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DETERMINATION OF FLIGHT CHARACTERISTICS OF SUPERSONIC TRANSPORTS DURING THE LANDING APPROACH WITH A LARGE JET TRANSPORT IN-FLIGHT SIMULATOR

by Staff of the Langley Research Center

Langley Research Center
Langley Station, Hampton, Va.

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PREFACE

This compilation contains results of in-flight simulator tests made to determine the low-speed flight characteristics of several generalized supersonic transport configurations. A large jet transport was used as an in-flight dynamic simulator. This investigation was made by members of the staff of the NASA Langley Research Center and is reported in six parts, each covering one aspect of the study. These parts contain discussions of procedures, equipment, performance characteristics, longitudinal handling qualities, lateral-directional handling qualities, and an evaluation of the pilot workload.

CONTENTS

SYMBOLS

The units for the physical quantities used herein are presented in both the U.S. Customary System of Units and the International System of Units. Factors relating these two systems of units may be found in NASA SP-7012.[1]

The moments of inertia are with respect to the body axes. The stability derivatives are given with respect to the stability axes. However, the simulation was set up so that all these parameters were transferred to the stability axes.

b	span, feet (meters)
$\bar{c}$	mean aerodynamic chord, feet (meters)
$C_{1/2}$	cycles to damp to one-half amplitude
D	drag, pounds (newtons)
F_c	force input to control column, pounds (newtons)
f_n	natural frequency, cycles/second (hertz)
G	frequency dependent parameter
g	acceleration due to gravity, feet/second^2 (meters/second^2)
h	geometric altitude, feet (meters)
h_p	pressure altitude, feet (meters)
i_w	wing incidence, degrees
I_X,I_Y,I_Z	moments of inertia about X-, Y-, and Z-axes, respectively, slug-feet^2 (kilogram-meters^2)
I_{XZ}	product of inertia, slug-feet^2 (kilogram-meters^2)
K	constant
L	lift, pounds (newtons)

[1] E. A. Mechtly: The International System of Units – Physical Constants and Conversion Factors. NASA SP-7012, 1964.

L_α	lift per unit angle of attack per unit of momentum, $C_{L_\alpha}qS/mV$, per second
l	distance from angle-of-attack and sideslip vanes to center of gravity, feet (meters)
m	mass of airplane, slugs (meters)
$N'_{\delta a}$	aileron coupling parameter, positive for adverse yaw
n	load factor, g units
P	period, seconds
q	dynamic pressure, $\frac{1}{2}\rho V^2$, pounds/foot^2 (newtons/meter^2)
q_o	dynamic pressure at trim conditions, pounds/foot^2 (newtons/meter^2)
S	wing area, feet^2 (meters^2)
s	Laplace transform operator
T	thrust, pounds (newtons)
T_R	roll time constant, seconds
T_2	time to double amplitude, seconds
$T_{1/2}$	time to damp to one-half amplitude, seconds
t	time, seconds
V	true airspeed, knots
V_e	equivalent airspeed, knots
V_o	trim airspeed, knots
v_e	equivalent side velocity, feet/second (meters/second)

W	weight, pounds (newtons)
α	angle of attack, degrees
β	sideslip angle, degrees
γ	flight-path angle, degrees
δ_a	aileron deflection, positive with right aileron down, degrees
δ_C	deflection command, degrees
δ_c	control column deflection, degrees
δ_e	elevator deflection, positive with trailing edge down, degrees
δ_m	thrust modulator deflection, degrees
δ_r	rudder deflection, positive with trailing edge left, degrees
δ_s	spoiler deflection, degrees
δ_T	thrust-modulator deflection, degrees
δ_w	wheel deflection, positive with wheel right, degrees
ζ	damping ratio
θ	pitch attitude, degrees
Λ	sweepback angle, degrees
ρ	air density, slugs/foot^3 (kilograms/meter^3)
ϕ	bank angle, degrees
ψ	heading angle, degrees
ω_D	damped natural frequency of short-period longitudinal mode, radians/second

ω_d	undamped natural frequency of Dutch roll oscillation, radians/second
ω_n	undamped natural frequency of short-period longitudinal mode, radians/second
ω_ϕ	undamped natural frequency from lateral numerator quadratic, radians/second
C_D	drag coefficient
C_L	lift coefficient
C_l	rolling-moment coefficient
C_m	pitching-moment coefficient
C_n	yawing-moment coefficient
C_{l_p}	damping-in-roll parameter
C_Y	side-force coefficient

Subscripts:

basic	basic configuration
max	maximum
trim	trim conditions
wh	wheel
SST	supersonic transport
-80	367-80 airplane configuration

Abbreviations:

c.g.	center of gravity
IFR	instrument flight rules
ILS	instrument landing system
PIO	pilot-induced oscillation
PR	pilot rating
rms	root mean square
SAS	stability augmentation system
SST	supersonic transport
VFR	visual flight rules

The method of indicating partial derivatives is as follows:

$$C_{m_\delta} = \frac{\partial C_m}{\partial \delta}$$

$$C_{l_{\dot{\phi}}} = \frac{\partial C_l}{\partial \dot{\phi}}$$

A dot over a symbol represents a derivative with respect to time.

1. INTRODUCTION

By Robert O. Schade

The presently proposed configurations of the supersonic transport (SST) are different from any existing commercial airplane. These airplanes, primarily designed for supersonic cruise performance, introduce geometric and design features which are expected to affect the low-speed flight characteristics adversely and to cause problems during instrument-flight-rules (IFR) approaches. For example, the following table, which shows a comparison of the characteristics of two supersonic transport configurations (see fig. 1-1) and a typical large subsonic jet transport, indicates that the pitch inertia is approximately 3.5 times that of current subsonic jet transports. This increased pitch inertia may have detrimental effects on pitch-response times, and, consequently, glide-path control, sink-speed control, and touchdown accuracy. The large increases in the yaw-to-roll moments of inertia (3 to 4 times greater than those of the subsonic jet transports) will possibly introduce new or unusual lateral-directional cross-coupling characteristics. The low frequencies of the longitudinal short-period and Dutch roll motion resulting from the high inertias may result in undesirable transient response characteristics. In addition, delta-type configurations will be making landing approaches with speed-thrust instability or on the "back side" of the thrust-required curve (at currently proposed approach speeds) in a region where a decrease in airspeed requires an increase in thrust. These, and other potential problem areas, need to be further explored and design parameters changed as required to provide acceptable low-speed handling qualities and to insure adequate flight safety for future SST configurations.

The current military and civil handling-quantities requirements are a useful guide but, in some cases, they have already been proven obsolete by experience with present subsonic jet transports. The requirements for the Dutch roll and longitudinal stability appear to be too restrictive and others, such

	Fixed-geometry SST / Present jet transport	Variable-geometry SST / Present jet transport
Ratio -		
Landing weight	1.8	1.8
Moment of inertia		
Pitch	3.6	3.5
Roll	0.6	0.8
Yaw	2.4	2.4
Damped period		
Longitudinal short-period motion	2.3	1.3
Dutch roll motion	1.2	1.5

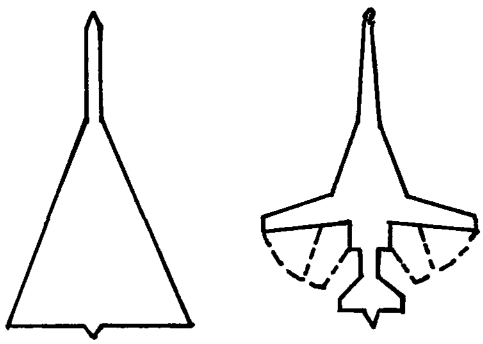


Figure 1-1.- SST configurations.

as lateral-control response, appear to be not restrictive enough. It therefore appears that further flight experience is needed on the SST configurations to shed additional light on the possible updating of the handling-qualities requirements and criteria for this type of airplane.

Ground-simulation techniques provide answers for handling-qualities problems of cruise and instrument flight; however, they are not as satisfactory for evaluating landing characteristics as an in-flight simulator since, during the final landing phase, the pilot relies on a combination of airplane and outside visual references and is subjected to situations which can only be fully experienced in flight. It appeared, therefore, that the best presently available method for evaluating the SST approach and landing characteristics would be a large in-flight dynamic simulator which both simulates the airplane being tested and places the pilot in the most realistic flight environment possible.

As a result, a contract was negotiated with The Boeing Company to modify a large four-engine transport airplane as a low-speed in-flight simulator. The modified in-flight simulator was flown in a simulated IFR low-speed approach and landing investigation at the NASA Langley Research Center from May to October, 1965; variations in generalized configurations of the fixed-geometry and variable-geometry SST concepts were incorporated in the flights.

The main objectives of this investigation were to:

(1) Study the handling qualities of the basic SST configurations and evaluate potential handling-qualities problem areas

(2) Obtain preliminary indications of stability-augmentation requirements for satisfactory handling qualities

(3) Obtain some indications of the tolerable or minimum acceptable handling qualities by parameter variation of:

(a) Aerodynamic characteristics

(b) Center-of-gravity location (variable-geometry configuration only)

(4) Determine effects of speed-thrust instability or operation on the "backside" of the power-required curve (fixed-geometry configuration only)

(5) Obtain approach and landing data applicable to criteria and certification requirements for SST airplanes

The basic SST configurations and variations that were tested in this investigation are as follows:

<u>Variable-Geometry Configurations</u>

(1) Basic airplane

(2) Pitch-rate augmentation

(3) Pitch-rate and angle-of-attack augmentation

(4) Aft center of gravity

(5) Aft center of gravity with pitch-rate and angle-of-attack augmentation

(6) Dutch roll augmentation

(7) Dutch roll and adverse-yaw degradation

Basic Variable-Geometry Emergency-Landing (Cruise-Sweep) Configuration

Fixed-Geometry Configurations

(1) Basic airplane

(2) Pitch-rate and angle-of-attack augmentation

(3) Improved speed-thrust stability

(4) Roll-damping augmentation

(5) Dutch roll and adverse-yaw degradation

For the configurations, the pilot-evaluation tasks were simulated IFR or hooded landing approaches along prescribed flight paths. The pilots' comments along with various measured flight data were used to evaluate each of the conditions flown; the results of these evaluations are included in the following parts of this paper.

2. PROCEDURES AND EQUIPMENT

By Harold L. Crane

SUMMARY

An in-flight simulation has been made to determine the handling qualities of several supersonic transport configurations during the landing approach. This part of the compilation describes the test program, the SST test configurations, the simulator, and the stability augmentation for the SST test configurations. The discussion of the simulator covers several topics including the test airplane, the simulation technique, the simulation equations, the simulator specifications, the simulation procedures, and examples of the quality of simulation.

INTRODUCTION

This part of the report includes a discussion of the procedures and equipment used in the investigation. The research program and test conditions are discussed and the test airplane and simulation system are described. The test airplane was the Boeing 367-80, a jet transport prototype. The selection of a five-degree-of-freedom simulation using the response feedback technique is discussed. An example block diagram and the complete simulation equations are presented. Details of the control system and response specifications for the five simulation input systems are presented. The selection of stability-augmentation techniques for the SST test configurations is discussed. Simulation test procedures, quality of simulation obtained, and operational experience with this simulator are also discussed.

PROGRAM AND TEST CONDITIONS

The object of this program was to investigate the landing-approach and touchdown characteristics of SST configurations by means of in-flight simulation. The configurations were designed to represent the fixed-geometry and variable-geometry concepts of the supersonic transport. The variable-geometry configuration was tested mainly at the minimum sweep angle of 20° with a brief investigation of the fully swept 72° emergency-landing (or cruise) configuration. The dimensions and design aerodynamic parameters for the simulated configurations are given in tables 2-1 and 2-2 on pages 33 and 34.

The test program included: (1) pilot familiarization and VFR (visual-flight-rules) evaluation of the three SST landing-approach configurations at an altitude of 4000 to

8000 feet (1220 to 2440 meters) and (2) the evaluation of instrument-landing-approach characteristics and visual-flare and touchdown characteristics of the three SST configurations. The approach speed was 135 knots except for the 72° emergency-landing configuration for which an approach speed of 150 knots was used to simulate 182 knots.

The VFR evaluations consisted of seven basic tests which were as follows:

1. Evaluate static longitudinal and speed-thrust stability and longitudinal control capability by varying speed ±10 knots with the elevator only.

2. Evaluate the steady-maneuver characteristics by a wind-up turn to a 45° bank angle.

3. Evaluate the transient-maneuver characteristics by performing a 10°-pitch-attitude change as rapidly and accurately as possible by using the flight director.

4. Evaluate trim characteristics by cutting power and then reestablishing trim speed.

5. Evaluate Dutch roll characteristics by releasing the airplane from a 10° sideslip angle.

6. Evaluate roll-control-response characteristics by a 10°-wheel input with the rudder fixed.

7. Evalute the ease of making a precise heading change by performing heading changes of 10° and 30°.

Following these tests, final pilot evaluation was obtained under conditions of simulated (hooded) instrument flight rules (IFR) during approaches to landing. Hooded approaches were used in order to provide a precision pilot task that was representative of actual flight operations.

For this task, an intercept of the localizer was made with landing gear down approximately 8 miles (12.8 kilometers) from the runway at an altitude of 1500 feet (460 meters). The flaps and airspeed were then adjusted for the landing approach as required by the simulation. At the intercept of the glide slope, approximately 5 miles (8 kilometers) from the runway, a descent was initiated and the pilot attempted to fly the prescribed flight path as closely as possible down to approximately 200 feet (61 meters) and, if conditions were favorable, continue visually to touchdown. Some tests were made with the localizer offset 200 feet (61 meters) from the runway center line during the approach to evaluate the lateral maneuverability. Following the simulated IFR breakout at 200 feet (61 meters) with the lateral offsets, the pilot performed a visual sidestep maneuver in order to line up with the runway. Other tests were also made with square-wave vertical offsets of the glide slope approximately halfway down the glide slope to study the speed-thrust stability and longitudinal maneuverability while the pilot was under the hood.

All flight tests were conducted during good ceiling and visibility conditions with light-to-moderate winds of 15 knots or less and gusts below 5 knots.

The following variations and changes were included in the basic SST aircraft configurations being simulated during the flight-test program:

1. Variable-geometry variations
    a. A longitudinal stability-augmentation system was developed which consisted of adding pitch-rate feedback and increasing the gearing between the elevator and the column. A final system similar to the preceding one also included angle-of-attack feedback.
    b. An aft center-of-gravity configuration was used to simulate the airplane flying with the center-of-gravity location near the maximum allowable aft position. (The final augmentation system described in (a) was also used during a portion of these tests.)
    c. A lateral-directional stability-augmentation system was used to improve the Dutch roll damping.
    d. Degraded lateral-directional characteristics were obtained by increasing adverse yaw and reducing Dutch roll damping.
2. Variable-geometry cruise configuration (only the basic configuration was flown)
3. Fixed-geometry variations
    a. A longitudinal stability-augmentation system identical to the one on the variable-geometry configuration was used.
    b. A lateral-directional stability-augmentation system was used which improved the roll damping.
    c. Degraded lateral-directional characteristics were obtained by increasing adverse yaw and reducing Dutch roll damping.
    d. Improved speed-thrust stability was obtained by making the thrust versus velocity characteristics of the simulated SST stable.

Most of the evaluation flights were flown by two NASA Langley Research Center pilots. However, brief evaluations of the two basic test configurations were made by two pilots from industry and one from the FAA. An NASA Ames Research Center pilot and a third Langley pilot also briefly evaluated both the basic and the augmented SST configurations. Besides the descriptive comments from each pilot, Cooper pilot ratings (ref. 1) were obtained for each configuration. (The Cooper rating system is shown in table 2-3.

The Cooper ratings presented are usually the average of two or more pilot ratings.) A standard questionnaire was used during all postflight debriefings to assure that the comments obtained for all pilots and all test configurations would cover the same topics.

TEST AIRPLANE

The design of the simulation system was, of course, strongly influenced by the test airplane. The Boeing 367-80 is a prototype airplane which is similar to a Boeing 707, but has a somewhat shorter fuselage. The pilots are located about 55 feet (17 meters) ahead of the center of gravity, or about half as far ahead of the center of gravity as in proposed SST designs. The airplane configuration is shown in figures 2-1 and 2-2, and the mass and inertia characteristics are given in table 2-1. Aerodynamic parameters for the 367-80 airplane with the spoiler and flap deflections required for SST simulation are presented in table 2-4. For this project, the airplane was equipped with quick-acting, precise, irreversible servo-operated control systems. The servo specifications are presented in a subsequent section of this part of the compilation.

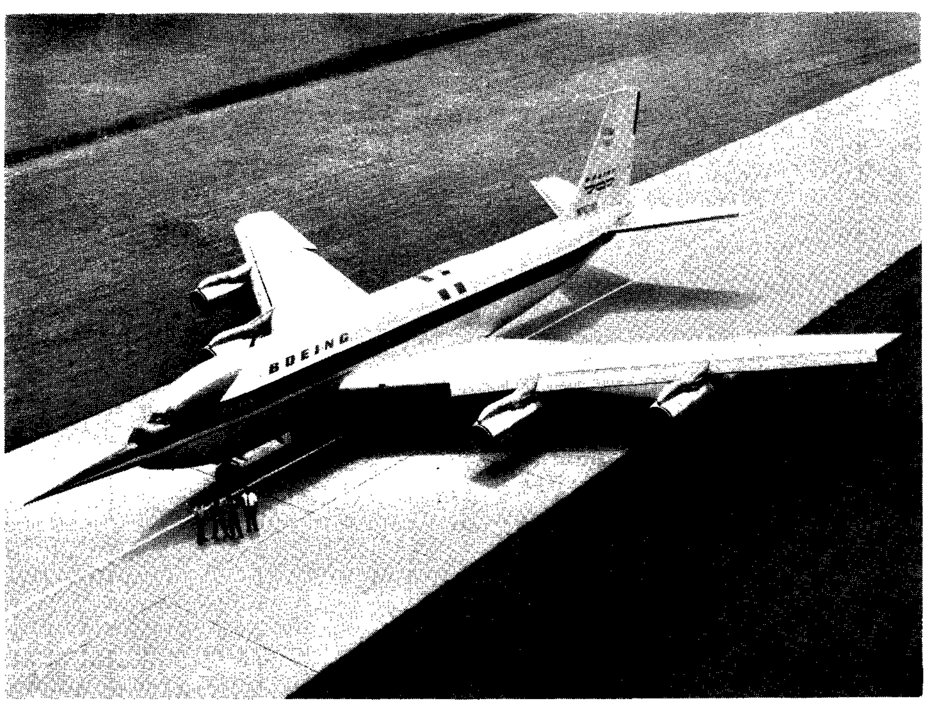


Figure 2-1.- Test airplane as equipped for SST landing-approach simulation. L-65-5431

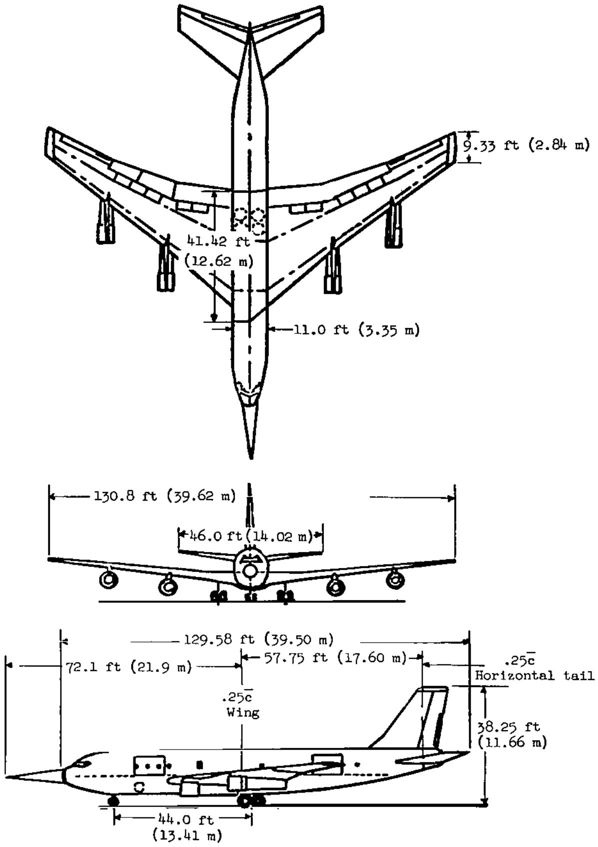


Figure 2-2.- Three-view drawing of test airplane.

SIMULATION SYSTEM

Simulation Technique

The response feedback technique was selected for this simulation project. This choice was influenced by the fact that the simulator was intended for short-term use and by the desire to complete the SST landing-approach tests as soon as possible. With the response feedback technique, an analog computer is programed to modify the test airplane stability derivatives to represent derivatives and mass and inertia characteristics of the simulated configuration. The proper response for the configuration being simulated is thereby obtained. Although feedback loops are used to modulate control deflections, the response feedback simulation technique uses an open-loop computation. Some cut-and-try manual adjustment of gains is usually required. The response feedback technique should not be confused with the closed-loop model-analog simulation technique with which the airplane response is continuously and automatically matched to that of an analog-computer model.

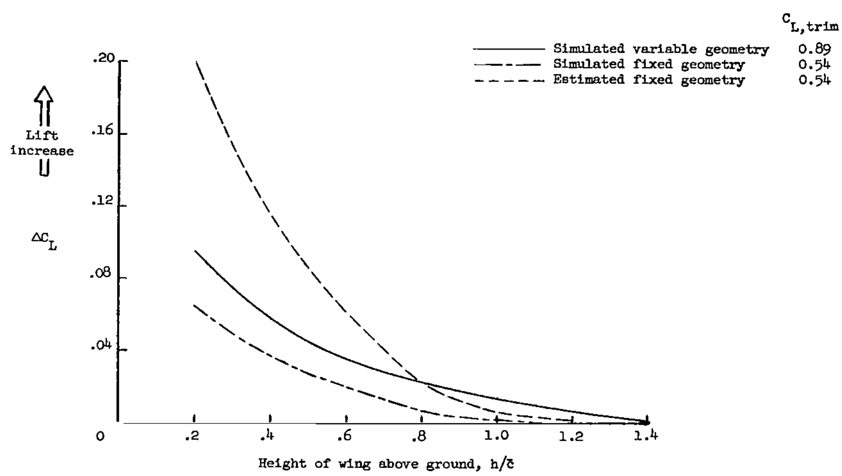
To apply the response feedback technique of simulation, it is necessary to know all the mass and aerodynamic parameters (stability derivatives) of the test airplane. Flight tests were therefore required to measure the 367-80 airplane characteristics in the simulation test configurations (such as, at a speed of 135 knots with 30° flap deflection, landing gear down, for spoiler deflections up to 10°).

The simulation was designed to match five degrees of freedom of the SST. The force and moment characteristics which were varied for the simulation included lift, drag, pitching moment, rolling moment, and yawing moment. Lift was varied by modulating the spoilers or air brakes with respect to a 6° initial deflection. Nonlinear spoiler effectiveness was compensated for by driving the spoilers through nonlinear function generators. Thrust and drag were varied by modulating the clamshell doors of the standard Boeing 707 thrust reversers from an initial deflection of 30°. The thrust response of the simulator, which is indicated in the specifications, was probably slightly faster than it will be for the SST. Moments were produced by supplementary deflections of the elevator, rudder, and the lateral-control system.

Side force was not modified from the basic 367-80 airplane characteristics. Simulation of side force would require expensive modification of the test airplane, such as the addition of an all-movable vertical surface. However, a comparison of transient response, including sideslip and lateral acceleration as well as angular velocities, from five- and six-degree-of-freedom analog-computer tests showed that a five-degree-of-freedom simulation using unmodified 367-80 side-force characteristics would be adequate in this case.

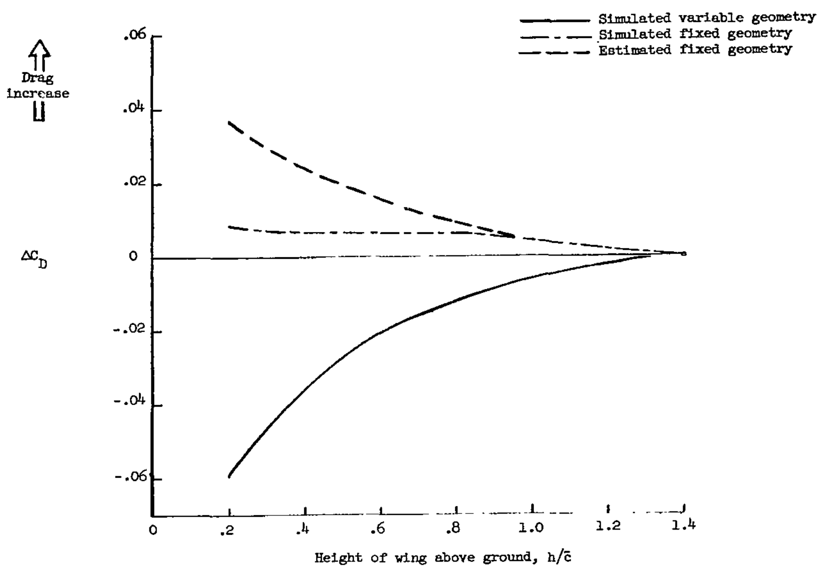
Thrust settings were adjusted for the effects of altitude and temperature. However, because the test program was to be made at altitudes from sea level to about 5000 feet (1520 meters), no other corrections for altitude effects were considered to be necessary.

The simulation system was designed to permit flare and touchdown in the simulation mode. Nonlinear function generators were used to modify the estimated 367-80 ground effects to simulate the predicted SST ground effects. Parameters adjusted for the effects of ground proximity were lift, drag, and pitching moment. Altitude was obtained for this purpose during flare and touchdown from a radar altimeter located near the center of gravity. The ground-effect functions used for the fixed- and variable-geometry configurations are presented in figure 2-3. These data are based on unpublished wind-tunnel data from several sources. (No ground effects were simulated for the variable-geometry emergency-landing configuration.) It was beyond the capability of the spoiler system (from a 6° trim setting) to simulate the full ground effects on the lift of the fixed-geometry configuration. Therefore, as shown in figure 2-3, only 35 percent of the estimated incremental lift could be simulated. In order to maintain the



(a) ΔC_L as a function of $h/\bar{c}$.

Figure 2-3.- Incremental lift, drag, and pitching moments due to ground effect for the SST test configurations.

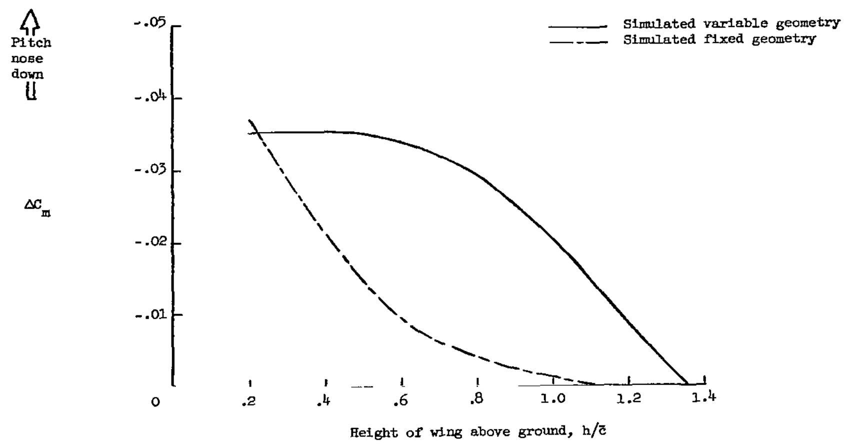


(b) ΔC_D as a function of $h/\bar{c}$.

Figure 2-3.- Continued.

proper lift-drag ratio, the simulation of incremental drag was also restricted to 35 percent of the estimated value.

It was considered important to make actual touchdowns in the simulation mode, even though in that case neither SST attitude nor pilot height above the ground for approach and touchdown could be simulated. Away from the ground, this flying simulator could be configured to fly within about 4^{o} of the attitude of even the more highly swept test configurations. However, during flare and touchdown, the match could not be this close, and, in the interests of safe operation, no increase in normal 367-80 touchdown attitude was used in the simulation mode. The approach-body attitude used for this test program was 0.5^{o} compared with estimated approach attitudes of 3.6^{o} for the variable-geometry SST configuration and 9^{o} for the fixed-geometry SST configuration.



(c) ΔC_m as a function of $h/\bar{c}$.

Figure 2-3.- Concluded.

Equations for Simulation

The moments of inertia of table 2-1 are with respect to body axes. The stability derivatives given in tables 2-2 and 2-4 are with respect to stability axes. The angular-velocity sensors measured angular velocities with respect to body axes. However, the simulation system was set up so that all these parameters were transferred to the stability axes. The equations of motion for the airplane were arranged as follows for this simulation project:

Lift –

$$(\dot{\theta} - \dot{\alpha}) = \frac{C_{L_\alpha}}{mV_o/qS}\Delta\alpha + \frac{2C_L/V_o}{mV_o/qS}\Delta V + \frac{C_{L_{\delta_s}}}{mV_o/qS}\delta_s$$

Drag –

$$\dot{V} = \frac{-C_D/V_o}{m/2qS}\Delta V - \frac{\frac{1}{2}\left(C_{D_\alpha} - C_L\right)}{m/2qS}\Delta\alpha - \frac{C_L/2}{m/2qS}\Delta\theta + \frac{\frac{\partial T}{\partial\delta_m}\delta_m\Big/2qS}{m/2qS}$$

Pitching moment –

$$\ddot{\theta} = \frac{C_{m_\alpha}}{I_Y/qS\bar{c}}\Delta\alpha + \frac{C_{m_{\dot{\alpha}}}}{I_Y/qS\bar{c}}\dot{\alpha} + \frac{C_{m_{\dot{\theta}}}}{I_Y/qS\bar{c}}\dot{\theta} + \frac{C_{m_{\delta_e}}}{I_Y/qS\bar{c}}\delta_e$$

Rolling moment –

$$\ddot{\phi} = \frac{C_{l_\beta}}{I_X/qSb}\beta + \frac{C_{l_{\dot{\phi}}}}{I_X/qSb}\dot{\phi} + \frac{C_{l_{\dot{\psi}}}}{I_X/qSb}\dot{\psi} + \frac{C_{l_{\delta_w}}}{I_X/qSb}\delta_w + \frac{C_{l_{\delta_r}}}{I_X/qSb}\delta_r$$

Yawing moment –

$$\ddot{\psi} = \frac{C_{n_\beta}}{I_Z/qSb}\beta + \frac{C_{n_{\dot{\phi}}}}{I_Z/qSb}\dot{\phi} + \frac{C_{n_{\dot{\psi}}}}{I_Z/qSb}\dot{\psi} + \frac{C_{n_{\delta_w}}}{I_Z/qSb}\delta_w + \frac{C_{n_{\delta_r}}}{I_Z/qSb}\delta_r$$

Inputs to the control surfaces, spoilers, and thrust modulators in the control-fixed simulation mode were determined by the following equations:

Elevator –

$$\delta_e = \frac{\partial\delta_e}{\partial\alpha}\Delta\alpha + \frac{\partial\delta_e}{\partial\dot{\alpha}}\dot{\alpha} + \frac{\partial\delta_e}{\partial\dot{\theta}}\dot{\theta}$$

Spoilers (symmetric mode) –

$$\delta_s = \frac{\partial\delta_s}{\partial\alpha}\Delta\alpha + \frac{\partial\delta_s}{\partial V}\Delta V$$

Thrust modulators –

$$\delta_m = \frac{\partial\delta_m}{\partial T}\left(\frac{\partial\delta_T}{\partial\alpha}\Delta\alpha + \frac{\partial\delta_T}{\partial\theta}\Delta\theta + \frac{\partial\delta_T}{\partial V}\Delta V\right)$$

Wheel (lateral-control system) –

$$\delta_w = \frac{\partial\delta_w}{\partial\beta}\beta + \frac{\partial\delta_w}{\partial\dot{\phi}}\dot{\phi} + \frac{\partial\delta_w}{\partial\dot{\psi}}\dot{\psi}$$

Rudder –

$$\delta_r = \frac{\partial\delta_r}{\partial\beta}\beta + \frac{\partial\delta_r}{\partial\dot{\phi}}\dot{\phi} + \frac{\partial\delta_r}{\partial\dot{\psi}}\dot{\psi}$$

The gains for these simulation inputs, based on linearized theory for small perturbations, were calculated as follows:

Let $A = m/qS$, $B = I_Y/qS\bar{c}$, $C = I_X/qSb$, $D = I_Z/qSb$, then

$$\frac{\partial\delta_e}{\partial\alpha} = \frac{\left(C_{m_\alpha}/B\right)_{SST} - \left(C_{m_\alpha}/B\right)_{-80}}{\left(C_{m_{\delta_e}}/B\right)_{-80}}$$

Similar expressions can be written for the other elevator, wheel, and rudder gains. The spoiler gains were:

$$\frac{\partial\delta_s}{\partial\alpha} = \frac{\left(C_{L_\alpha}/AV_o\right)_{SST} - \left(C_{L_\alpha}/AV_o\right)_{-80}}{\left(C_{L_{\delta_s}}/AV_o\right)_{-80}}$$

$$\frac{\partial\delta_s}{\partial V} = \frac{\left(\frac{2C_L/V_o}{AV_o}\right)_{SST} - \left(\frac{2C_L/V_o}{AV_o}\right)_{-80}}{\left(C_{L_{\delta_s}}/AV_o\right)_{-80}}$$

For cases which can be flown at the actual speed of the simulation, the denominator V_o values cancel out and m/S can be substituted for A.

The thrust-modulator gains were proportional to

$$\frac{\partial T}{\partial\alpha} = -\left[\left(\frac{C_{D_\alpha} - C_L}{A}\right)_{SST} - \left(\frac{C_{D_\alpha} - C_L}{A}\right)_{-80}\right]m_{-80}$$

$$\frac{\partial T}{\partial\theta} = -\left[\left(C_L/A\right)_{SST} - \left(C_L/A\right)_{-80}\right]m_{-80}$$

$$\frac{\partial T}{\partial V} = -\left[\left(\frac{2C_D/V_o}{A}\right)_{SST} - \left(\frac{2C_D/V_o}{A}\right)_{-80}\right]m_{-80}$$

The following expressions were used to compensate for interaction or cross-control effects:

$$\frac{\partial T}{\partial\delta_s} = \frac{\partial C_D}{\partial\delta_s}qS \qquad \frac{\partial\delta_r}{\partial\delta_w} = -\frac{C_{n_{\delta_w}}}{C_{n_{\delta_r}}}$$

$$\frac{\partial\delta_e}{\partial\delta_s} = -\frac{C_{m_{\delta_s}}}{C_{m_{\delta_e}}} \qquad \frac{\partial\delta_w}{\partial\delta_r} = -\frac{C_{l_{\delta_r}}}{C_{l_{\delta_w}}}$$

Control-surface authority was simulated as follows:

$$\frac{\partial\delta_{r,-80}}{\partial\delta_{r,SST}} = \frac{\left(\dfrac{C_{n_{\delta_r}}\delta_{r,max}}{D}\right)_{SST}}{\left(\dfrac{C_{n_{\delta_r}}\delta_{r,max}}{D}\right)_{-80}}$$

$$\frac{\partial\delta_{w,-80}}{\partial\delta_{w,SST}} = \frac{\left(\dfrac{C_{l_{\delta_w}}\delta_{w,max}}{C}\right)_{SST}}{\left(\dfrac{C_{l_{\delta_w}}\delta_{w,max}}{C}\right)_{-80}}$$

$$\frac{\partial\delta_{e,-80}}{\partial\delta_{e,SST}} = \frac{\left(\dfrac{C_{m_{\delta_e}}\delta_{e,max}}{B}\right)_{SST}}{\left(\dfrac{C_{m_{\delta_e}}\delta_{e,max}}{B}\right)_{-80}}$$

Since there were large differences between the attitude of the test airplane and the estimated approach attitudes of the SST configurations, it became necessary to adjust the inertia values and stability derivatives to account for product of inertia differences. An inertia cross-product transformation was used. By using moments of inertia about the stability axes, the rolling and yawing moments of inertia were replaced as follows:

$$I_X \text{ by } I_X - \frac{{I_{XZ}}^2}{I_Z}$$

and

$$I_Z \text{ by } I_Z - \frac{{I_{XZ}}^2}{I_X}$$

The aerodynamic stability and control coefficients were transformed as follows:

$$C_{l_\beta} \rightarrow C_{l_\beta} + \frac{I_{XZ}}{I_Z} C_{n_\beta} \qquad C_{n_\beta} \rightarrow C_{n_\beta} + \frac{I_{XZ}}{I_X} C_{l_\beta}$$

$$C_{l_{\dot\phi}} \rightarrow C_{l_{\dot\phi}} + \frac{I_{XZ}}{I_Z} C_{n_{\dot\phi}} \qquad C_{n_{\dot\phi}} \rightarrow C_{n_{\dot\phi}} + \frac{I_{XZ}}{I_X} C_{l_{\dot\phi}}$$

$$C_{l_{\dot{\psi}}} \rightarrow C_{l_{\dot{\psi}}} + \frac{I_{XZ}}{I_Z} C_{n_{\dot{\psi}}} \qquad C_{n_{\dot{\psi}}} \rightarrow C_{n_{\dot{\psi}}} + \frac{I_{XZ}}{I_X} C_{l_{\dot{\psi}}}{}^{*}$$

$$C_{l_{\delta_w}} \rightarrow C_{l_{\delta_w}} + \frac{I_{XZ}}{I_Z} C_{n_{\delta_w}} \qquad C_{n_{\delta_w}} \rightarrow C_{n_{\delta_w}} + \frac{I_{XZ}}{I_X} C_{l_{\delta_w}}$$

$$C_{l_{\delta_r}} \rightarrow C_{l_{\delta_r}} + \frac{I_{XZ}}{I_Z} C_{n_{\delta_r}} \qquad C_{n_{\delta_r}} \rightarrow C_{n_{\delta_r}} + \frac{I_{XZ}}{I_X} C_{l_{\delta_r}}$$

The rolling and yawing velocities which were measured about the body axes were transferred to stability axes to be used in simulation equations.

Simulation Equipment

To implement the simulation, the right-hand column and wheel were mechanically disconnected from the normal control system and connected into an electrical system which operated the control surfaces through an interface and analog computer. The interface console, shown in figure 2-4, receives electric signals from the airplane control system and the airplane response transducers and modifies these signals to make them compatible with the analog computer. For example, the interface demodulates ac signals from airplane instruments to dc for use in the computer. Switching circuits to engage or automatically disengage the simulation are also contained in the interface.

The simulation computer is shown in figure 2-5. The computer was slightly modified for flight use.

