correction.

Ground Effects

Because of the piloting problems associated with the visual display, mainly the lack of adequate clues for judging height just prior to touchdown, the pilot's assessments of the ground effects were limited, and all comments pertaining to the flare and touchdown were qualified as being only possibilities for such an airplane. In the real world the problems may not be as pronounced. The incremental changes in lift, drag, and pitching-moment coefficients due to ground effects that were used in the simulation (fig. 5) indicate that the jet-flap STOL airplane will experience a nose-down pitching moment, a loss in lift, and a decrease in drag as it approaches the ground.

Autospeed off.- With the automatic speed controller off and the pilot using the column for airspeed control and throttles for flight path, the "suck-down" effect due to the loss in lift when in close proximity to the ground was quite obvious. Also, although it was not obvious from the visual presentation, it could be seen from the airspeed indicator that the decrease in drag due to ground effects caused the airspeed to increase considerably just prior to touchdown. Since the pilot has to maintain a tight control on the pitch attitude during the entire approach when autospeed is not used, the pitching moment due to ground effect was not readily apparent.

Autospeed on.- When the pilots attempted to land the jet-flap STOL airplane with the ground effects being simulated and with the autospeed controller on, the most obvious effect of being in close proximity to the ground was the nose-down pitching moment experienced just prior to touchdown. The suck-down or loss in lift due to ground effect was also apparent when the autospeed controller was on, in that the pilot did not have to reduce the throttle setting in the flare. (When the ground effects were not simulated, the pilot had to decrease the thrust in order to maintain a rate of sink as he pulled back on the column to get the nose of the airplane above the horizon.) The loss in drag due to ground effect could not be detected since the autospeed controller balanced the drag loss to keep the speed constant.

It could probably be said that with the automatic speed control operative the simulated ground effects were not detrimental to the landing flare and possibly even had a favorable effect. The nose-down pitching moment forces the pilot into a positive flare, and the loss in lift allows him to rotate the nose of the airplane and still maintain a rate of sink. Thus he does not have to assist the flare with throttles, and the tendency to overcontrol during the flare, with subsequent "ballooning" or floating down the runway, is reduced.

SUMMARY OF RESULTS

A fixed-base simulator program was conducted to determine the flight characteristics of a representative STOL transport, equipped with an external-flow jet flap in combination with high-bypass-ratio fan-jet engines, during the approach and landing. The results may be summarized as follows:

1. Considerable stability augmentation was required, especially on the lateral-directional axes, before the handling qualities were rated satisfactory.

2. In general, the type and amount of augmentation required for this jet-flap STOL airplane agree with the established requirements for other STOL airplanes, as well as with existing handling-qualities criteria for conventional airplanes.

3. All of the pilots who participated in the simulation program agreed that some form of automatic speed control was mandatory for satisfactory landing approaches with the subject STOL airplane.

4. No problems were experienced when flying approaches in 90° cross winds as high as 30 knots; however, because of the lack of rudder power with the stability augmentation system used, it was impossible to correct the heading adequately when landing in cross winds higher than approximately 10 knots.

5. The ground effects used in the simulation, although adverse, caused no large problems during landings when the autospeed control was operative.

6. With the autospeed control operative, the pilots could easily capture the glide slope for any of the approach angles simulated (angles from 3° to 7.5°). With the autospeed control inoperative, it was difficult to intercept and maintain a glide slope of 3°, and impossible to fly an approach steeper than approximately 6°.

7. As implemented in the present study, symmetrical spoiler deflection or thrust modulation for direct-lift control (DLC), in conjunction with autospeed control, was found to be beneficial for tracking the glide slope during the approach.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., January 11, 1971.

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TABLE I.- SIMULATOR CONTROL CHARACTERISTICS

Control	Gearings from cockpit control to control surface	Breakout force,		Force gradient,	
		N	lbf	N/cm	lbf/in.
Pitch	δ_e/δ_c = -4.0 deg/deg	13.3	3.0	14.0	8.0
Roll	δ_a/δ_w = 1.25 deg/deg	11.1	2.5	5.3	3.0
Yaw	δ_r/δ_p = -3.7 deg/cm (-9.41 deg/in.)	31.1	7.0	28.9	16.5

TABLE II.- MASS AND DIMENSIONAL CHARACTERISTICS

Weight, N (lbf)	1 215 840	(273 333)
Wing area, m^2 (ft^2)	339	(3 644)
Wing span, m (ft)	51	(168)
Mean aerodynamic chord, m (ft)	6.61	(21.68)
Center-of-gravity location, percent $\bar{c}$		40.0
I_X, kg-m^2 (slug-ft^2)	7.67×10^6	(5.66×10^6)
I_Y, kg-m^2 (slug-ft^2)	7.70×10^6	(5.68×10^6)
I_Z, kg-m^2 (slug-ft^2)	14.4×10^6	(10.62×10^6)
I_{XZ}, kg-m^2 (slug-ft^2)	0.64×10^6	(0.47×10^6)
Maximum control-surface deflections:		
δ_e, deg		±30
δ_t, deg		±10
δ_a, deg		±60
δ_r, deg		±40

TABLE III.- BASIC AERODYNAMICS USED IN SIMULATOR

$\left[\delta_{f1}/\delta_{f2} = 25^{\circ}/50^{\circ}\right]$

(a) Nonlinear derivatives

α, deg	$C_T = 0$	$C_T = 1.94$	$C_T = 3.50$	$C_T = 0$	$C_T = 1.94$	$C_T = 3.50$	$C_T = 0$	$C_T = 1.94$	$C_T = 3.50$	$C_T = 0$	$C_T = 1.94$	$C_T = 3.50$	$C_T = 0$	$C_T = 1.94$	$C_T = 3.50$	$C_T = 0$	$C_T = 1.94$	$C_T = 3.50$
	C_X			C_Z			C_m			$C_{X_{\delta_{f2}}}$, per deg			$C_{m_{\delta_{f2}}}$, per deg			C_{m_q}, per rad		
-5	-0.201	-0.145	0.329	-0.285	-3.947	-4.847	0.20	0	-0.22	-0.0055	-0.0403	-0.0633	0	-0.0035	-0.0120	-33	-38	-38
0	-.230	-.070	.400	-1.000	-4.700	-5.470	0	-.16	-.26	-.0060	-.0405	-.0610	0	-.0015	-.0065	-39	-42	-42
5	-.168	.100	.376	-1.675	-5.392	-6.241	-.11	-.30	-.40	-.0074	-.0391	-.0595	-.0035	.0015	-.0045	-44	-46	-46
10	-.080	.294	.558	-2.247	-5.990	-6.908	-.16	-.40	-.50	-.0092	-.0355	-.0577	-.0020	0	-.0050	-48	-52	-52
15	.004	.501	.753	-2.263	-6.383	-7.592	-.10	-.48	-.59	-.0097	-.0337	-.0535	-.0015	-.0040	-.0065	-50	-57	-57
20	.034	.723	.986	-2.303	-6.871	-8.176	-.05	-.50	-.60	-.0099	-.0343	-.0520	-.0015	-.0030	-.0050	-34	-69	-69
	$C_{Y_{\delta_a}}$, per deg			$C_{n_{\delta_a}}$, per deg			$C_{l_{\delta_a}}$, per deg			$C_{Y_{\delta_r}}$, per deg			$C_{n_{\delta_r}}$, per deg			$C_{l_{\delta_r}}$, per deg		
-5	-0.0005	-0.0050	-0.0060	0.0003	0.0001	0.0001	0.0007	0.0033	0.0037	0.0119	0.0167	0.0143	-0.0044	-0.0052	-0.0050	0.0019	0.0021	0.0023
0	-.0013	-.0062	-.0063	.0003	.0002	.0002	.0011	.0036	.0039	.0119	.0167	.0143	-.0043	-.0052	-.0050	.0019	.0021	.0023
5	-.0017	-.0068	-.0068	.0003	.0002	.0002	.0011	.0039	.0042	.0119	.0167	.0143	-.0040	-.0052	-.0059	.0017	.0021	.0023
10	-.0013	-.0075	-.0077	.0002	.0003	.0002	.0009	.0042	.0046	.0117	.0155	.0143	-.0038	-.0050	-.0048	.0015	.0020	.0021
15	-.0007	-.0080	-.0083	.0001	.0005	.0003	.0006	.0046	.0049	.0105	.0143	.0143	-.0036	-.0046	-.0046	.0013	.0019	.0019
20	0	-.0085	-.0083	0	.0007	.0005	.0002	.0048	.0051	.0088	.0119	.0143	-.0031	-.0042	-.0045	.0009	.0015	.0017
	C_{Y_β}, per deg			C_{n_β}, per deg			C_{l_β}, per deg			C_{Y_p}, per rad			C_{n_p}, per rad			C_{l_p}, per rad		
-5	-0.018	-0.009	-0.020	0.0030	0.0021	0.0055	-0.0012	-0.0080	-0.0080	0.02	0.04	0.05	-0.04	-0.09	-0.11	-0.63	-0.65	-0.62
0	-.020	-.025	-.025	.0030	.0052	.0064	-.0038	-.0057	-.0057	.03	.06	.07	-.05	-.12	-.15	-.61	-.62	-.63
5	-.020	-.037	-.030	.0032	.0065	.0067	-.0038	-.0050	-.0050	.05	.08	.09	-.10	-.16	-.18	-.57	-.58	-.63
10	-.022	-.040	-.033	.0033	.0068	.0066	-.0044	-.0056	-.0060	.06	.09	.10	-.13	-.18	-.20	-.41	-.53	-.62
15	-.022	-.037	-.032	.0032	.0068	.0067	-.0055	-.0070	-.0075	.04	.08	.10	-.07	-.17	-.21	-.27	-.47	-.54
20	-.023	-.040	-.032	.0030	.0068	.0068	-.0040	-.0082	-.0087	.01	.03	.09	-.02	-.06	-.08	-.25	-.40	-.49
	C_{Y_r}, per rad			C_{n_r}, per rad			C_{l_r}, per rad											
-5	0.70	1.15	1.20	-0.175	-0.291	-0.245	0.23	0.23	0.23									
0	.68	1.02	1.08	-.185	-.255	-.259	.26	.26	.26									
5	.62	.88	.91	-.180	-.298	-.252	.32	.32	.32									
10	.56	.77	.78	-.175	-.291	-.245	.39	.39	.39									
15	.50	.67	.67	-.168	-.231	-.235	.52	.52	.52									
20	.52	.68	.67	-.185	-.255	-.259	.57	.57	.57									