Commands for control-surface deflection went from the computer to the interface to autopilot electric servovalves which operated the hydraulic servos. The servotab-operated elevator and aileron systems were replaced with the irreversible servosystems used on the Boeing 727 airplane. The spoiler servos were replaced with an improved system which provided spoiler positioning accuracy of about $\pm 1/4^{\circ}$. The thrust-reverser-system actuator was located in the fuselage with cable runs to the four engines.

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*The simulator was designed to properly represent SST response. However, when there was a large difference between 367-80 attitude and simulated SST attitude the 367-80 cockpit motions approximated those of the SST nose wheel. The result was an unrealistic adverse yawing of the 367-80 cockpit during rolling maneuvers. A partial remedy for this situation was to reduce the gain of $C_{n_{\delta_w}}$. This adjustment was applied to the fixed-geometry configuration to provide realistic cockpit response without appreciably degrading the simulation. The static directional stability derivative $\partial\delta_r/\partial\beta$ for steady sideslips was made about 20 percent too high by this modification. Attempts to apply the same fix very quickly to the cruise-sweep configuration were not successful.

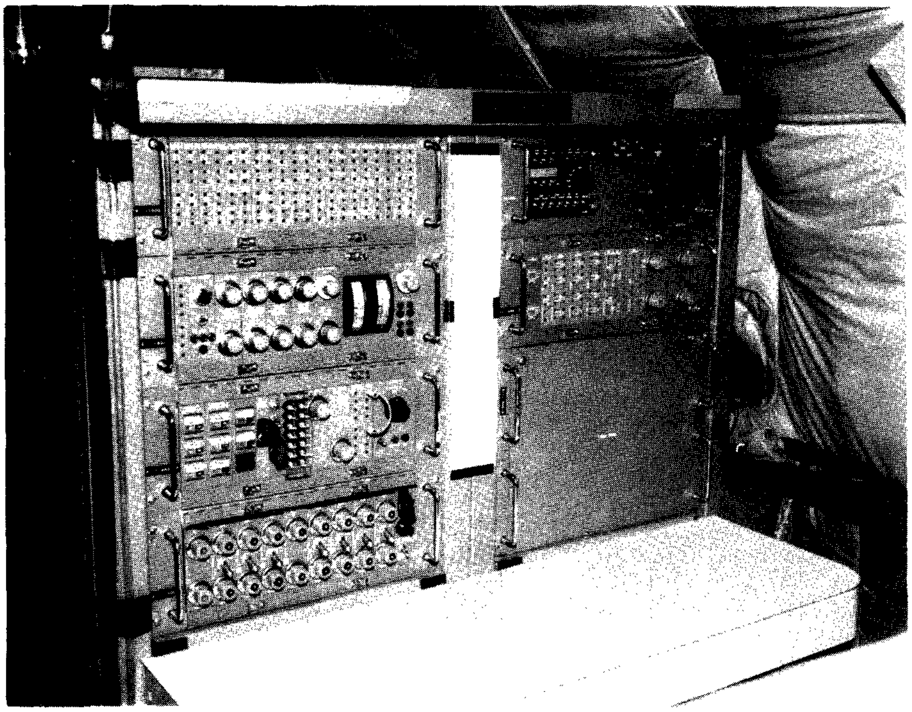


Figure 2-4.- Interface console in the test airplane. L-65-6776

A simplified block diagram of the pitch-control system is shown in figure 2-6. The other four systems for roll, yaw, lift, and drag were similar to the pitch system. Block diagrams of all five control systems are given in reference 2.

Specifications of Simulation System

The following specifications obtained from reference 2 are listed in terms of 367-80 airplane control deflections to show the approximate system response to pilot and analog-computer inputs.

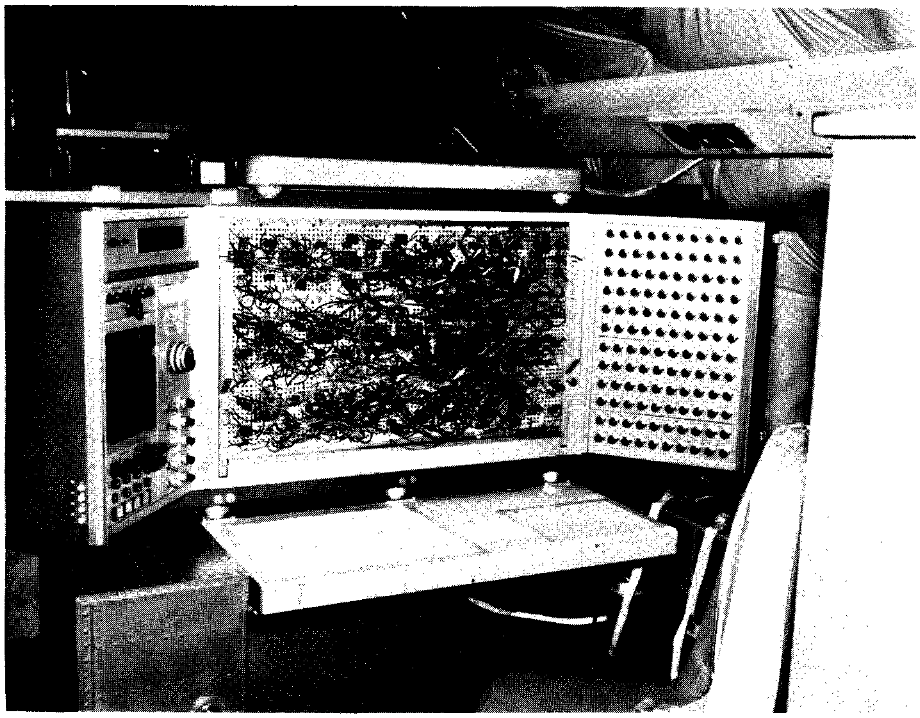


Figure 2-5.- Analog computer installed in test airplane. L-65-6772

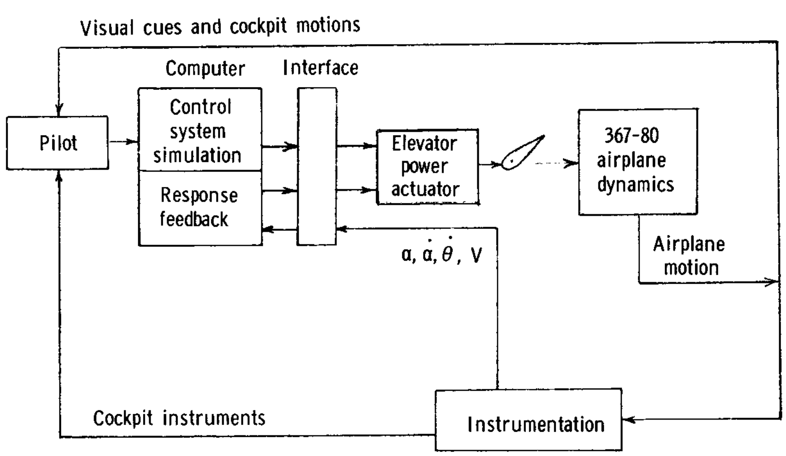


Figure 2-6.- Block diagram of response feedback technique as applied to pitch-control system.

Rudder system:

Electrical-command limit	$\pm 10^{\circ}$
Rudder-deflection limit	$\pm 26^{\circ}$
Maximum no-load rudder rate	33°/sec
Open-loop calculated transfer function	$\frac{\delta_r}{\delta_C} = KG(s) = \frac{K}{(0.063s + 1)(0.028s + 1)}$
Typical response to step command for 5° –	
Initial response	0.06 sec
63% response	0.17 sec
Final response	0.33 sec

Elevator:

Electrical-command limit at 135 knots		$\approx \pm 9^{\circ}$
Elevator-deflection limits		15°, -25°
Maximum no-load surface rate –		
Normal system (safety pilot)		50°/sec
Simulation mode		25°/sec
Open-loop calculated transfer function		$\frac{\delta_e}{\delta_C} = KG(s) \approx \frac{K}{0.06s + 1}$
Frequency response (master)* is down		3 dB at 2.8 cps
Phase lag exceeds 90° at		>2.25 cps
Frequency response (slave) is down		>3 dB at 1.8 cps
Typical response to step command for 5° –	Right hand (master)	Left hand (slave)
Initial response	0.03 sec	0.09 sec
63% response	0.18 sec	0.22 sec
Final response	0.3 sec	0.3 sec

Ailerons:

Electrical-command limit (wheel deflection)	63°
Aileron-deflection limit	$\pm 25^{\circ}$
Maximum no-load aileron rate	68°/sec
Open-loop calculated transfer function	$\frac{\delta_a}{\delta_C} = \frac{K}{(0.014s + 1)(0.05s + 1)}$
Frequency response is down	3 dB at 1.25 cps
Phase angle exceeds 90° at	1.25 cps
Typical response to step command for 5° –	
Initial response	0.05 sec

*Either of the two elevator systems, left or right, may be selected as the master, then the other elevator system becomes a slave system which follows and closely approximates the response of the master.

63% response . . . . $\approx$0.12 sec
Final response . . . . 0.13 sec
Hysteresis . . . . $\approx 0.2^{\circ}$

Spoilers:
Electrical-command limit (when used symmetrically) from initial setting of 6° . . . . 10°, -6°
Spoiler-deflection limits . . . . 0° to 48°
Maximum no-load rates –
Wheel rate (simulation mode) . . . . 180°/sec
Surface rate (simulation mode) . . . . 50°/sec
Open-loop calculated transfer functions –
For lateral control . . . . $\frac{\delta_s}{\delta_C} \approx \frac{K}{s^2 + 0.7(23)s + (23)^2}$
For lift control . . . . $\frac{\delta_s}{\delta_C} = \frac{K}{(0.1s + 1)(0.03s + 1)}$
Frequency response is down . . . . 3 dB at 1.6 cps
Phase lag exceeds 90° at . . . . 5.5 cps
Typical response to step command for 2.7° –
Initial response . . . . $<$0.01 sec
63% response . . . . 0.09 sec
Final response . . . . 0.5 sec
Hysteresis . . . . $<0.1^{\circ}$
Gearing (typical) . . . . $\delta_s/\delta_{wh} \approx 0.26$

Thrust modulators (clamshell doors):
Electrical-command limits (from initial 30°) . . . . $\pm 12^{\circ}$
Normal-deflection limits . . . . 0° to 55°
Maximum-deflection rate . . . . 14°/sec
Open-loop calculated transfer function . . . . $\frac{\delta_m}{\delta_C} \approx \frac{K}{(0.04s + 1)(0.19s + 1)}$
Typical response to 10° step command –
Initial response . . . . 0.3 sec
63% response . . . . 0.7 sec
Final response . . . . 0.9 sec

The static gain of this system produced a simulated thrust increment of 3000 pounds (13 kilonewtons) per degree of SST throttle deflection. ($\Delta T/W \approx 0.01$ per degree.)

Control-System Details

The pitch and roll control systems of the simulator worked in parallel with the standard 367-80 control systems. Therefore the safety pilot's controls moved with the

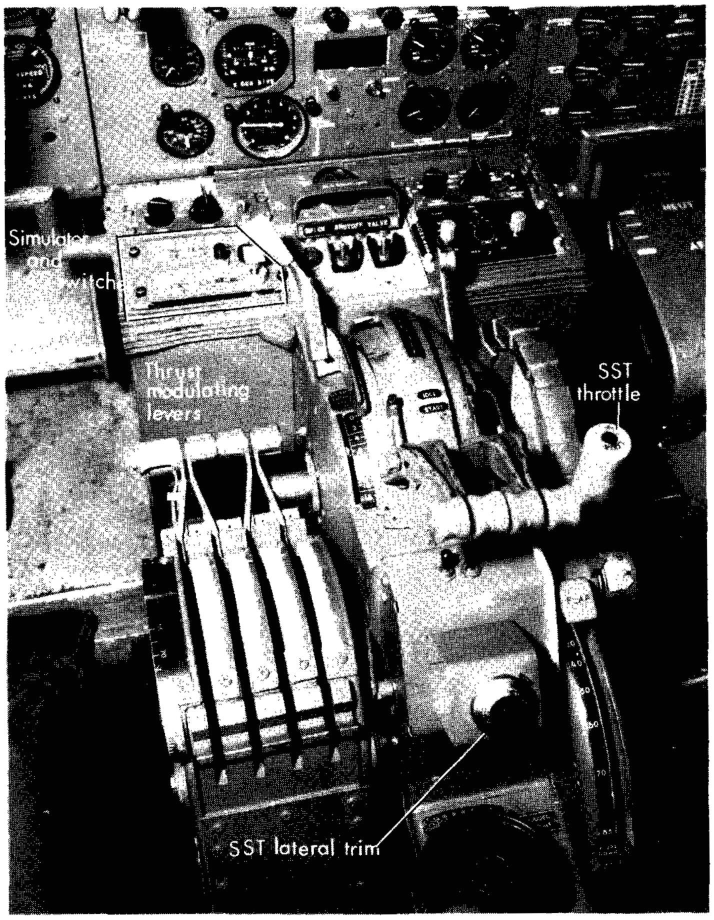


Figure 2-7.- Details of cockpit center console. L-65-6775

control surfaces and provided him with an indication of the control inputs. However, simulation inputs to the rudder were fed into the existing yaw-damper system and did not move the rudder pedals. To permit the safety pilot to monitor overall rudder inputs, a position indicator was installed in the cockpit.

The existing experimental thrust-modulation system on the test airplane was operated by four thrust levers located on the center console to the left of the throttles as shown in figure 2-7. For the simulation mode, the evaluation pilot was provided with a single electric throttle also located on the center console as shown in figure 2-7. Deflection of the electric throttle drove the complete thrust-reverser system including the four manual thrust levers. The safety pilot could therefore observe all inputs to the thrust-modulation system which were made by either the evaluation pilot or by the analog computer. The position of each set of clamshell doors was also shown by an indicator on the center instrument panel as shown in figure 2-8.

A set of saturation indicator lights and a disengage indicator light (shown in fig. 2-8) were provided to keep the evaluation pilot aware of the simulation status. The tests were designed to stay within the saturation limits.

The evaluation pilot was provided with control "feel" from preloaded centering springs. The pitch-control "feel system" used a hydraulic spring which provided an adjustable gradient. The usual gradient was 4 pounds (18 newtons) per degree of column deflection with a 4-pound (18-newton) breakout force. Pitch trim was provided for the

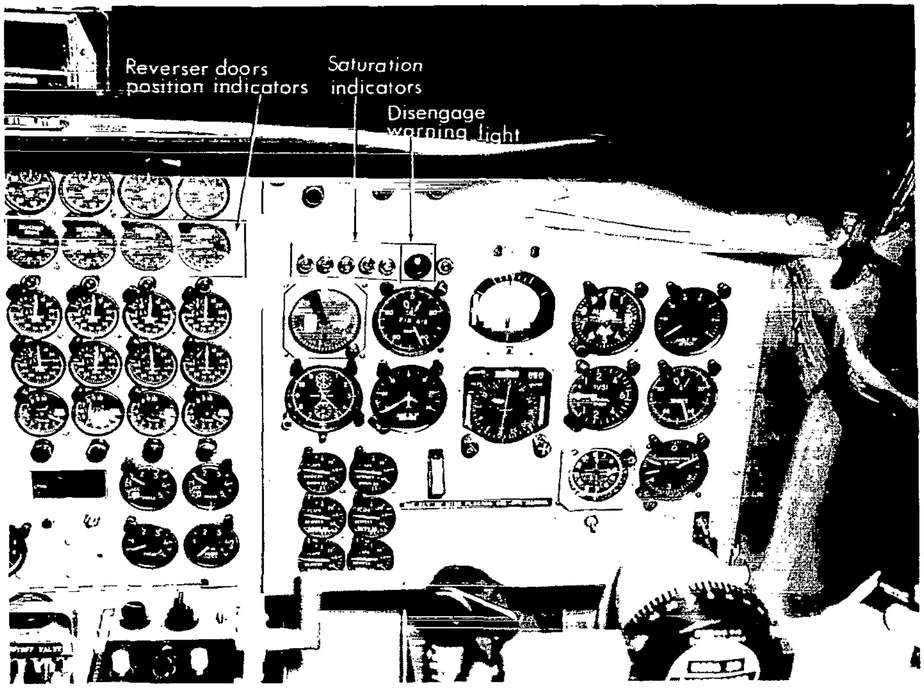


Figure 2-8.- Evaluation pilot's instrument panel. L-65-6774

evaluation pilot through the normal trim button which actuated the elevator instead of the stabilizer. Pitch trim rates were 2.3° per second for the fixed-geometry configuration and 1.8° per second for the variable-geometry configuration. The wheel force gradient included a $2\frac{1}{2}$-pound (11-newton) breakout force and required $12\frac{1}{2}$ pounds (55.6 newtons) for full 75° wheel deflection. Rudimentary roll trim was provided by a potentiometer at the rear of the center console that biased the roll-control signal from the computer. The rudder pedal force in the simulation mode was 40 pounds (180 newtons) for the maximum pedal travel of 1.5 inches (3.8 centimeters). Normal rudder trim was used.

Safety Provisions

The safety pilot is in command of the airplane and has the primary responsibility for the safety of the flight. In the simulation mode, the safety pilot monitors the total control inputs, which are the sum of evaluation pilot's inputs and the simulation system inputs. The safety pilot is prepared to take over the controls if a hardover input occurs or if a maneuver becomes excessive. The simulation can be disconnected electrically by either pilot. It will also disconnect automatically if the interface detects a malfunction in the computer. If the electrical disconnects should fail to operate, the safety pilot can overpower the system with manual inputs. The control forces required to overpower the system are:

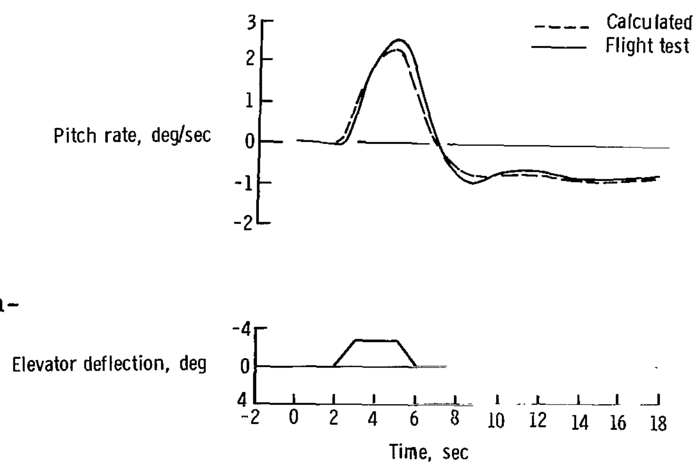
Elevator	25 pounds (111 newtons)	
Lateral control	45 pounds (200 newtons)	at 75° wheel
Rudder	13 pounds (58 newtons)	at $\delta_r = 10^{\circ}$
Thrust modulators	60 pounds (267 newtons)	(total)

In this test program the safety pilot occasionally disconnected the simulation and took over the controls near the ground when he felt that a poor landing touchdown was in prospect. A large red warning light (shown in fig. 2-8) notified the evaluation pilot that disconnect had occurred. Flight safety was further augmented by the limited authority of the simulation system which was designed to prevent overloading the structure. Simulator authority limits for each control system are shown in the specifications.

SIMULATION CHECKOUT PROCEDURES

Each SST configuration tested was programed on a separate computer patchboard. Each patchboard was wired to modify the 367-80 characteristics to simulate the response of the desired SST. Each patchboard included an analog model of the 367-80 airplane. With this model, it was possible to run ground checks on the simulation prior to flight tests. The ground checkout procedure was to pulse the 367-80 controls from the computer in the simulation mode and determine the response of the analog model of the 367-80. The transient response was then compared with six-degree-of-freedom digital-computer results and modified, if necessary, by potentiometer adjustments.

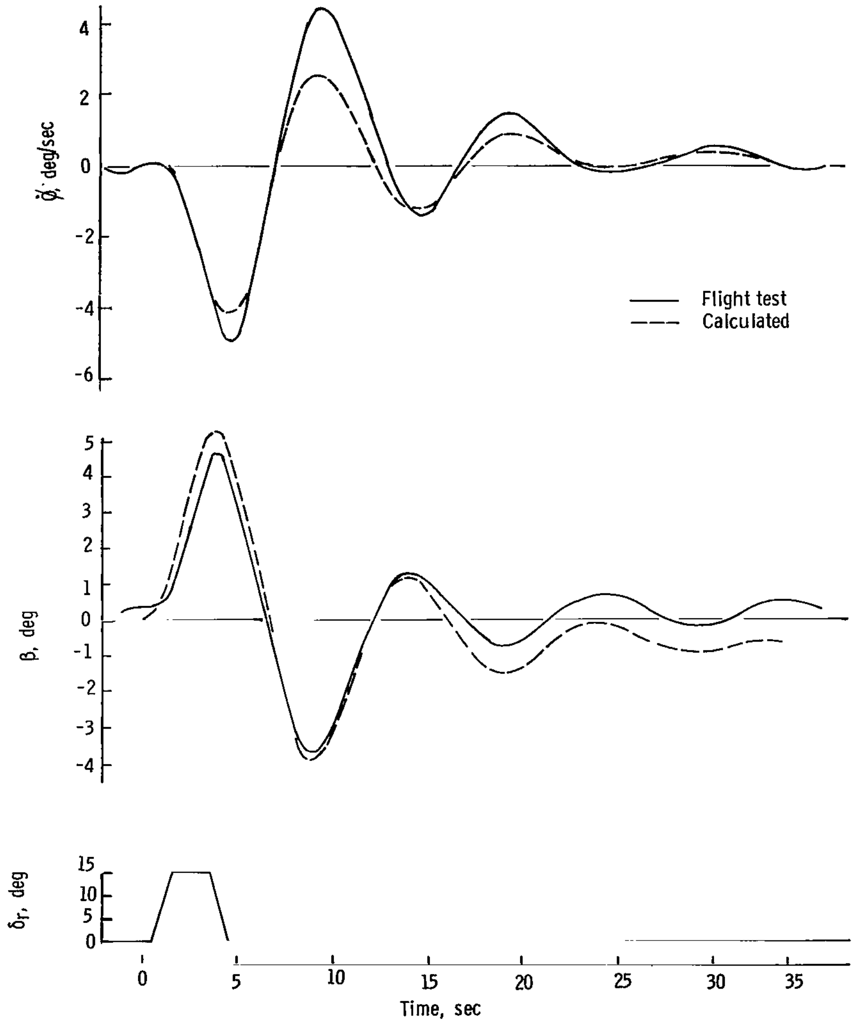
After a good match of transient responses was obtained on the ground, the analog model of the 367-80 airplane was disconnected and the same check pulses were repeated in flight. The controls which were pulsed included the elevator, rudder, wheel, and spoilers. (Transient response to thrust inputs was checked with step inputs of the thrust modulators.) Each pulse had a 1-second rise time, 2-second dwell, and 1-second return. The magnitudes



(a) Pitch-rate response to elevator pulse.

Figure 2-9.- Examples of response to pulses in simulation mode. Variable-geometry configuration at 9000 ft (460 m) and 136 knots.

of the pulses were limited to produce moderate airplane response. The in-flight pulse responses were recorded on a direct-writing 18-channel oscillograph and immediately compared with six-degree-of-freedom digital-computer results which were plotted on transparencies for convenient in-flight comparison. Such comparisons of short-period and phugoid responses are shown in figures 2-9 and 2-10 for elevator and rudder pulses. Some adjustment of parameters by means of potentiometer adjustment was usually



(b) Lateral and directional response to a rudder pulse.

Figure 2-9.- Concluded.

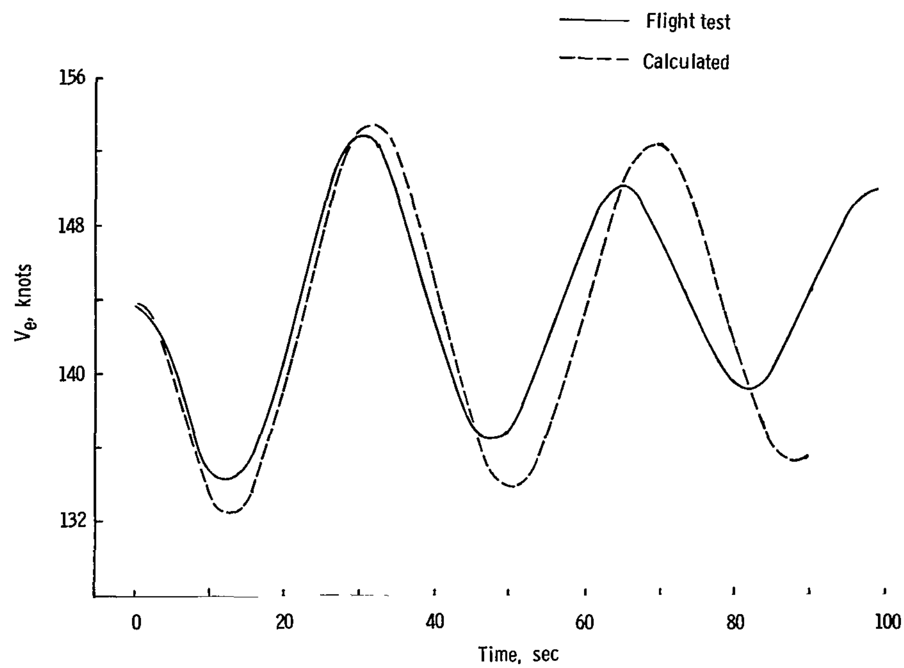


Figure 2-10.- Comparison of measured and calculated phugoid oscillatory mode of variable-geometry SST configuration.

required to obtain the proper SST transient responses. The fact that such adjustments were somtimes required was an indication that some of the 367-80 characteristics were not known with sufficient accuracy or that approximations used or assumptions of linearity were not completely valid.

When the oscillatory modes and transient responses were considered to be satisfactory, the static characteristics of the SST configuration were documented. These characteristics include the variation of lift coefficient with angle of attack, the variation of drag or power required with airspeed, control force and deflection for steady turns, static longitudinal stability, control power in pitch and roll, and steady sideslip parameters.

TEST INSTRUMENTATION

A comprehensive system of recording instruments was used for this investigation. The data were recorded on 1-inch (2.5-cm) magnetic tape which was processed by an automatic data-reduction and machine-plotting system. More than 200 parameters were recorded but about half of these were intended only for troubleshooting. Most parameters were sampled 2.5 times per second. However, this sampling rate was not always adequate, and therefore 40 variables were recorded continuously. The nominal instrument accuracy was 2 percent of full scale. Sensitivities and full-scale values were adjusted to be compatible with the test program.

Input quantities which were recorded included the deflection of control column, wheel, rudder pedals, elevator, ailerons, spoilers, rudder, stabilizer, electric throttle, and thrust-modulator levers. Engine data were recorded to permit determination of thrust. The commands to the airplane from the analog computer were also recorded.

The recorded airplane response quantities included airspeed, pressure altitude, geometric altitude (when over the runway), ILS localizer and glide-slope errors, angular velocities, linear accelerations, pitch and roll attitude, incremental heading change, angle of attack, and sideslip.

The angle-of-attack and sideslip sensor was a four-element cruciform wooden vane assembly with a natural frequency greater than 20 cycles per second which was mounted on a 17-foot (5.2-meter) conical boom ahead of the airplane nose. (See fig. 2-1.) Since the vanes were less than 1.5 fuselage diameters ahead of the nose and approximately three mean chord lengths ahead of the wing-fuselage juncture, the vane errors due to upwash and sidewash were large and required correction. The angle-of-attack vane was calibrated in flight by the plumb-bob method, and the upwash correction was determined to be between 29 and 30 percent. The sideslip vane correction for sidewash was estimated to be 20 percent based on vector analysis of Dutch roll data. The vane angles were corrected for the error due to angular velocity. The vane data were also corrected with a lag function for the time required for the airflow measured by the vanes to reach the airplane center of gravity. The expressions for corrected flow angles were of the following form:

$$\alpha = \frac{1.29\alpha_{indicated}}{\left(1 + s\frac{l}{V}\right)} + \dot{\theta}\frac{l}{V}$$

$$\beta = \frac{1.2\beta_{indicated}}{\left(1 + s\frac{l}{V}\right)} - \dot{\psi}\frac{l}{V}$$

DATA REDUCTION

Most of the data were reduced automatically from the tape by using routine methods and machine plotted. However, some discussion of the determination of lift and drag is desirable.

The incremental values of lift coefficient and angle of attack from the trim point are used to show the measured variation of normalized lift $\Delta C_L q_o S/mV_o$ with angle of attack for the simulator.

The flight conditions used for the lift data were also used for obtaining the drag variation with speed since the thrust was held constant and equal to the value required for level flight at the initial trim speed. Measurement of drag in flight is very difficult and usually contains a rather large amount of scatter. Since, in most cases, the airplane was not completely stabilized at a steady speed at any time, the following expression was used to determine the drag or thrust required for the supersonic transport:

$$D_{SST} = \left[T - \frac{W}{g}\left(\frac{dV_e}{dt}\right) - W\left(\frac{dh_p/dt}{V_o}\right)\right]_{-80} \times \left(\frac{m_{SST}}{m_{-80}}\right)$$

The slopes dV_e/dt and dh_p/dt were measured from 3- to 4-second time histories of V_e and h_p when the rates were nearly constant. For the purpose of data reduction the thrust T for each set of data was assumed to be a value which would make the drag for the trim condition agree with that calculated for the SST. Thus the datum for drag variation with speed was somewhat arbitrary; however, the incremental variation of drag with speed was not influenced by the assumed thrust value. That is, the value of $\frac{\partial T/W}{\partial V_e}$ is measured correctly.

STABILITY AUGMENTATION

Quickened Pitch Response

The probable need for quickened longitudinal response of very large airplane configurations, in particular for the flare and touchdown, has been widely recognized. Therefore, provisions were made to investigate the effects of augmented pitch response on the landing-approach characteristics of the configurations used in this program. A ground-based simulator investigation was made to evaluate techniques for augmenting the pitch response.

As a result of this study, it was decided to use a pitch damper ($\dot{\theta}$ feedback) in combination with increased gearing between the column and the elevator as the stability-augmentation device. The augmentation system can be represented by the expression $\delta_e = \left(\frac{\delta_e}{\delta_c}\right)_{basic} K_1 \delta_c + K_2 \dot{\theta}$ where K_1 is 2.0 and K_2 is 1.46. Such a system has the advantage of being easier to implement on the test airplane than a second-order lead-lag system. Figure 2-11 illustrates the effect of a pitch-rate feedback system on the response to a step column input. It is evident that the $\dot{\theta}$ feedback washes out the elevator deflection as the pitching velocity builds up. Therefore it is possible to increase the gearing between the column and the elevator gearing to increase the initial pitching moment due to column deflection and thereby to quicken the pitch response without any tendency for the peak pitching velocity to become excessive. However, the static stability apparent to the pilot is reduced.

The proposed pitch-augmentation system was further refined by adding angle-of-attack feedback. In this case the equation for elevator deflection (not including simulation inputs) is

$$\delta_e = \left(\frac{\delta_e}{\delta_c}\right)_{basic} K_1\delta_c + K_2\dot{\theta} + K_3\,\Delta\alpha$$

The ratio of elevator to column gearing K_1 was increased to 4. The gain on the $\dot{\theta}$ feedback K_2 was still 1.46. The gain on the $\Delta\alpha$ feedback K_3 was selected to keep the static longitudinal stability $\left(\frac{d\delta_c}{d\alpha}\right)$ approximately equal to the unaugmented value. The values selected for K_3 were 1.5 for the variable-sweep configuration and 1.0 for the fixed-geometry configuration. Figure 2-11 indicates that the estimated value of elevator deflection in response to a step column input is initially much larger than the unaugmented value, but then, as $\dot{\theta}$ and $\Delta\alpha$ build up, it approaches the unaugmented value. As is discussed in part 4 of this compilation, this type of augmentation improves the pitch response by increasing the frequency of the short-period oscillation. Although these augmentation systems were not optimized, the gain settings selected initially were found to be satisfactory for this test program.

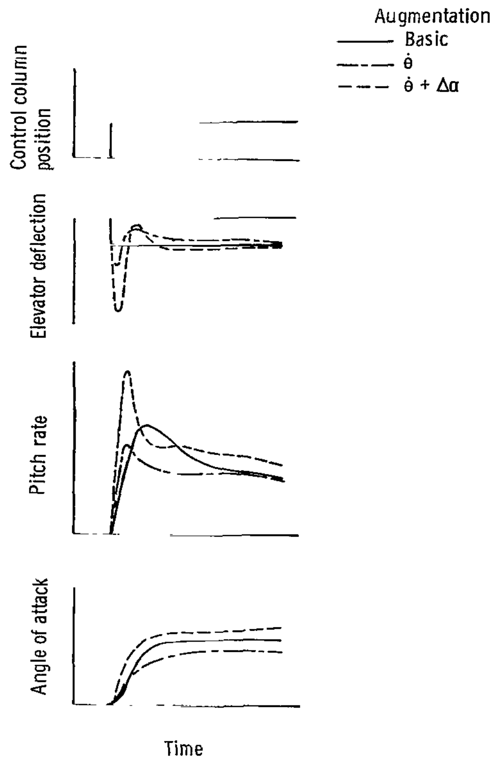


Figure 2-11.- Examples of longitudinal response to a step column input using two types of stability augmentation with increased control gearings.

Dutch Roll Augmentation

Dutch roll augmentation was used in some tests of the variable-geometry SST configuration to increase the damping ratio from approximately 0.2 to 0.3. The increased damping was provided by a sideslip rate yaw damper. The sideslip rate was computed from the expression

$$\dot{\beta} = \frac{g}{V}\,\phi - \dot{\psi}$$

The rudder was driven to oppose the sideslip rate with a gain of -1, so that

$$\Delta\delta_r = -\dot{\beta}$$

This type of augmentation was devised at the NASA Ames Research Center and is discussed in reference 3.

Augmented Roll Damping

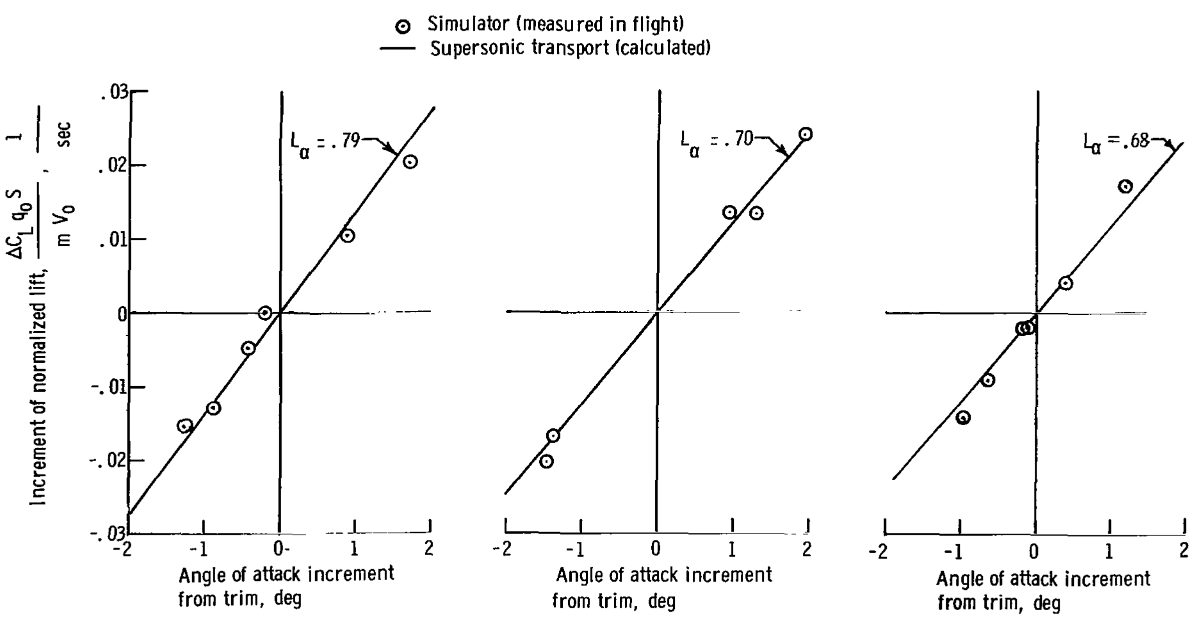
To increase the roll damping of the fixed-geometry SST configuration, the augmented version of this configuration included the following equivalent incremental wheel input

$$\Delta\delta_W = -0.45\dot{\phi}$$

As a result of this input the calculated roll time constant was decreased from 0.80 to 0.58 second.

QUALITY OF SIMULATION

The simulation was believed to be valid for a speed range of ±10 knots, an angle-of-attack range of ±2° to ±3°, and for a range of normal acceleration values of ±0.3 to ±0.4g. A complete documentation of the simulated configurations is given in reference 4. The simulated steady-state flying-qualities data usually matched the design values within ±25 percent. Figure 2-9 compares examples of measured transient short-period response to elevator and rudder pulses with six-degree-of-freedom computed data. Figure 2-10 shows a typical example of the realized phugoid mode for one test configuration compared with the calculated phugoid oscillation. Since this simulator has the capability of varying lift characteristics, which is not common to other in-flight simulators, it does permit simulation of the phugoid mode.



(a) Fixed geometry. (b) Variable geometry. (c) Variable geometry (cruise).

Figure 2-12.- Variation of normalized lift with angle of attack using increments from trim.

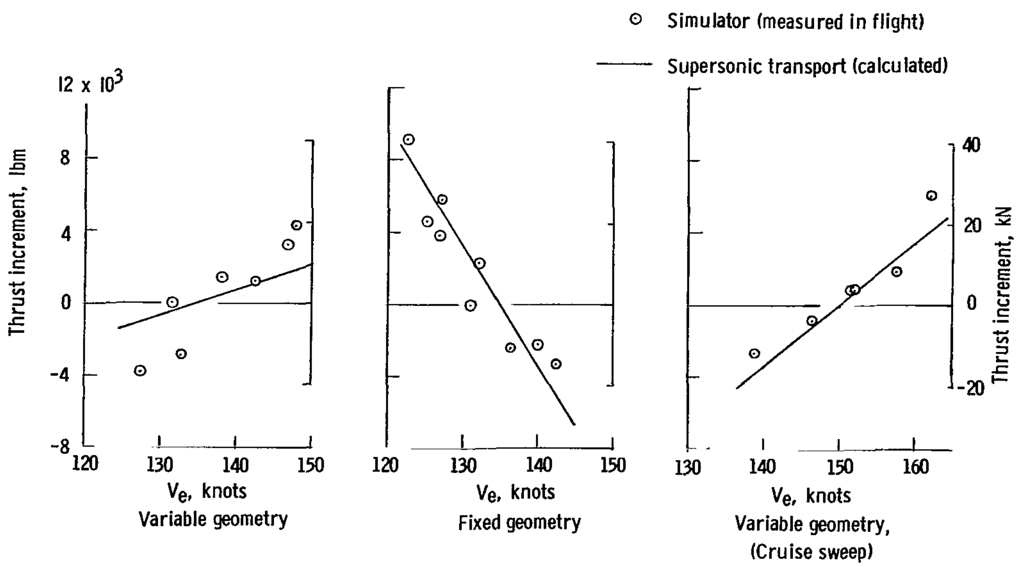


Figure 2-13.- Variation of thrust required with airspeed for supersonic transport configurations. (Landing-approach condition.)

Figure 2-12 shows the calculated and measured variations of normalized lift with angle of attack. The agreement was good, except for the emergency, cruise-sweep landing configuration for which the measured value of L_α was about 15 percent high. Figure 2-13 presents the calculated and measured variation of power required for speed changes from the trim speed.

REMARKS ON OPERATIONAL EXPERIENCE

The 367-80 airplane was flown approximately 125 hours in connection with this test program. The simulation equipment proved to be very reliable with small loss of flight time due to equipment malfunction. The approximate efficiency of this simulator in terms of productive use of flight time for its initial test program is indicated by the following tabulation:

	Approximate percent of flight time
Flight tests required to determine 367-80 airplane characteristics with spoilers at 0° to 10°	5
Functional check of simulation equipment	10
Setup and checkout of test configurations	25
Simulation check runs (on each flight)	15
Documentation of test configurations	15
Pilot evaluation of SST configurations at altitude and during landing approach	30

The percentage of flight time required for setup and checkout should be lower for additional test programs with this system. However, it should be noted that the setup and checkout times as well as the simulator capabilities are influenced by the characteristics which are to be simulated. For example, the 367-80 airplane with the center of gravity at 30 percent $\bar{c}$ had a large static stability margin. It was found to be difficult and time consuming to set up the simulator for the small static margin of the fixed-geometry configuration. This problem might be alleviated in other such projects by actually shifting the center of gravity of the test airplane.

The accuracy of simulation is affected by the amount of time that can be allotted to setting up and checking out a simulated configuration. In the SST landing-approach simulation program, the relatively small amount of flight time which could be budgeted to each test configuration required that the matching of actual to desired response be done as quickly as possible. Therefore, the accuracy of simulation obtained in this program may not represent the full potential of the simulation equipment.

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TABLE 2-1.- MASS AND DIMENSIONAL CHARACTERISTICS OF SIMULATED TEST CONFIGURATIONS

Characteristics (a)	Variable-geometry SST (b)	Fixed-geometry SST	Variable-geometry SST (cruise sweep)	367-80 airplane
Weight:				
lb	280 000	280 000	270 000	150 000
N	1 245 500	1 245 500	1 201 020	667 000
Center-of-gravity location, percent $\bar{c}$	46	35	46	30
I_X:				
slug-ft^2	2.86×10^6	2.22×10^6	1.667×10^6	2.57×10^6
kg-m^2	7.11×10^6	5.52×10^6	4.14×10^6	6.38×10^6
I_Y:				
slug-ft^2	17.57×10^6	18.11×10^6	18.58×10^6	2.25×10^6
kg-m^2	43.65×10^6	45.00×10^6	46.16×10^6	5.59×10^6
I_Z:				
slug-ft^2	20.00×10^6	20.00×10^6	20.00×10^6	4.73×10^6
kg-m^2	49.69×10^6	49.69×10^6	49.69×10^6	11.76×10^6
I_{XZ}:				
slug-ft^2	0	0	0	0.160×10^6
kg-m^2	0	0	0	0.22×10^6
Λ, deg	20	63	72	35
S:				
ft^2	5000	8000	5000	2821
m^2	464.50	743.20	464.50	257
$\bar{c}$:				
ft	70	89	70	20.1
m	21.336	27.127	21.336	6.12
b:				
ft	85	111	85	130.8
m	25.91	33.83	25.91	39.8
V_{trim}, knots	135	135	182	135 for variable-geometry SST 135 for fixed-geometry SST 150 for SST at cruise sweep
α_{trim}, deg	6.6	12	12.3	5.45 for variable-geometry SST 5.45 for fixed-geometry SST 5.3 for SST at cruise sweep
i_w, deg	0	0	0	2.0

[a]Moments of inertia are with respect to body axes.

[b]All parameters for variable-geometry configuration are based on geometry of cruise-sweep configuration.

TABLE 2-2.- DESIGN AERODYNAMIC PARAMETERS OF SIMULATED SST CONFIGURATIONS

Parameter	Fixed geometry				Variable geometry							Emergency 72° swept configuration
	Basic	Augmented $(\dot{\theta} + \Delta\alpha)$ changed $C_{l_{\dot{\phi}}}$, $C_{n_{\dot{\phi}}}$	Degraded $C_{n_{\dot{\beta}}}$, $C_{n_{\dot{\phi}}}$	Increase speed-thrust stability $C_{D_{\alpha}}$	Basic	Augmented $\dot{\theta}$, $\dot{\beta}$	Augmented $(\dot{\theta} + \Delta\alpha)$, $\dot{\beta}$	Augmented $(\dot{\theta} + \Delta\alpha)$, $\dot{\beta}$, aft c.g.	Augmented $\dot{\beta}$, aft c.g.	Augmented $(\dot{\theta} + \Delta\alpha)$ degraded $C_{n_{\dot{\phi}}}$, $C_{n_{\dot{\beta}}}$	Degraded $C_{n_{\dot{\phi}}}$, $C_{n_{\dot{\beta}}}$	
$C_{D,trim}$	0.125	0.125	0.125	0.125	0.115	0.115	0.115	0.115	0.115	0.115	0.115	0.145
$C_{D_{\alpha}}$, per radian	1.203	1.203	1.203	.61	.418	.418	.418	.418	.418	.418	.418	.573
$C_{L,trim}$	.54	.54	.54	.54	.893	.893	.893	.893	.893	.893	.893	.4507
$C_{L_{\alpha}}$, per radian	3.266	3.266	3.266	3.266	4.7	4.7	4.7	4.7	4.7	4.7	4.7	3.209
$C_{L_{\delta_e}}$, per radian	.8022	.8022	.8022	.8022	.487	.487	.487	.487	.487	.487	.487	.487
$C_{m_{\alpha}}$, per radian	-.0802	[a]-.3672	[a]-.3672	-.0802	-.4584	-.4584	[a]-1.533	[a]-1.215	-.141	[a]-1.533	-.4584	-.3438
$C_{m_{\dot{\alpha}}}$, rad/sec	0	0	0	0	-.1335	-.1335	-.1335	-.1335	-.1335	-.1335	-.1335	-.0288
$C_{m_{\dot{\theta}}}$, rad/sec	-.1757	-.5947	-.5947	-.1757	-.2149	[a]-1.261	[a]-1.261	[a]-1.261	-.2149	[a]-1.261	-.2149	-.1596
$C_{m_{\delta_e}}$, per radian	-.287	-.287	-.287	-.287	-.7163	-.7163	-.7163	-.7163	-.7163	-.7163	-.7163	-.7163
$C_{m_{\Delta T}}$, per pound	$.045 \times 10^{-6}$	$.045 \times 10^{-6}$	$.045 \times 10^{-6}$	$.045 \times 10^{-6}$	$.231 \times 10^{-6}$	$.231 \times 10^{-6}$	$.231 \times 10^{-6}$	$.231 \times 10^{-6}$	$.231 \times 10^{-6}$	$.231 \times 10^{-6}$	$.231 \times 10^{-6}$	$.1275 \times 10^{-6}$
per newton	$.0101 \times 10^{-6}$	$.0101 \times 10^{-6}$	$.0101 \times 10^{-6}$	$.0101 \times 10^{-6}$	$.052 \times 10^{-6}$	$.052 \times 10^{-6}$	$.052 \times 10^{-6}$	$.052 \times 10^{-6}$	$.052 \times 10^{-6}$	$.052 \times 10^{-6}$	$.052 \times 10^{-6}$	$.0287 \times 10^{-6}$
$C_{l_{\beta}}$, per radian	-.0825	-.0825	-.0825	-.0825	-.1547	-.1547	-.1547	-.1547	-.1547	-.1547	-.1547	-.1891
$C_{l_{\dot{\phi}}}$, rad/sec	-.0438	-.0696	-.0438	-.0696	-.2269	-.2269	-.2269	-.2269	-.2269	-.2269	-.2269	-.0249
$C_{l_{\dot{\psi}}}$, rad/sec	.073	.073	.073	.073	.0744	.0744	.0744	.0744	.0744	.0744	.0744	.0208
$C_{l_{\delta_w}}$, per radian	.0573	.0573	.0573	.0573	.1146	.1146	.1146	.1146	.1146	.1146	.1146	.0129
$C_{l_{\delta_r}}$, per radian	0	0	0	0	0	0	0	0	0	0	0	0
$C_{n_{\beta}}$, per radian	.131	.131	.131	.131	.2006	.2006	.2006	.2006	.2006	.2006	.2006	.1604
$C_{n_{\dot{\phi}}}$, rad/sec	-.0049	-.0152	-.0352	-.0152	-.0223	-.0223	-.0223	-.0223	-.0223	-.076	-.076	-.0067
$C_{n_{\dot{\psi}}}$, rad/sec	-.102	-.102	-.102	-.102	-.0874	-.0874	-.0874	-.0874	-.0874	-.0874	-.0874	-.0554
$C_{n_{\dot{\beta}}}$, rad/sec	0	0	-.138	0	0	.0859	.0859	.0859	.0859	-.1204	-.1204	0
$C_{n_{\delta_w}}$, per radian	.0229	.0229	.0229	.0229	.0424	.0424	.0424	.0424	.0424	.0424	.0424	.002
$C_{n_{\delta_r}}$, per radian	-.0745	-.0745	-.0745	-.0745	-.086	-.086	-.086	-.086	-.086	-.086	-.086	-.086
$C_{Y_{\beta}}$, per radian	-.5272	-.5272	-.5272	-.5272	-.573	-.573	-.573	-.573	-.573	-.573	-.573	-.4928
$C_{Y_{\dot{\phi}}}$, rad/sec	.0487	.0487	.0487	.0487	.0253	.0253	.0253	.0253	.0253	.0253	.0253	.0346
$C_{Y_{\dot{\psi}}}$, rad/sec	.146	.146	.146	.146	.093	.093	.093	.093	.093	.093	.093	.0692
$C_{Y_{\delta_w}}$, per radian	0	0	0	0	0	0	0	0	0	0	0	0
$C_{Y_{\delta_r}}$, per radian	.1146	.1146	.1146	.1146	.1146	.1146	.1146	.1146	.1146	.1146	.1146	.1146
Short-period frequency, rad/sec	0.754	1.46	1.46	0.754	0.885	1.303	1.743	1.63	0.641	1.743	0.885	0.981
Short-period damping ratio	.867	.793	.793	.846	.672	.938	.705	.755	.945	.705	.672	.569
Phugoid frequency, rad/sec	.117	.126	.126	.117	.170	.114	.156	.149	.132	.156	.168	.129
Phugoid damping ratio	-.024	.057	.057	.113	.019	.177	.093	.102	.047	.093	.022	.170
Dutch roll frequency, rad/sec	.811	.829	.982	.829	.628	.621	.621	.621	.621	.642	.692	1.24
Dutch roll damping ratio	.381	.379	.05	.379	.186	.282	.282	.282	.282	.051	.051	.172
Spiral-divergence time constant, sec	74.9	109.2	99.6	109.2	349.0	345.0	345.0	345.0	345.0	397.0	397.0	-17.6
Roll-convergence time constant, sec	.802	.573	.885	.573	.48	.48	.48	.48	.48	.49	.49	1.7
δ_e/δ_c	-1.0	-4.0	-4.0	-1.0	-1.3	-2.6	-5.2	-5.2	-1.3	-5.2	-1.3	-1.3
$\delta_e/\dot{\theta}$	0	1.46	1.46	0	0	1.46	1.46	1.46	0	1.46	0	0
$\delta_e/\Delta\alpha$	0	1.0	1.0	0	0	0	1.5	1.5	0	1.5	0	0
F_c/g, pounds (pullups)	32.8	27.9	27.9	32.8	30.8	33.6	28.2	24.8	14.2	28.2	30.8	29.7
newtons	143	190	190	143	138	155	165	136	64	165	138	132
$\dfrac{\partial \frac{T}{W}}{\partial V}$, per knot	.0024	-.0024	-.0024	.0006	.0005	.0005	.0005	.0005	.0005	.0005	.0005	.0013
Center-of-gravity location, percent $\bar{c}$	35	35	35	35	46	46	46	53	53	46	46	46

[a]Values with augmentation on.

TABLE 2-3.- COOPER PILOT-RATING SYSTEM

Mode of operation	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only: Failure of stability augmenter	Doubtful	Yes
Inoperable	Unacceptable	7	Unacceptable even for emergency condition: Failure of stability augmenter	No	Doubtful
		8	Unacceptable – Dangerous	No	No
		9	Unacceptable – Uncontrollable	No	No
Inoperable	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

TABLE 2-4.- AERODYNAMIC CHARACTERISTICS OF 367-80 AIRPLANE

Parameter	Fixed and variable geometry	Variable geometry at maximum sweep
$C_{D,trim}$	0.1165	0.0892
C_{D_α}, per radian	0.515	0.327
$C_{L,trim}$	0.856	0.6935
C_{L_α}, per radian	4.9	4.55
$C_{L_{\delta_e}}$, per radian	0.244	0.244
C_{m_α}, per radian	-1.008	-1.11
$C_{m_{\dot\alpha}}$, rad/sec	-0.261	-0.361
$C_{m_{\dot\theta}}$, rad/sec	-0.594	-0.425
$C_{m_{\delta_e}}$, per radian	-0.85	-0.9
$C_{m_{\Delta T}}$, per pound	2×10^{-6}	2×10^{-6}
per newton	45×10^{-8}	45×10^{-8}
C_{l_β}, per radian	-0.1572	-0.143
$C_{l_{\dot\phi}}$, rad/sec	-0.1569	-0.136
$C_{l_{\dot\psi}}$, rad/sec	0.0817	0.0320
$C_{l_{\delta_w}}$, per radian	0.0653	0.077
$C_{l_{\delta_r}}$, per radian	0.0179	0.0202
C_{n_β}, per radian	0.0797	0.1167
$C_{n_{\dot\phi}}$, rad/sec	-0.0225	-0.0166
$C_{n_{\dot\psi}}$, rad/sec	-0.0467	-0.0189
$C_{n_{\dot\beta}}$, rad/sec	-0.043	-0.027
$C_{n_{\delta_w}}$, per radian	0.0082	0.0156
$C_{n_{\delta_r}}$, per radian	-0.0725	-0.068
$C_{n_{\delta_s}}$, per radian	0.0245	0.0245
C_{Y_β}, per radian	-0.831	-0.825
$C_{Y_{\dot\phi}}$, rad/sec	0.1492	0.0864
$C_{Y_{\dot\psi}}$, rad/sec	0.0865	0.0764
$C_{Y_{\delta_w}}$, per radian	-0.0128	-0.0128
$C_{Y_{\delta_r}}$, per radian	0.1712	0.0177
Short-period frequency, rad/sec	1.53	1.68
Short-period damping ratio	0.702	0.698
Phugoid frequency, rad/sec	0.134	0.138
Phugoid damping ratio	0.282	0.096
Dutch roll frequency, rad/sec	0.799	0.844
Dutch roll damping ratio	0.0419	0.091
Spiral-divergence time constant, sec	-188.8	127
Roll-convergence time constant, sec	0.665	0.657
Flap deflection, deg	30	20
Initial δ_s, deg	-6	-6

3. PERFORMANCE CHARACTERISTICS

By Albert W. Hall

SUMMARY

Some performance characteristics are presented which were determined during the in-flight simulation study of supersonic transport landing-approach configurations. The normal load factor and attitude changes resulting from maneuvers during instrument approaches and landing flares are presented. The landing flare and effects of speed-thrust stability are illustrated and discussed.

INTRODUCTION

In this part are presented results which are applicable to some of the future performance certification requirements of supersonic transports during the landing approach. The normal load factor and attitude changes resulting from maneuvers during instrument approaches and during the landing flare are given for approaches made during this investigation. The landing-flare characteristics and the effects of speed-thrust stability are illustrated and discussed. These results are presented both as flight test data and pilot opinions. The emergency landing configuration (variable geometry with the wings swept in the cruise position) is not discussed in this part because the limited time of this preliminary investigation allowed only one instrument approach with this configuration.

RESULTS AND DISCUSSION

ILS Approaches

Selection of approach speeds.- The design requirements for economical high-speed cruise flight can result in high body attitudes for both the variable-geometry and fixed-geometry supersonic transports in the landing configuration. For the fixed-geometry configuration, the minimum approach speed which gives adequate tail clearance during a landing probably will be greater than the presently required value of 1.3 times the stall speed. Therefore, approach speeds for the fixed-geometry SST configuration may be based on attitude rather than on speed margin. It is conceivable, though less likely, that the approach speeds for the variable-geometry SST configuration may also be based on attitude.

The approach and landing attitude requirements should allow a sufficient tail clearance margin for operational variations in speed and unexpected maneuvers near the ground. This problem could not be examined during the present investigation because the tail clearance and body attitude at touchdown were not simulated and therefore only the incremental attitude changes could be correctly simulated. (A comparison of touchdown attitude for the simulator and SST configurations is shown in figure 3-1.) Therefore, the approach speed was selected prior to this investigation rather than being an objective of the investigation. The selected approach speed was 135 knots since one of the early design objectives of the United States supersonic transport program was to have an approach speed no greater than 135 knots at the maximum landing weight.

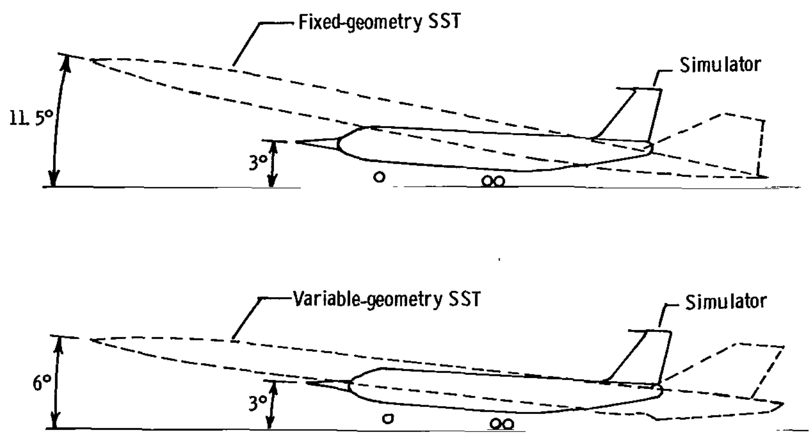


Figure 3-1.- Touchdown attitude for simulator and SST configurations.

Longitudinal maneuvers during approach.- The selected approach speed margin and corresponding maneuver capability are expected to be more than adequate for the fixed- and variable-geometry SST configurations of this investigation. The maximum variations of attitude and load factor measured during instrument approaches with these configurations are presented in table 3-1. These approaches were made in calm air with no interfering traffic and no cockpit distractions. The attitude and load factor variations are probably smaller than those which might occur in turbulent air with minimum weather conditions at a busy terminal with a maximum of aircraft-ground communications after a long flight which has induced pilot fatigue. These data were also affected by the fact that the pilots were trying to keep the airspeed within ±10 knots of the trimmed approach speed (135 knots) in order to maintain a valid simulation as discussed in part 2 of this paper. This is an artificial restriction which would not be present in the actual supersonic transport and the effect of this restriction on the approach techniques used herein is not known.

The pitch attitude data for each approach shown in table 3-1 represent the maximum increments above and below the nominal simulator attitude ($1/2^{\circ}$ nose up for the glide slope). The maximum nose-up attitude increments during each approach were generally less than 4^{0} and the maximum nose-down increments were usually less than the nose-up value. (See table 3-1.)

The distribution of maximum normal load factor is shown in figure 3-2 for the 54 approaches given in table 3-1 for both fixed- and variable-geometry configurations. From figure 3-2 it is seen that 35 percent of the approaches had a maximum load factor between 1.15 and 1.2, only 9 percent of the approaches had load factors between 1.25 and 1.3, and the load factor did not exceed 1.3 for any of the approaches.

Time histories of altitude, load factor, body attitude, and flight path for the latter part of one instrument approach with the variable-geometry configuration are presented in figure 3-3 to illustrate the data given in table 3-1.

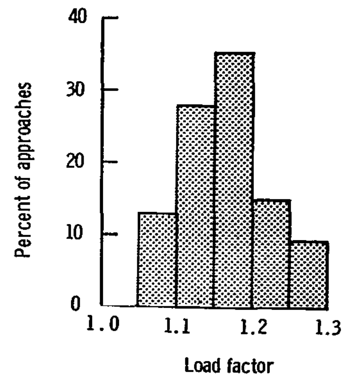


Figure 3-2.- Distribution of maximum normal load factor resulting from maneuvers during 54 instrument approaches for the supersonic transport configurations investigated.

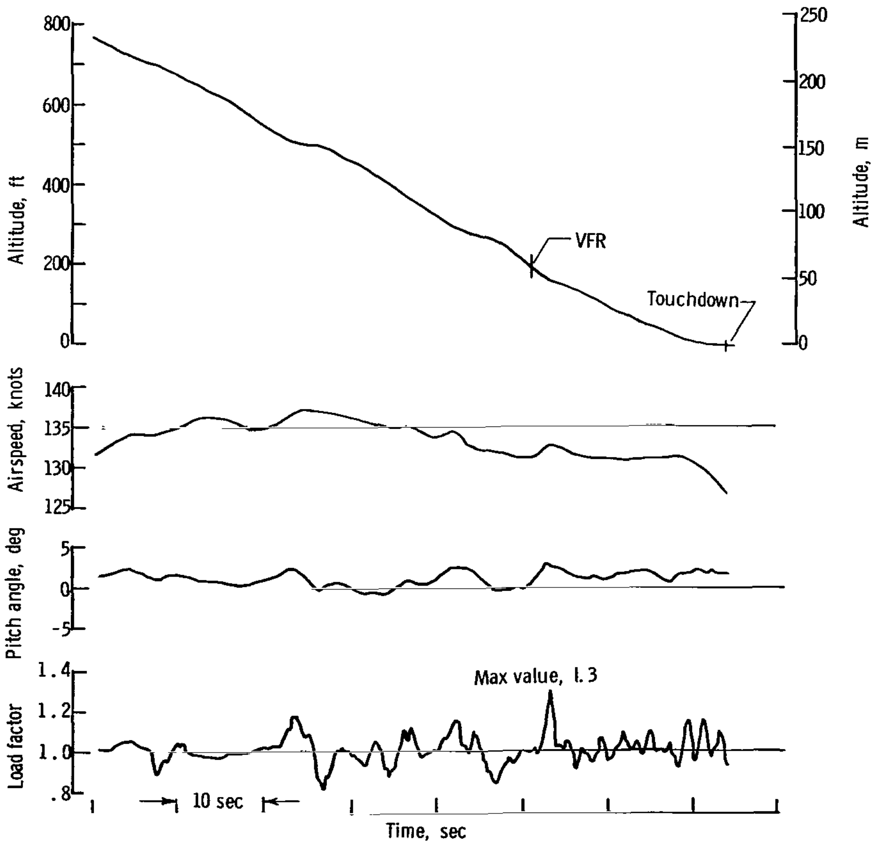


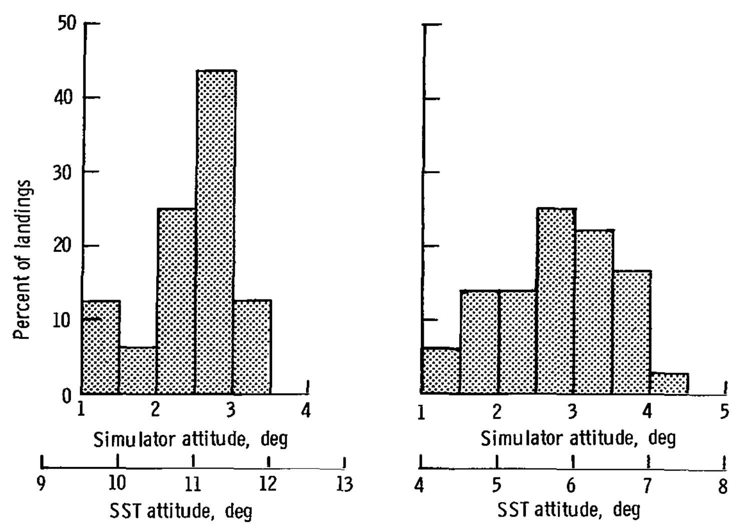
Figure 3-3.- Time histories during the latter part of an instrument approach with the variable-geometry configuration having $\dot{\theta}$ and $\dot{\beta}$ augmentation.

Just prior to the transition from instrument to visual flight the attitude dropped to a negative value. At the transition to visual flight the pilot increased the attitude rather abruptly to about 2.8°, which resulted in a 1.3 load factor. This happened for several approaches where the highest load factor during the approach occurred during the transition from instrument to visual flight.

Landing Flare

Touchdown attitude.- The distribution of body attitude at touchdown is shown in figure 3-4 for both the fixed- and variable-geometry configurations. These distributions include data from several visual approaches in addition to the instrument approach data of table 3-1. As mentioned in the discussion of lift characteristics in this section, the supersonic-transport attitude was not matched by the simulator. The relation between simulator attitude and SST attitude is described in part 2. The simulator and corresponding SST attitudes are shown in figure 3-4.

The measured touchdown attitudes are $7\frac{1}{2}^{\circ}$ to $8\frac{1}{2}^{\circ}$ less than the maximum ground attitude of the simulator but present indications are that some SST configurations will be landing at an attitude very close to the maximum ground attitude. The pilots, therefore, were landing the simulated configurations with no apprehension of tail-first contact; this is not a realistic simulation and it is very probable that the distribution of touchdown



(a) Fixed-geometry SST (16 landings).

(b) Variable-geometry SST (36 landings).

Figure 3-4.- Distribution of touchdown attitude for two supersonic transport configurations.

attitudes would be lower (further from the tail-drag limit) than that shown in figure 3-4. The lower touchdown attitudes would be accompanied by increased approach speeds.

As indicated in part 2, the simulation was only valid for a speed range 10 knots above and below the trim speed. Therefore, during the landing flare the pilots had an unrealistic task of keeping the airspeed above 125 knots. The effect of the two simulation deficiencies is not known; however, they tend to be compensating. The improper ground attitude allows higher than normal touchdown attitudes, while the minimum speed restriction causes lower than normal touchdown attitudes.

In flying the 3° approach path, the body attitude for the simulator was about $1/2^{\circ}$ nose up for both the fixed- and variable-geometry simulations. From figure 3-4 it can be seen that, generally, the final touchdown attitude for the simulator was from about 2° to $3\frac{1}{2}^{\circ}$. This attitude increase represents the increment $\left(1\frac{1}{2}^{\circ}\text{ to }3^{\circ}\right)$ that will be required during the landing flare for these configurations with the ground effects that were simulated for this investigation.

Because of simulator limitations only about one-third of the estimated increase in lift coefficient resulting from ground effect could be simulated for the fixed-geometry configuration. If no change in lift-curve slope is assumed, the difference between the ground-effect lift increment estimated for the fixed-geometry SST and that actually simulated was equivalent to a 2° angle-of-attack increment. In other words, the touchdown lift coefficient represented by the data of figure 3-4(a) would have occurred at a body attitude 2° lower than that shown and a large portion of the touchdowns would have occurred with the attitude close to that for the approach. These results would then be in agreement with preliminary data from various sources which have indicated that some fixed-geometry configurations tend to be "automatically flared" through favorable ground effect when the approach attitude is held constant.

The term "estimated ground effect" is used in this discussion and is fairly descriptive of most of the available ground effect information applicable to SST configurations. Considering the relationship between ground effect, touchdown attitude, and approach speed, it is therefore very important that efforts be made to obtain reliable data on ground effects for SST configurations.

Flare-path control.- Precise flare-path control is required in order to have the airplane touch down at a particular point with a low rate of sink (vertical velocity). The ability to touch down near a given runway location is required if each landing is to be completed within a predictable landing-field length. As discussed in part 4, longitudinal augmentation was required to improve longitudinal control of the flare path. The longitudinal augmentation was found to be very effective in allowing more precise control of the flare path for both the fixed- and variable-geometry configurations.

The pilots reported that the variable-geometry configuration had an unusually large floating tendency near the ground during the landing flare. The floating tendency was not as pronounced for the fixed-geometry configuration but it should be remembered that the full amount of estimated ground effect was not mechanized in this simulation. Although the ground effect could not be changed by longitudinal augmentation, it appeared that the more precise control characteristics of the augmented configuration made it easier to overcome the floating tendency.

Measured and calculated flare paths.- The major effort in the estimation of landing performance involves the determination of the landing-flare distance.

The calculated and measured flare paths for the fixed-geometry supersonic transport configuration are shown in figure 3-5. The measured data are representative of a good landing where the touchdown occurred near the desired location, with a low rate of sink and with no floating or "feeling for the ground." The calculated flare is based on a method explained in reference 1 which involves a point mass moving in a plane with two degrees of freedom under the action of known forces. For the calculated flare path, thrust was assumed to be constant at the value for a 3° approach and a constant load factor was assumed. For the measured flare path, the thrust was maintained at the approach value but the load factor varied considerably as shown in figure 3-5. For the calculations a constant load factor of 1.04 was required to decrease the rate of sink from 11.0 feet/sec to 1.2 feet/sec (3.4 to 0.37 m/sec) in a vertical distance of 50 feet (15 m). The initial conditions of forward speed and vertical velocity were taken from the flight test data at an altitude of 50 feet (15 m) and the terminal condition was taken from the vertical velocity measured at touchdown. The calculated flare path is very close to the measured path. The measured load factor varies considerably above and below the constant value used

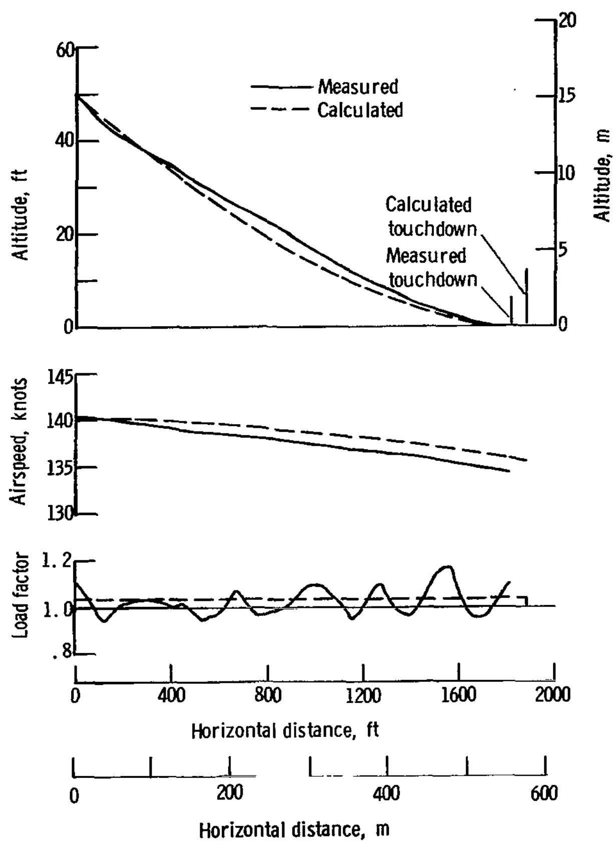


Figure 3-5.- Measured and calculated flare path for fixed-geometry supersonic transport configuration.

in the calculated flare; however, the constant factor represents a good average value. On the basis of this result and other results not shown herein, it is believed that the constant-load-factor method of computing landing-flare parameters (ref. 1) will give a good estimate of the supersonic transport flare characteristics if a load factor of the order of 1.05 is used.

From figure 3-5 it can be seen that the maximum load factor used during the flare is much greater than the average value. The oscillatory or pulsating variation of load factor shown here is typical in magnitude of all the landings recorded during this investigation. (See table 3-1 for comparison of maximum load factor values.)

The curve showing speed loss in figure 3-5 was based on a drag-lift ratio for free air but the use of the value for full ground effect gave less than 0.5 knot difference between that based on free air.

Speed-Thrust Stability

Limiting values of speed-thrust stability.- The fixed-geometry SST is expected to fly on the back side of the thrust-required curve during the landing approach; consequently, there has been much discussion concerning a possible criterion to define a tolerable level of speed-thrust stability. The piloting problems associated with back side operation are significant when flying under flight-path constraint such as during an instrument approach (ref. 2). Some investigations (such as ref. 3) have indicated that it is desirable to have stable speed-thrust characteristics (front side) for an instrument approach, whereas some other work (for example, ref. 4) has indicated that a certain amount of instability can be tolerated.

The parameter $\frac{\partial(T/W)}{\partial V}$ has been used as a measure of speed-thrust stability. For the aircraft characteristics investigated in reference 5 a speed-thrust level of $\frac{\partial(T/W)}{\partial V} = -0.0012$ per knot (unstable) degraded the longitudinal control characteristics sufficiently to be unacceptable for normal operation but acceptable for emergency operation during instrument approaches.

Demonstration of speed-thrust instability.- The time histories of airspeed, flight path, throttle position, and pitch attitude in figure 3-6 illustrate the differences between positive and negative speed-thrust stability. The data are for the basic fixed-geometry configuration with the normal unstable $\frac{\partial(T/W)}{\partial V}$ value of -0.0024 per knot in one case (solid lines) and a stable $\frac{\partial(T/W)}{\partial V}$ value of 0.0006 per knot in the other case (dash lines). A 100-foot (30.5 m) vertical offset of the glide slope was used as a precision and repeatable task in evaluating the effect of speed-thrust stability variation. For the task illustrated in figure 3-6 the pilot attempted to fly to the glide-slope offset, stabilize, and return without changing the original throttle setting.

The results shown in figure 3-6 for the configuration with stable speed-thrust characteristics indicate that large flight-path changes can be made without changing power. The result of not adding power is a reasonable exchange of altitude and airspeed - that is, the 100-foot (30.5 m) increase shown was attained while the airspeed dropped approximately 10 knots. With positive speed-thrust stability the airspeed would be expected to return to the original value after stabilizing on the new glide slope (at the original rate of descent). For the configuration with unstable speed-thrust characteristics, the airspeed dropped very rapidly following the attempt to increase the flight-path angle.

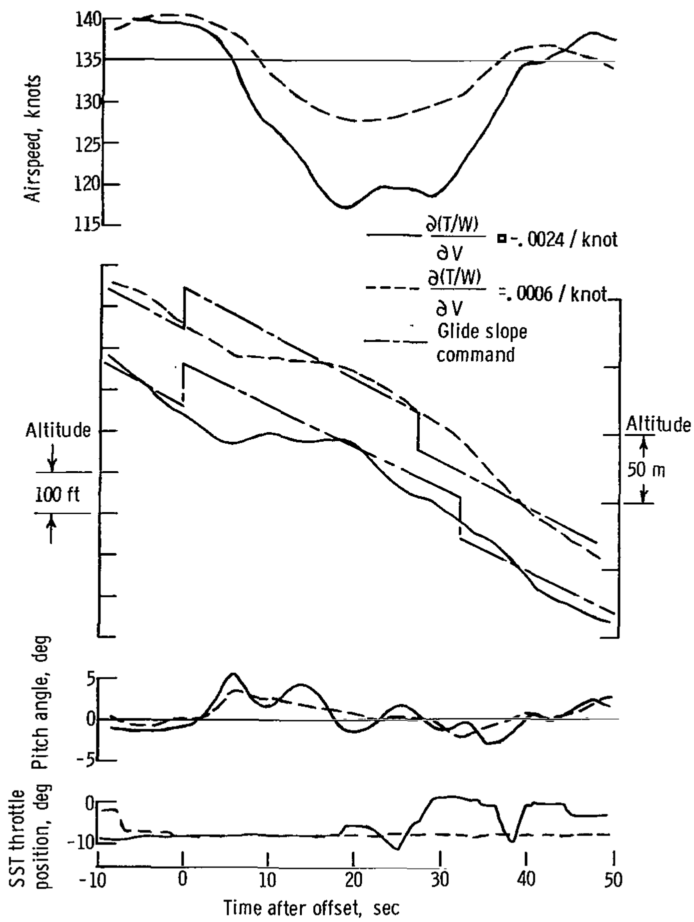


Figure 3-6.- Time histories showing glide-slope offset flown with two fixed-geometry supersonic transport configurations illustrating the effects of speed-thrust stability.

Except for one oscillation, the offset flight path could not be maintained and the attitude had to be decreased and power added to keep the airplane from stalling. The examples presented demonstrate the difference between the two values of speed-thrust stability and are not representative of normal operation where the pilot would use the throttle as required and would not be expected to let the airspeed drop for 20 seconds without taking some corrective action.

Effects of speed-thrust stability on supersonic transport configurations.- The speed-thrust stability of the SST configurations of this investigation is indicated by the slope of the thrust-required curves shown in part 2. The fixed-geometry configuration simulates unstable speed-thrust characteristics with a value of $\frac{\partial(T/W)}{\partial V} = -0.0024$ per knot, whereas the variable-geometry configuration had a stable $\frac{\partial(T/W)}{\partial V}$ value of 0.0005 per knot. In addition, a brief investigation was conducted with the fixed-geometry configuration having a C_{D_α} value which resulted in positive speed-thrust stability $\left(\frac{\partial(T/W)}{\partial V} = 0.0006 \text{ per knot}\right)$. The results and opinions of this investigation conducted with experimental test pilots apply only to the conditions of these tests – that is, large thrust margins, quick engine response, calm air, no emergencies, and no abnormal cockpit distractions.

For the fixed-geometry configuration where all other characteristics were identical except the value of C_{D_α} the change in $\frac{\partial(T/W)}{\partial V}$ from -0.0024 per knot to 0.0006 per knot resulted in an improved Cooper pilot rating of 1/2 to 1 rating number based on speed control characteristics during an instrument approach. The results of reference 5 indicate about the same change in pilot rating for less than one-half of this change in the parameter $\frac{\partial(T/W)}{\partial V}$.

According to the pilot's comments the negative speed-thrust stability $\left(\frac{\partial(T/W)}{\partial V} = -0.0024 \text{ per knot}\right)$ of the fixed-geometry configuration did not have any serious effect on the instrument approach capability as compared with the effect of positive stability $\left(\frac{\partial(T/W)}{\partial V} = 0.0006 \text{ per knot}\right)$ of the same configuration or with the effect of positive stability $\left(\frac{\partial(T/W)}{\partial V} = 0.0005 \text{ per knot}\right)$ of the variable-geometry configuration.