TABLE III.- BASIC AERODYNAMICS USED IN SIMULATOR – Concluded

$[\delta_{f1}/\delta_{f2} = 25^{o}/50^{o}]$

(b) Linear derivatives

$C_{X_{\delta_e}} = -0.005$, per deg

$C_{Z_{\delta_e}} = -0.022$, per deg

$C_{m_{\delta_e}} = -0.0447$, per deg

$C_{Z_{\delta_{f2}}} = 0$

$C_{X_{\delta_t}} = -0.016$, per deg

$C_{Z_{\delta_t}} = -0.066$, per deg

$C_{m_{\delta_t}} = -0.134$, per deg

TABLE IV.- PILOT RATING SYSTEM

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
			Good, pleasant, well behaved.	2
			Fair. Some mildly unpleasant characteristics. Good enough for mission without improvement.	3
		UNSATISFACTORY Reluctantly acceptable. Deficiencies which warrent improvement. Performance adequate for mission with feasible pilot compensation.	Some minor but annoying deficiencies. Improvement is requested. Effect on performance is easily compensated for by pilot.	4
			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
	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
			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
UNCONTROLLABLE Control will be lost during some portion of mission.			Uncontrollable in mission.	10

TABLE V.- CONTROL RESPONSE CHARACTERISTICS OF SIMULATED JET-FLAP STOL AIRPLANE AND THREE OTHER STOL AIRPLANES

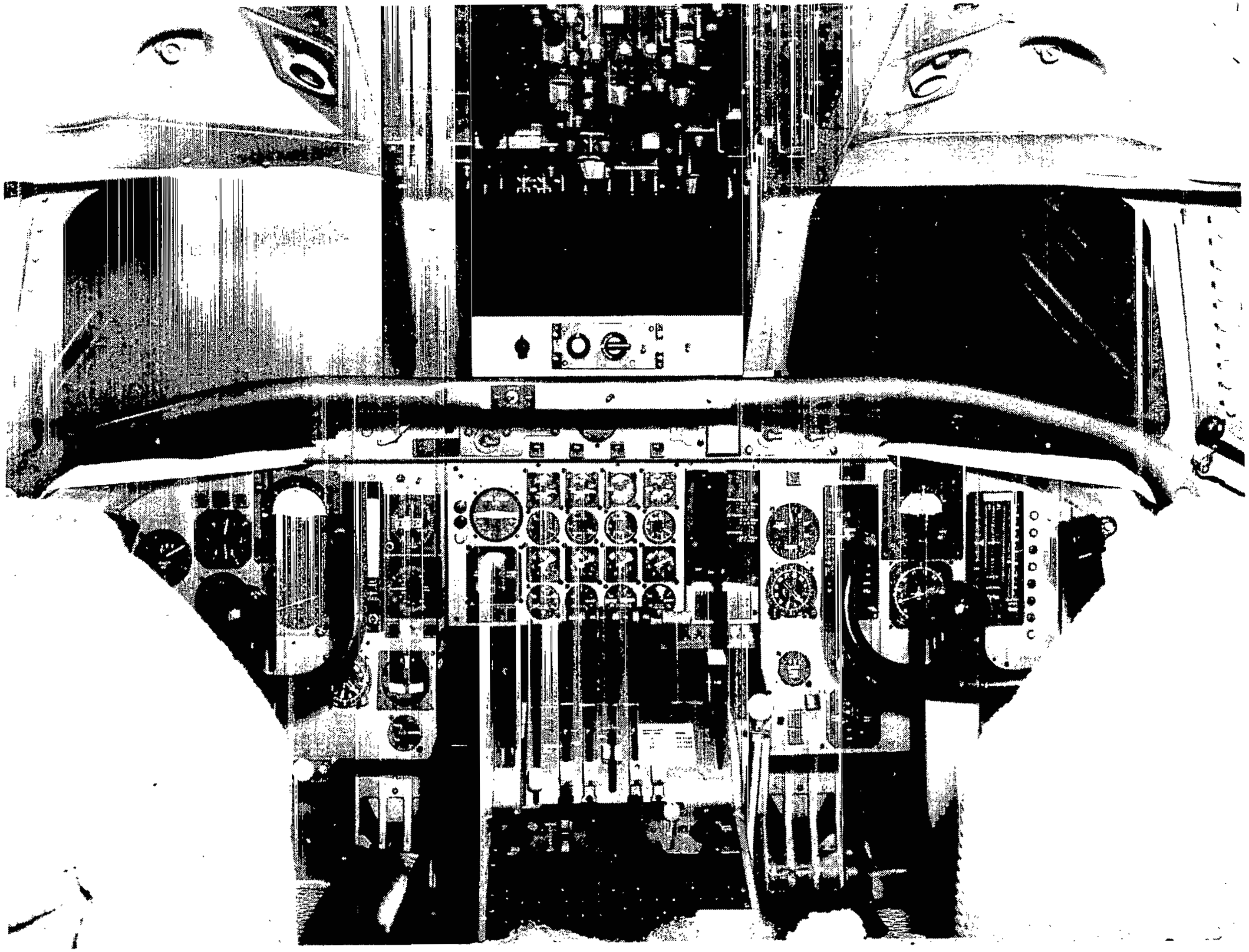
Parameter	Simulated jet-flap STOL		BR 941	NC-130(Mod.), SAS off	[a]367-80, SAS off	Minimum level for satisfactory operation (ref. 5)
	SAS off	SAS on				
Airspeed, knots	69	69	60	70	85 to 90	-------------
$\ddot{\theta}_{max}$, rad/sec^2	0.30	0.45	0.50	0.65	0.24	See fig. 9
$\Delta\theta_{t=1}$, deg	5.0	5.3	6.6	8.0	-------	-------------
$t_{\Delta\theta=10^o}$, sec	1.7	1.8	1.2	1.2	-------	1.2
$\ddot{\varphi}_{max}$, rad/sec^2	0.38	0.57	0.48	0.32	0.55	See fig. 12
$\Delta\varphi_{t=1}$, deg	10.0	10.0	4.0	4.1	7.0	-------------
$t_{\Delta\varphi=30^o}$, sec	2.0	2.0	2.2	3.0	2.0	2.4
β_1/φ_1, deg/deg	0.71	0.21	0.40	0.80	0.75	0.3
$\Delta\theta/\Delta\varphi$, deg/deg	0.2	0.1	-----	-----	-------	Not noticeable
$\ddot{\psi}_{max}$, rad/sec^2	0.17	0.11	0.18	0.21	0.09	See fig. 16
$\Delta\psi_{t=1}$, deg	3.3	3.5	3.0	3.3	1.5	-------------
$t_{\Delta\psi=15^o}$, sec	2.0	3.0	2.0	1.9	2.7	2.2
$\Delta\theta/\delta_{p,max}$, deg	9.0	1.0	-----	-----	-------	Not noticeable

[a]With boundary-layer control.