Most of the comments were similar to the thought expressed by one pilot who in comparing the unstable with the stable speed-thrust characteristics said ". . . larger variations (in airspeed) occur due to the unstable thrust-velocity relationship and an increased requirement is placed on proper coordination between elevator and throttle."

Most of the pilot comments relative to speed-thrust stability were based on evaluation of the fixed- and the variable-geometry configurations where in addition to speed-thrust stability other parameters were also different. One of the pilots indicated that for the variable-geometry configuration $\left(\frac{\partial(T/W)}{\partial V} = 0.0005 \text{ per knot}\right)$ the glide path was primarily controlled by elevator and the throttle was used only when the approach was definitely high and fast or low and slow. Generally the pilots said that elevator was used for glide-path control and throttle for airspeed control with one pilot indicating an occasional need for a reversal of this combination.

The control techniques used for the fixed-geometry configuration $\left(\frac{\partial(T/W)}{\partial V} = -0.0024 \text{ per knot}\right)$ tended toward a mixture of techniques – that is, a combined or coordinated use of elevator and throttle to control both airspeed and glide slope. Only two pilots reported a definite use of elevator to control glide path and throttle to control airspeed, and one of these indicated that a lack of time precluded an evaluation of reverse or other techniques. The problem of flight-path control for this airplane was summed up very well by one pilot in comparing the fixed-geometry configuration with other airplanes that he had flown which operate on the back side of the thrust-required curve. He said, "Other airplanes that I have flown on the back side require less attention to speed; you tend to control your speed with your nose attitude and your rate of sink with your throttle, although you can't divorce one from the other. If you make an input one place, you have to make another to compensate for it. The airplane (fixed-geometry configuration) is, probably down to 300 feet using the flight director, not too difficult to control. The majority of the problems come below that (altitude). It does not fly as well as other airplanes I have flown on the back side of the thrust required (curve)."

Although no serious problems were encountered during the instrument approaches with the fixed-geometry configuration as a result of speed-thrust instability, several pilots pointed out that the rapid speed or altitude loss during a turn could cause a problem. For example, a rapid turn necessitated for an avoidance maneuver while near the ground at a low speed could result in a serious speed or altitude loss at a time when the pilot has little time to observe or correct for these changes.

It does appear that instrument approaches with a fixed-geometry airplane, such as that simulated during this investigation, could be managed if necessary, provided the pilots had been trained and maintained a proficiency for instrument approach with this type of airplane. Therefore, if some form of automatic speed control is to be used, there should be no necessity for a redundant system to provide for equipment failure.

CONCLUDING REMARKS

A flight test investigation of the instrument approach and landing characteristics of simulated fixed- and variable-geometry supersonic transport configurations has indicated the following results:

The maximum normal load factor used during instrument approaches with either configuration was generally between 1.15 and 1.2 with the highest value at 1.3.

The airplane attitude at touchdown was generally about 2° higher than during the approach for both configurations; however, it should be pointed out that for the fixed-geometry configuration only about one-third of the estimated ground effects were simulated.

Landing-flare paths computed on the basis of a constant load factor of 1.05 give a good approximation to measured flare paths.

The unstable speed-thrust characteristics of the fixed-geometry configuration caused no serious problems for the experimental test pilots during these simulated instrument approaches which were conducted in calm air with no emergencies or abnormal cockpit distractions.

For the fixed-geometry configuration, a change in speed-thrust characteristics from unstable to stable resulted in an improved pilot rating of about 1/2 to 1 rating number for the instrument approach task.

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TABLE 3-1.- PEAK VALUES OF ATTITUDE AND NORMAL LOAD FACTOR FOR INSTRUMENT APPROACHES WITH VARIOUS SUPERSONIC TRANSPORT CONFIGURATIONS

Configuration	Glide slope: Maximum attitude increment during approach, deg		Glide slope: Load factor		Maximum flare load factor	Simulator attitude at touchdown, deg
	Nose up	Nose down	Maximum	Minimum		
Fixed geometry (basic)	1.9	-4.1	1.23	0.90	1.08	3.0
	2.2	-2.0	1.15	.89	1.20	2.0
	2.5	-.7	1.18	.82	1.10	2.8
	2.5	0	1.17	.91	(a)	(a)
	2.0	-1.7	1.16	.78	(a)	(a)
Fixed geometry (C_{l_p} and $(\dot{\theta} + \Delta\alpha)$ augmented)	2.0	-1.5	1.16	0.90	(a)	(a)
	1.5	-2.0	1.13	.86	1.20	2.3
	2.3	-2.1	1.13	.84	1.18	2.6
	2.5	-1.5	1.18	.77	1.32	3.0
	1.9	-1.5	1.24	.78	1.16	2.5
Fixed geometry ($(\dot{\theta} + \Delta\alpha)$ augmented) with degraded Dutch roll damping and $C_{n_{\dot{\phi}}}$	2.5	-1.3	1.20	0.82	1.16	3.2
	2.7	-3.7	1.27	.75	1.16	2.5
	1.3	-2.0	1.16	.62	1.16	2.5
	1.7	-2.7	1.17	.83	(a)	(a)
Variable geometry (basic)	3.5	-2.5	1.14	0.86	(a)	(a)
	1.5	-2.5	1.20	.72	1.10	2.0
	.7	-3.1	1.16	.82	1.10	2.5
	4.3	-2.6	1.18	.84	1.08	(b)
	3.5	-3.2	1.30	.82	1.06	(b)
	4.4	-2.0	1.20	.79	1.16	(b)
Variable geometry ($\dot{\beta}$ and $\dot{\theta}$ augmented)	6.5	-4.0	1.16	0.84	1.12	3.0
	1.7	-3.1	1.14	.91	1.08	(b)
	2.5	-2.3	1.14	.89	1.06	1.5
	2.0	-.7	1.09	.89	(b)	(b)
	2.2	-1.0	1.16	.87	1.11	(b)
	2.3	-1.5	1.30	.81	1.16	(b)
Variable geometry ($\dot{\beta}$ and $(\dot{\theta} + \Delta\alpha)$ augmented)	2.0	-1.1	1.07	0.94	1.08	3.8
	2.0	-1.1	1.07	.91	(b)	3.4
	1.5	-1.2	1.12	.91	1.17	3.0
	2.5	-1.7	1.17	.80	1.21	3.3
	2.1	-2.3	1.20	.85	1.12	3.3
	2.5	-1.5	1.23	.80	1.19	3.0
Variable geometry ($\dot{\beta}$ augmented) with aft c.g.	4.0	-2.2	1.25	0.78	1.14	(b)
	1.9	-1.3	1.11	.89	(a)	(a)
	1.5	-2.3	1.07	.88	(a)	(a)
	3.0	-2.5	1.14	.80	(a)	(a)
	2.0	-1.5	1.12	.88	1.06	3.0
	2.8	-2.0	1.15	.90	1.10	3.2
	2.0	-2.0	1.09	.91	1.06	3.0
Variable geometry ($\dot{\beta}$ and $(\dot{\theta} + \Delta\alpha)$ augmented) with aft c.g.	2.1	-2.0	1.22	0.78	1.22	1.8
	1.5	-2.0	1.22	.82	1.15	2.0
	.7	-2.0	1.12	.81	1.24	2.5
	1.3	-2.2	1.08	.90	1.13	3.6
	.1	-2.1	1.07	.89	1.11	2.8
	.5	-2.9	1.12	.84	1.11	3.0
Variable geometry with degraded Dutch roll damping and $C_{n_{\dot{\phi}}}$	3.1	-2.7	1.22	0.72	1.24	3.5
	3.0	-4.0	1.30	.76	(a)	(a)
	2.5	-4.0	1.22	.72	1.20	2.5
Variable geometry ($(\dot{\theta} + \Delta\alpha)$ augmented) with degraded Dutch roll damping and $C_{n_{\dot{\phi}}}$	3.5	-1.0	1.28	0.82	1.16	4.5
	2.7	-1.5	1.14	.82	1.11	3.2
	2.0	-1.2	1.14	.84	1.16	3.0
	1.1	-2.1	1.17	.85	1.13	3.2
	1.5	-2.5	1.17	.87	1.14	3.0
	1.0	-2.0	1.17	.80	(a)	(a)

[a]No touchdown.
[b]Touchdown but data missing.

4. LONGITUDINAL HANDLING QUALITIES

By William D. Grantham and Lee H. Person

SUMMARY

An in-flight simulation study has been made to determine the handling qualities of several supersonic transport configurations during the landing approach. This report discusses the longitudinal portion of the study. The longitudinal handling qualities of the variable-geometry and the fixed-geometry SST configurations were considered unsatisfactory because of the sluggish initial pitch response and the apparent low damping. The use of stability augmentation and an increase in control gearing made the longitudinal characteristics of both configurations satisfactory.

INTRODUCTION

This report presents the results of the longitudinal portion of the study which was undertaken to determine (1) the handling qualities of several SST configurations during the landing approach, and (2) possible criteria for low-speed handling qualities which would be applicable for the establishment of certification requirements for the SST.

The basic configurations flown during the study are listed in part 1 of this publication and in general were a variable-geometry configuration with the wings in the forward position ($\Lambda = 20^{\circ}$), a variable-geometry configuration with the wings in the fully swept position ($\Lambda = 72^{\circ}$), and a fixed-geometry (delta wing) configuration. The pilot evaluation procedures are discussed in part 2 of this publication; in general, these procedures included evaluation of the aircraft (a) at altitude, (b) during a visual approach and landing, and (c) during several instrument approaches down to an altitude of approximately 200 feet from which the flare and landing was performed visually.

RESULTS AND DISCUSSION

For the most part, the longitudinal characteristics of the various SST configurations simulated are presented and discussed in relation to pilot ratings and opinions. The individual Cooper pilot ratings and comments for each test condition are presented as table 4-1. All configurations were evaluated by a minimum of two pilots, with some pertinent configurations being evaluated by seven pilots; however, the average pilot rating presented throughout the discussion was taken as an average of the two pilots that flew all configurations (pilots A and B).

Variable-Geometry Configuration

Basic.- The average pilot rating of the longitudinal handling characteristics of the variable-geometry SST configuration was 4.1, with the objection being the sluggish pitch response and apparent low damping as evidenced by some overshoot in pitch attitude changes. The pilots reported that a large portion of the total effort was used to control the glide path and airspeed on ILS approaches.

Static longitudinal stability: The static longitudinal stability of this variable-geometry configuration was considered by the pilots to be adequate. Plots showing the stick-fixed $\left(\delta_c \text{ against } V_e\right)$ and stick-free $\left(F_c \text{ against } V_e\right)$ static stability are presented as figure 4-1. As can be seen, the stick-fixed stability is approximately -0.099 deg/knot, and the stick-free stability is approximately -0.380 lbf/knot (1.69 N/knot).

This configuration was flown on the stable side (front side) of the thrust-required curve. The variation of thrust required with velocity $\left(\partial \frac{T}{W} \middle/ \partial V\right)$ was approximately +0.0005 for this variable-geometry configuration and is discussed in detail in part 3 of this publication.

Dynamic longitudinal stability: The short period undamped natural frequency ω_n and damping ratio ζ of this configuration are indicated in figure 4-2(a) and are compared with some subsonic jet transports. As can be seen, the damping ratio of this SST configuration compares favorably with the damping ratios of the indicated subsonic transports, whereas the undamped frequency of this SST is lower than those indicated for the various subsonic transports. Pilots are not aware of the magnitude of ω_n, however, but instead see the damped natural frequency (the damped period of the short period oscillation). See figure 4-2(b) for a plot of damped frequency ω_D against ζ. The relative difference between the SST and the subsonic jet transports is more pronounced for damped frequency conditions than for the undamped frequency conditions. (It should be mentioned that the indicated short period characteristics of the subsonic transports are normally considered acceptable by pilots.) As stated previously, the pilots objected to the dynamic longitudinal stability characteristics of this variable geometry SST configuration because of the sluggish initial pitch response and the apparent low damping. These pilot comments can best be explained by examining figure 4-3, which shows the aircraft pitch rate response to an elevator pulse. This figure indicates a pitch rate time constant of approximately 1.6 seconds, and also shows that the pitch rate continues to increase even during the release of the control. The long pitch rate time constant would appear to the pilot as sluggish initial response, and the integral of the pitch rate following control release (shaded area) would appear to the pilot as an overshoot in pitch attitude (low pitch damping). These two characteristics of the short period dynamics forced the pilot to anticipate and to check the pitch motion during maneuvers to avoid overshooting the desired pitch attitude. During instrument approaches, precise attitude control was difficult, thus the pilots tended to oscillate about the glide path – hunting for the desired glide path and airspeed.

Maneuvering characteristics: Longitudinal maneuverability was considered to be adequate for any normal situation encountered during the approaches. The longitudinal maneuvering stability in a wind-up turn, is shown in figure 4-4 as column deflection δ_c and stick force F_c as a function of normal acceleration n. (The value of δ_c/n is approximately 0.90 deg/g, and F_c/n is approximately 33 lbf/g (147N/g); both were considered by the pilots to be adequate.) It should be noted that the simulation was limited to approximately 1.3g and that the data at higher accelerations are not reliable.

Control: The pilots commented that the initial pitch response to column inputs was sluggish. This sluggish response, which was caused by the high pitch inertia, is illustrated in figure 4-5. When compared with a present subsonic jet transport, the initial SST response is rather sluggish; however, the steady state response is considerably better than the subsonic transport. This figure also shows that, because of the sluggish pitch response of the SST, a longer time was required for small glide path changes, which of course made it difficult for the pilot to make quick and precise glide path corrections. In order to fly the airplane on an ILS approach, the pilot had to quicken the initial pitch response to a more acceptable level by supplying a forcing function. This procedure involved the use of an increased initial input of the column, followed by a reverse input, in order to avoid overshooting the desired pitch attitude. (An illustrative example is shown as fig. 4-6.)

The pilots found the control and trim activity required to establish and hold a desired rate of descent and airspeed to be quite high during ILS approaches. This trim difficulty was due, in part, to the sluggish pitch response and the apparent low damping (low frequency short period).

The trim change with thrust was in the normal direction experienced with large subsonic jet transports (nose-up with increased thrust). Furthermore, the trim change was small – which the pilots stated helped in stabilizing on the glide slope. The thrust response was considered to be excellent. The pilots controlled the speed mainly with the throttle, and the speed control was considered adequate. Some of the possible factors contributing to good speed control were (1) excellent thrust response, (2) smooth air, and (3) the use of a sensitive airspeed indicator.

Landing characteristics: The flare characteristics were poor. As stated previously, this variable-geometry configuration had sluggish pitch response and apparent low damping; these characteristics caused control problems during the instrument approach, but 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 at a proper landing attitude. Most of the pilots felt that there was a tendency to overcontrol during the flare and occasionally rather severe cases of low frequency control pumping occurred. The flare time history of figure 4-7(a) is one example; this landing occurred on a clear calm day in the early stages of the flight test program. Even though pilot training may eliminate this type of oscillation, poor conditions such as turbulence and/or low visibility might produce dangerous situations during landings.

The control forces required for flare were considered acceptable in that a maximum force of only about 10 lbf (44 N) was used.

The ground effects presented no problem insofar as the incremental pitching moment experienced. However, during the flare, the aircraft tended to "float" down the runway. (The pilots commented that this floating tendency seemed unrealistic when compared with present-day subsonic jet transports.)

Pitch rate $\dot{\theta}$ augmentation.- The first longitudinal stability augmentation system (hereinafter referred to as SAS) evaluated during the flight tests of the variable-geometry concept was a pitch rate damper which produced the frequency and damping characteristics shown in figure 4-8. (As can be seen, the frequency was increased approximately 50 percent, and ζ was increased from 0.672 to 0.940.) In addition to the $\dot{\theta}$ SAS, the elevator to column gearing was increased from -1.3 to -2.6. (This increase in elevator to column gearing was made in an effort to maintain the same F_c/g, and this change in control gearing appeared to the pilot as a reduction in speed stability δ_c/V_e.) This $\dot{\theta}$ augmentation was better than the unaugmented, but it still had several somewhat undesirable features. The average Cooper pilot rating of the longitudinal handling qualities with the $\dot{\theta}$ SAS was 3.4, the objections being the still less than good pitch response and the deterioration of speed control.

Pitch rate plus alpha $(\dot{\theta} + \Delta\alpha)$ augmentation.- The second and most satisfactory longitudinal SAS used during the flight tests of the variable-geometry concept was a pitch rate plus angle of attack $(\dot{\theta} + \Delta\alpha)$ feedback system. (The elevator to column gearing was increased to -5.2.) The average Cooper rating of this configuration was 2.5, compared with 4.1 for the unaugmented configuration and 3.4 for the $\dot{\theta}$ augmented configuration. The effect of the $(\dot{\theta} + \Delta\alpha)$ SAS on ω_n and ζ is also shown in figure 4-8 for comparison with the unaugmented and the $\dot{\theta}$ augmented configurations.

Static longitudinal stability: The stick-fixed and stick-free static stability were adequate and very similar to that of the unaugmented configuration. Figure 4-9 presents plots of δ_c and F_c against V_e for the basic and the $(\dot{\theta} + \Delta\alpha)$ augmented configurations. It should be noted that the increase of the elevator to column gearing did not appear to the pilot as a deterioration in speed stability when the $(\dot{\theta} + \Delta\alpha)$ augmentation was used because of the increase in the effective C_{m_α}, brought about by the $\Delta\alpha$ or static stability SAS.

Dynamic longitudinal stability: The pitch damping was said to be very good; small or large pitch attitude changes could be made without overshooting the desired angle. Actually, the damping ratio ζ was approximately the same as that for the unaugmented configuration; however, the short period frequency was increased approximately 100 percent, which appeared to the pilot as an increase in pitch damping. The damping parameter $2\zeta\omega_n$ was approximately equal to 2.46 for this augmented configuration compared with 1.19 for the unaugmented configuration.

Maneuvering characteristics: The maneuvering capability was quite adequate; see figure 4-10 for plots of δ_c and F_c against n ($\delta_c/n \approx 11$ deg/g and $F_c/n \approx 45$ lbf/g (200 N/g)).

Control: All of the pilots agreed that the $(\dot{\theta} + \Delta\alpha)$ SAS appreciably improved the pitch response over the unaugmented configuration and, in fact, felt that the pitch response was now quite satisfactory. An illustrative example of the response of an airplane with the $(\dot{\theta} + \Delta\alpha)$ SAS is compared with an unaugmented airplane in figure 4-11. This SAS works thusly: The increased control gearing δ_e/δ_c initially causes an increased pitch rate and angle of attack response, but as both pitch rate and angle of attack build up, the SAS, which is sensitive to both of these, washes out the increased elevator deflection. In this way the initial response is considerably improved without making the already adequate steady-state response overly sensitive. The pitch control sensitivity was generally thought to be good; however, a few pilots felt that it was possibly higher than desirable.

This configuration was very easy to trim and/or establish a desired rate of descent when flying the glide slope. The pilots commented that it was easy to change the rate of descent by approximately ±100 ft/min (±0.5 m/sec), and then to stabilize again at the original rate of descent.

Landing characteristics: The flare characteristics of the $(\dot{\theta} + \Delta\alpha)$ augmented variable-geometry configuration were quite satisfactory. (See figs. 4-7(a) and 4-7(b) for comparison of flare time histories between the unaugmented and the $(\dot{\theta} + \Delta\alpha)$ augmented configurations.) The pilots commented that the pitch response was good, that the attitude control was precise, and that no tendency to oscillate in pitch occurred during the flare when the $(\dot{\theta} + \Delta\alpha)$ SAS was engaged.

The ground effects were of no consequence except for the previously mentioned floating tendency, which affected touchdown accuracy. It should be mentioned, however, that although the effects of ground could not be changed by longitudinal augmentation, it appeared that the more precise control characteristics of the augmented configuration made it easier to overcome the floating tendency.

Aft center of gravity (no augmentation).- For the present in-flight SST simulation program, the center of gravity has thus far been held constant at 46 percent $\bar{c}$ for the variable-geometry configuration. (This center of gravity location corresponds to a static margin of 9.75 percent $\bar{c}$.) However, it was believed that it would be desirable to determine what effects might be expected should the center of gravity position be altered appreciably. For the variable-geometry concept, the center of gravity location was moved aft to 52.75 percent $\bar{c}$ (static margin, 3 percent $\bar{c}$).

It should be mentioned that when the center of gravity was varied, the elevator to column gearing was not changed from the basic value and, therefore, F_c/g varied and may have had some effect on the pilot's evaluation.

The average Cooper pilot rating of the longitudinal axis of this aft center of gravity configuration was 5.1, the major objections being the low level of static stability and the low pitch damping.

Static longitudinal stability: The stick-fixed and stick-free static stability were low. (See fig. 4-12 for plots of δ_c and F_c against V_e for the basic and the aft center of gravity locations.) This configuration was said to be very difficult to trim; it was easily excited in pitch and had a very slow or almost nonexisting tendency to return to the trim condition. One pilot (pilot A) made the following general comment: "I think that as a single-axis airplane you could handle it, but if you had anything else to do other than spend your time on the longitudinal axis, it would be very difficult to fly and probably unsafe."

Dynamic longitudinal stability: The damping in pitch was low, and the need for the pilot to supply the necessary damping made maneuvers, such as the flare, very difficult. The damping parameter $2\zeta\omega_n$ is approximately the same for this aft center of gravity configuration as it was for the basic configuration ($2\zeta\omega_n = 1.21$ and 1.19, respectively). During the landing approach the airplane seemed to oscillate in both attitude and airspeed around the desired trim point.

Control: The pitch response was sluggish, however, once the pitching motion was started, the pitch rate and pitch rate per degree of column were very good. The control sensitivity, in terms of angular velocity, seemed adequate but was actually masked by the slow initial response. The low level of static stability, the low pitch damping, and the large pitch trim change with thrust (resulting from the low static stability) all combined to make this configuration very difficult to trim.

Landing characteristics: The sluggish pitch response and the need for the pilot to supply the pitch damping made a precise flare to proper touchdown attitude quite difficult – even in calm air.

Aft center of gravity; $\dot{\theta} + \Delta\alpha$ augmentation.- The variable geometry aft center of gravity configuration (c.g. = 52.75 percent $\bar{c}$; static margin, 3 percent $\bar{c}$) was briefly flown with the same SAS as was used for the basic variable-geometry configuration ($\dot{\theta} + \Delta\alpha$) to see if the previously used augmentation would also make a significant improvement in the longitudinal flying qualities of the aft center of gravity configuration. (The elevator to column gearing was -5.2.) The average Cooper pilot rating of the longitudinal axis of this configuration was 3.0. The pilots commented that this configuration was not difficult to trim, had a feeling of almost immediate pitch response, and had good pitch damping.

Because of the good response and damping, the flare capability was good with very little tendency to overshoot the desired attitude. Also, the touchdown accuracy was considered to be good.

Fixed-Geometry Configuration

Basic.- The average Cooper pilot rating of the longitudinal handling qualities of this fixed-geometry SST concept was 5.4. The objections to this configuration were sluggish pitch response, apparent low damping, and difficult airspeed control. The pilots stated that they spent over 50 percent of their time controlling the longitudinal axis of this configuration.

Static longitudinal stability: The pilots felt that the static stick-fixed and stick-free longitudinal stability were low; at an airspeed of 135 knots, $\delta_c/\Delta V \approx -0.042$ deg/knot and $F_c/\Delta V \approx -0.168$ lbf/knot (0.75 N/knot). (See fig. 4-13 for plots of δ_c and F_c against V_e.) It should be mentioned that this low level of static stability (static margin, 3 percent $\bar{c}$) may very well be characteristic of some SST aircraft since higher levels of static stability may tend to compromise the cruise performance by increasing the supersonic trim drag.

This fixed-geometry configuration was more difficult to trim than the variable-geometry concept. It should be noted, however, that the variable-geometry configuration was also difficult to trim when the center of gravity was moved rearward. This trim difficulty seemed to be associated with the apparent low damping and the lack of static stability and left the pilot hunting for correct attitude and airspeed.

This configuration had negative speed-thrust stability $\partial\frac{T}{W}/\partial V \approx -0.0024$, which also made it somewhat difficult to hold any given airspeed. This factor is discussed in detail in part 3 of this publication.

Dynamic longitudinal stability: The apparent low damping caused the pilots to have a tendency to overshoot any small pitch attitude changes. The reason for this apparent low damping is similar to that encountered with the variable-geometry SST configuration and is discussed under that section. The short period damping ratio ζ was approximately 0.87, and the damping parameter $2\zeta\omega_n \approx 1.3$. (See fig. 4-2.)

In addition to the apparent low damping (the damping appeared low because of the low frequency of the short period mode), the initial pitch response was said by the pilots to be poor. The pilots had to overcontrol in order to obtain the desired response to a control input. An illustrative example was discussed earlier in regard to the response characteristics of the variable-geometry configuration. (See fig. 4-6.)

Maneuvering characteristics: The pilots felt that the longitudinal maneuver capability was generally sufficient. Plots of δ_c and F_c against load factor n are presented in figure 4-14. As can be seen, $\delta_c/n \approx 11$ deg/g and $F_c/n \approx 50$ lbf/g (220 N/g).

Control: The initial pitch response, illustrated in figure 4-5, was considered to be sluggish by the pilots although they did think it may have been somewhat better than that of the variable-geometry configuration.

The sensitivity of the pitch control $\dot{\theta}/\delta_c$ was poor. The maximum control power $\ddot{\theta}_{max}$ was considered to be adequate (better than some present-day subsonic jet transports).

For straight and level flight as well as for an established rate of descent, constant attention was required to maintain the desired attitude and airspeed. It was obvious to the pilot that this configuration had speed-thrust instability.

The thrust response of the fixed-geometry configuration was considered to be excellent. The trim change with thrust was in the normal direction and was quite mild.

Landing characteristics: Because of the sluggish pitch response, the flare characteristics were quite similar to those of the variable-geometry configuration, that is, poor.

The incremental pitching moment due to ground effects was bothersome to the pilots; a large nose-down pitching moment was experienced at an altitude of approximately 30 feet (9 m). (The values of ΔC_m used to simulate the ground effect for this configuration are presented in part 2 of this publication.) However, it was stated by the pilots that this ground effect on pitch would not constitute a problem if the pitch response characteristics were improved. Since some difficulty was experienced in simulating ground effects on lift and drag for the fixed-geometry configuration (see discussion in part 2), the effects of the ground on lift and drag will not be discussed.

Pitch rate plus alpha augmentation.- Since the $(\dot{\theta} + \Delta\alpha)$ augmentation was found to be the best longitudinal SAS tested for the variable-geometry configuration, and since the longitudinal characteristics of the fixed-geometry configuration were quite similar to those of the variable geometry, the $(\dot{\theta} + \Delta\alpha)$ was the only longitudinal SAS tested for the simulated fixed-geometry SST.

Generally, the longitudinal axis of the $(\dot{\theta} + \Delta\alpha)$ augmented configuration was said to be quite good and easy to fly, the only adverse comment being the constant attention required to control airspeed. The average Cooper pilot rating of this augmented configuration was 2.9, compared with 5.4 for the unaugmented configuration.

Static longitudinal stability: The stick-fixed and stick-free static stability were improved over the unaugmented configuration and appeared adequate. See figure 15-4 for plots of δ_c and F_c against V_e for the augmented and unaugmented configurations.

Dynamic longitudinal stability: The pitch damping was considered to be very good for the $(\dot{\theta} + \Delta\alpha)$ augmented configuration. Both small and large pitch attitude changes could be made very easily with essentially no tendency to overshoot the desired angle. The short period damping parameter $2\zeta\omega_n$ was 2.3 for this configuration compared with 1.3 for the unaugmented.

Maneuvering characteristics: The maneuvering capability was adequate and essentially unchanged from the unaugmented configuration. Plots of δ_c and F_c against load factor n are shown in figure 4-16 comparing these parameters with and without augmentation.

Control: The pitch response was considerably improved over the unaugmented configuration and with augmentation was considered to be very good. The control sensitivity was adequate for any maneuver encountered during the approach and landing.

The augmented configuration was still somewhat difficult to trim, but was said to be less difficult than the unaugmented. The speed control was not good since it was obvious to the pilot that the fixed-geometry configuration was operating on the backside of the power required curve $\left(\partial\frac{T}{W}/\partial V \approx -0.0024\right)$. The ability to hold a desired trim speed was better with the $(\dot{\theta} + \Delta\alpha)$ SAS, not because of any improvement in speed-thrust stability, but because of the ability to make small and precise pitch attitude corrections more easily.

Landing characteristics: The pitch response, damping, and attitude control during the flare were good. The augmentation eliminated the control-induced oscillations and thus improved the touchdown accuracy.

Ground effects produced no significant problems. A nose-down pitching moment was noticeable below 30 to 40 feet (9 to 12 m), but was easily controlled with the column.

Variable-Geometry Emergency Configuration ($\Lambda = 72^o$)

The variable-geometry SST concept was tested briefly in the emergency landing configuration ($\Lambda = 72^o$), the sole objective being to see whether a variable-geometry airplane could be safely flown during the landing approach should the wings become inoperative when in the swept (cruise) position. Only one pilot (pilot A) flew this particular configuration and made no attempt to complete the landing approaches to touchdown. The pilot commented that this configuration was easier to trim and had better pitch response than either the basic variable-geometry ($\Lambda = 20^{\circ}$) or the basic fixed-geometry configurations. The pitch damping was similar to the other two basic (unaugmented) configurations, however, and was poor. It should be mentioned that this variable-geometry emergency configuration ($\Lambda = 72^{\circ}$) was flown at a simulated airspeed of 182 knots, compared with 135 knots for the fixed- and variable-geometry ($\Lambda = 20^{\circ}$) configurations.

The Cooper pilot rating of the longitudinal handling qualities of this variable-geometry emergency landing configuration ($\Lambda = 72^{\circ}$) was 4.0, the major objection being the poor pitch damping characteristics. As stated previously, no landing approaches were completed to touchdown; however, the pilot stated that he believed he could have landed this configuration safely. No longitudinal stability augmentation was used on this configuration.

Longitudinal Criteria and Requirements

For many years aerodynamicists have striven to establish adequate handling qualities criteria. Although various criteria have been developed and used, it has been necessary to alter these periodically, because of the expansion of flight envelopes, the increase of airplane size, and the diversification of operational usage. An often used longitudinal handling qualities criterion is the short period damping requirement appearing in the military specification of 1959, designated MIL-F-8785. This specification requires that the short period oscillation be damped to 1/10 amplitude in no more than 1 cycle, which is a minimum damping ratio of 0.34. However, this requirement applies only to cases where the short period frequency is greater than 0.167 cps (0.167 Hz) and gives no damping requirement for the lower frequency cases. (See fig. 4-17 for longitudinal short period damping requirements of MIL-F-8785.) A plot, related to this requirement, of the short period frequency and damping ratio of the various SST configurations simulated during the present flight test program is presented as figure 4-18.

As mentioned previously, MIL-F-8785 gives no short period damping requirement for aircraft having short period frequencies as low as those for aircraft the size of an SST. To illustrate the effect of frequency on pilot opinion, a plot of pilot rating against short period undamped natural frequency is presented in figure 4-19, with the various configurations simulated for the variable-geometry concept indicated. The figure indicates that, as the short period frequency varied from 0.10 to 0.30 cps (0.10 to 0.30 Hz), the ratings of the longitudinal characteristics varied from approximately 5 to 2. In the past, various longitudinal stability and control requirement criteria have been suggested that involve the frequency and damping ratio of the longitudinal short period. Several of these are briefly discussed in the following paragraphs.

Reference 1 used a short period requirement criterion which involved the damping parameter $2\zeta\omega_n$ and the short period natural frequency squared ω_n^2. This criterion was developed for aircraft much smaller than the SST, however, and therefore was much too restrictive and is not presented in this report.

Reference 2, which presents the results of an extensive flight test program that was conducted to obtain data on the optimum and minimum acceptable longitudinal stability and control characteristics for fighter and bomber airplanes during cruise flight, also developed a criterion for the longitudinal response and damping. Figure 4-20 shows this criterion as a plot of short period frequency f_n against damping ratio ζ. Ratings for the SST configurations simulated during the present study, as well as those for some present-day subsonic jet transports, are located in this figure. Although the pilot ratings for some of these configurations were satisfactory or acceptable, all of the configurations would be interpreted as being unacceptable on the basis of the criterion of reference 2, which, as mentioned previously, was developed for cruise flight conditions.

It has been proposed that the plot of f_n against ζ, as shown in figure 4-21, be used as a longitudinal requirement criterion. (Note that these boundaries are similar to those of ref. 2, presented in fig. 4-20.) Some subsonic transports and the simulated SST configurations are also located on this chart. In regard to this longitudinal requirements criterion, reference 3 stated the need to modify the boundaries for better agreement with flight test results. Figure 4-22 presents an estimate of the type of boundaries that might be drawn to indicate an area of acceptable longitudinal short period dynamics for low-speed operation of large aircraft similar to an SST. (The scales have been omitted from this graph since the knowledge required to establish definite boundaries does not exist at the present time.) This estimated boundary was presented and discussed in reference 3 and agrees with the results of the present SST simulation program in that it proceeds in the proper direction.

Reference 4 stated that factors other than ω_n and ζ should be considered when attempting to establish longitudinal handling qualities criteria and pointed out one that is very significant, that is, the ability to change flight path with normal acceleration, which is related to L_α. By using this parameter and by recognizing that the pilot's mode of control is not constant for all flight regimes, two criteria for satisfactory short period characteristics were developed that correlate well with current airplane experience, as well as with various simulation experiments. All of the configurations studied in this program fall in the class for which the criterion recommended in reference 4 was developed and is expressed as a plot of L_α/ω_n against ζ. (It should be noted that the definition of L_α, as used in this case, is $L_\alpha = \frac{qSC_{L_\alpha}}{mV}$, where C_{L_α} is measured per radian and V is in ft/sec (m/sec).) This criterion is presented in figure 4-23, and several of the configurations studied during the present in-flight SST simulation program and some subsonic jet transports are located. Upon comparing the location of these SST configurations with the Cooper pilot ratings of the longitudinal handling qualities, presented in table 4-2, it can be seen that this short period requirements criterion agrees with the results of the present SST simulation study. It should be noted, however, that because of the limited number of configurations flown during the present study, much more work is needed before it can be said that this criterion, or any other discussed in this report, can be said to be an adequate longitudinal stability and control requirement criterion.

CONCLUDING REMARKS

Based on the results obtained during the in-flight simulation program the following remarks are made summarizing the longitudinal characteristics of the various configurations tested.

Variable Geometry

The dynamic stability of the variable-geometry configuration was considered to be poor because of the low frequency of the longitudinal short period, which made the pitch damping appear low to the pilots. Although the damping ratio was quite good, the long period of the oscillation made the damping parameter $2\zeta\omega_n$ too low. This low frequency oscillation made precise pitch control difficult during instrument approaches and also resulted in poor flare characteristics in that it caused the pilots to induce pitch oscillations when trying to position the airplane for landing. The initial pitch response was sluggish which made it difficult to make quick and precise glide path corrections. The sluggish response also contributed to the previously mentioned poor flare characteristics. Because of the apparent low damping and the sluggish initial pitch response, the longitudinal handling qualities of this variable-geometry configuration were considered unsatisfactory (average Cooper pilot rating of 4.1).

The use of stability augmentation, and an increase in control gearing made the longitudinal characteristics of this variable-geometry configuration quite satisfactory (Cooper pilot rating of 2.5). The augmentation used was a combination of pitch rate and angle of attack which increased the frequency of the longitudinal short period and appeared to the pilot as improved pitch damping. The increased control gearing increased the initial pitch response and as the pitch rate and angle of attack built up, the augmentation system washed out the effects of increased elevator gearing. The use of stability augmentation also eliminated the tendency toward control-induced oscillations during the landing flare.

In tests where the static margin was changed from 9.75 percent $\bar{c}$ to 3 percent $\bar{c}$, the flight characteristics became worse and the pilot ratings changed from 4.1 to 5.1 for the unaugmented condition and from 2.5 to 3.0 for the augmented condition.

Fixed Geometry

The basic fixed-geometry configuration generally had the same low frequency of the longitudinal short period and sluggish initial pitch response problems as that discussed for the unaugmented variable-geometry configuration. The longitudinal flight characteristics of this configuration were also considered to be unsatisfactory (average Cooper pilot rating of 5.4). During instrument approaches with this fixed-geometry configuration, speed thrust instability resulted in an excessive number of throttle adjustments to maintain airspeed. In the flare, the incremental nose-down pitching moments caused by ground effects were somewhat bothersome to the pilot.

The same augmentation system that was used on the variable-geometry configuration also made the longitudinal flight characteristics of the fixed-geometry configuration satisfactory (average Cooper pilot rating of 2.9).

Handling Qualities Criteria

Several longitudinal handling qualities criteria, which have been used in the past and involve only short period frequency and damping ratio, were found inadequate to predict the pilot ratings obtained in this program. One previously published criterion which involves short period frequency, damping ratio, and an effective flight path response parameter agreed well with the results of the present investigation.

REFERENCES

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4. Shomber, H. A.; and Gertsen, W. M.: Longitudinal Handling Qualities Criteria: An Evaluation. AIAA Paper No. 65-780, Nov. 1965.

TABLE 4-1.- PILOT OPINION OF THE LONGITUDINAL HANDLING QUALITIES

OF THE VARIOUS SST CONFIGURATIONS SIMULATED

Configuration	Control parameters	Pilot	Pilot rating of longitudinal handling qualities	Pilot comments
Basic variable geometry (Static margin = 9.75 percent $\bar{c}$)	$\delta_e/\delta_c = -1.3$ $\delta_e/\dot{\theta} = 0$ $\delta_e/\Delta\alpha = 0$	A	4.50	1. Pitch response is sluggish; there is a 1 to $1\frac{1}{2}$ second lag in α response once the column is moved. 2. Pitch control sensitivity is adequate. 3. A long time is required to trim for hands-off condition. 4. Trim speed band of 2 to 3 knots. Speed control in descent is very good. 5. Thrust control response is very good. Trim changes with power are very light. 6. Phugoid oscillation was apparent with some small variations in approach speed. Had to hunt glide path. 7. Maneuverability is adequate for any normal situation encountered during normal approaches. 8. Glide path control: When glide path control is thrown in on top of the rate of descent and airspeed control the precise θ, α, and V must be sought to give the right glide path. Seemed to be hunting all the way down. 9. Attitude control on touchdown leaves a little bit to be desired. 10. Work level in the approach is very high on glide path. 11. The major reasons for downgrading this configuration are the sluggish pitch response, low damping, and the workload required on the glide path.
Basic variable geometry (Static margin = 9.75 percent $\bar{c}$)	$\delta_e/\delta_c = -1.3$ $\delta_e/\dot{\theta} = 0$ $\delta_e/\Delta\alpha = 0$	B	3.50 - 3.75	1. The pitch response could be better but as long as the pilot doesn't mind moving the column large amounts it is adequate. 2. The airplane is relatively hard to trim, but once trim is acquired it stays for a long period of time. It will fly 2 to 3 knots above or below trim speed. The airplane definitely has speed stability. It is not difficult to hold trim speed as long as θ is kept constant. 3. The phugoid oscillation is apparent in trying to find the glide slope. There are many oscillations on the glide slope. 4. On small θ changes, there is a tendency to overshoot, and damping must be provided by the pilot. The pitch damping is low. 5. The maneuverability seemed to be fine. 6. The ability to establish a desired rate of descent at altitude was amazingly easy; but more difficult when flying the glide path. 7. The major reasons for not giving this configuration a better rating were the pitch response characteristics and the lack of pitch damping.
Basic variable geometry (Static margin = 9.75 percent $\bar{c}$)	$\delta_e/\delta_c = -1.3$ $\delta_e/\dot{\theta} = 0$ $\delta_e/\Delta\alpha = 0$	C	4.0	1. The aircraft is difficult to trim possibly because of the low control power and sensitivity, low angular velocity damping, and high rate of trim actuator. 2. The pitch response to large control inputs and pitch control sensitivity are adequate, but more control sensitivity is preferred. 3. The ability to hold trim speed is acceptable but not good. 4. The short period damping is acceptable but not good; there is a tendency to overshoot when making small attitude changes which requires the pilot to reverse the control input in or to damp the pitch motion. 5. The longitudinal maneuverability seems adequate. The longitudinal forces are satisfactory but lower values of F_c/δ_c and F_c/g might be preferable. The breakout forces are a little high but satisfactory. 6. Glide path control is satisfactory and the ability to establish a desired rate of descent is good. 7. Thrust control response is good for a jet engine; it is not as good as thrust reverser modulation. Trim change with thrust is in the normal direction but a little high. 8. Pitch response and pitch damping during the flare are poor. 9. The touchdown accuracy is poor because of too much float. 10. The ground effects produced a moderate nose-down pitch but was readily handled if the correction was started soon enough. The floating seems unrealistically prevalent.

TABLE 4-1.- PILOT OPINION OF THE LONGITUDINAL HANDLING QUALITIES OF THE VARIOUS SST CONFIGURATIONS SIMULATED – Continued

Configuration	Control parameters	Pilot	Pilot rating of longitudinal handling qualities	Pilot comments
Basic variable geometry (Static margin = 9.75 percent $\bar{c}$)	$\delta_e/\delta_c = -1.3$ $\delta_e/\dot{\theta} = 0$ $\delta_e/\Delta\alpha = 0$	D	3.5 - 4.0	1. It is not particularly difficult to trim at the desired speed. 2. Pitch response to large control inputs is satisfactory. Pitch response to small control inputs is adequate for airwork, but marginal when close to the ground. 3. The damping in pitch was inadequately evaluated, but appeared to be too low. There was a tendency to overshoot when attempting to stop a pitch motion. 4. The ability to hold desired airspeed was satisfactory. There was only a 2 to 3 knot variation in speed except when larger errors were purposely introduced. 5. Some long period oscillation of airspeed was apparent but was felt to be largely due to high throttle gearing which caused some overcontrolling with thrust initially. The trim change with thrust was satisfactory, but probably somewhat larger than desirable. The speed change with thrust lags the attitude change by several seconds. 6. The longitudinal maneuverability was quite adequate. 7. Glide path control was satisfactory. Glide path was controlled primarily with elevator. Throttle was used only when glide path was definitely high and fast or low and slow. 8. It was not particularly difficult to maintain desired approach speed – only occasional thrust changes were required. The reasons for good speed control were good thrust response, small effect of maneuvering on speed, and relatively small attitude changes required with flight director. 9. The ability to control attitude during the flare is marginal. There are definite overcontrolling tendencies. 10. No pitching tendencies due to ground effects were noticed, but there were very strong floating tendencies. 11. The touchdown accuracy is satisfactory if initial flared attitude is correct. An overflare results in some extension of touchdown point. 12. The longitudinal characteristics of this configuration were rated 3.5 to 4.0, but this rating would be 3.0 except for the flare problem.
Basic variable geometry (Static margin = 9.75 percent $\bar{c}$)	$\delta_e/\delta_c = -1.3$ $\delta_e/\dot{\theta} = 0$ $\delta_e/\Delta\alpha = 0$	E	4.25	1. It is not unduly difficult to establish the desired speed within $1\frac{1}{2}$ to 2 knots, but is a bit hard to hold in trim. 2. Pitch response to large control inputs is satisfactory but there is some lag and a slight tendency to overshoot in θ. Pitch response to small control inputs is too slow. 3. The pitch damping is fair. There is no excessive tendency to overshoot during attitude changes. 4. Trim change with thrust is excessive, but is in the proper direction (increased thrust results in nose-up). The speed change with thrust is obscured by attitude change – the speed change does have normal response if the attitude is held constant. 5. The longitudinal maneuverability characteristics are normal. 6. The glide path control is satisfactory. The glide path was controlled with elevator and the airspeed with throttle. There was no problem in maintaining the desired approach speed within +4 to -3 knots. 7. The flare and landing portion of the evaluation clearly shows lag in control of attitude when close to the ground. This lag in pitch response near the ground forces the pilot to perform a mild push-pull in the flare. The attitude control during the flare and the touchdown accuracy is not good because of this pitch response delay. 8. There was no apparent pitching or floating tendency due to ground effects.

TABLE 4-1.- PILOT OPINION OF THE LONGITUDINAL HANDLING QUALITIES OF THE VARIOUS SST CONFIGURATIONS SIMULATED – Continued

Configuration	Control parameters	Pilot	Pilot rating of longitudinal handling qualities	Pilot comments
Basic variable geometry (Static margin = 9.75 percent $\bar{c}$)	$\delta_e/\delta_c = -1.3$ $\delta_e/\dot{\theta} = 0$ $\delta_e/\Delta\alpha = 0$	F	3 plus	1. It was very easy to trim at the desired airspeed; there were some short period oscillations however. 2. Pitch response to large control inputs is satisfactory; there is some tendency to overshoot pitch attitude and to PIO, but only on IFR. No problem on VFR. Pitch response to small control inputs was satisfactory on VFR (pitch time constant not annoying). It was hard not to PIO small amplitudes when on IFR. 3. The phugoid damping seemed about neutral. The short period damped but caused some PIO when IFR. 4. It was very easy to hold desired speed and the change in speed with thrust was very fast; in fact, the engine thrust response seems optimistic for an SST. 5. Glide path control was satisfactory. The airspeed was controlled with throttle and glide path with elevator except when it seemed appropriate to use throttle for glide path. Both techniques are easily applicable. 6. The desired approach speed can be maintained within ±3 knots with normal attention because of the excellent thrust response. 7. During the flare, the pitch response, pitch damping, and attitude control were satisfactory – but there was a slight tendency to set up PIO. 8. Ground effects: There was a slight nose-down pitch, but this may be due to thrust and speed decrease. There was a noticeable tendency to float and this floating tendency at idle power and constant pitch attitude is detrimental to the touchdown accuracy. This floating tendency seems unrealistic compared with present-day subsonic jet transports.
Basic variable geometry (Static margin = 9.75 percent $\bar{c}$)	$\delta_e/\delta_c = -1.3$ $\delta_e/\dot{\theta} = 0$ $\delta_e/\Delta\alpha = 0$	G	4.5	1. The aircraft was fairly difficult to trim. 2. Pitch response to either large or small control inputs is not satisfactory. The airplane responds sluggishly. 3. The pitch damping appeared to be satisfactory. No tendency to overshoot was noted during attitude changes. 4. The ability to maintain desired speed is poor. It requires careful monitoring of rate of climb and pitch attitude. The attention required to control speed is high because there seems to be no apparent help from natural stability of aircraft. 5. The maneuvering forces are much too light, should be about twice as heavy per unit $\dot{\theta}$ or per g. 6. Glide path control is fair. The flight director and the good sensitivity of the airspeed indicator help considerably. The low static stick-free stability detracts from what could be called good speed control. 7. Flare: There was a tendency to pump the control which is a symptom of a too sluggish response in pitch. The pitch damping seemed adequate. Attitude control is poor, relative to making changes, but once a change is made it does hold attitude fairly well. 8. Some floating tendency was noticed near the ground. 9. The approach is 100 percent work level.
Variable geometry with pitch rate $\dot{\theta}$ augmentation (Static margin = 9.75 percent $\bar{c}$)	$\delta_e/\delta_c = -2.6$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 0$	A	3.5	1. Pitch response is quicker than that for the unaugmented configuration. The pitch damping is also better and has eliminated any tendency to overshoot small attitude changes and has also eliminated any tendency of low frequency pumping of the controls during flare and landing. 2. The apparent static stability, as speed is displaced from trim condition, seems lower than that for the unaugmented variable sweep configuration. 3. The $\dot{\theta}$ SAS reduces the longitudinal workload from 80 percent to about 60 percent. If an autospeed control were added to the system, it would reduce the workload of the pilot, on this axis, to probably 30 percent. 4. There was little difference between approaches with and without simulated ground effects. The $\dot{\theta}$ SAS has completely eliminated the pitch-down that was noticed for the unaugmented configuration.

TABLE 4-1.- PILOT OPINION OF THE LONGITUDINAL HANDLING QUALITIES OF THE VARIOUS SST CONFIGURATIONS SIMULATED – Continued

Configuration	Control parameters	Pilot	Pilot rating of longitudinal handling qualities	Pilot comments
Variable geometry with pitch rate $\dot{\theta}$ augmentation (Static margin = 9.75 percent $\bar{c}$)	$\delta_e/\delta_c = -2.6$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 0$	B	3.25	1. The $\dot{\theta}$ SAS has definitely increased the pitch damping and has slightly increased the pitch response. The major benefit is the increased damping which allows better attitude hold. (If the airplane has poor pitch response the pilot can learn to live with it, it is just a matter of pilot anticipation and pilot lead time; whereas, poor damping makes the workload much higher all the time.) 2. With the $\dot{\theta}$ SAS giving a good approach attitude hold, some static or speed stability is lost; thus, the speed control is noticeably more difficult. The total task is still far easier. 3. No ground effect on C_m or C_D was noticed; however there was quite a bit of additional C_L. On a couple of approaches the aircraft descended to within 4 to 5 feet (1.2 to 1.5 m) of the runway and just sort of floated along.
Variable geometry with pitch rate plus angle of attack feedback ($\dot{\theta}$ + $\Delta\alpha$) augmentation (Static margin = 9.75 percent $\bar{c}$)	$\delta_e/\delta_c = -5.2$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 1.5$	A	3.0	1. The aircraft is not difficult to trim. It takes from 45 to 60 seconds to trim it but it can be trimmed and then it will stay essentially there at about ±2 knots. The aircraft has positive static stability. It feels nice through the trim position – it is fairly linear in the pull and push forces to slow and speed up the aircraft at about one pound per knot (4.4 N/knot) within 10 knots on either side of trim speed. 2. Pitch control sensitivity is very high. The pitch rate per degree of column is higher than desirable for landings, although it feels good in the air. 3. The response to control input is satisfactory. Pitch rate and angle of attack response is very very rapid, occurring probably within a half second after the column input. 4. The pitch damping is very good. Small attitude changes are quite easy to make, with no tendency to overshoot and no tendency toward PIO. 5. The maneuverability is very good. 6. The glide path control is satisfactory. About 30 percent of the time was spent on the longitudinal axis (20 percent on speed and 10 percent on attitude to follow the flight director). The ability to establish a desired rate of descent is fairly easy. 7. Thrust response is good. There is a light, but noticeable, trim change with thrust. 8. Flare control: The pitch response is snappy, almost too snappy for good landings. The pitch damping is excellent. Attitude control is very precise, but a very light touch is required on the column to prevent overcontrolling. 9. Touchdown accuracy seems very good – much better than the two previous variable-geometry configurations. 10. Generally, the longitudinal control is the best in the program to this point. The response is good, no apparent lag in the pitch rate. The stick gearing and the gains on $\dot{\theta}$ and α are a little high. The longitudinal characteristics of this configuration are rated 3.0, but the system could be optimized to a rating of 2 to 2.5.
Variable geometry with pitch rate plus angle of attack feedback ($\dot{\theta}$ + $\Delta\alpha$) augmentation (Static margin = 9.75 percent $\bar{c}$)	$\delta_e/\delta_c = -5.2$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 1.5$	B	2.0	1. The aircraft is not difficult to trim. It is probably the easiest trimmable configuration flown thus far in the program and the aircraft stays within 2 to 3 knots of trim which is about all that could be expected of an airplane with such large inertia. 2. Pitch response to large or small control inputs is quite satisfactory. The control sensitivity is good. 3. Pitch damping is at a good level. Small and large attitude changes are easy to make without overshooting. There is no tendency toward PIO. 4. In the approach, glide path control is easy. It is easy to establish a desired rate of descent, but more important, it is easy to change it slightly – to take off a 100 ft/min (0.5 m/sec) or to add a hundred ft/min, briefly and then stabilize at the original rate of descent. The thrust control response is good. 5. The pitch response, pitch damping, and attitude control were good in the flare. 6. The δ_e/δ_c gearing is at a very good level, but if the same gearing had to be used at high speeds, without a mechanical advantage change, a lower gearing might be desirable. 7. No ground effects whatsoever were noticed.

TABLE 4-1.- PILOT OPINION OF THE LONGITUDINAL HANDLING QUALITIES

OF THE VARIOUS SST CONFIGURATIONS SIMULATED – Continued

Configuration	Control parameters	Pilot	Pilot rating of longitudinal handling qualities	Pilot comments
Variable geometry with pitch rate plus angle of attack feedback ($\dot{\theta} + \Delta\alpha$) augmentation (Static margin = 9.75 percent $\bar{c}$)	$\delta_e/\delta_c = -5.2$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 1.5$	C	4.0	1. The aircraft can be trimmed satisfactorily. The chief problem seems to be the high rate of the trim actuator. 2. The pitch response to large control inputs is satisfactory and the pitch control sensitivity is very good. 3. The pitch damping is good. When making small attitude changes, there is no tendency to overshoot; however, there is a strong tendency to "spring back" after the control input is relaxed. This is mildly undesirable. 4. The maneuverability is good. 5. On the approach, the glide path control is satisfactory and the ability to establish a desired rate of descent is good. The speed control is good if throttle is fixed. The thrust control response is good and the trim change with thrust is satisfactory but a little high. 6. In the flare, the pitch response, the pitch damping, and the ability to control attitude are good. 7. The touchdown accuracy is poor because of excessive floating. 8. The nose-down trim change due to ground effects is noticed below 50 feet (15 m) but is of no consequence to the final landing – provided correction for it is started promptly. 9. The strong tendency for speed to decrease with normal use of controls following retardation of throttle for glide path correction is bothersome. It seems strange that this happens considering the prevailing nose-down trim change with thrust reduction and the fact that the $\Delta\alpha$ term is in the augmentation. 10. The rating of the longitudinal characteristics of this configuration is 4.0 because of the excessive floating tendency near the ground; this rating would be 2.5 if not for the floating.
Variable geometry with pitch rate plus angle of attack feedback ($\dot{\theta} + \Delta\alpha$) augmentation (Static margin = 9.75 percent $\bar{c}$)	$\delta_e/\delta_c = -5.2$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 1.5$	D	3.0	1. It is not difficult to trim at the desired speed. 2. Pitch response is definitely improved over the unaugmented variable sweep configuration, but it is not too sensitive for small corrections – and a control gearing δ_e/δ_c change would be required for pitch control. There is a tendency to overshoot during attitude changes because of this high control sensitivity. 3. It is relatively easy to hold desired speed within ±3 knots. This augmented configuration is harder to control than the unaugmented configuration, however, because of the increased sensitivity in pitch control. 4. The trim change and speed change with thrust are the same as that for the unaugmented configuration. 5. The longitudinal maneuverability is quite adequate. 6. The glide path control was satisfactory and there was no problem in maintaining the desired approach speed. The increased pitch sensitivity was bothersome, however. 7. The attitude control during the landing flare is unsatisfactory but acceptable; the response is very good but there is a tendency toward overcontrolling. 8. There was a severe floating tendency due to ground effects if the aircraft was over-rotated during the flare, but it was satisfactory if proper flare is executed and attitude is held for slight sink rate. 9. The touchdown accuracy was satisfactory except for the floating tendency. This is a technique problem rather than a control problem, however. 10. The longitudinal characteristics of this augmented configuration were rated 3.0 in spite of too high column sensitivity – as this would appear to be easily optimized.
Variable geometry with pitch rate plus angle of attack feedback ($\dot{\theta} + \Delta\alpha$) augmentation (Static margin = 9.75 percent $\bar{c}$)	$\delta_e/\delta_c = -5.2$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 1.5$	E	3.25	1. It is easy to trim at the desired speed in smooth air. 2. Pitch response to either large or small control inputs is satisfactory. 3. Pitch damping is adequate, there is no tendency to overshoot during attitude changes. 4. The trim change with thrust is almost discernible and the speed change with thrust is normal. 5. Glide path control is satisfactory. It is quite easy to maintain the desired approach speed within ±2.5 knots, and the major reason for good speed control is the good response to pitch attitude commands (control is predictable and repeatable). 6. The pitch response and ability to control attitude during the flare are good. The pitch damping during the flare is adequate. 7. Very little pitching due to ground effects was noticed, but there definitely was a tendency to float. 8. The touchdown accuracy for this augmented configuration is more consistent than it was for the unaugmented.

TABLE 4-1.- PILOT OPINION OF THE LONGITUDINAL HANDLING QUALITIES

OF THE VARIOUS SST CONFIGURATIONS SIMULATED – Continued

Configuration	Control parameters	Pilot	Pilot rating of longitudinal handling qualities	Pilot comments
Variable geometry with pitch rate plus angle of attack feedback ($\dot{\theta} + \Delta\alpha$) augmentation (Static margin = 9.75 percent $\bar{c}$)	$\delta_e/\delta_c = -5.2$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 1.5$	F	2.5	1. The aircraft is not difficult to trim but the phugoid oscillation is noticeable. 2. The pitch response to either large or small control inputs is satisfactory and is noticeably better than the unaugmented variable sweep configuration. 3. It is very easy to hold the desired airspeed and there is no noticeable oscillation in speed. 4. The speed change with thrust seems to be quite fast. The trim change with thrust is in normal direction. 5. Glide path control is satisfactory. Glide path was controlled with the elevator and the airspeed with throttle – however, this technique could easily be reversed. 6. The desired speed can be maintained within ±3 knots with normal attention. The reasons for good speed control are excellent thrust response, smooth air, and having a precise airspeed indicator. 7. The pitch response and pitch damping in the flare were very good. The phugoid oscillation was noticeable when trying to control the attitude, but this was no problem in smooth air. 8. Ground effects: There was a noticeable tendency to float, but no serious nose-down pitch. This floating tendency is detrimental to the touchdown accuracy. This floating tendency occurring even at idle thrust is hard to believe.
Variable geometry with pitch rate plus angle of attack feedback ($\dot{\theta} + \Delta\alpha$) augmentation (Static margin = 9.75 percent $\bar{c}$)	$\delta_e/\delta_c = -5.2$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 1.5$	G	4.0	1. The ability to trim this configuration was the same as that for the unaugmented variable sweep – fairly difficult. 2. The pitch response is still sluggish but not as sluggish as the unaugmented configuration. 3. There was no tendency to overshoot during attitude changes and no tendency toward PIO's. 4. Longitudinal maneuverability was the same as that for the unaugmented configuration, but the glide path control was a little bit easier. 5. In the flare, the pitch damping appeared to be good but the pitch response was sluggish which made it hard to change attitude precisely. 6. The floating tendency near the ground was noticeable and the touchdown accuracy was poor. 7. The ease with which the airplane can be controlled on approach and during the flare was similar in both augmented and unaugmented and it is questionable whether the differences could be determined in anything but extremely smooth air. The longitudinal augmentation is far from optimum.
Basic variable geometry (Static margin = 3 percent $\bar{c}$)	$\delta_e/\delta_c = -1.3$ $\delta_e/\dot{\theta} = 0$ $\delta_e/\Delta\alpha = 0$	A	5.5	1. The aircraft is very difficult to trim longitudinally – it is easily excited in pitch and has a very slow or almost nonexisting tendency to return to the trimmed condition. 2. Pitch response to column inputs is very sluggish; however, once δ_c is in and the response takes hold, the pitch rate and pitch rate per degree of δ_c seems adequate. However, the sensitivity is really masked by the low response. 3. The phugoid is apparent and appeared to be neutrally damped. The airplane seems to oscillate in both attitude and airspeed around the desired trim point. 4. The static stability is very light and is nonlinear through the trim point. 5. Any pitch rate damping has to be supplied by the pilot to prevent overshoot of pitch attitude. 6. No tendency toward PIO was noticed. 7. Glide path control is satisfactory, but it requires about 80 percent of the pilot's attention, about 50 percent to control attitude with δ_c and 30 percent to control the airspeed, which is done primarily with throttle. 8. Thrust response is good. The trim change with thrust is noticeable. 9. The sluggish pitch response and need for pilot-supplied damping make the precise flare to proper attitude very difficult – even in calm air. 10. As a single-axis airplane this configuration is fair but if the pilot had anything to do other than control the longitudinal axis, it would be very difficult to fly and probably unsafe.

TABLE 4-1.- PILOT OPINION OF THE LONGITUDINAL HANDLING QUALITIES OF THE VARIOUS SST CONFIGURATIONS SIMULATED – Continued

Configuration	Control parameters	Pilot	Pilot rating of longitudinal handling qualities	Pilot comments
Basic variable geometry (Static margin = 3 percent $\bar{c}$)	$\delta_e/\delta_c = -1.3$ $\delta_e/\dot{\theta} = 0$ $\delta_e/\Delta\alpha = 0$	B	4.5 - 5.0	1. There is a definite lack of static stability. 2. The airplane has good pitch response, but low pitch damping. 3. The trim change with thrust seemed quite large. 4. In the approach, the workload is very high on glide path control. This is because of the very low level of static stability and no apparent pitch rate damping. Another objection is the seemingly very high pitch trim change with power. All three combined to make the airplane very difficult to trim, to hold in a stabilized rate of descent, to hold in a stabilized attitude, and to hold at a stabilized speed. So what you are doing is just pumping, pushing, and pulling – spending 70 to 80 percent of the time on longitudinal control going down the glide path. 5. The flight director on a configuration like this makes a world of difference.
Variable geometry with pitch rate plus angle of attack feedback ($\dot{\theta} + \Delta\alpha$) augmentation (Static margin = 3 percent $\bar{c}$)	$\delta_e/\delta_c = -5.2$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 1.5$	A	3.5	1. The aircraft is not difficult to trim but it requires patience to get hands-off condition (speed band of 2 to 3 knots). 2. Control power is quite adequate. 3. Response is snappy – there is almost an immediate feeling of g and buildup of $\dot{\theta}$ with control input. 4. Pitch rate and α are nicely damped – very little tendency to overshoot small or large pitch attitude changes. 5. The longitudinal maneuverability is good. 6. The glide path control is satisfactory and the ability to establish a desired rate of descent was very good. 7. Thrust response is adequate. The trim change with thrust is still noticeable, but much lighter than that for the unaugmented variable-geometry configuration with this same 3 percent static margin. 8. In the flare, the pitch response, pitch damping, and attitude control are good. 9. There is some difficulty in controlling the airspeed during the approach.
Variable geometry with pitch rate plus angle of attack feedback ($\dot{\theta} + \Delta\alpha$) augmentation (Static margin = 3 percent $\bar{c}$)	$\delta_e/\delta_c = -5.2$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 1.5$	B	2.5	1. The aircraft is not difficult to trim. The pitch response and control sensitivity are good. The pitch damping is quite good and the longitudinal maneuverability is good. Speed control is acceptable. 2. Glide path control is satisfactory. The ability to establish a desired rate of descent is good and the speed control was quite easy. Actually, speed control in itself is probably not much easier on this augmented configuration than it was for the unaugmented, it is just that about 50 percent more time is available to devote to speed control. The trim change with thrust is much less than on the unaugmented configuration which again makes attitude control much easier. 3. This configuration has very very good response, probably the best response to this point. Actually, it is preferable to give up some static stability on an airplane in order to get more response. All in all, it is a very fine configuration. 4. The touchdown accuracy is actually about as good as possible. It is just a matter of practice and education.

TABLE 4-1.- PILOT OPINION OF THE LONGITUDINAL HANDLING QUALITIES OF THE VARIOUS SST CONFIGURATIONS SIMULATED – Continued

Configuration	Control parameters	Pilot	Pilot rating of longitudinal handling qualities	Pilot comments
Basic fixed geometry (Static margin = 2.45 percent $\bar{c}$)	$\delta_e/\delta_c = -1.0$ $\delta_e/\dot{\theta} = 0$ $\delta_e/\Delta\alpha = 0$	A	6.0	1. The airplane is difficult to trim. For straight and level flight, as well as for an established rate of descent, constant attention is required to airspeed and attitude control. 2. Indicated α response is sluggish and lags column inputs by about 1 second. Discernible changes in θ appeared to lag column inputs by about $1\frac{1}{2}$ seconds. 3. Trim changes with thrust are pretty mild. 4. Although the phugoid mode is present, it is not obvious at altitude or on the glide slope and is not bothersome to the pilot. 5. A low pitch damping combined with the large inertia produces a tendency to overshoot any small θ change. 6. Glide path control is not too difficult with the flight director, but it requires constant attention to airspeed and a great deal of throttle manipulation. The response to the throttle is fairly slow if the airspeed is off more than 3 to 4 knots. 7. During the landing flare, control of attitude and sink rate are very difficult, and there is a tendency to overdrive the controls. 8. The major reasons that this configuration was downgraded are lack of static stability, lack of pitch damping, and very sluggish pitch response.
Basic fixed geometry (Static margin = 2.45 percent $\bar{c}$)	$\delta_e/\delta_c = -1.0$ $\delta_e/\dot{\theta} = 0$ $\delta_e/\Delta\alpha = 0$	B	4.5 - 5.0	1. The aircraft is difficult to trim. It can be finally trimmed, but if left alone it seems to start to diverge after just a few seconds. 2. The pitch response is slightly better than the unaugmented variable-geometry configuration – but, more is desirable. 3. Low speed stability: it is difficult to hold a desired speed and requires a large percentage of the workload. 4. On the glide slope, a 10 to 15 second period oscillation was noticed – just constant nose-up and nose-down at about that frequency. 5. The pitch damping is low. The aircraft would be hard to fly in turbulence. Small attitude changes are difficult because of this low damping. 6. No tendency toward PIO was noticed either in the flare or on the glide slope. 7. The ability to establish a desired rate of descent was fine as long as there is no concern with calibrating that rate of descent with something else – e.g., the glide slope; but, when rate of descent is changed, e.g., from 500 to 450 ft/min (2.5 to 2.3 m/sec) for a few seconds and back to 500 ft/min, to correct a glide slope error, it is pretty rough. 8. The trim change with thrust does not seem to be at quite as high a level as the unaugmented variable-sweep configuration. 9. Ground effects cause a very abrupt nose-down pitch at an attitude of about 30 feet (9m). An increase in C_D is also evidenced by the additional amount of power needed to maintain speed for stabilizing and sort of feeling around for the ground. No change was noticed in C_L, but, of course, this could be masked quite a bit by the other problems. 10. The flight director makes a great difference in flying the approaches – much more so than it did when flying the unaugmented variable geometry. 11. The major reasons for downgrading this configuration are sluggish pitch response, low pitch damping, difficult speed control, and the nose-down pitch due to ground effects.
Basic fixed geometry (Static margin = 2.45 percent $\bar{c}$)	$\delta_e/\delta_c = -1.0$ $\delta_e/\dot{\theta} = 0$ $\delta_e/\Delta\alpha = 0$	C	5.0	1. The aircraft is difficult to trim within ±3 knots of desired speed. 2. The pitch response to large control inputs is satisfactory but the pitch control sensitivity is poor (very low). 3. It is difficult to hold desired trim speed within ±3 knots and this is even worse in turns. 4. Pitch response to small or normal control inputs is poor (low), the damping is low, and there is a strong tendency to overshoot when making small attitude changes. 5. The longitudinal maneuverability is satisfactory. 6. Glide path control: there were large pitch excursions. 7. The ability to establish rate of descent seemed adequate but when changing throttle, excessive longitudinal controlling was required to maintain speed. 8. The thrust control response is good but the trim change with thrust is high. This trim change does not really help get the nose down – for instance, when you pull off power for a glide path correction, you have to force the nose down with the elevator control; and when you have established the desired speed after this maneuver, you are left holding a pull force excessive for trim. 9. For the landing flare control, the very large trim change in ground effect posed the question of whether there was enough control to complete the landing. Pitch response is low for normal displacements of the column. The pitch damping is poor, therefore, attitude control is poor and the tendency is for large overshoots. Touchdown accuracy is poor.

TABLE 4-1.- PILOT OPINION OF THE LONGITUDINAL HANDLING QUALITIES

OF THE VARIOUS SST CONFIGURATIONS SIMULATED – Continued

Configuration	Control parameters	Pilot	Pilot rating of longitudinal handling qualities	Pilot comments
Basic fixed geometry (Static margin = 2.45 percent $\bar{c}$)	$\delta_e/\delta_c = -1.0$ $\delta_e/\theta = 0$ $\delta_e/\Delta\alpha = 0$	D	3.5 - 4.0	1. It is not difficult to trim at the desired speed once the pilot becomes accustomed to the pitch and airspeed sensitivity. 2. Pitch response to either large or small control inputs is satisfactory. 3. The pitch damping appears to be adequate – there is some minor tendency to overshoot when making small attitude changes. No tendency toward PIO. 4. It is somewhat difficult to hold exact desired airspeed, but to hold within ±5 knots, no problem. The airspeed varies ±4 to 5 knots from trim. 5. The trim change and speed change with thrust are satisfactory. 6. Longitudinal maneuverability: the F_c/g during wind-up turns is satisfactory. Moderate to large thrust adjustments are required at and beyond 30° banked turns to hold level flight. Normally, however, the angle of bank would never be larger than 20° to 30°. 7. On the approach, the glide path control is satisfactory and the speed control is good although somewhat larger variations in speed occur with unstable thrust-velocity relationship. Because of this, an increased requirement is placed on proper coordination of throttle and elevator. 8. Subjectively, the pitch sensitivity and damping appeared greater on this unaugmented fixed-geometry configuration than it did on the unaugmented variable-geometry configuration, thereby making the pitch response appear better. The control of flight path and airspeed required somewhat increased pilot attention over the unaugmented variable geometry – this is particularly true in increased thrust adjustments and need for coordinating those with pitch corrections.
Basic fixed geometry (Static margin = 2.45 percent $\bar{c}$)	$\delta_e/\delta_c = -1.0$ $\delta_e/\theta = 0$ $\delta_e/\Delta\alpha = 0$	E	4.5	1. The ability to trim at the desired speed is acceptable. 2. For large control inputs, the lag in initial response is apparent but the pitch attitude overshoot appears to be too great – about 2-1/2° in roller coaster maneuver where 1° would be expected. The pitch response to small control inputs is slow but sure. 3. The pitch damping is no problem, but the tendency to overshoot during attitude changes is quite evident. There is definitely a tendency toward PIO, especially in maneuvering turns, where the long short period is apparent. 4. The ability to hold desired speed depends on the degree of concentration; seems easier under the hood. The oscillation of airspeed seems very small in static condition but is apparent in maneuvering. The trim change with thrust is apparent but not objectionable. The speed change with thrust is secondary. The primary effect seems to be on rate of climb. A direct connection between throttle and rate of climb is evident, which may be a desirable feature if properly used in IFR approaches. 5. Longitudinal maneuverability: a fair amount of concentration is required because of tendency to slow down, to pitch nose down, and to oscillate in airspeed. The F_c/g does not have a steady feel because of these tendencies. 6. When trying to control glide path one must concentrate on attitude, but not excessively. The ability to maintain the desired approach speed requires an appreciable amount of work, especially in rough air. 7. During the flare, pitch response, pitch damping, and attitude control are adequate. 8. No apparent pitching or floating tendency near the ground was noticed. The touchdown accuracy was rather consistent. However, the rather rapid airspeed decrease in ground effect is undesirable.
Basic fixed geometry (Static margin = 2.45 percent $\bar{c}$)	$\delta_e/\delta_c = -1.0$ $\delta_e/\theta = 0$ $\delta_e/\Delta\alpha = 0$	F	3.0	1. The ability to trim at the desired speed is very good. No short period oscillations were noticed. 2. Pitch response to either large or small control inputs is satisfactory. The phugoid seemed to be neutrally damped and no short period PIO tendency was noticed. 3. It is easy to hold the desired speed within ±5 knots, but the pilot has to be alert. There is no apparent oscillation of airspeed. The trim change with thrust was very mild and in the proper direction. The speed change with thrust did not seem to be as responsive as the unaugmented variable sweep configuration, but the desired speed could be held to within ±5 knots easily. 4. The longitudinal maneuverability is good. 5. Glide path control is satisfactory. A mixed technique of throttle for speed and elevator for attitude and vice versa was used. Either technique is satisfactory. 6. In the flare, the pitch response and pitch damping were very good. Only small control applications were required for which there was little lag in response. The attitude could be controlled very precisely in smooth air. 7. There were no apparent ground effects and the touchdown accuracy of this configuration is equal to current jet transports.

TABLE 4-1.- PILOT OPINION OF THE LONGITUDINAL HANDLING QUALITIES OF THE VARIOUS SST CONFIGURATIONS SIMULATED – Continued

Configuration	Control parameters	Pilot	Pilot rating of longitudinal handling qualities	Pilot comments
Basic fixed geometry (Static margin = 2.45 percent $\bar{c}$)	$\delta_e/\delta_c = -1.0$ $\delta_e/\dot{\theta} = 0$ $\delta_e/\Delta\alpha = 0$	G	4.7	1. This configuration would be somewhat difficult to trim in anything but very smooth air. 2. Pitch response was sluggish for either large or small control inputs. The pitch damping was good. There was no tendency to overshoot during attitude changes and no tendency toward PIO. 3. It was quite difficult to maintain desired speed. No trim change with thrust was detected, and speed changes with thrust were satisfactory. 4. Longitudinal maneuverability: The stick forces were too light, and the speed bleed-off due to drag, resulting from the normal acceleration, was excessive. High rates of descent occurred, as high as 1500 to 2000 ft/min (7.6 to 10.2 m/sec) in a 45° bank. 5. Glide path control was satisfactory. It required a lot of attention to control speed with throttle. The reasons are the drag variation due to the normal acceleration and also the low static longitudinal stability. The forces and the moments generated at off trim speed seemed quite low in terms of effectiveness in trying to keep it on speed. 6. Because of excessive turbulence, landing evaluations were not attempted. The longitudinal characteristics of this unaugmented fixed-geometry configuration were given a Cooper rating of 4.7, primarily because this configuration was a little bit worse than the unaugmented variable-geometry configuration.
Fixed geometry with pitch rate plus angle of attack feedback $(\dot{\theta} + \Delta\alpha)$ augmentation (Static margin = 2.45 percent $\bar{c}$)	$\delta_e/\delta_c = -4.0$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 1.0$	A	2.75	1. The aircraft was difficult to trim for hands-off flight. There appears to be a trim speed band of 3 to 4 knots on either side of the desired trim speed. Precise control of trim speed requires constant attention. 2. Very snappy pitch response. Good sensitivity rate which is adequate for any maneuvering encountered in approach or landing. Pitch damping is very good. Essentially no tendency to overshoot. 3. Longitudinal maneuverability is good. 4. Glide path control is satisfactory. Corrections can be made easily. There is no problem in establishing a desired rate of descent, thanks to good pitch control. Speed control requires much attention. Both speed and trim changes with thrust are adequate. 5. Flare control is good; there is a slight tendency to bobble but this is pilot induced and would disappear with learning. The pitch response, pitch damping, and attitude control during the flare are all good. The touchdown accuracy is improved over the unaugmented fixed-geometry configuration. 6. Generally, the longitudinal characteristics are very good. The snappy response and excellent damping allow precision control of pitch at a greatly reduced work level. There are no real adverse characteristics on this axis, other than the bothersome effect of flying on the backside of the thrust-required curve and having a very light gradient with speed.
Fixed geometry with pitch rate plus angle of attack feedback $(\dot{\theta} + \Delta\alpha)$ augmentation (Static margin = 2.45 percent $\bar{c}$)	$\delta_e/\delta_c = -4.0$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 1.0$	B	3.0	1. The aircraft is difficult to trim. 2. Pitch response is quite adequate. There is more response than would ever be needed. Pitch control sensitivity was very good. 3. The difficulty of holding trim speed may possibly be improved somewhat over the unaugmented fixed-geometry configuration – but not because of the speed stability – it would be because of being able to make small attitude corrections. 4. Response to control inputs is quite satisfactory. The pitch damping was very good – there was no tendency to overshoot and no tendency toward PIO. 5. The longitudinal maneuverability is good. The ability to establish desired rate of sink was fine. 6. The trim change with power is at a very low level – very acceptable. 7. A slight nose-down pitching moment due to ground effects was noticed around 30 to 40 feet (9 to 12 m), which was easily controlled with the column. 8. The longitudinal characteristics of this configuration were given a pilot rating of 3.0, and the reason it is not even better is the mildly unpleasant characteristics of speed control – but it flys so well in other respects that the time is available to devote to speed control.