TABLE VI.- DYNAMIC STABILITY CHARACTERISTICS OF SIMULATED JET-FLAP STOL AIRPLANE AND THREE OTHER STOL AIRPLANES

Parameter	Simulated jet-flap STOL		BR 941	NC-130(Mod.), SAS off	[a]367-80, SAS off	Level for satisfactory operation (ref. 7)
	SAS off	SAS on				
Airspeed, knots	69	69	60	70	85 to 90	---------
Short-period mode						
ω_{sp}, rad/sec	0.796	1.137	-----	-----	-------	See fig. 8
P, sec	12.8	6.4	-----	-----	-------	---------
ζ_{sp}	0.786	1.321	-----	-----	-------	>0.35
Long-period (phugoid) mode						
P, sec	30.0	37.0	-----	-----	-------	---------
ζ	0.021	0.127	-----	-----	-------	>0.04
Roll mode						
t_R, sec	1.03	0.76	1.0	0.9	1.0	<1.4
Spiral mode						
$t_{1/2}$, sec	297	------	10	-----	-------	---------
t_2, sec	-------	28	-----	-----	12	>20
Dutch roll mode						
ω_d, rad/sec	0.655	0.807	0.7	0.5	0.8	>0.4
ζ_d	0.042	0.562	0.1	0.12	-0.1	>0.08
$\zeta_d\omega_d$, rad/sec	0.028	0.454	0.07	0.06	-0.08	>0.15
P, sec	9.6	9.4	8.5	12.0	8.6	---------

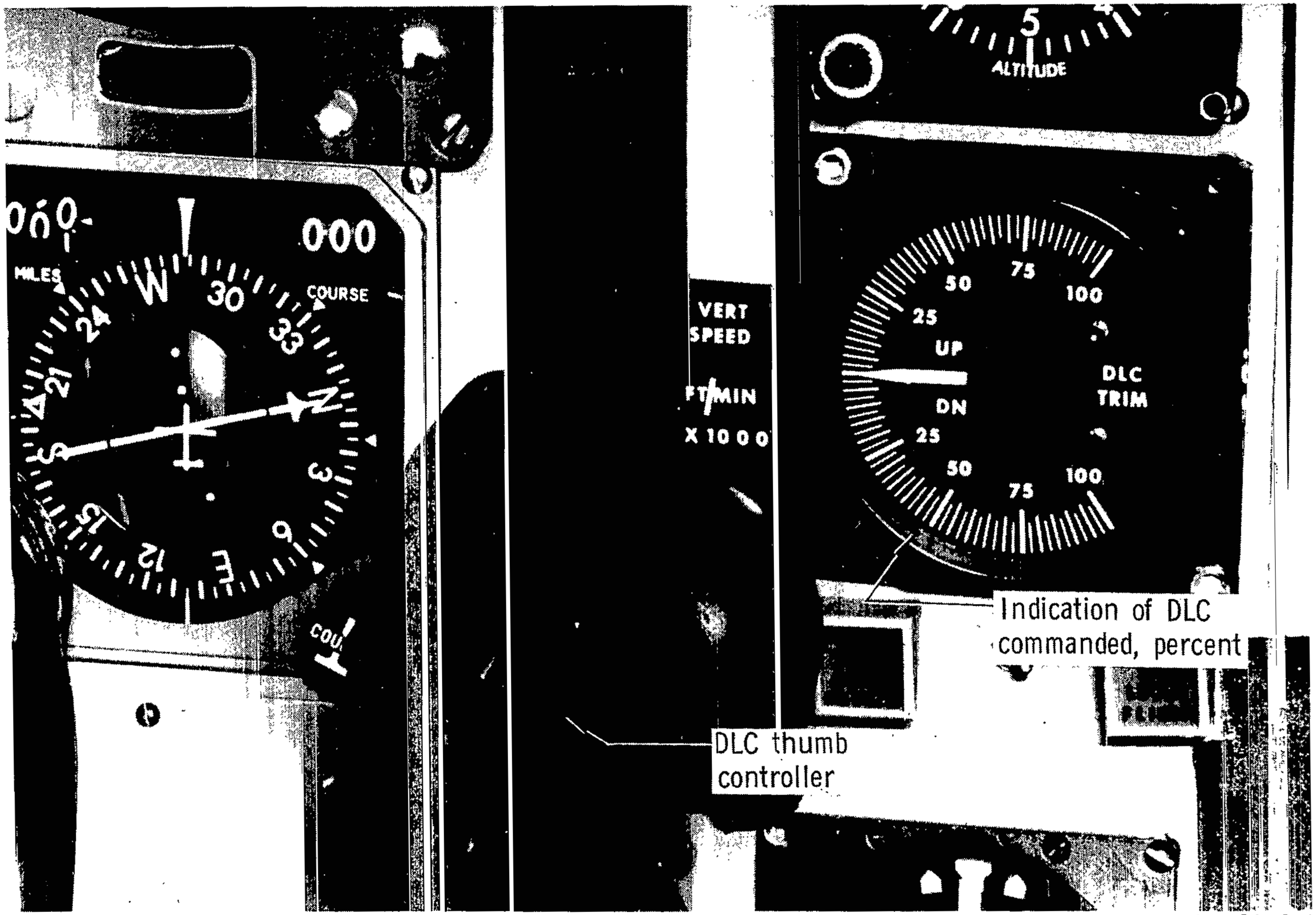
[a]With boundary-layer control.



L-69-4124

(a) Simulator cockpit.

Figure 1.- Simulator cockpit and instrument display.



L-70-8358.1

(b) Direct lift controller and amount of DLC commanded.

Figure 1.- Concluded.

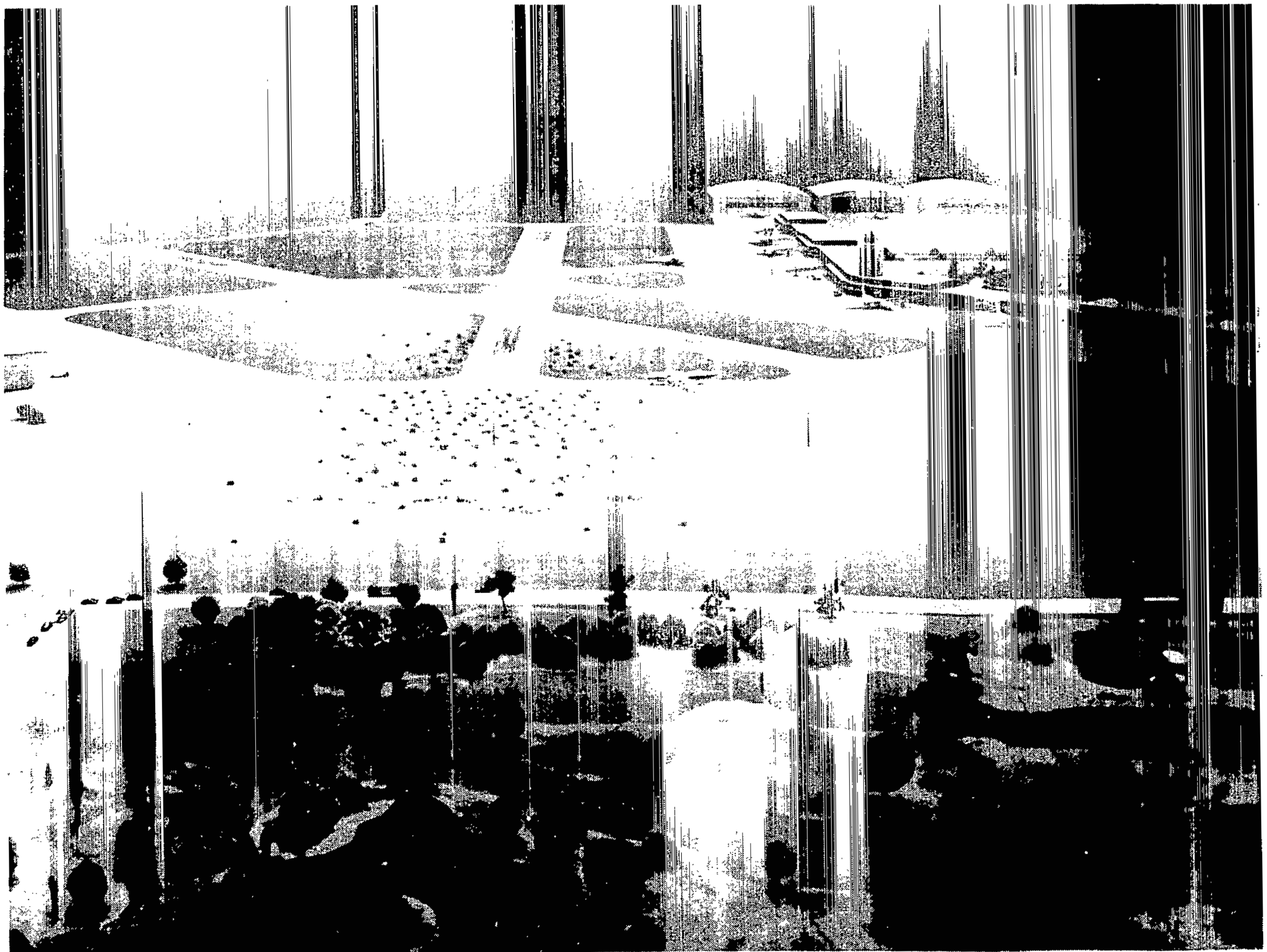


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Figure 2.- Photograph of 1/300-scale airport model.

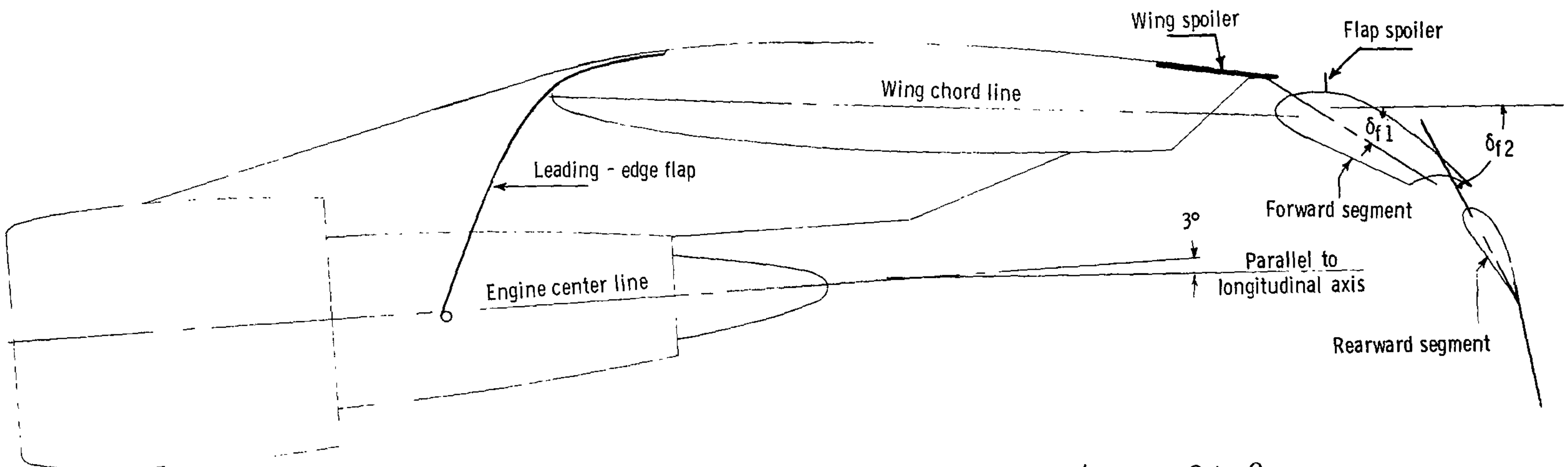
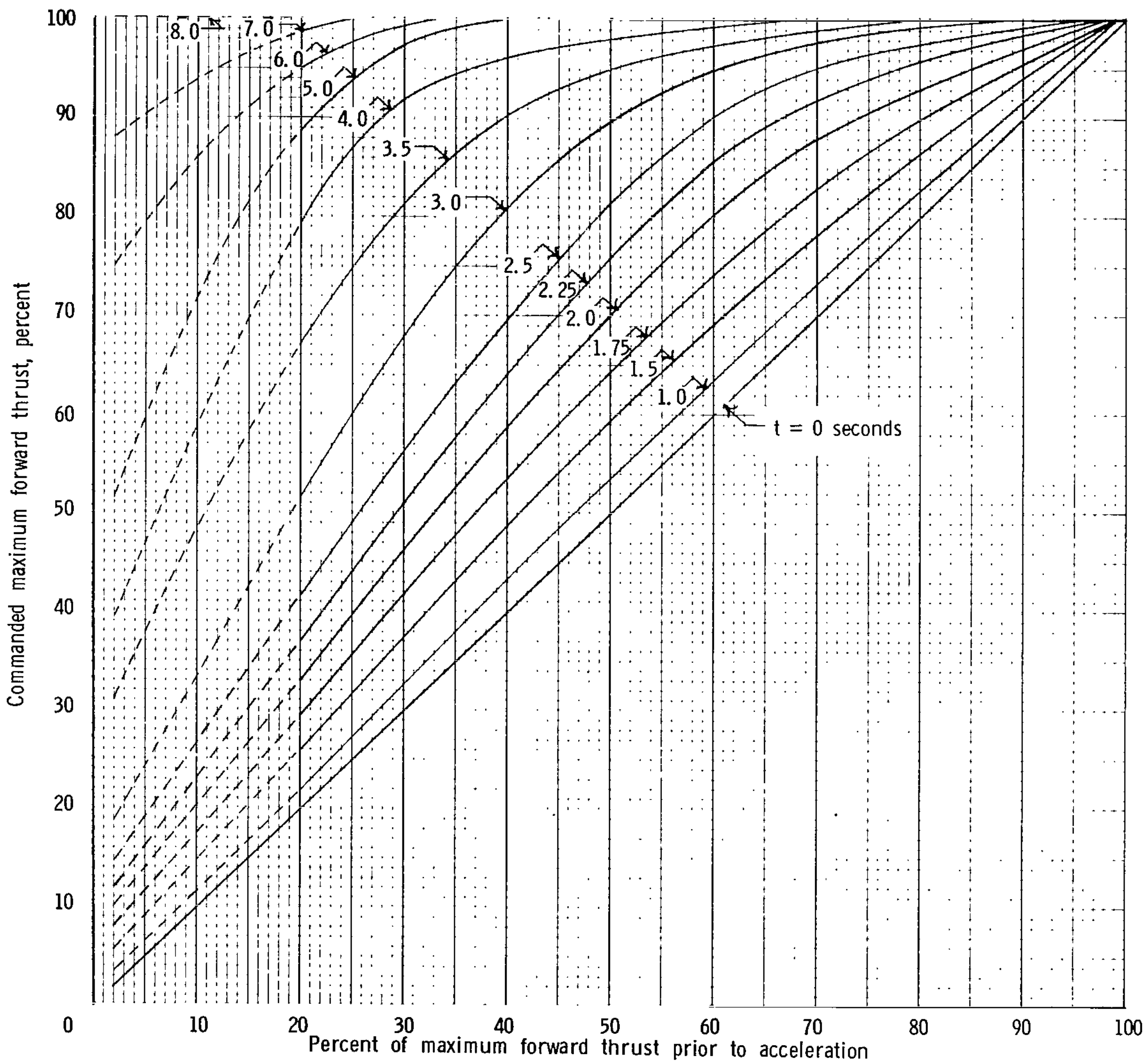
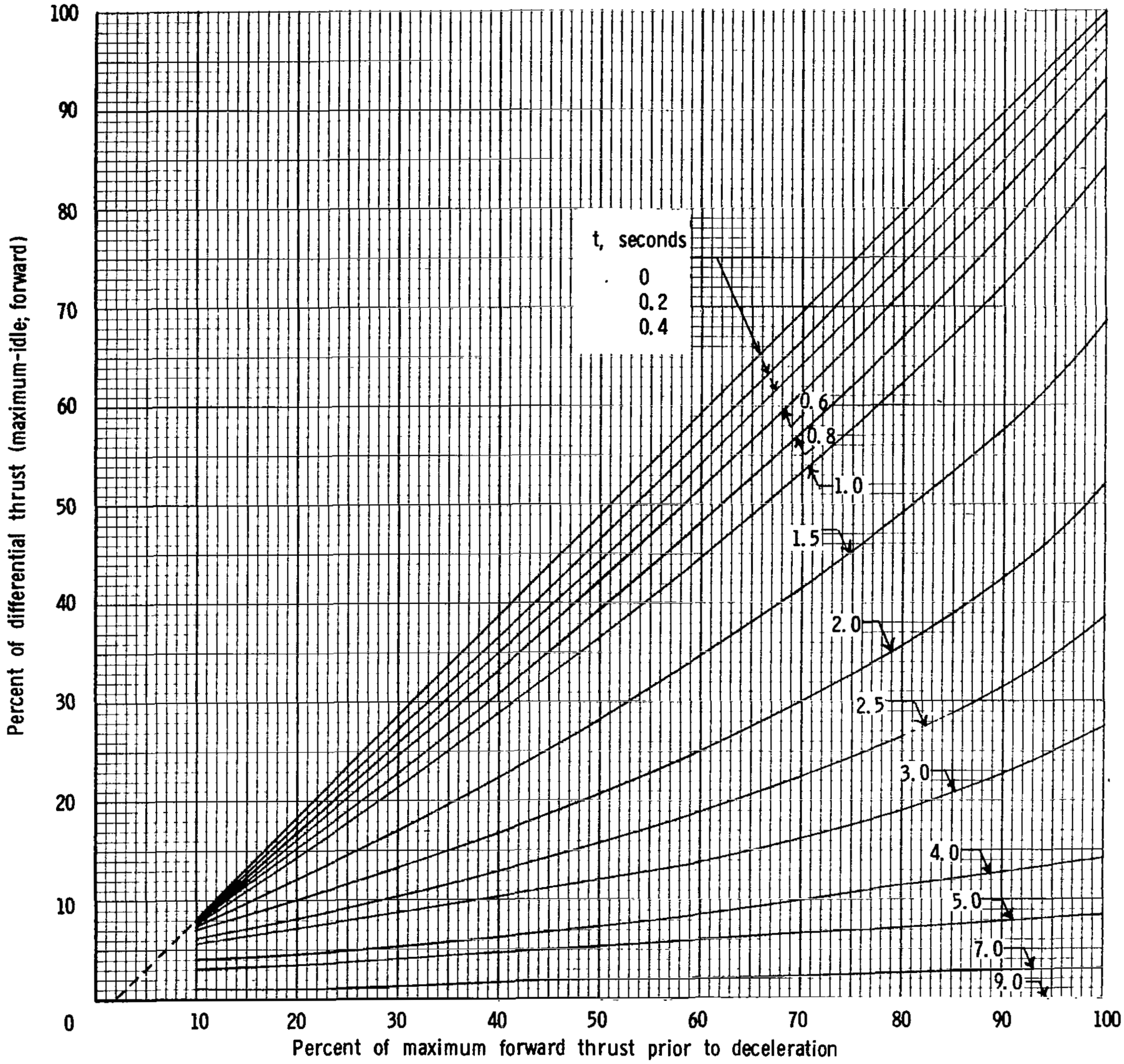