TABLE 4-1.- PILOT OPINION OF THE LONGITUDINAL HANDLING QUALITIES

OF THE VARIOUS SST CONFIGURATIONS SIMULATED – Continued

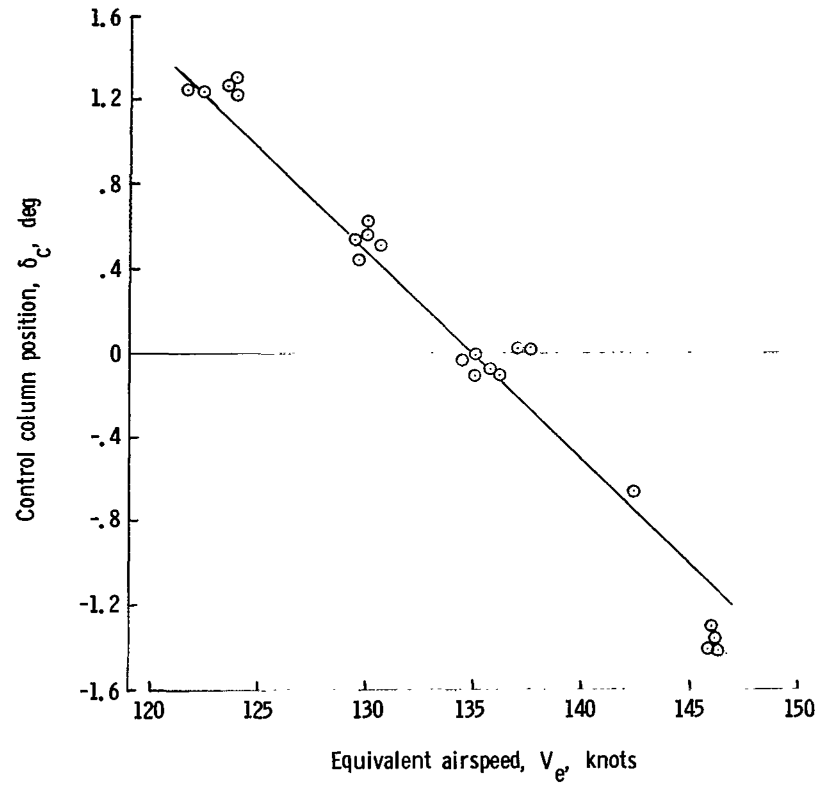
Configuration	Control parameters	Pilot	Pilot rating of longitudinal handling qualities	Pilot comments
Fixed geometry with pitch rate plus angle of attack feedback ($\dot{\theta} + \Delta\alpha$) augmentation (Static margin = 2.45 percent $\bar{c}$)	$\delta_e/\delta_c = -4.0$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 1.0$	C	4.0	1. The aircraft is not difficult to trim. 2. Pitch response to large control inputs is satisfactory and pitch control sensitivity is good. 3. The pitch damping is good; small attitude changes can be made with precision – no overshoot. 4. Longitudinal maneuverability is good. 5. Glide path control was not easy because of the problem of controlling the speed. When thrust is reduced for glide path correction, speed immediately falls. The attitude must be forced nose down with the elevator to regain speed. As speed is regained, a pull force is now required at the original speed – the nose is down and more altitude than desired is lost, and the speed continues to go up. As a pull-up is made to correct back to glide path, some thrust is added to stabilize on the desired path, but the speed stays up, thus requiring another thrust reduction, and probably initiating a similar chain of events again. Characteristics of the "backside" of the thrust-required curve probably play a part in the sequence, but the initiating factor seems to be the large inertia which prevents the airplane from responding to a change in pitching moments quickly enough. 6. The flare control pitch response was good, pitch damping was good, and attitude control was good. 7. The touchdown accuracy is poor because of excessive floating tendency caused by ground effects. It is possible that in the actual case the nose-down trim change will tend to offset the floating tendencies, depending on pilot techniques. The major reason the longitudinal characteristics of this configuration were not given a better rating is because of this excessive floating tendency near the ground; the Cooper rating would be 2.0 otherwise.
Fixed geometry with pitch rate plus angle of attack feedback ($\dot{\theta} + \Delta\alpha$) augmentation (Static margin = 2.45 percent $\bar{c}$)	$\delta_e/\delta_c = -4.0$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 1.0$	D	3.5	1. It is not seriously difficult to trim at the desired speed once the pilot becomes accustomed to the pitch and airspeed sensitivities. 2. Pitch response to large control inputs is satisfactory. Response to small control inputs is good. 3. Pitch damping is good – there is little or no tendency to overshoot during attitude changes. 4. The ability to hold desired speed is about the same as that for the unaugmented fixed-geometry configuration – relatively easy to hold within ±5 knots. 5. Trim change with thrust is small. Speed sensitivity to pitch attitude is high. 6. The longitudinal maneuverability is the same as that for the unaugmented fixed-geometry configuration – satisfactory. 7. Glide path control is satisfactory and is controlled by coordinated use of throttle and elevator. 8. In the flare, pitch damping and attitude control are good. Pitch response is improved over the unaugmented fixed-geometry configuration. 9. The pitching and floating tendencies due to ground effects are minor, and the touchdown accuracy is satisfactory. 10. The increased pitch response and even better damping helps the control during the flare.
Fixed geometry with pitch rate plus angle of attack feedback ($\dot{\theta} + \Delta\alpha$) augmentation (Static margin = 2.45 percent $\bar{c}$)	$\delta_e/\delta_c = -4.0$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 1.0$	E	3.5	1. It is relatively easy to trim at the desired speed. 2. Pitch response to either large or small control inputs is satisfactory. 3. The pitch damping is good. There is no tendency to overshoot during attitude changes and no tendency toward PIO. 4. Definite concentration is required to hold desired speed. 5. Trim change with thrust is not too apparent. Speed change with thrust is more apparent and seems normal. 6. The longitudinal maneuverability is greatly improved over the unaugmented fixed-geometry configuration. The augmented configuration seems stiffer and appears to have a slightly higher F_c/g. 7. Glide path control is satisfactory. The glide path was controlled with elevator and airspeed with throttle. It was not difficult to maintain desired approach speed, but required concentrated effort. The better pitch response and better damping helped speed control. 8. In the flare, the pitch response, pitch damping, and attitude control are good. No pitching or floating tendency due to ground effects was noticed, but airspeed does decrease rather rapidly in the flare. The touchdown accuracy was rather consistent.

TABLE 4-1.- PILOT OPINION OF THE LONGITUDINAL HANDLING QUALITIES OF THE VARIOUS SST CONFIGURATIONS SIMULATED – Concluded

Configuration	Control parameters	Pilot	Pilot rating of longitudinal handling qualities	Pilot comments
Fixed geometry with pitch rate plus angle of attack feedback ($\dot{\theta} + \Delta\alpha$) augmentation (Static margin = 2.45 percent $\bar{c}$)	$\delta_e/\delta_c = -4.0$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 1.0$	F	3.0	1. No essential change in the longitudinal characteristics was noticed between the unaugmented and augmented fixed-geometry configurations. 2. The longitudinal characteristics were rated the same for augmentation on and off.
Fixed geometry with pitch rate plus angle of attack feedback ($\dot{\theta} + \Delta\alpha$) augmentation (Static margin = 2.45 percent $\bar{c}$)	$\delta_e/\delta_c = -4.0$ $\delta_e/\dot{\theta} = 1.46$ $\delta_e/\Delta\alpha = 1.0$	G	3.0	1. The aircraft is still fairly difficult to trim. 2. The pitch response was considerably improved over the unaugmented fixed-geometry configuration. There is still a little bit of lag, but it looked like more elevator power, shorter time constant, and in general would be a more controllable configuration. 3. Pitch damping appeared lower than the unaugmented because the response was faster; however, for step inputs the amount of pitch attitude springback was actually about like we see in large present day airplanes. There was some small tendency to overshoot or undershoot when making small attitude changes. 4. The speed change with thrust was satisfactory. There was no trim change with thrust.

TABLE 4-2.- LONGITUDINAL SHORT PERIOD CHARACTERISTICS OF THE VARIOUS SST CONFIGURATIONS TESTED

Configuration	Damped period, sec	Undamped f_n, cps	ζ	$2\zeta\omega_n$, per sec	Average rating by pilots A & B
Variable geometry, basic	9.6	0.141	0.672	1.190	4.1
Variable geometry, $\dot{\theta}$ augmentation	14.1	0.208	0.940	2.456	3.4
Variable geometry, $(\dot{\theta} + \Delta\alpha)$ augmentation	5.1	0.278	0.705	2.462	2.5
Variable geometry, aft c.g. unaugmented	30.0	0.102	0.945	1.211	5.1
Variable geometry, aft c.g. $(\dot{\theta} + \Delta\alpha)$ augmentation	5.9	0.206	0.755	1.953	3.0
Fixed geometry, basic	16.8	0.120	0.869	1.310	5.4
Fixed geometry, $(\dot{\theta} + \Delta\alpha)$ augmentation	7.1	0.231	0.793	2.301	2.9



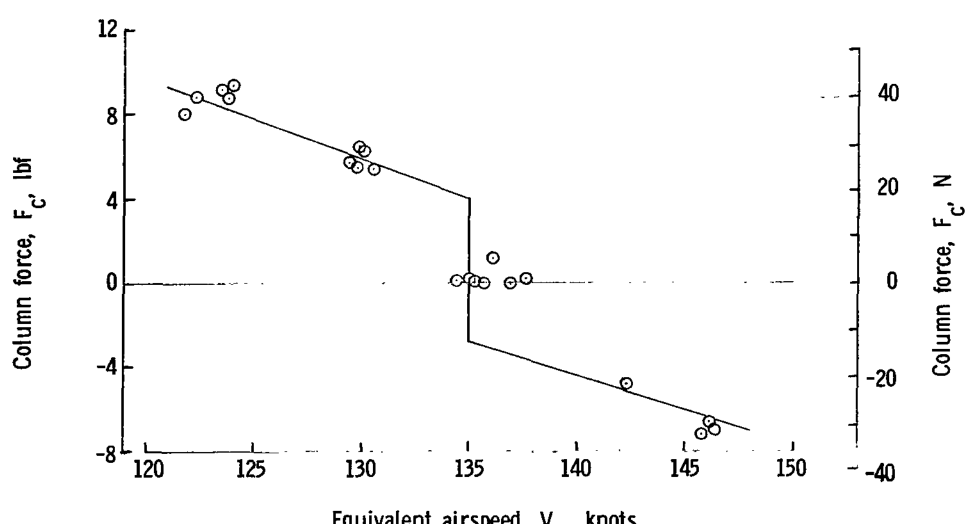


Figure 4-1.- Indication of stick-fixed and stick-free static stability for simulated unaugmented basic variable-geometry SST configuration.

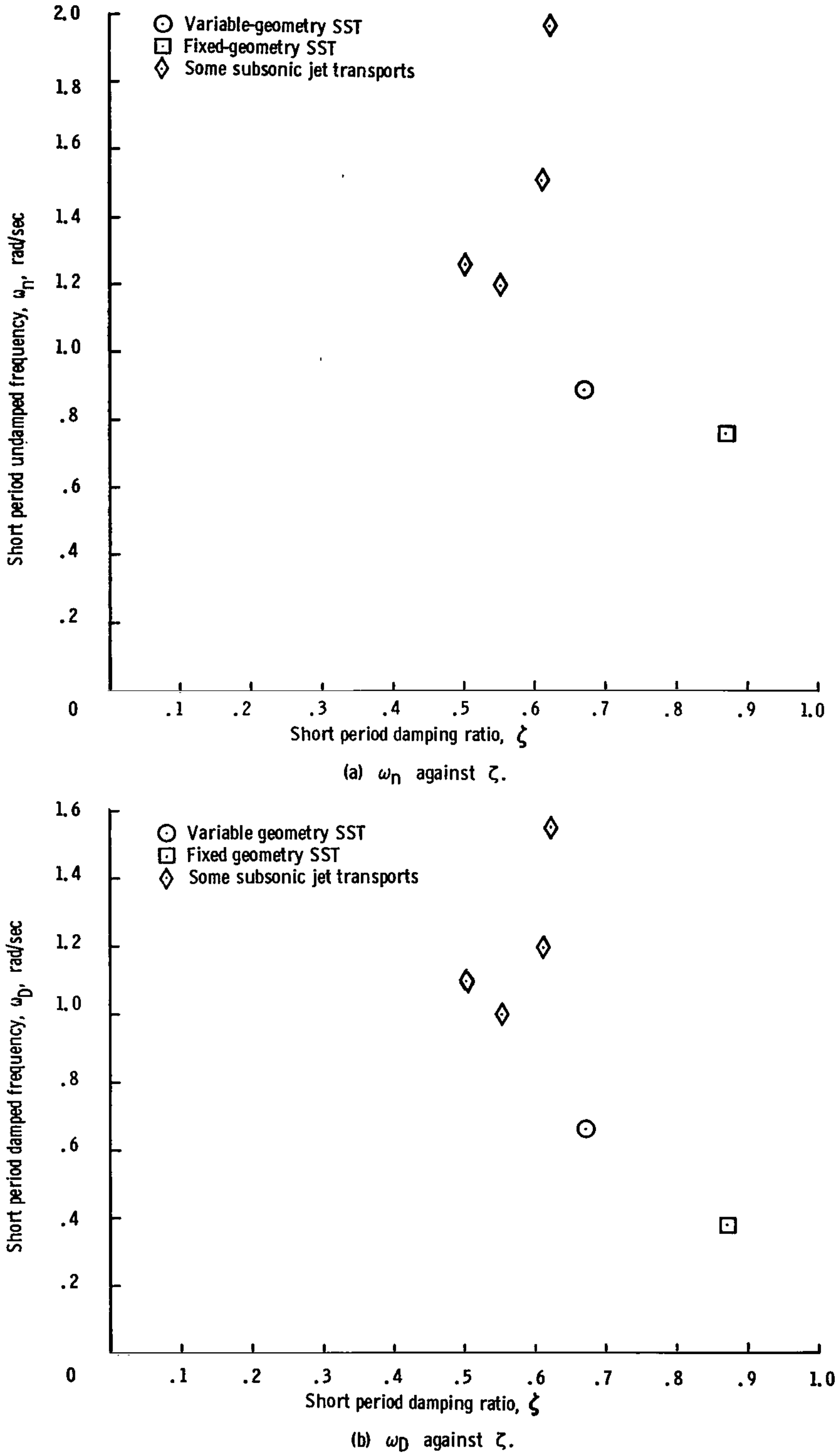


Figure 4-2.- Comparison of short period frequency (undamped and damped) and damping ratio of unaugmented variable- and fixed-geometry SST configurations with some present-day subsonic jet transports.

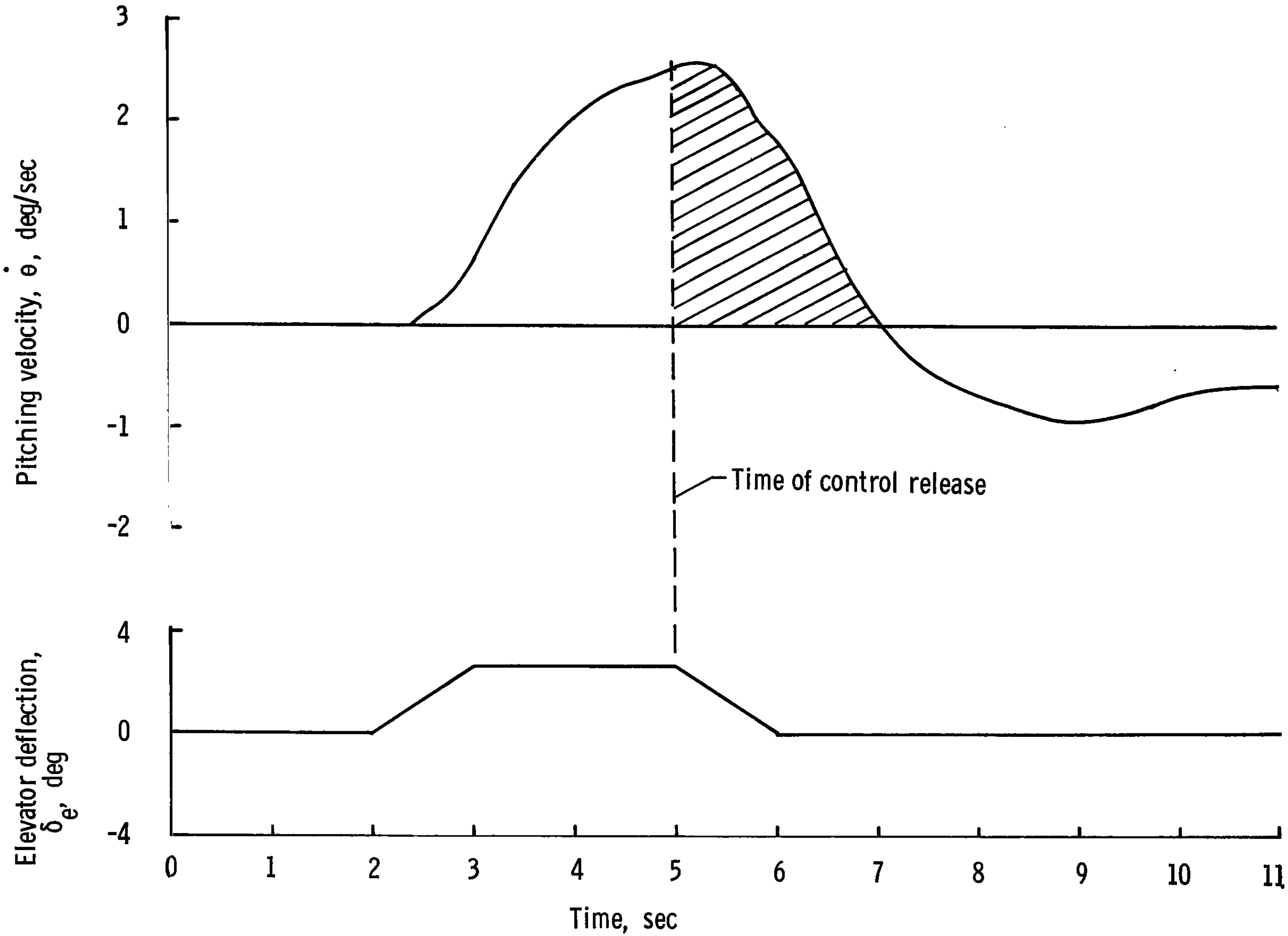
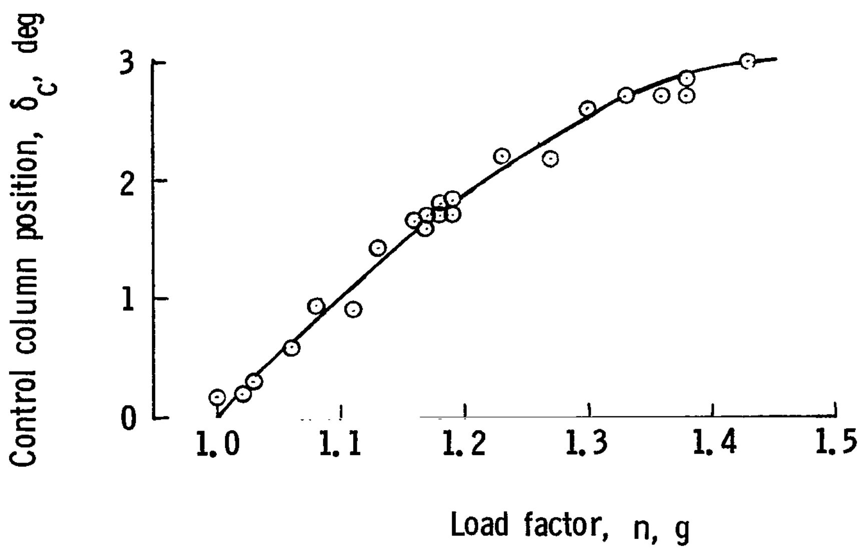


Figure 4-3.- Aircraft pitch rate response to an elevator pulse.



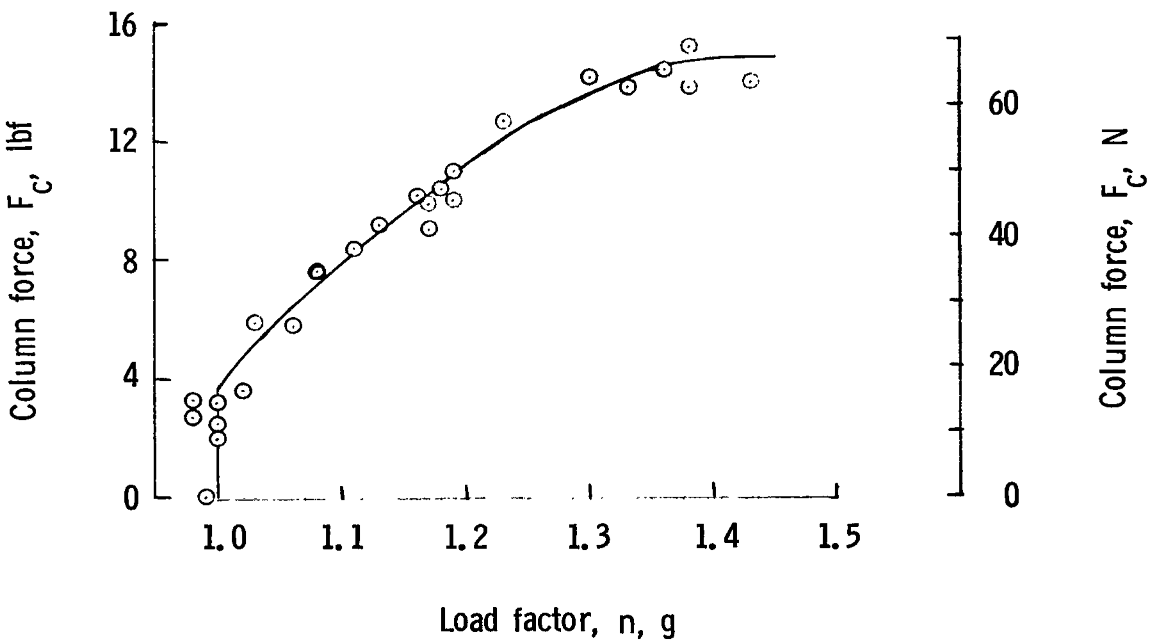


Figure 4-4.- Indication of longitudinal maneuvering stability in a wind-up turn for simulated basic unaugmented variable-geometry SST configuration.

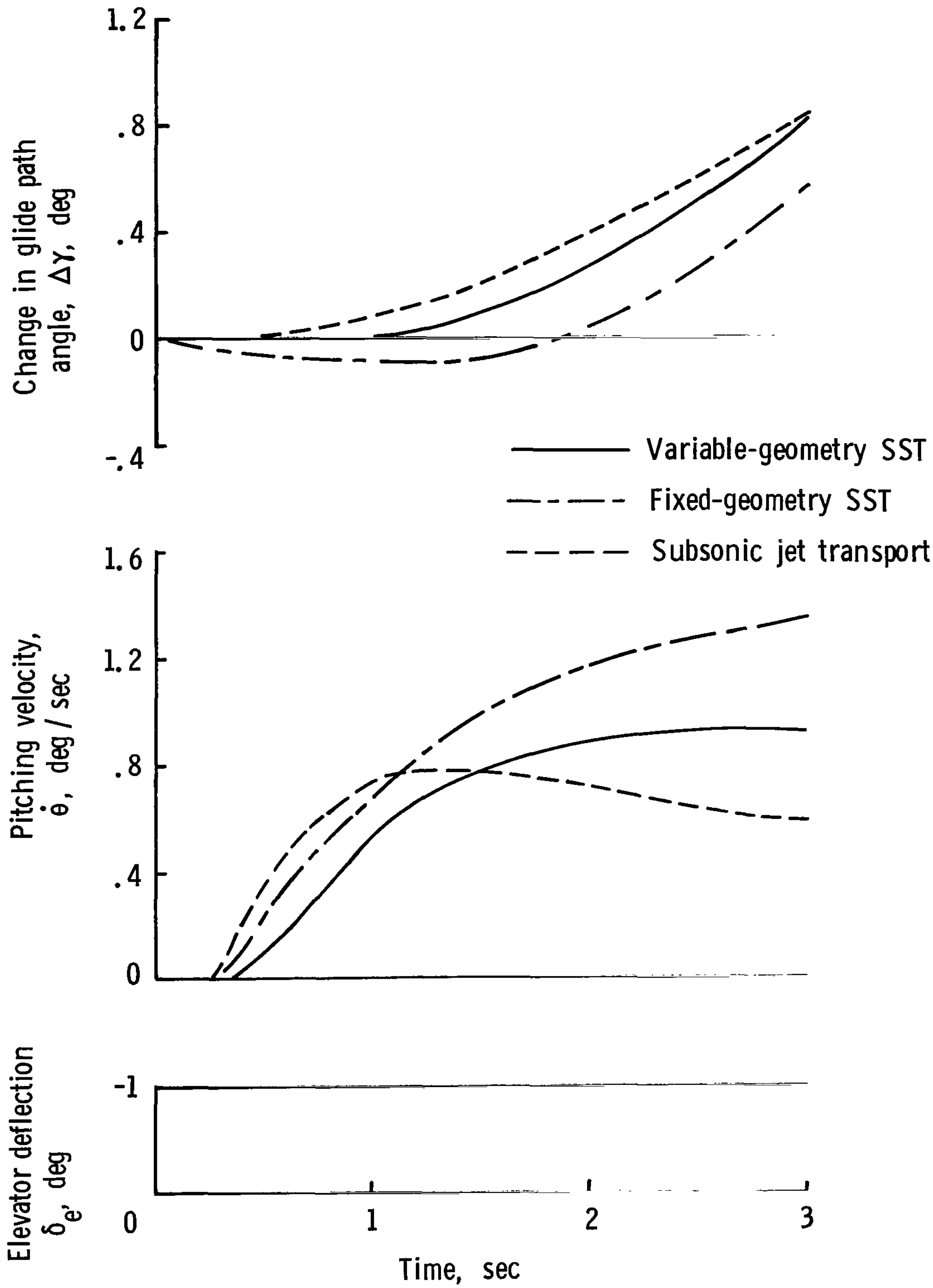


Figure 4-5.- Comparison of pitch response for the variable- and fixed-geometry SST configurations with a subsonic jet transport.

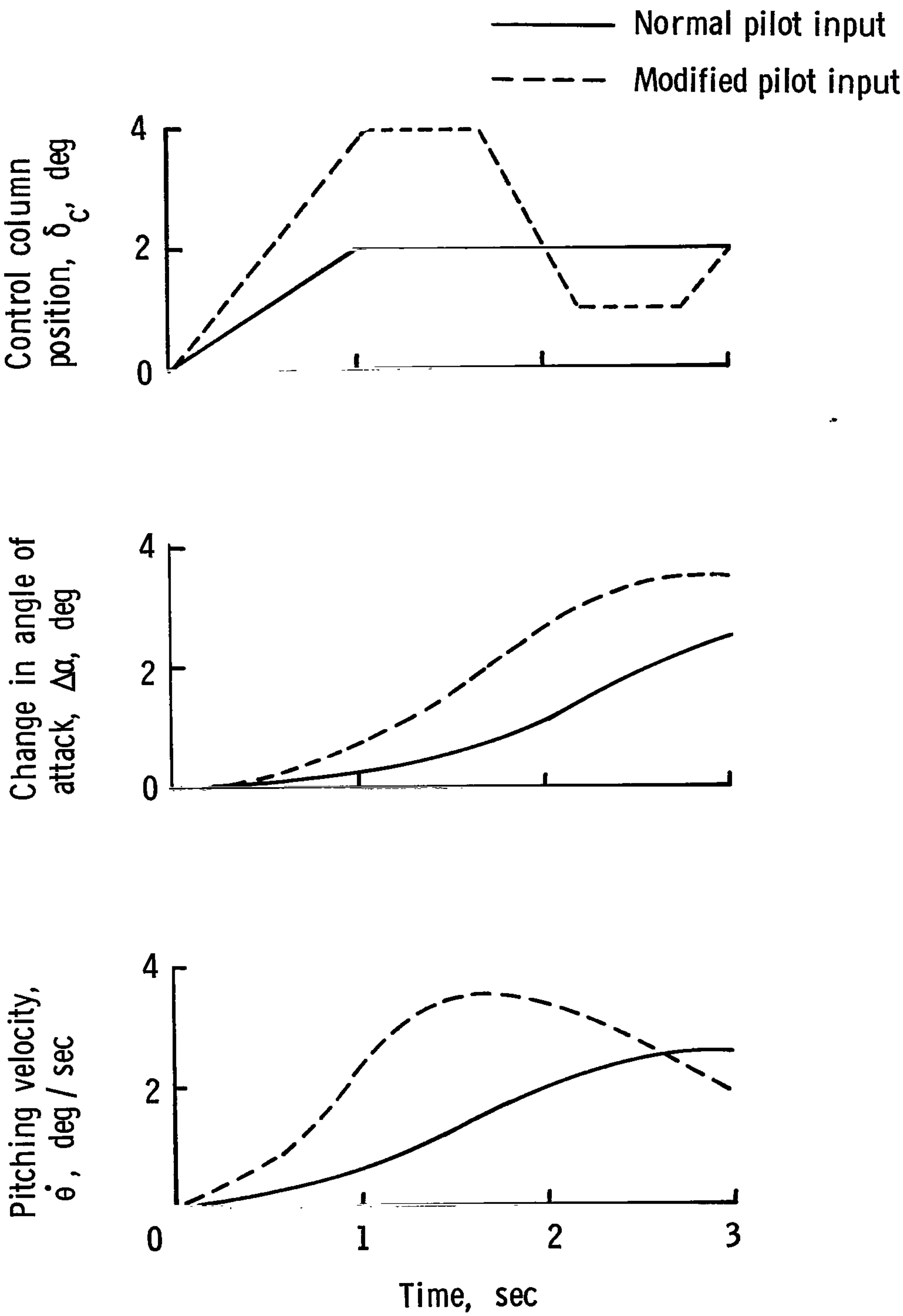


Figure 4-6.- Example of pilot over-controlling in order to compensate for inherent sluggish pitch response.

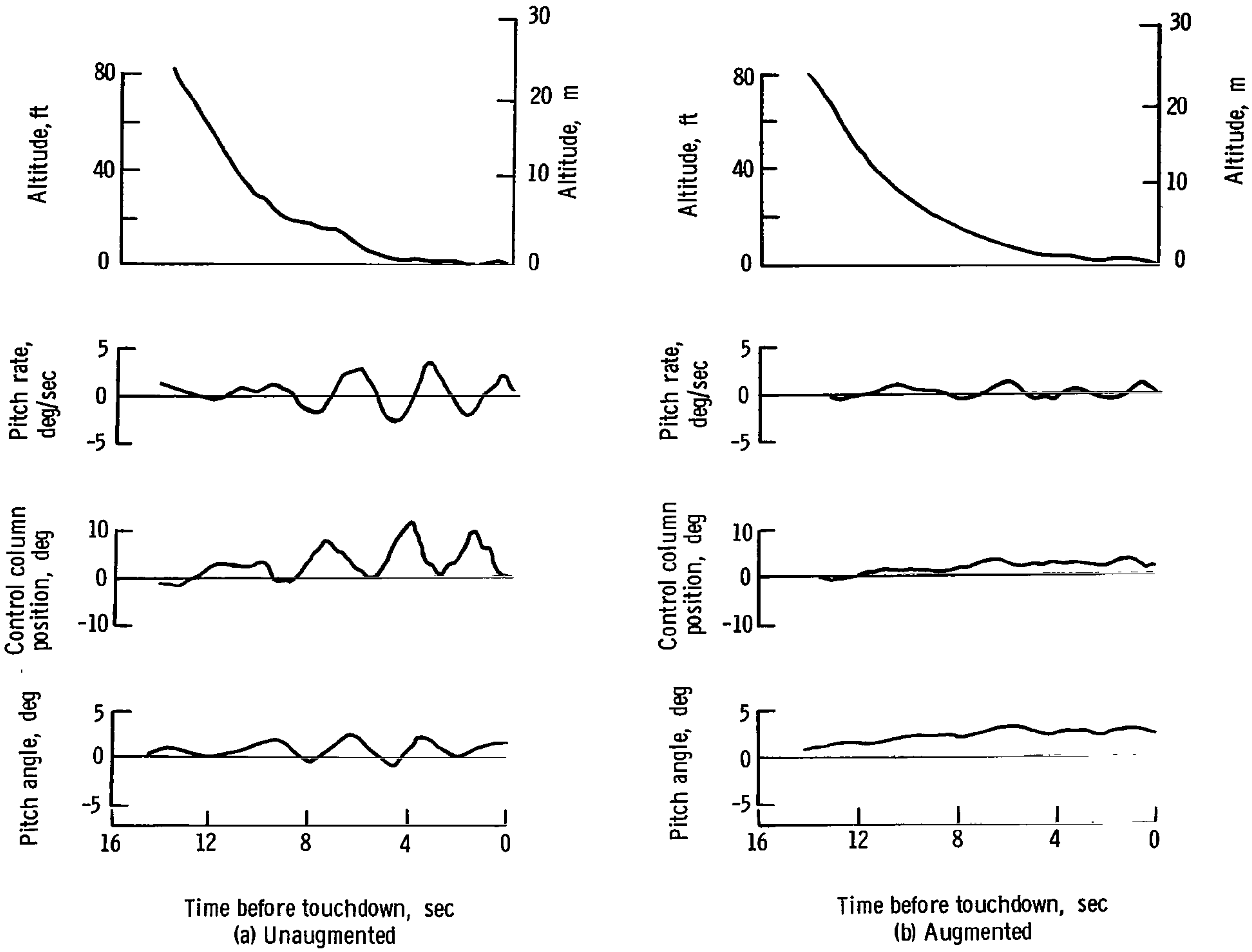


Figure 4-7.- Landing time histories for the variable-geometry supersonic transport configuration showing effects of ($\dot{\theta}$ + $\Delta\alpha$) SAS.

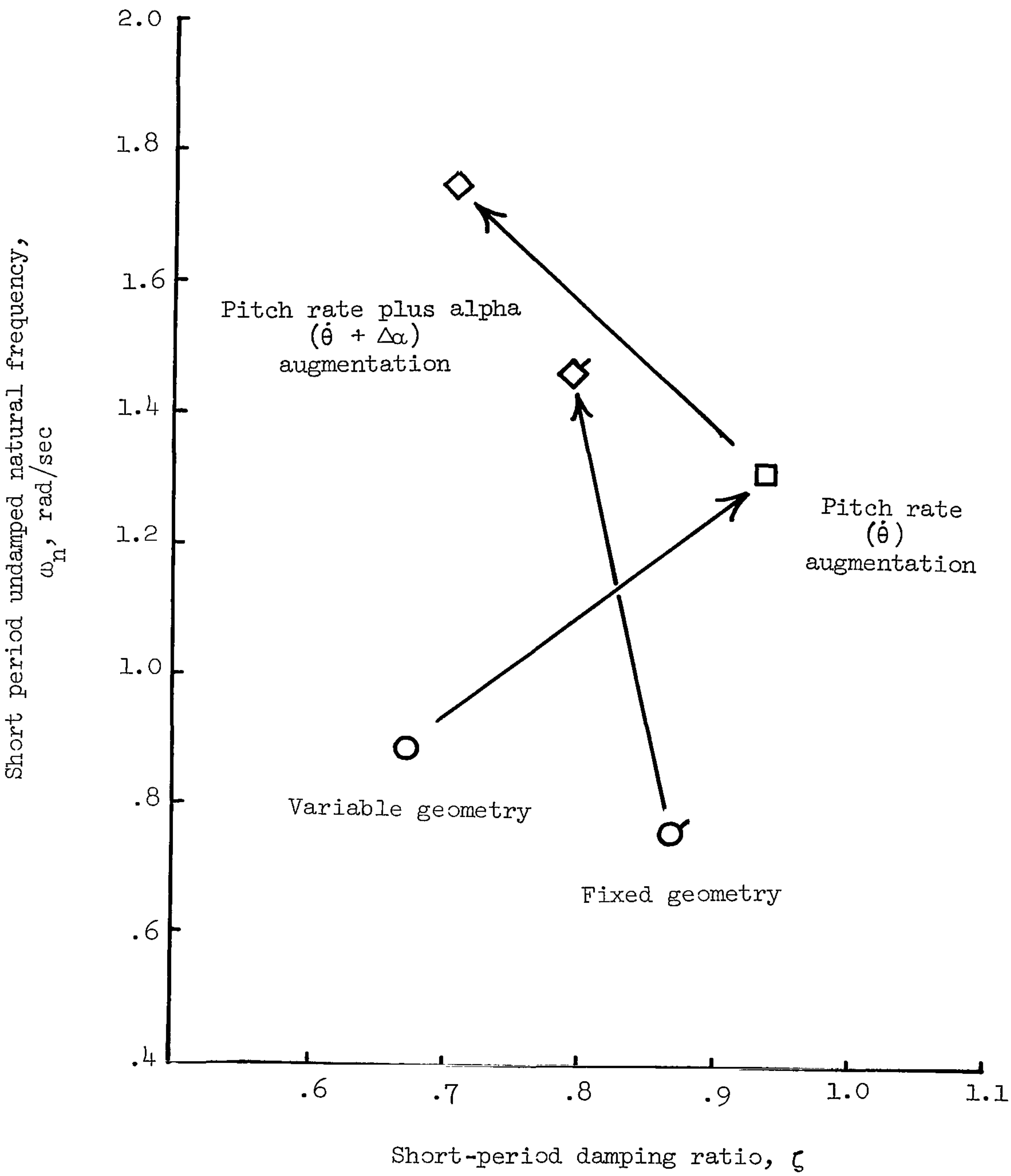


Figure 4-8.- Effect of $\dot{\theta}$ and $(\dot{\theta} + \Delta\alpha)$ SAS on the short period damping ratio and natural frequency.

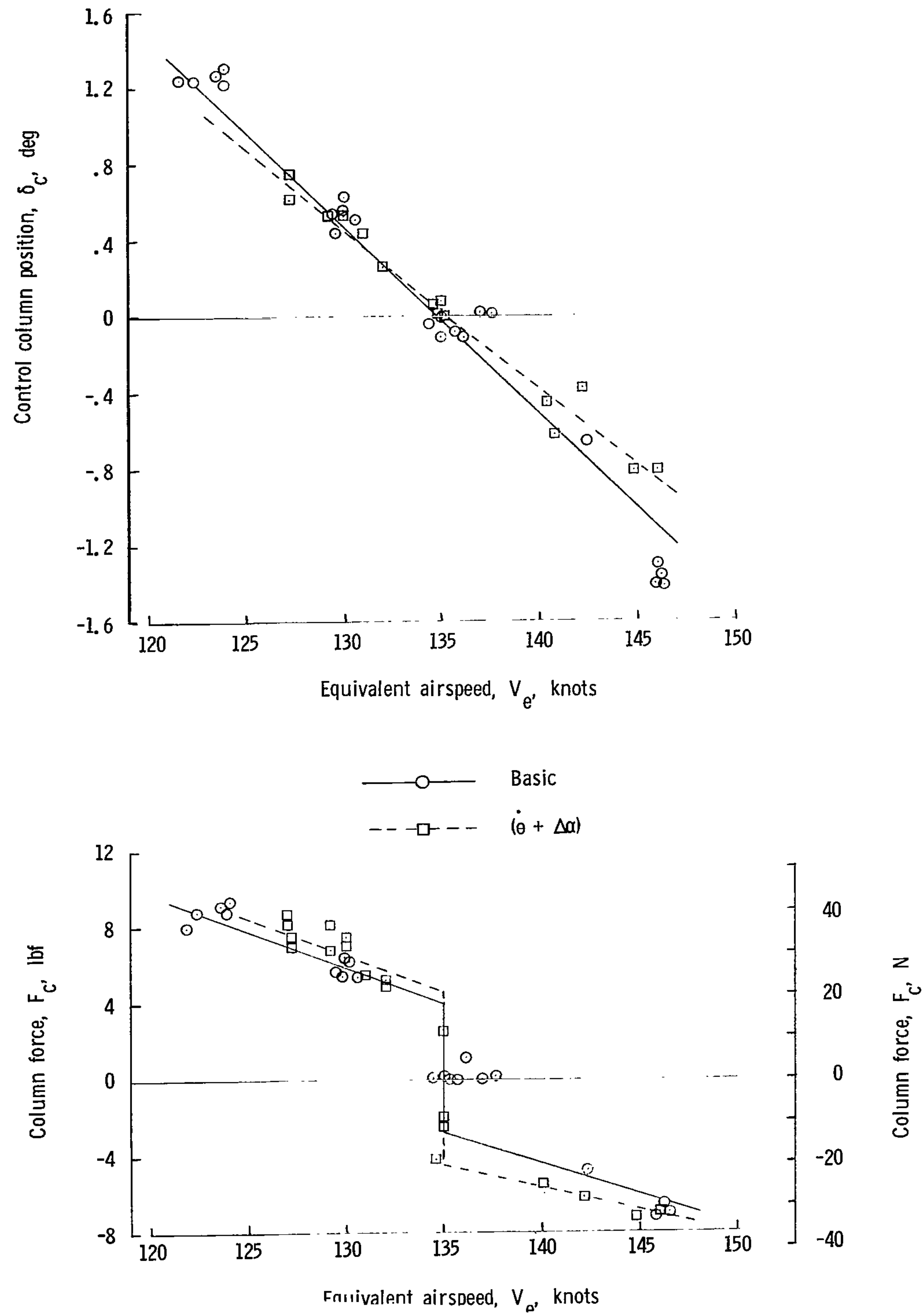


Figure 4-9.- Comparison of stick-fixed and stick-free static stability for the variable-geometry, basic and $(\dot{\theta} + \Delta\alpha)$ augmented, configurations.