Figure 3.- Flap assembly and engine-pylon detail. $\delta_{f1}/\delta_{f2} = 25^{\circ}/50^{\circ}$.



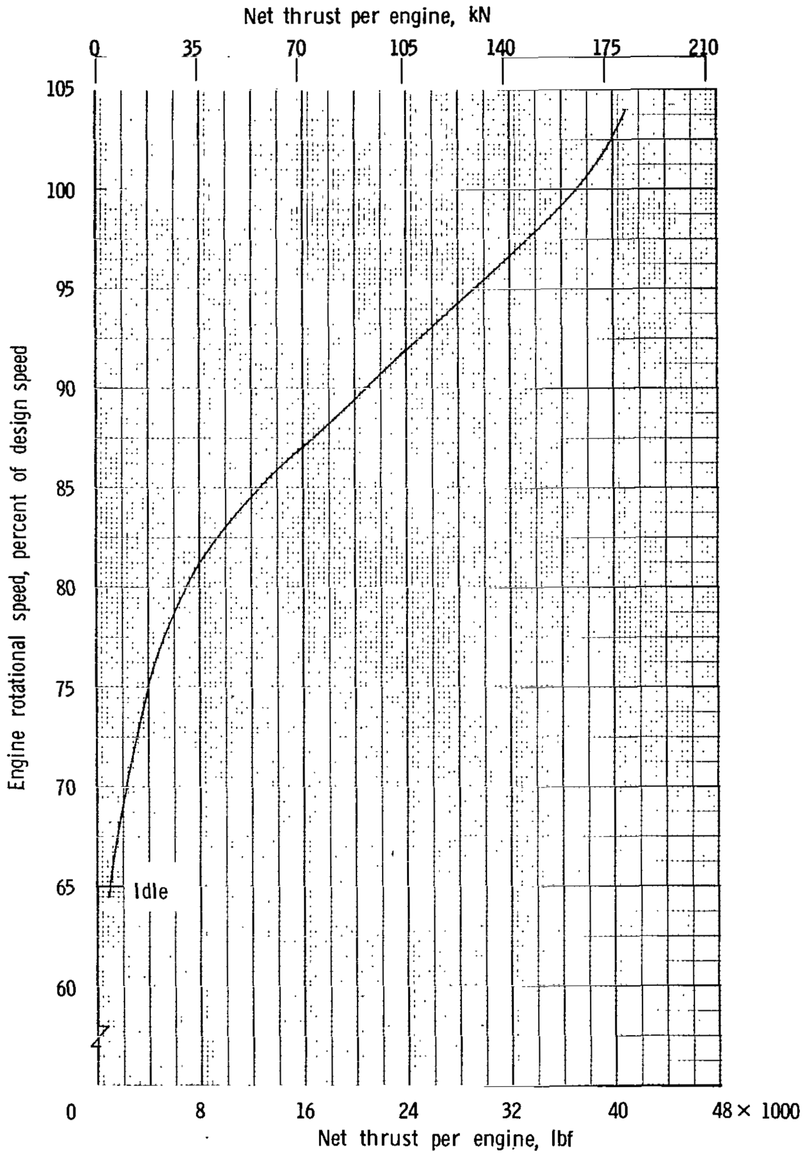
(a) Thrust response for acceleration. (Example: From T = 50 percent to T = 90 percent, t = 3 sec.)

Figure 4.- Engine thrust characteristics used in simulation.



(b) Thrust response for deceleration.

Figure 4.- Continued.



(c) Engine rotational speed-thrust relationship.

Figure 4.- Concluded.