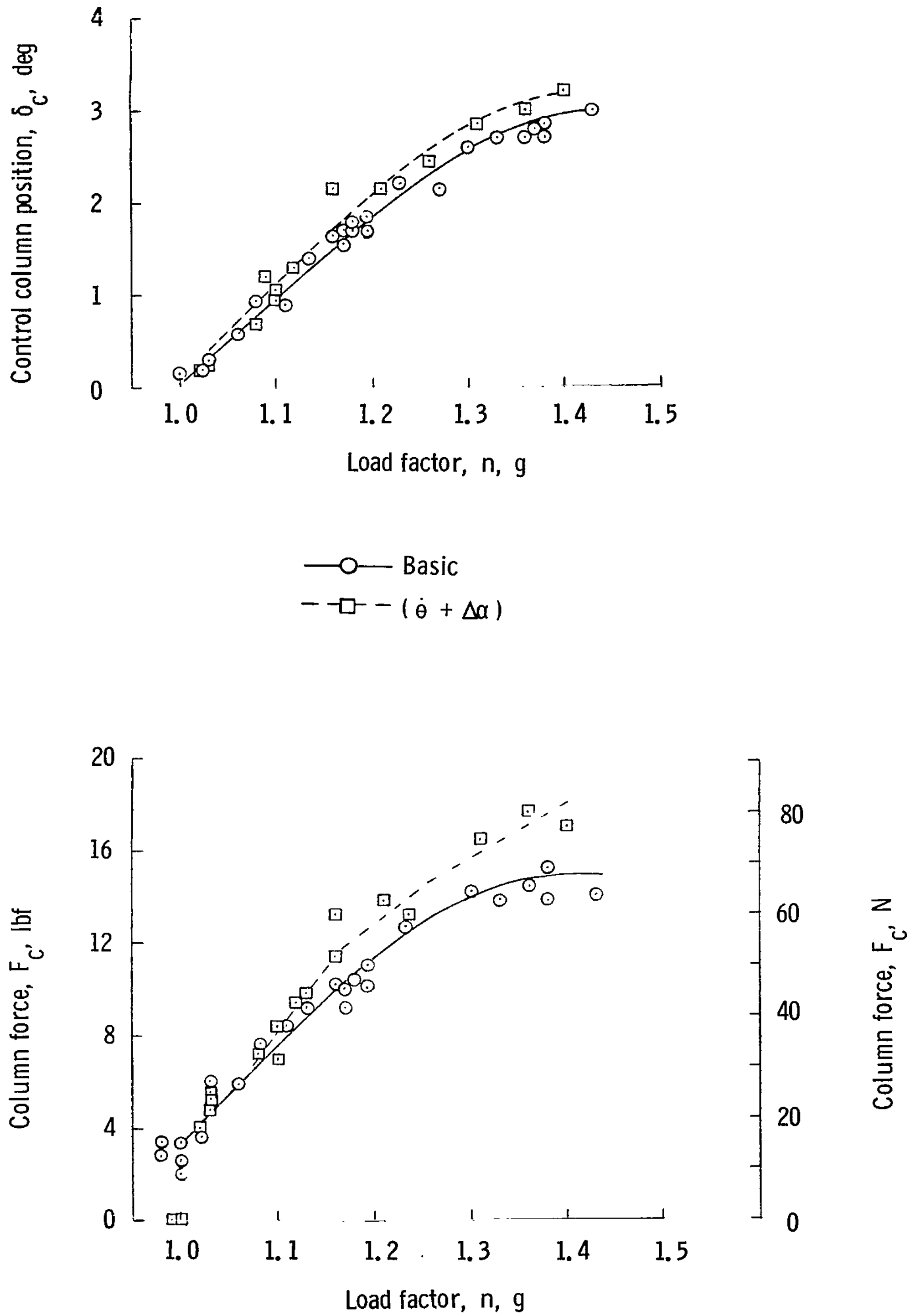


Figure 4-10.- Comparison of longitudinal maneuvering stability in a wind-up turn for variable-geometry, basic and $(\dot{\theta} + \Delta\alpha)$ augmented, configurations.

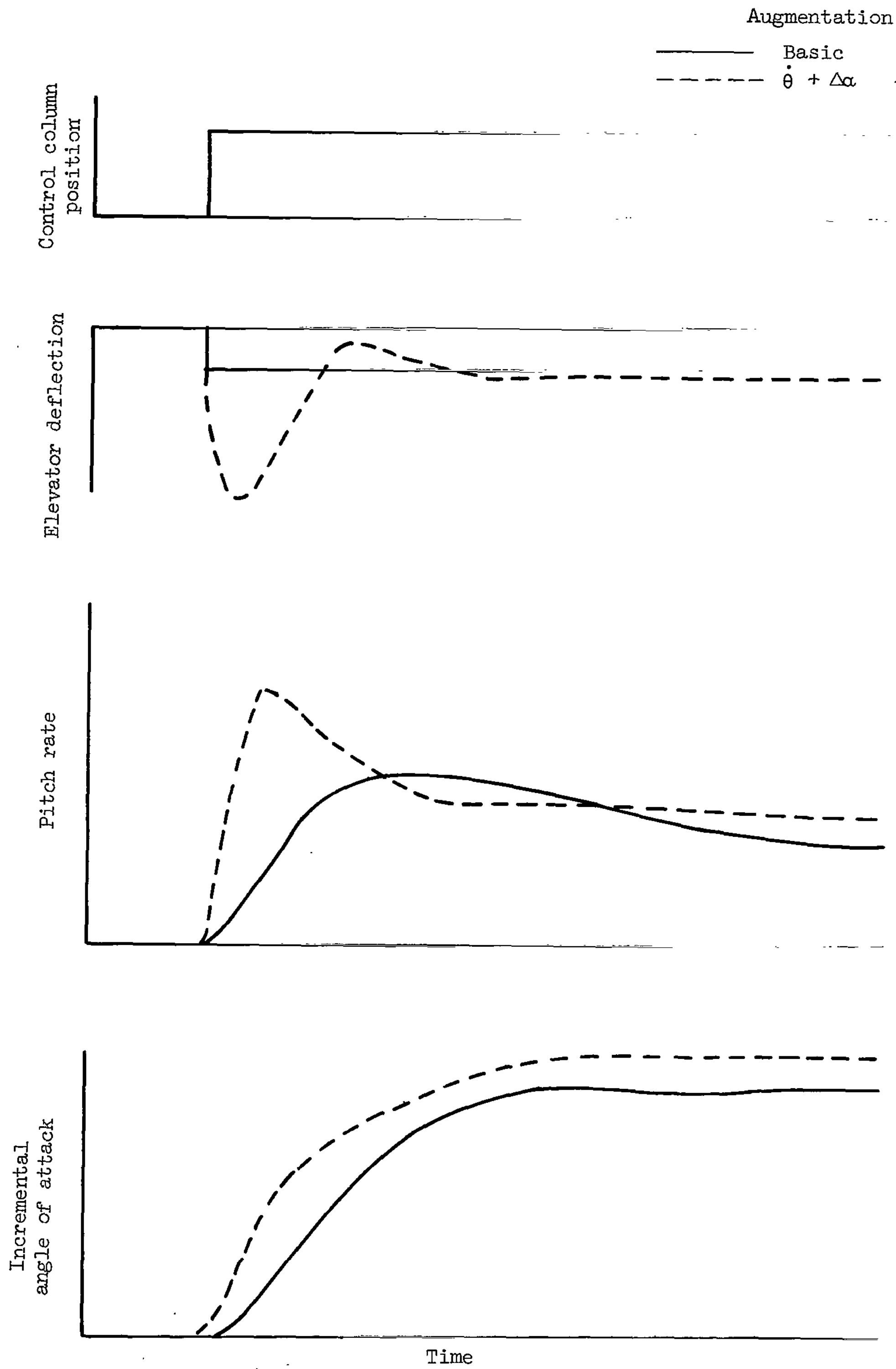


Figure 4-11.- Indication of initial response for basic and augmented configurations for a step column input.

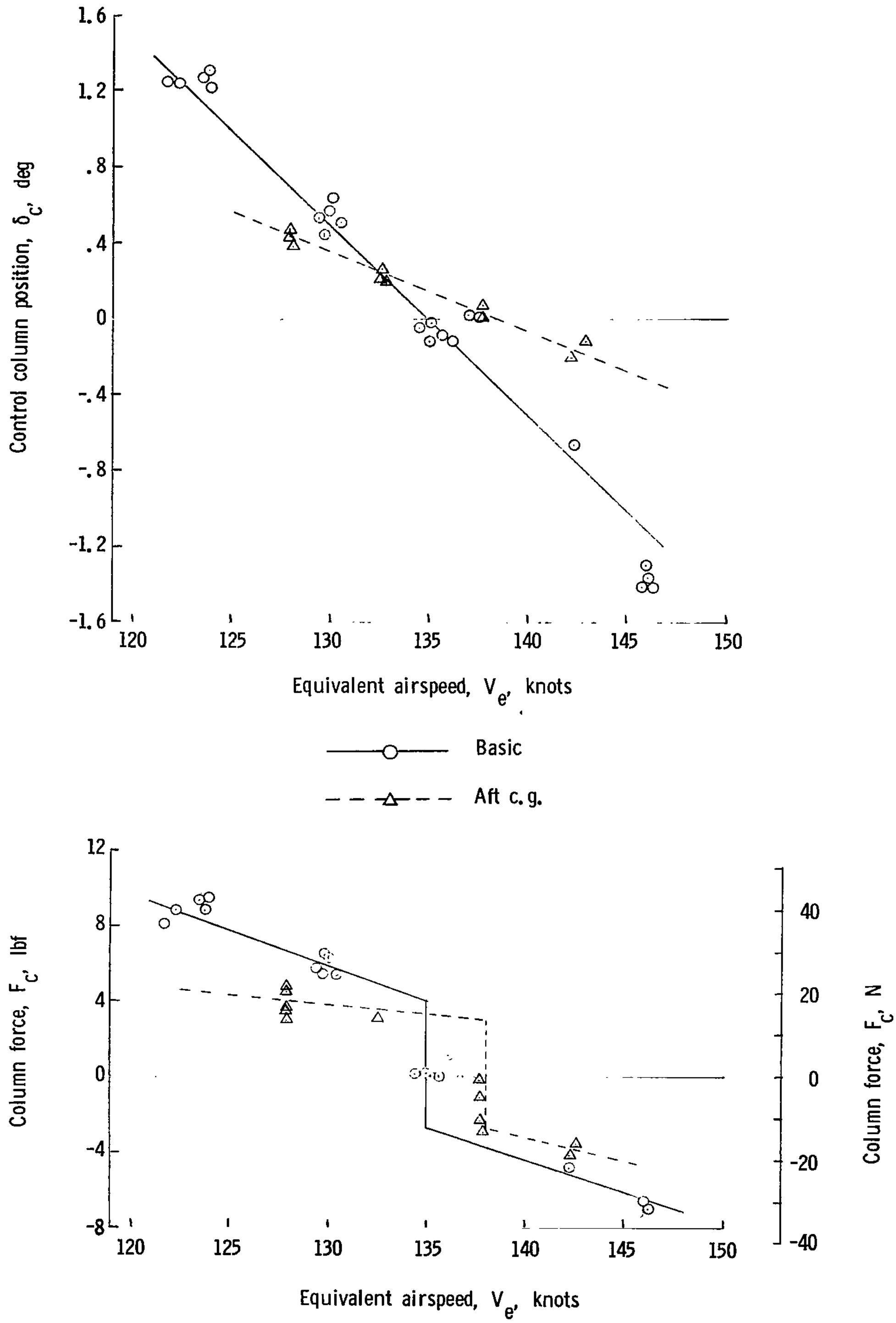


Figure 4-12.- Comparison of stick-fixed and stick-free static stability for the variable-geometry, basic and aft center of gravity, configurations.

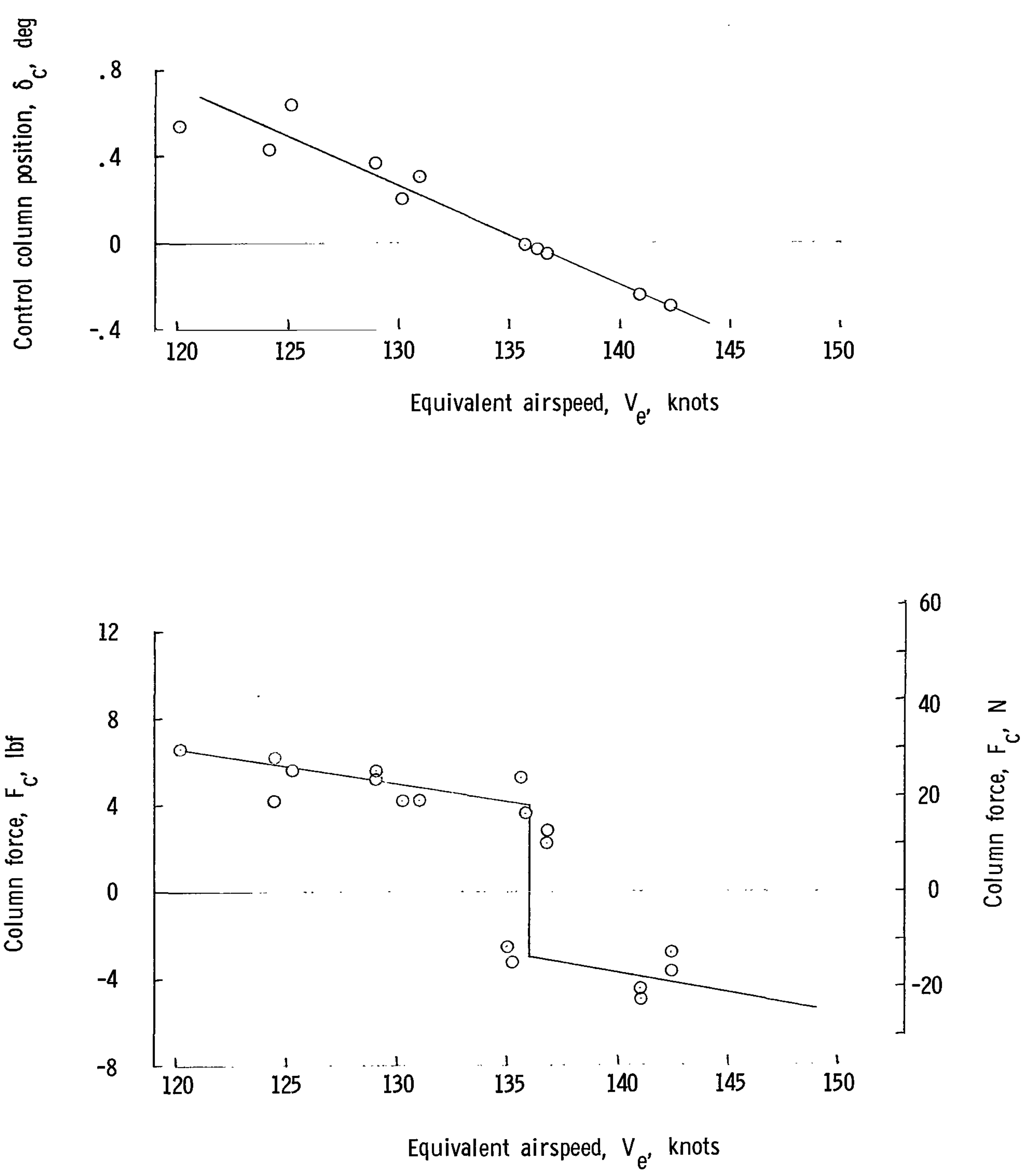
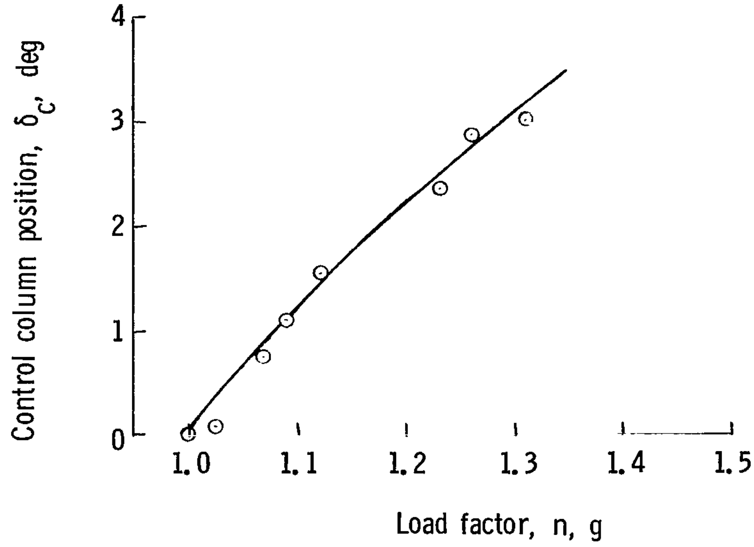


Figure 4-13.- Indication of stick-fixed and stick-free static stability for the simulated fixed-geometry SST configuration.



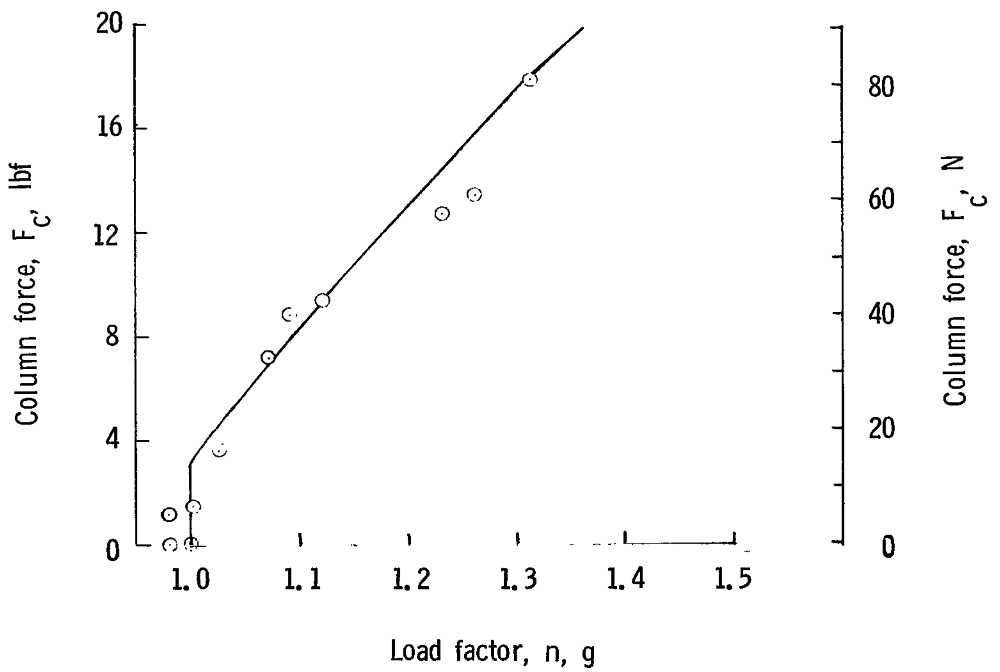


Figure 4-14.- Indication of longitudinal maneuvering stability in a wind-up turn for simulated fixed-geometry SST configuration.

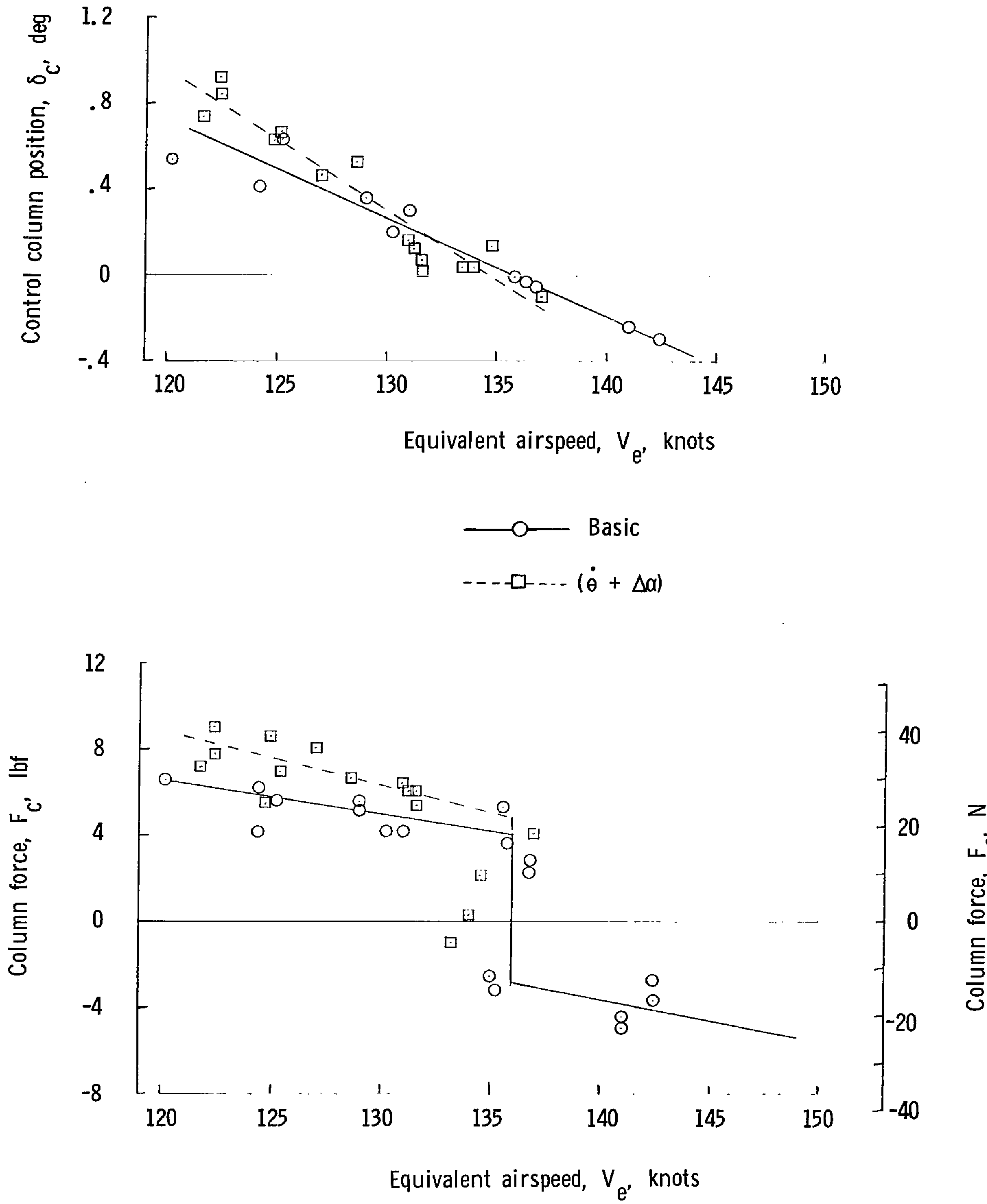


Figure 4-15.- Comparison of stick-fixed and stick-free static stability for fixed-geometry, basic and ($\dot{\theta} + \Delta\alpha$), configurations.

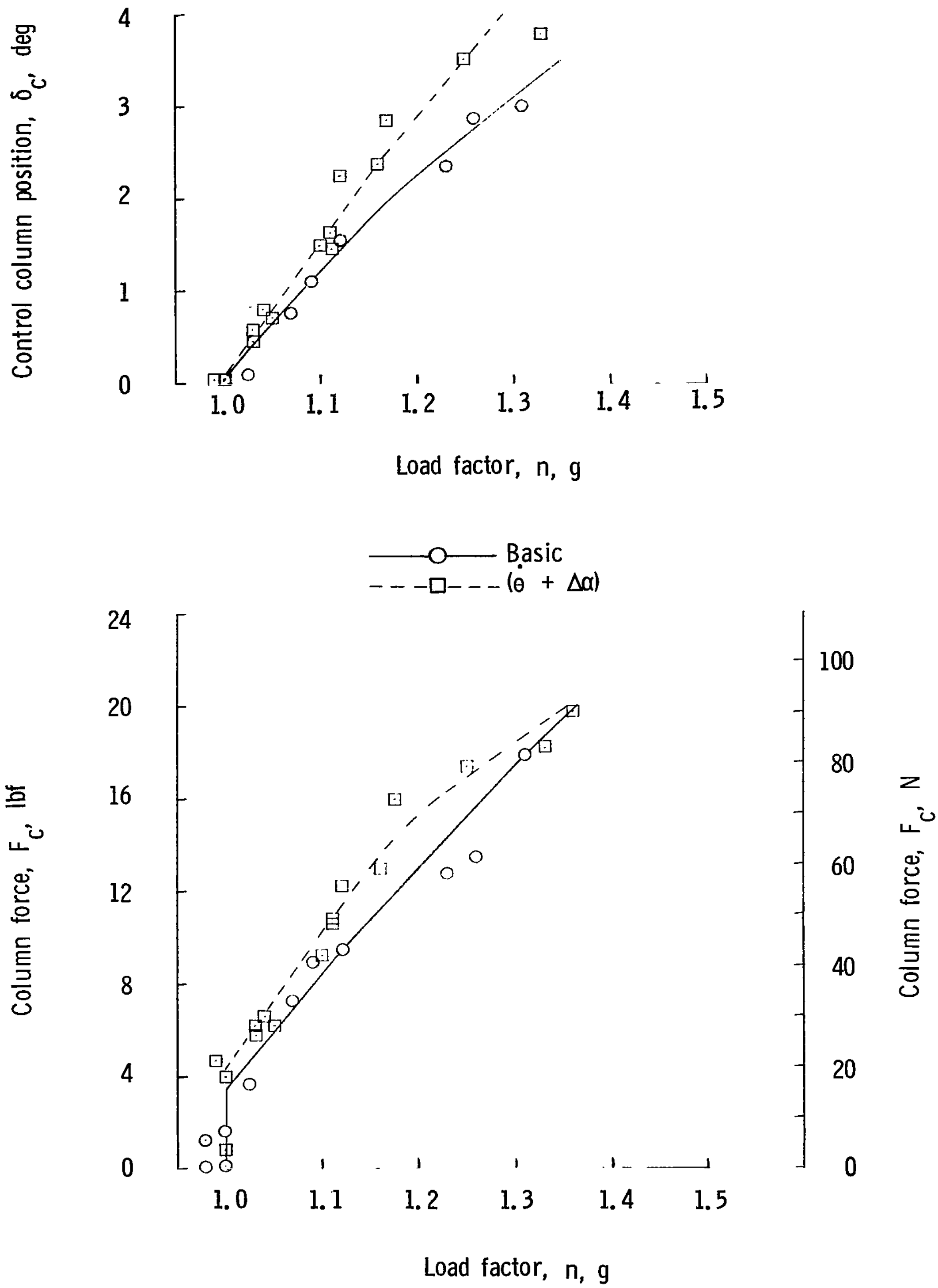


Figure 4-16.- Comparison of longitudinal maneuvering stability in a wind-up turn for fixed-geometry, basic and $(\dot{\theta} + \Delta\alpha)$, configurations.

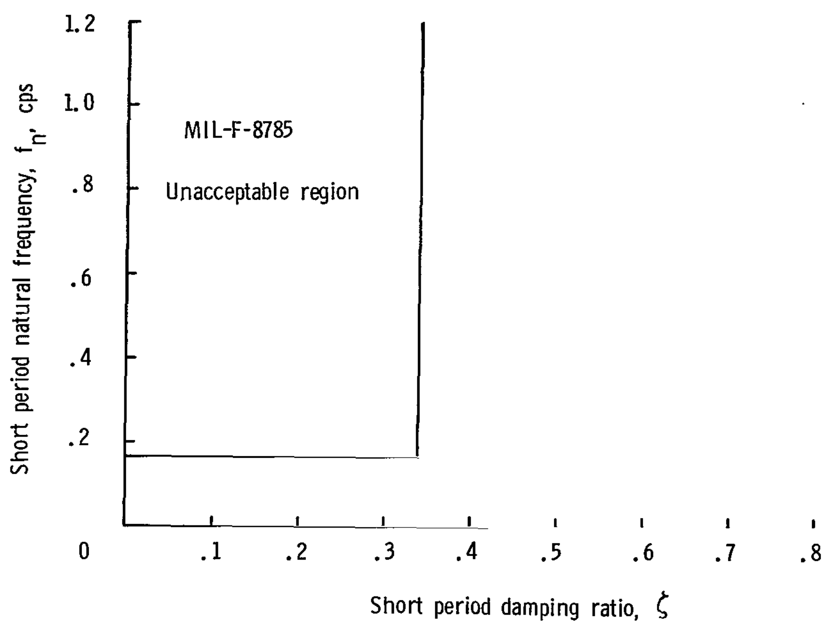


Figure 4-17.- Longitudinal short period damping requirements of MIL-F-8785.

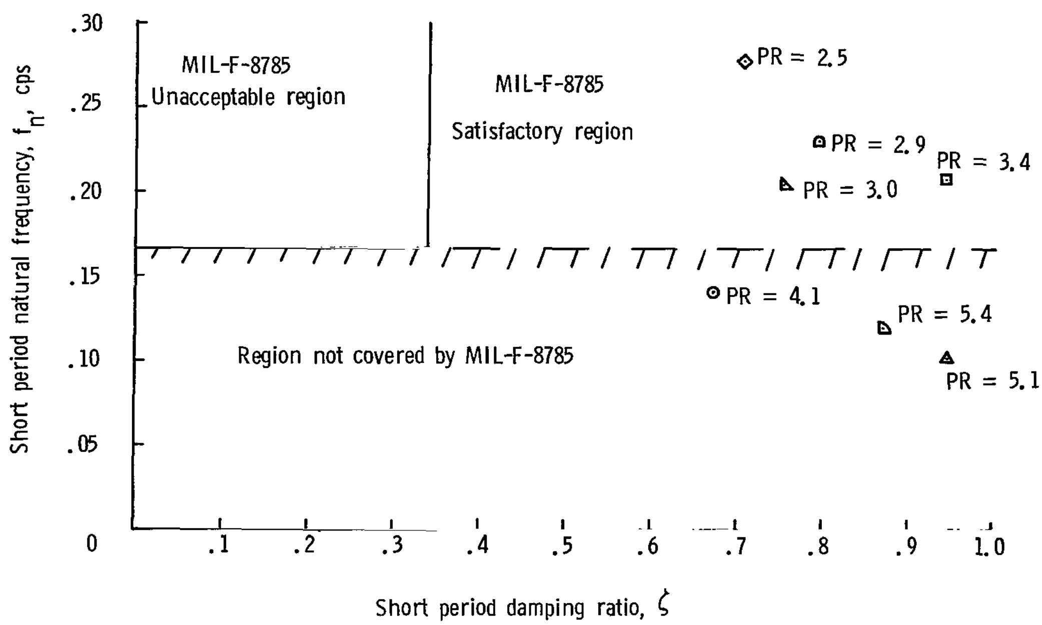


Figure 4-18.- Location of short period frequency and damping ratio of various SST configurations simulated on damping requirements specification chart of MIL-F-8785.

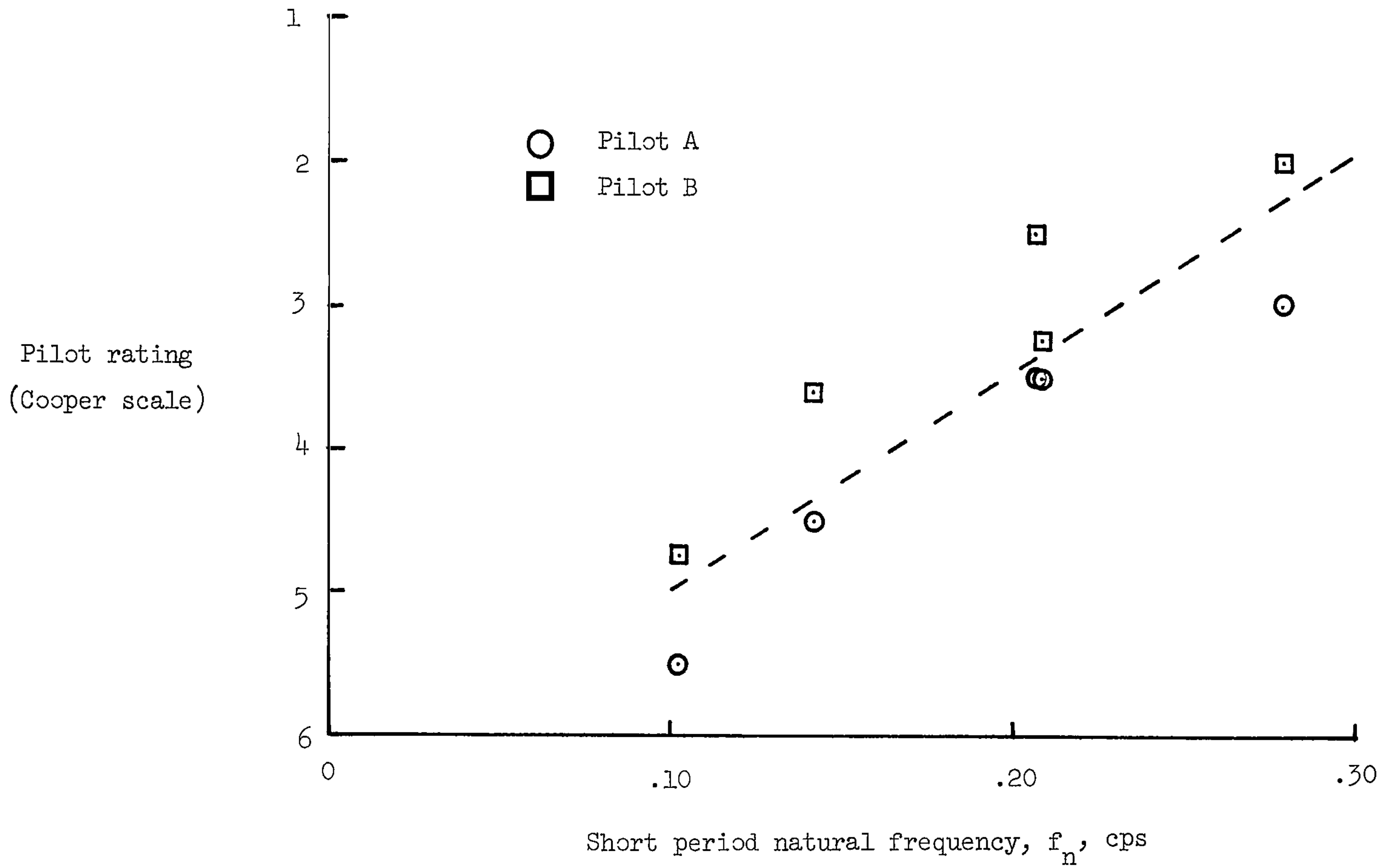


Figure 4-19.- Variation of pilot ratings of longitudinal characteristics of variable-geometry configurations simulated with short period natural frequency.

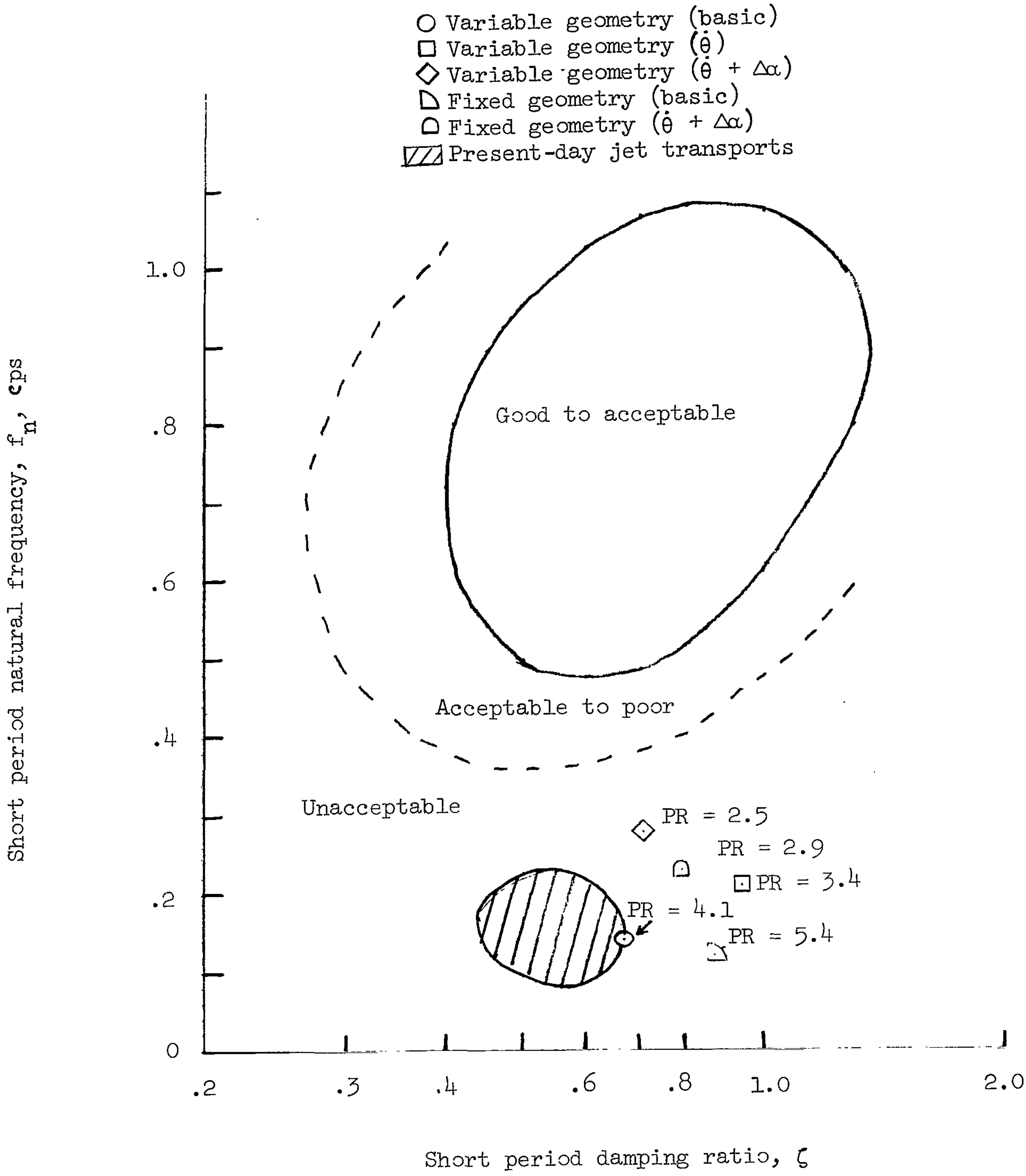


Figure 4-20.- Longitudinal short period criterion of reference 2.