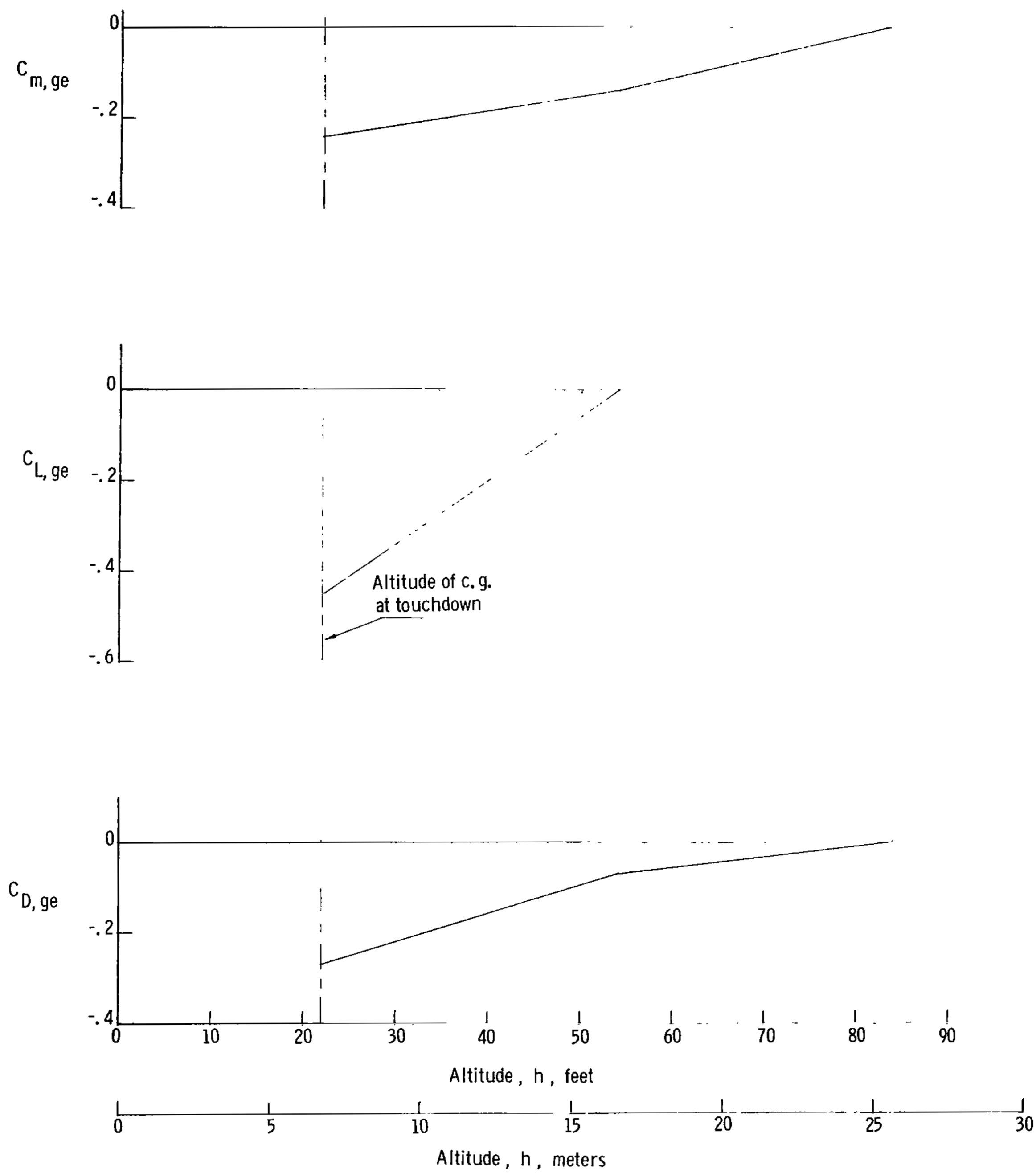


Figure 5.- Incremental changes in pitching-moment, lift, and drag coefficients due to ground effects.

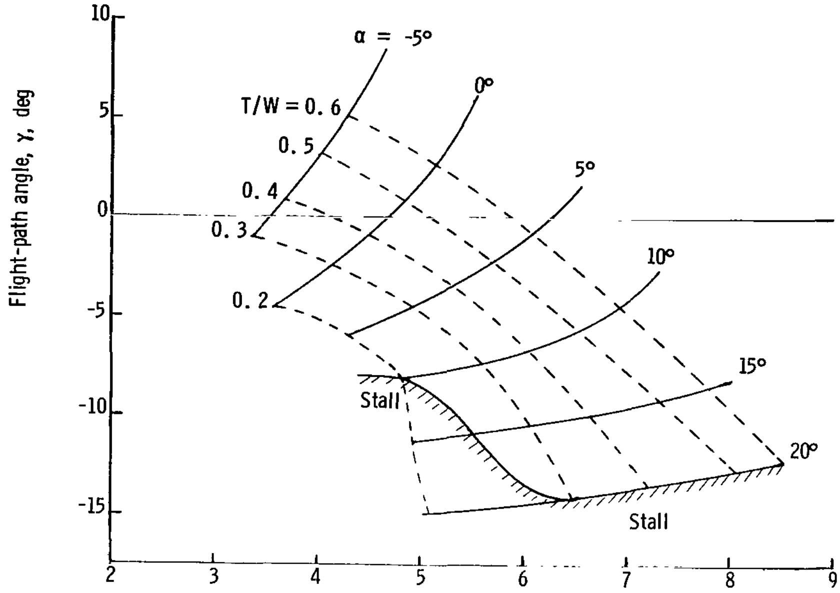


Figure 6.- Effects of engine thrust on trim lift coefficient and flight-path angle. $\delta_{f1}/\delta_{f2} = 25^{\circ}/50^{\circ}$.

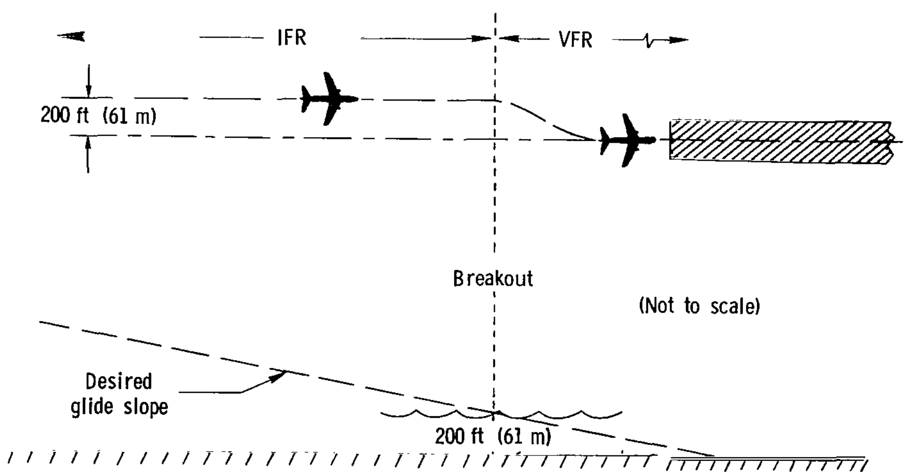


Figure 7.- Schematic drawing of the offset correction task used in the simulator.

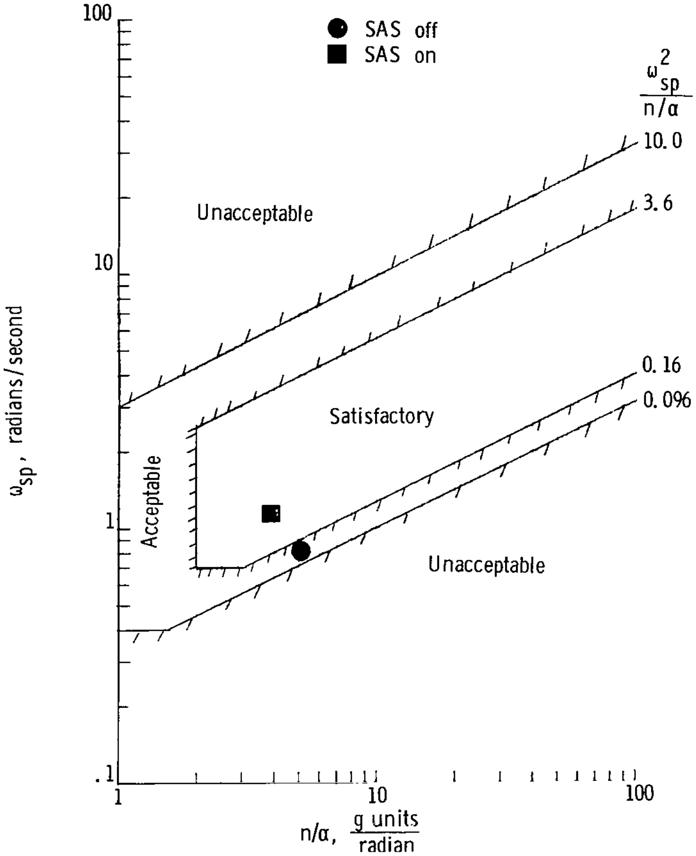


Figure 8.- Comparison of longitudinal short-period characteristics with requirements of reference 7.

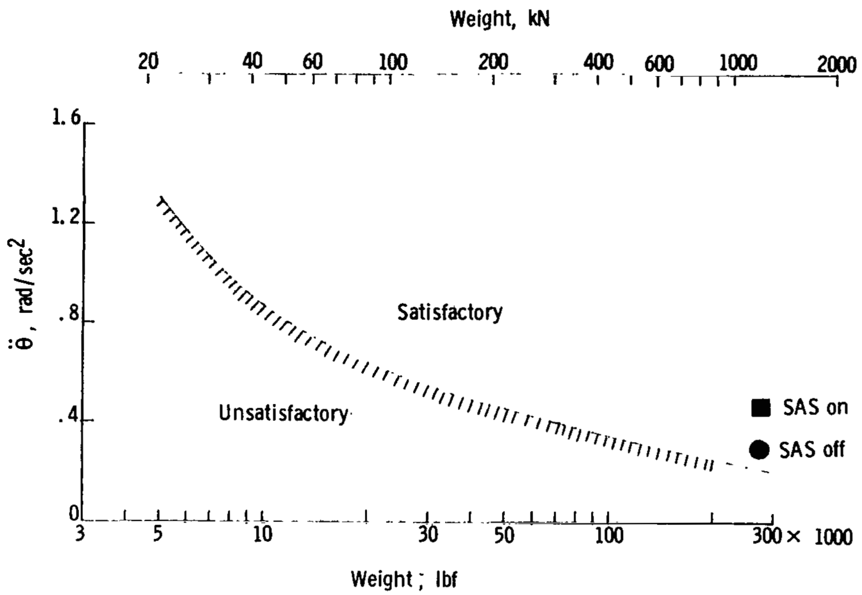


Figure 9.- Pitch-acceleration capability required for various-size STOL airplanes. Boundary is from reference 5.

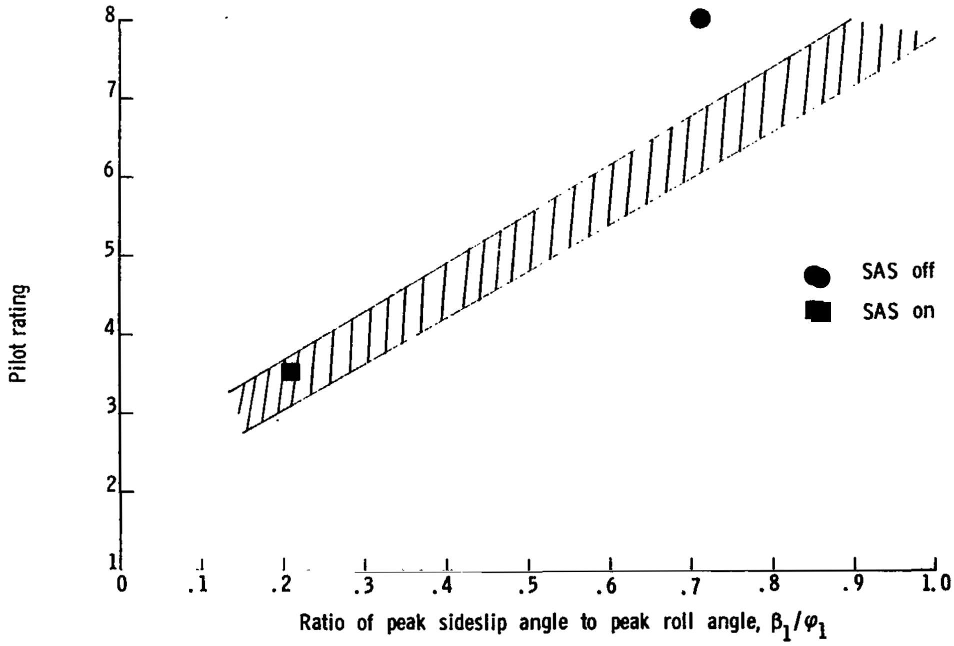


Figure 10.- Variation of pilot rating with ratio of peak sideslip angle to peak roll angle for turn entries. Boundaries are from reference 8.

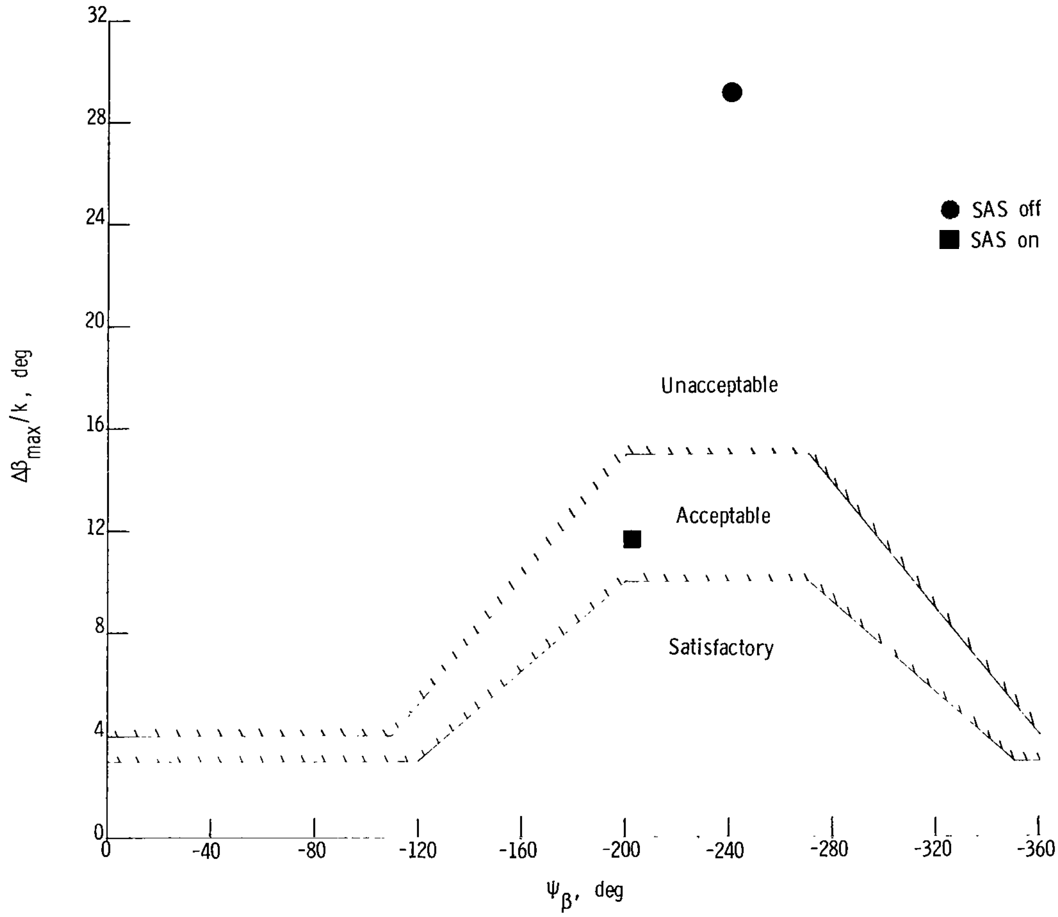


Figure 11.- Comparison of sideslip excursion criterion of reference 7 with characteristics of simulated STOL airplane.

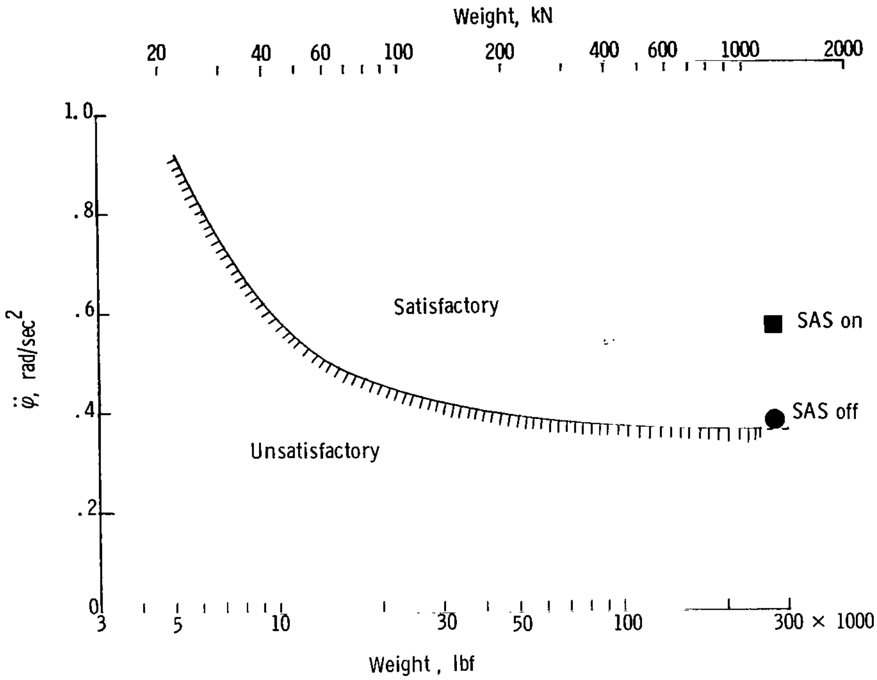


Figure 12.- Roll-acceleration capability required for various-size STOL airplanes. Boundary is from reference 5.

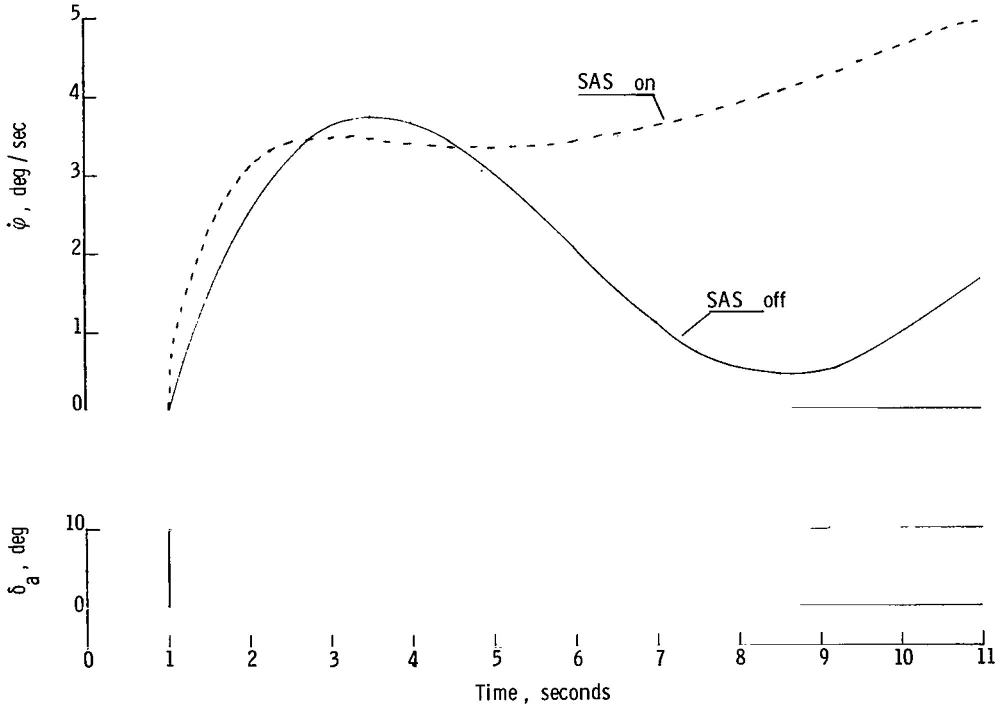


Figure 13.- Roll-rate response to a step aileron input.

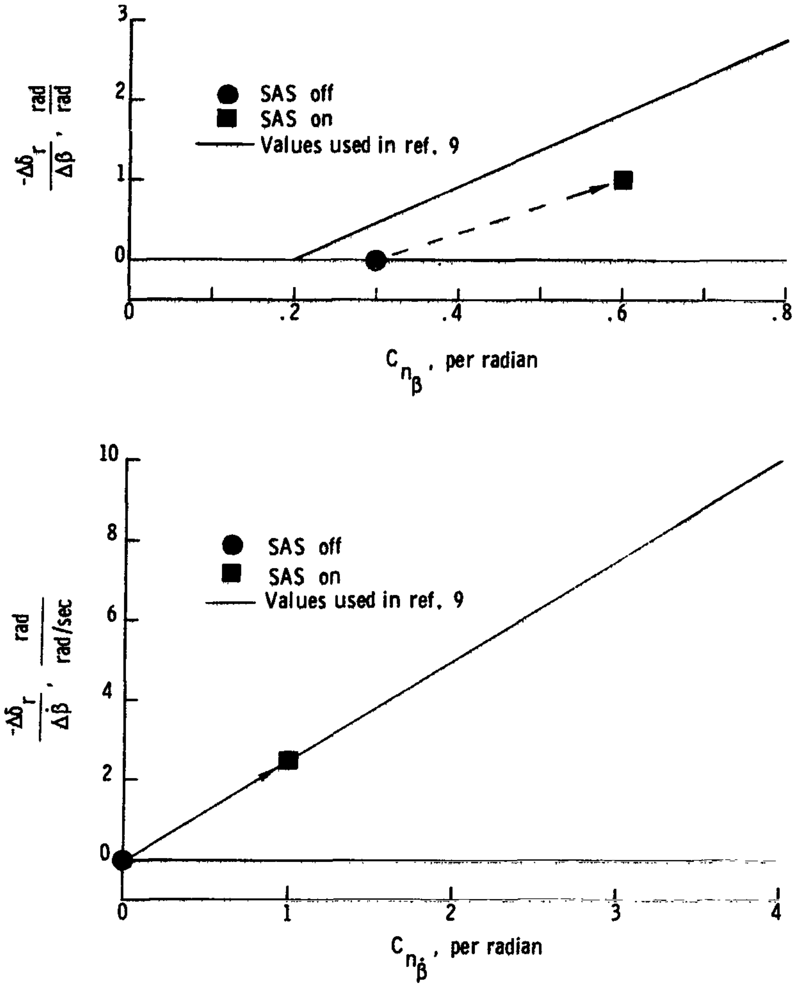


Figure 14.- Stability-augmentation gains required to generate some of the coefficients used in the simulation.

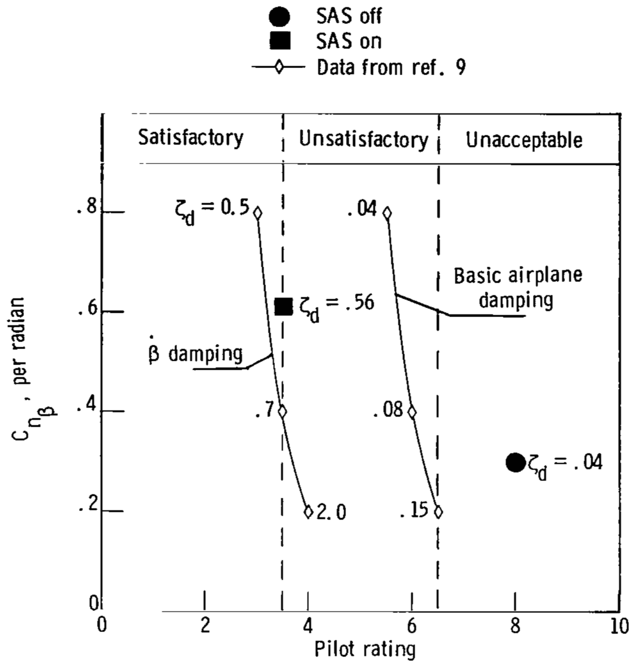


Figure 15.- Relative effects of directional stability and $\dot{\beta}$ damping on pilot rating.

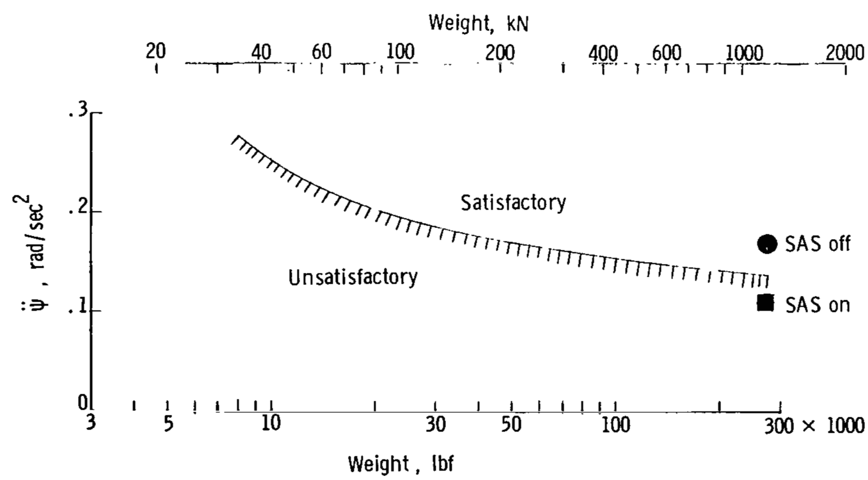


Figure 16.- Yaw-acceleration capability required for various-size STOL airplanes. Boundary is from reference 5.

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