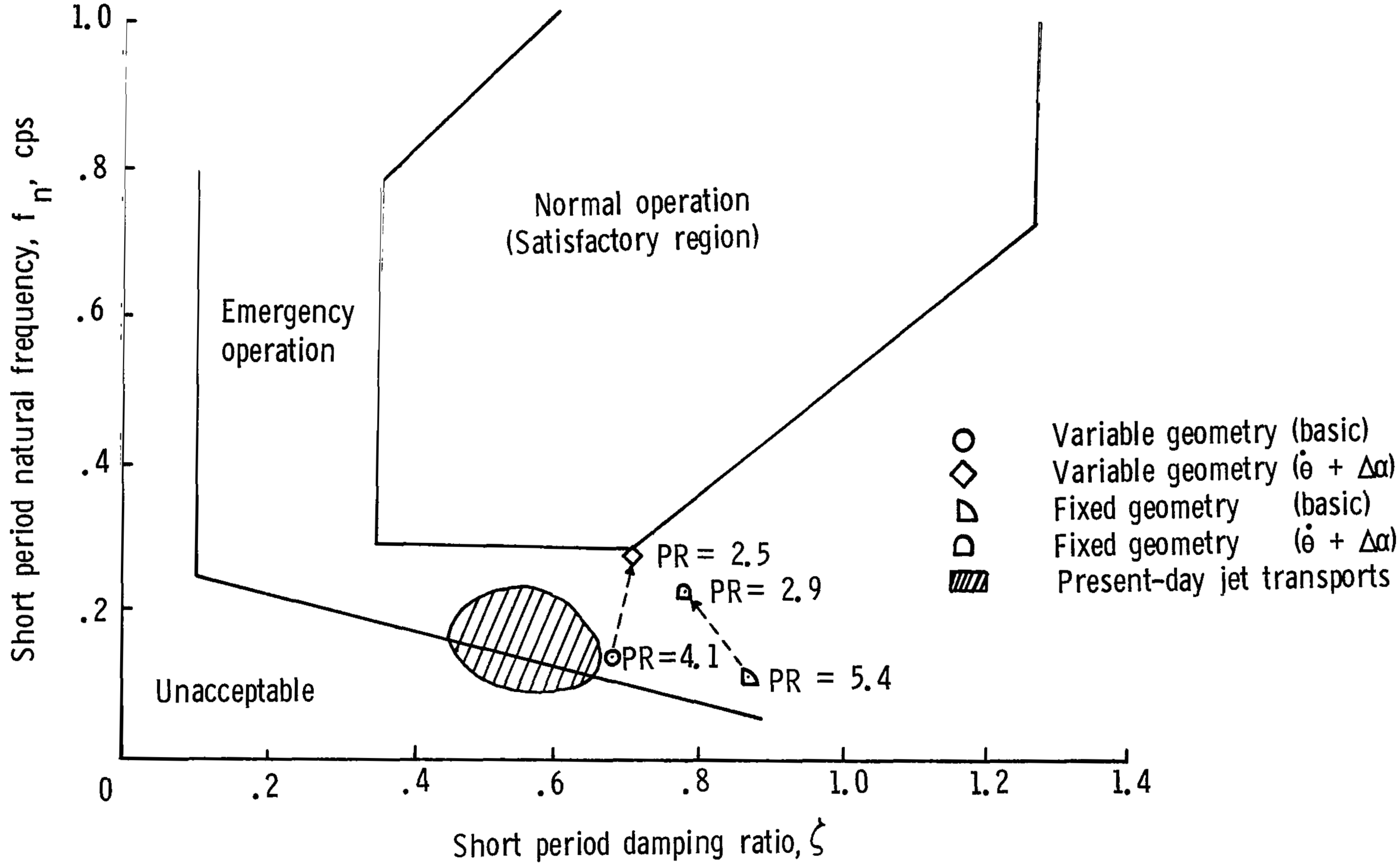


Figure 4-21.- Longitudinal short period criterion of reference 3.

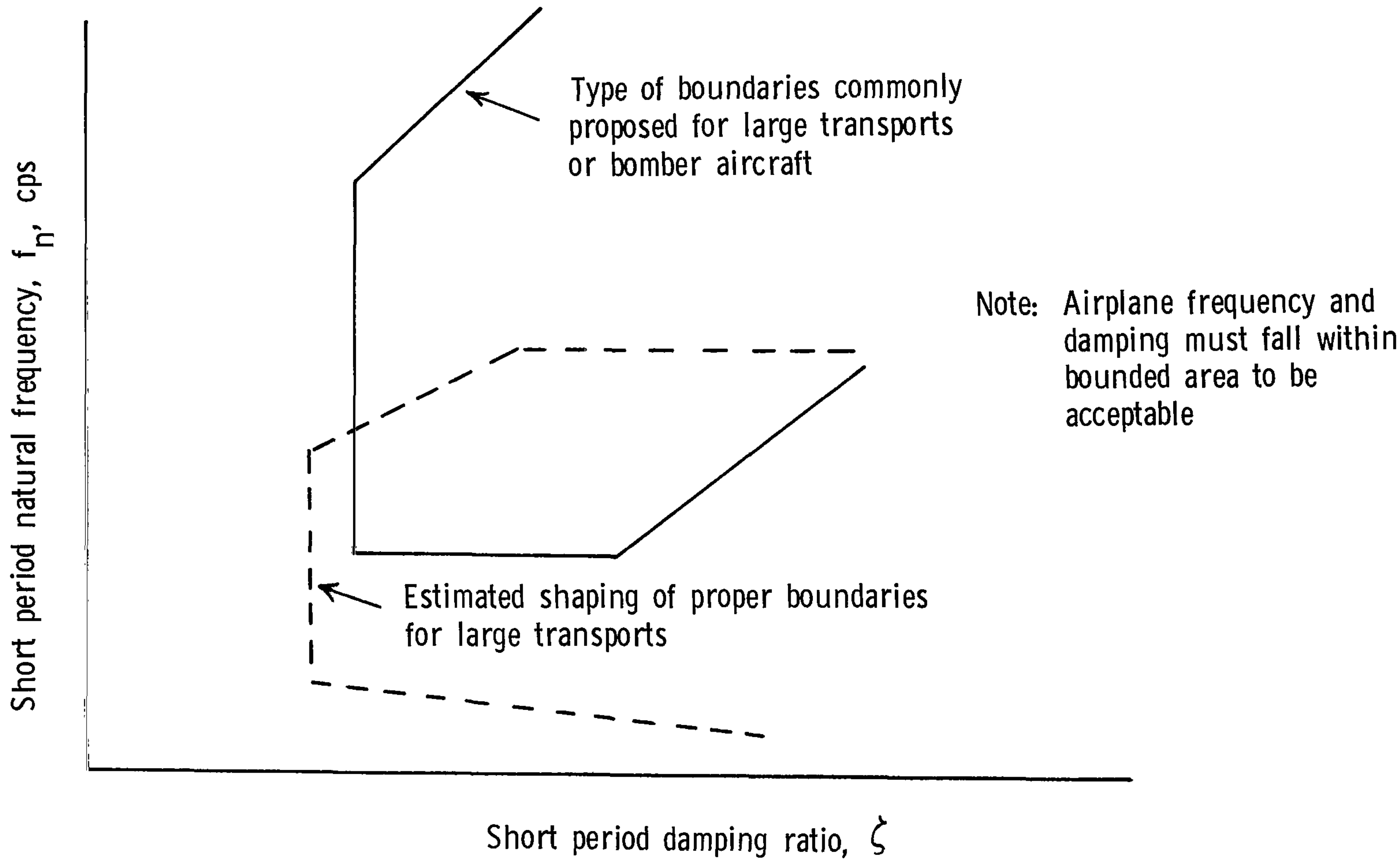


Figure 4-22.- Estimated reshaping of an existing longitudinal short period criterion (reshaping as proposed in ref. 4).

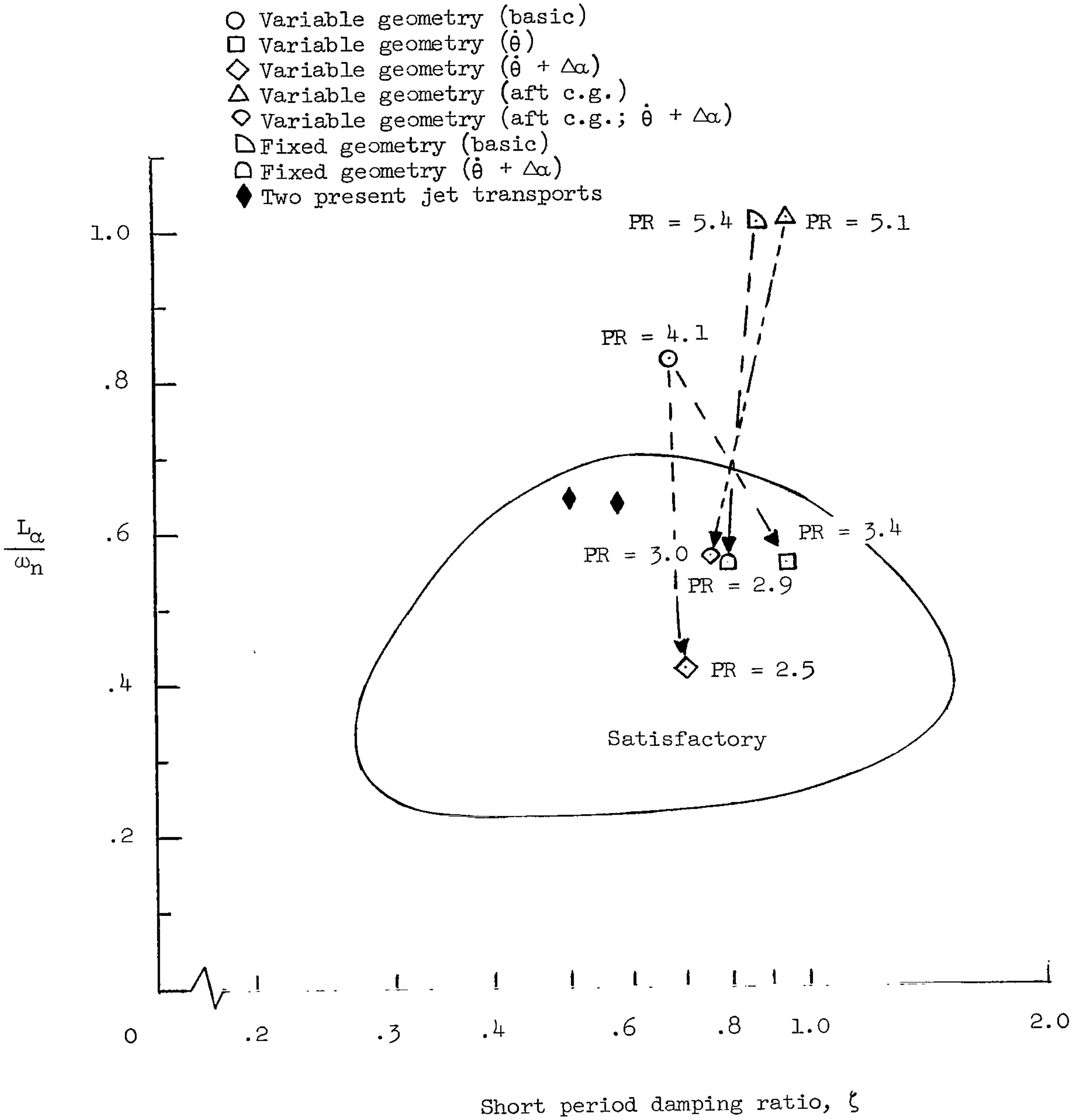


Figure 4-23.- Longitudinal short period criteria of reference 4.

5. LATERAL-DIRECTIONAL HANDLING QUALITIES

By Robert E. Shanks, Samuel A. Morello,
and Jere B. Cobb

SUMMARY

An investigation was made to determine the lateral-directional handling qualities of several supersonic transport configurations during the landing approach. The basic variable-geometry and fixed-geometry configurations were found to have satisfactory handling characteristics. Although the characteristics of the variable-geometry emergency-landing configuration (wings in sweptback position) were considered to be unsatisfactory, it was determined that it would be possible to make landings with this configuration.

INTRODUCTION

As pointed out in the introduction, part 1, the proposed supersonic transports differ markedly from current large subsonic jet transports and might therefore be expected to have different handling qualities. For instance, it was suggested in reference 1 that changes in pilot techniques may be required because of the large difference between the relatively high lateral control sensitivity and the reduced control response in yaw of such configurations. The tests discussed in this part were made to determine the effects of supersonic transport characteristics on the lateral-directional handling qualities.

RESULTS AND DISCUSSION

The lateral-directional results of the flight tests are summarized in tables 5-1 and 5-2 and in figures 5-1 to 5-17. Table 5-1 presents qualitative results in the form of pilot ratings and comments for the flight-test configurations. The numerical ratings assigned each configuration by the pilots are based on the Cooper pilot evaluation scale (presented in table 2-3). All the configurations, except one, were evaluated by a minimum of two pilots, some configurations being evaluated by seven pilots; however, the average pilot ratings presented throughout the discussion were taken as an average of the ratings of pilots A and B. In addition to the overall rating for each configuration, pilots A and B also assigned ratings based only on the Dutch roll characteristics for correlation with the criteria dealing particularly with the characteristics of the Dutch roll oscillation.

The data of table 5-2 and figures 5-1 to 5-9 present quantitative results obtained from flight tests. The data presented in figures 5-1 to 5-3 are taken from reference 2, but it should be noted that the sideslip angles have been reduced by 20 percent. This reduction approximates the sidewash correction to the angles indicated by the sideslip vane, whereas, in reference 2 this correction has not been applied.

Basic Variable-Geometry Configuration

The basic variable-geometry configuration represents a supersonic transport of the variable-wing-sweep concept with the wings at minimum sweep angle in the normal landing configuration. In general, the lateral-directional characteristics of the basic variable-geometry configuration were good and were characterized by good Dutch roll damping, approximately neutral spiral stability, good static directional stability, positive effective dihedral, good roll response and roll damping, and low workload. Although some adverse sideslip (sideslip right with right roll) was noted in performing heading changes, it was felt to be of small consequence and the heading-change precision was found to be good. The basic variable-geometry configuration was given an overall Cooper pilot opinion rating of 3.0 (see table 5-1) and one pilot (pilot C) gave it an unusually good rating of 2.

Static lateral-directional stability characteristics.- The static lateral-directional stability characteristics obtained from flight in steady sideslip are shown in figure 5-1(a). The pilot comments of table 5-1 correlated with the data of this figure in that they showed this configuration to have good directional stability and satisfactory positive effective dihedral.

Dynamic lateral-directional stability characteristics.- The measured characteristics of the Dutch roll oscillation following a rudder input are illustrated in figure 5-2(a). The characteristics of the Dutch roll oscillation of the basic variable-geometry configuration were obtained from these data and are shown in figure 5-6 in comparison with those of current large jet transports. The data of figure 5-6 and table 5-2 show that the oscillation is fairly well damped, but has a low natural frequency or long period (9.6 seconds).

The rather long period of the Dutch roll oscillation apparently was not objectionable to the pilots. Pilot D, however, did note that although the damping of the lateral oscillation appeared to be satisfactory in terms of cycles to damp to half-amplitude, the actual time to damp to half-amplitude was greater than desirable because of the long period of the oscillation. From observation of a sensitive sideslip indicator, he also noted a tendency to induce the Dutch roll oscillation but otherwise he was not conscious of it because the motion was slow and gentle. The increased damping for this configuration compared with that of current jet transports apparently compensates for the undesirable effect of low frequency. For example, the comparisons of table 5-2 show that the time to damp to half-amplitude for this configuration is appreciably less than those of several representative large subsonic jet transports. Figure 5-6 also shows fairly good damping and a ratio of roll angle to sidewise velocity ϕ/v_e (which is also a measure of roll angle to sideslip angle) which is about the same as those for current large subsonic jet transports. The pilots generally considered the damping of the Dutch roll oscillation to be good and most of the pilots stated that the motion was predominately yawing.

The basic variable-geometry configuration had essentially neutral spiral stability with a calculated time to double amplitude of approximately 240 seconds. The roll-subsidence mode was heavily damped with a roll time constant of about 0.5 second. The flight-test results are in agreement with these predicted results since the pilots found this configuration to have neutral or slightly divergent spiral stability and good roll damping. (See table 5-1.)

Lateral control characteristics.- The variations of maximum rolling velocity and maximum rolling acceleration with wheel deflection as obtained from rudder-fixed wheel step and wheel step reversal maneuvers, respectively, are shown in figure 5-3(a) for the basic variable-geometry configuration. The pilots generally felt that the roll response characteristics of this configuration were good but did note a small amount of adverse sideslip on turn entries. Heading-change precision was considered to be good in spite of the adverse sideslip when these maneuvers were made with only lateral control (no rudder).

Landing approach.- The lateral-directional control activity and airplane displacements for a typical approach and landing are presented for the basic variable-geometry configuration in figure 5-4. These time histories show small localizer deviations, normal bank and sideslip angles, and a low level of wheel and rudder pedal activity for the basic configuration.

Augmented Variable-Geometry Configuration

Although the Dutch roll damping was considered to be good for the basic configuration, the tests were conducted in smooth air and it was believed that greater damping would be desirable for more severe conditions. Therefore, a sideslip rate damper, as described in references 2 and 3, was used to increase the effective value of the parameter $C_{n_{\dot{\beta}}}$ from 0 to 0.086 to increase the damping ratio from 0.18 for the basic configuration to 0.28 for the augmented configuration with practically no change in the other lateral-directional characteristics.

Generally, there was no signficant change in the characteristics of the augmented configuration compared with the basic configuration other than a small increase in adverse sideslip during heading changes. Although the reason for this sideslip increase was not apparent, it was not felt to be important enough to warrant further flight testing to determine the exact cause since the handling qualities of the configuration were still considered to be good. The increase in Dutch roll damping was not significant since it had been well damped for the basic condition. The workload was found to be low and the pilot ratings for this configuration averaged 3.25 compared with 3.0 for the basic configuration, mainly because of the slight loss in heading-change precision due to adverse sideslip of the augmented configuration.

Static lateral-directional stability characteristics.- Since the augmentation did not affect the static stability characteristics, they are the same as for the basic variable-geometry configuration shown in figure 5-1(a).

Dynamic lateral stability characteristics.- The characteristics of the Dutch roll oscillation are illustrated in figure 5-2(b). The records show the oscillation to be well damped but the period is slightly longer than that for the basic configuration. The data of figure 5-6 show the damping to be good and the ratio of roll angle to side velocity to be lower than that for the basic configuration. Although the damping was higher, the pilots did not note any appreciable differences due to the improved Dutch roll characteristics on the handling qualities of the airplane, probably because the stability of the basic configuration was good and because the effects of the augmentation would probably have been more beneficial in rough air than in the relatively smooth air in which the flight tests were conducted.

The spiral and roll-subsidence modes were virtually the same as those for the basic configuration as shown in table 5-2.

Lateral control characteristics.- The roll-rate and roll acceleration characteristics of the augmented configuration were not noticeably affected by the sideslip rate damper and were essentially the same as those for the basic configuration. In the flight evaluations, however, two of the three pilots who evaluated the augmented configuration noted that the heading-change response was not quite as good as that for the basic configuration because of a slight increase in heading lag; this heading-lag increase (there had been a slight heading lag noted for the basic configuration) was attributed to a larger adverse sideslip in the turns. There is no apparent explanation for the increase in sideslip resulting from the augmentation because the sideslip rate damper should have reduced the sideslip angle rather than increased it. In spite of the increased heading lag, however, the pilots who noted it felt that the precision in the turns was still good and the average Cooper rating was only downgraded from 3.0 for the basic configuration to 3.25.

Landing approach.- The lateral-directional control activity and airplane displacements for a typical approach are presented for the augmented variable-geometry configuration in figure 5-4. The wheel displacements appeared to be a little smaller for the augmented configuration than for the basic configuration but otherwise the records for the two cases are generally the same. The workload was found to be low.

Degraded Variable-Geometry Configuration

In order to broaden the scope of the investigation, the lateral directional characteristics of both the variable-geometry and the fixed-geometry configuration were degraded to determine the effect, if any, on the handling qualities of airplanes of the size of these supersonic transport configurations. To obtain the desired characteristics, the damping of the Dutch roll oscillation was reduced and the adverse yaw due to rolling velocity was increased. A sideslip rate damper was used to increase the effective value of $C_{n_{\dot{\beta}}}$ (from 0 to -0.1204) and the rolling moment due to rolling velocity parameter was made more negative (from -0.023 to -0.076); as a result, the Dutch roll damping ratio was reduced to 0.05 and the desired degree of adverse yaw was obtained.

The pilots found that the principal results of the degraded characteristics compared with the basic variable-geometry configuration were a moderate increase in workload (especially when close to touchdown) and a reduction in heading-change precision. This configuration was given a Cooper rating of about 4.4.

Static lateral-directional stability characteristics.- The degradation affected only the Dutch roll characteristics; thus, the static stability characteristics are the same as those for the basic variable-geometry configuration. (See fig. 5-1(a).)

Dynamic lateral stability characteristics.- The characteristics of the Dutch roll oscillation for the degraded variable-geometry configuration are shown in figure 5-2(c). The damping is seen to be low and the period of the oscillation practically unchanged from the basic configuration. The pilots stated that the oscillation was easily excited by abrupt or moderate lateral control and seemed to be present most of the time. The data of figure 5-6 show that this configuration has damping and a ratio of roll angle to side velocity similar to present-day large subsonic jet transports but, like the basic configuration, has a lower frequency.

The spiral stability appeared to be neutral to the pilots and the roll-subsidence time constant was still desirably low. The calculated values for these modes are presented in table 5-2 and show no significant differences from the basic configuration.

Lateral control characteristics.- The variations of maximum roll rate and maximum roll acceleration with wheel position show that the degradation had virtually no effect on the acceleration but reduced the peak roll rate per degree wheel deflection to about 80 percent of that for the basic configuration (compare roll rates in figs. 5-3(a) and 5-3(b)), probably because of the increased adverse sideslip in combination with the fairly high dihedral effect. In addition, the roll rates were found to be oscillatory because of the effects of the lightly damped Dutch roll oscillation. The lateral control power was judged to be more than adequate but there was an appreciable heading lag due to the larger adverse yaw due to rolling velocity of the degraded configuration. The precision in heading changes was relatively poor and coordination with the rudder was found to be difficult.

Landing approach.- Typical time histories of control activity and airplane displacements for landing approach are presented in figure 5-4. These records show more rudder activity and larger sideslip displacements over most of the approach for the degraded than for the basic configuration but otherwise there were no significant differences. The increase in rudder activity is evidence of the difficulty in coordinating the rudder and wheel noted by both pilots.

In general, the workload was not found to be high in the approach, although it was higher than that for the basic variable-geometry configuration. The workload was not higher because throughout most of the approach, the pilots preferred to concentrate on keeping on the localizer and they permitted the airplane to oscillate, knowing that the Dutch roll motion was stable even if lightly damped. Only when the airplane neared touchdown was the Dutch roll motion closely controlled by the pilot to assure a good landing. The workload in this configuration, however, would probably be very sensitive to turbulence and would require more attention throughout the entire approach, especially when the comfort of the passengers is a consideration.

Variable-Geometry (Emergency Landing) Configuration

The variable-geometry configuration with wings at maximum or cruise sweep angle is an emergency landing configuration and, as such, was investigated only briefly to determine whether it would be flyable. Only one pilot flew and evaluated this configuration.

In general, the lateral-directional characteristics of the variable-geometry (emergency landing) configuration were unsatisfactory because of the weak roll control, large positive dihedral, and low Dutch roll damping. This configuration, however, was considered to be acceptable for emergency operation and was given a rating of 5.5.

Static lateral-directional stability characteristics.- The lateral-directional static stability characteristics obtained from flight in steady sideslip are shown in figure 5-1(b).

The largest difference in static characteristics between the variable-geometry (emergency landing) and the variable-geometry configurations previously described is the much lower lateral control effectiveness of emergency landing configuration. Otherwise, the data of figure 5-1(b) show that this configuration has good directional stability and positive effective dihedral. Qualitatively, the pilot found the directional stability to be fairly high; the effective dihedral, very high; and the lateral control, weak.

Dynamic lateral-directional stability characteristics.- The characteristics of the Dutch roll oscillation of the variable-geometry (emergency landing) configuration are illustrated in figure 5-2(d). The frequency and damping characteristics of the Dutch roll oscillation are shown in figure 5-7. The oscillation has fairly low damping ($\zeta = 0.09$), a high frequency $\left(\omega_d = 1.4\right)$, and a high ratio of roll angle to sideslip velocity $\left(\frac{\phi}{v_e} = 0.48\right)$ relative to the other configurations investigated and to current large jet transports. The Dutch roll damping appeared to be low to the pilot, and there was a tendency with normal frequency of control inputs to sustain the oscillation rather than to dampen it. Based only on the Dutch roll characteristics, the pilot assigned a rating of 4.5 to this configuration.

The spiral stability of the variable-geometry (emergency landing) configuration was high probably because of the high effective dihedral. The roll-subsidence mode was not heavily damped and had a roll-time constant of 1.7 seconds. The pilot could not estimate the roll damping because of the low damping of the Dutch roll oscillation. The high ratio of roll to yaw of the Dutch roll oscillation is also attributed to the low roll damping in addition to the high effective dihedral and to some extent to the appreciable decrease in the roll inertia.

Lateral control characteristics.- The variations of maximum rolling velocity and maximum rolling acceleration with wheel deflection are shown in figure 5-3(c) for the variable-geometry (emergency landing) configuration. The roll rate per degree wheel displacement is about the same as that for the basic variable-geometry configuration but the roll acceleration per degree wheel displacement of the cruise configuration is only about one-third that of the basic variable-geometry configuration. The responses to a wheel step control for the two configurations (basic and emergency landing) are compared in figure 5-8(a) to illustrate the poor response characteristics of the cruise configuration. The response to a 10° wheel input of the basic variable-geometry configuration shows a steady increase in roll angle, a maximum roll rate of about 3° per second initially which reduces gradually to about 2° per second in the interval shown, and a moderately large resulting sideslip angle. The variable-geometry (emergency landing) configuration, however, reaches approximately the same maximum roll rate initially but then the roll rate decreases to about zero because of the influence of the high effective dihedral; the oscillatory character of the motion is attributed to the fact that the Dutch roll mode was excited during the maneuver. This record also illustrates the pilot's comment that continuous wheel displacement was required to maintain the desired roll angle. (See table 5-1.) Because of the high effective dihedral of this configuration, the rudder was found to provide good roll control and could be used in conjunction with the wheel for this purpose (see fig. 5-8(b)); this combination might not always provide satisfactory roll control as will be pointed out under the discussion of the landing approach.

Landing approach.- The lateral-directional control activity and airplane displacements for a typical approach and landing are presented for the variable-geometry (emergency landing) configuration in figure 5-4. These time histories show relatively small localizer deviations, small bank and sideslip angles, a low level of rudder pedal activity but that a relatively high level of wheel activity and fairly large wheel displacements were used to keep the airplane displacements small. The evaluation pilot observed that the combination of high effective dihedral and weak lateral control of this configuration could result in a dangerous condition near the ground in a cross-wind landing. In such a situation, the approach would probably be made in a crabbed attitude which requires a rudder control just before touchdown to aline the airplane with the runway. The resulting sideslip and effective dihedral will cause the airplane to roll, but with weak lateral control, it would be difficult to hold the wings level for the landing. To illustrate the effect of high roll response to changes in sideslip, the records of roll angle and sideslip angle following a rudder pulse are compared in figure 5-8(b) for the two basic variable-geometry configurations. These records show the roll response of the variable-geometry (emergency landing) configuration to be about twice that of the variable-geometry configuration although the sideslip angles are approximately the same.

Basic Fixed-Geometry Configuration

The basic fixed-geometry configuration represents a concept in which the basic airplane geometry is the same for all flight conditions. In general, the lateral-directional characteristics of the basic fixed-geometry configuration were good and were characterized by good Dutch roll damping, good directional stability, positive effective dihedral, and the lateral-directional workload in the approach and flare was low. On the other hand, the low damping of the roll mode required a little extra care to make precise heading changes. A little sideslip was also noted in turns but was probably not significant. The average pilot rating for the basic fixed-geometry configuration was 3.5. (See table 5-1.)

Static lateral-directional stability characteristics.- The lateral-directional static stability characteristics obtained from flight in steady sideslip are shown in figure 5-1(c). Qualitatively, the pilots' comments in table 5-1 indicate good agreement with these data in that they stated that the directional stability was good and the effective dihedral was positive. Several of the pilots commented that the effective dihedral was high and they attributed the rather high sensitivity to rolling motions to the dihedral effect when rudder was used to keep the wings level.

Dynamic lateral-directional stability characteristics.- The characteristics of the Dutch roll oscillation of the basic fixed-geometry configuration are illustrated in figure 5-2(e). The frequency and damping characteristics of the Dutch roll oscillation of this configuration are shown in figure 5-9. The Dutch roll oscillation of the basic fixed-geometry configuration is well damped, and this configuration has a ratio of roll angle to sideslip velocity ϕ/v_e and an undamped natural frequency representative of current large subsonic jet transports. Although the actual damped period for this supersonic transport configuration is a little longer (about 33 percent) than that for the subsonic transports, no unfavorable pilot comments were made about the longer period.

Although the spiral mode of the basic fixed-geometry configuration should have been divergent (see table 5-2), the flight records show that it was convergent. In general, the pilots noted that the spiral stability was either neutral or positive; pilot C thought that the positive spiral stability was good but pilot G indicated a preference for neutral spiral stability.

The principal pilot criticism of this configuration resulted from the roll mode damping which most of the pilots felt to be a little low. It was not a serious deficiency, however, because the average of the pilot ratings for this configuration was 3.5. For the roll-time constant of 0.8 (see table 5-2), this evaluation is consistent with the results summarized in reference 4, which are shown in figure 5-10. It should be pointed out, however, that the curves shown in figure 5-10 are for smaller airplanes and may not be strictly applicable for supersonic transport configurations.

Lateral control characteristics.- The variations of rolling velocity and rolling acceleration with wheel deflection are shown in figure 5-3(d) for the basic fixed-geometry configuration. Comparison of the data of figures 5-3(a) and 5-3(d) shows that the roll acceleration was a little higher and the roll rate per degree wheel deflection about twice as high for the basic fixed-geometry configuration as it was for the basic variable-geometry configuration. Most of the pilots liked the high initial response and roll rate but several thought it might be a little too sensitive. This result combined with the low damping in roll mentioned previously produced a tendency for the pilots to overshoot in the turn maneuvers which required a little extra attention to the controls. Several of the pilots also noted some heading lag and adverse sideslip in turns made with aileron-alone control.

Landing approach.- The lateral-directional control activity and airplane displacements for a typical approach and landing are presented for the basic fixed-geometry configuration in figure 5-5. These time histories show small roll and sideslip angles and a low level of wheel and rudder pedal activity for this configuration. Although the localizer command signal was rather large over most of the approach, it represents an angular deviation and the airplane was actually converging on the runway throughout the approach. It was therefore a reflection of pilot technique rather than an indication of difficulty in tracking.

Fixed-Geometry Augmented Configuration

The purpose of the lateral augmentation used on the fixed-geometry configuration was to improve the roll damping and thus to eliminate or reduce the tendency to overshoot in turn maneuvers. Ground-based simulator results indicated that a 50-percent increase in the damping-in-roll parameter $C_{l_{\dot{\phi}}}$ would be desirable and this increased damping in roll was used in the airplane. The increased damping in roll was accompanied by an increase in $C_{n_{\dot{\phi}}}$. The effect of this augmentation was to improve the heading-change precision compared with the basic configuration; accordingly, the average rating was improved to 2.75 from 3.5 for the basic configuration.

Static lateral-directional stability characteristics.- The increased roll damping did not affect the static stability characteristics and they are the same as those presented in figure 5-1(c) for the basic fixed-geometry configuration.

Dynamic lateral stability characteristics.- The characteristics of the Dutch roll oscillation are illustrated in figure 5-2(f). Comparison of the records of figure 5-2(f) with those of the basic fixed-geometry configuration in figure 5-2(e) shows very little difference between the Dutch roll characteristics of the two configurations. The data of figure 5-9 show that the measured damping was somewhat higher for the basic configuration than that for the augmented configuration but both were at a high level of damping. The augmentation also reduced the ratio of roll angle to side velocity and the undamped natural frequency about 10 percent.

Although the predicted spiral instability was reduced somewhat by the augmentation, it was essentially neutral and the effect would be negligible. As in the case of the basic fixed-geometry configuration, the actual spiral stability was positive; the convergence, however, was slower for the augmented configuration. The intended effect on the roll-subsidence mode was achieved and the roll-time constant was reduced from 0.80 second for the basic configuration to 0.57 second for the augmented configuration. (See table 5-2.)

Lateral control characteristics.- As expected, the roll rate was appreciably affected by the improved roll damping and reduced to about 75 percent of that for the basic fixed-geometry configuration. (See fig. 5-3(e).) The roll rate, however, was still considered to be good and the tendency to overshoot or undershoot in turns was eliminated, at least in the evaluation of two of the pilots who flew this configuration. On the other hand, although pilot C was aware of a slightly reduced roll rate, he could detect very little difference between the augmented and basic fixed-geometry configurations. This result suggests that a further increase in roll damping might be beneficial.

Landing approach.- The lateral-directional control activity and airplane displacements for typical approach are presented for the augmented fixed-geometry configuration in figure 5-5. In general, the control inputs given for the augmented configuration during the approach are fewer, the sideslip displacements are about the same, the roll displacements are more frequent, and localizer tracking is better than those for the basic fixed-geometry configuration. The workload was generally considered to be low in the approach and heading-change precision was improved over the basic configuration.

Degraded Fixed-Geometry Configuration

The fixed-geometry configuration was degraded in the same manner and to the same degree as the variable-geometry configuration and with essentially the same effect on the handling qualities, namely, a little higher workload and lower precision in making heading changes than for the basic configuration. Both pilots gave the degraded fixed-geometry configuration a rating of 4.5.

Static lateral-directional stability characteristics.- The degradation did not affect the static characteristics; thus they are the same as those for the basic fixed-geometry configuration which is given in figure 5-1(c).

Dynamic lateral stability characteristics.- The characteristics of the Dutch roll oscillation for the degraded fixed-geometry configuration are shown in figure 5-2(g). The damping is low and the period of the oscillation about 0.6 second shorter than the period of the basic configuration. The pilots reported less of a tendency to excite the oscillation when using normal controls for this configuration than for the degraded variable-geometry configuration, although rapid lateral controls did cause the airplane to oscillate.

The spiral mode appeared to be neutral or slightly convergent; this result is about the same as that for the basic configuration which was slightly convergent. The pilots indicated that the roll damping was not quite as good as that for the basic configuration and the calculated roll time constant shown in table 5-2 is about 10 percent higher for the degraded configuration.

Lateral control characteristics.- The roll-acceleration characteristics for the degraded fixed-geometry configuration are virtually the same as for the basic fixed-geometry configuration but the roll rate is appreciably higher as shown by comparison of figures 5-3(d) with 5-3(f). This result is evidence of the lower roll damping which was previously noted in the discussion of the roll-subsidence mode. The principal objection to the lateral control was the lack of precision in making heading changes and the appreciable adverse yaw associated with rapid heading changes.

Landing approach.- The lateral-directional control activity and airplane displacements for a typical approach are presented for the degraded fixed-geometry configuration in figure 5-5. It should be noted that random rudder inputs shown in figure 5-5(c) at about 25, 65, and 93 seconds were given by the safety pilot to simulate gust disturbances to help the evaluation pilot to assess the handling qualities of the condition. Except in response to these rudder inputs, the records show little difference from the other fixed-geometry configurations. The resulting work level for the degraded configuration was, however, a little higher than that for the basic configuration.

REQUIREMENTS AND CRITERIA

Because the number of tests was limited and no parametric studies were made, criteria could not be established for supersonic transports in the landing approach. From the results of the flight tests, however, it was determined which configurations were satisfactory and which were not, and these results are compared with existing criteria and with data relating pilot rating and various Dutch roll stability or roll-control characteristics. The pilot ratings used in figures 5-11 to 5-13 were estimated by the pilots by considering only the Dutch roll characteristics and are the average of the ratings of pilots A and B as given in table 5-1. This procedure was followed to make a direct comparison with the other data in these figures which correlate the Dutch roll oscillation characteristics with handling qualities.

Variation of Dutch roll damping with rolling parameter.- Figure 5-11 presents the existing lateral directional damping requirements defined in the military specifications of reference 5 by the reciprocal of the cycles required for the Dutch roll oscillation to damp to half-amplitude and the roll-to-side velocity ratio ϕ/v_e. The Dutch roll characteristics of the supersonic transport configurations of this program and of current large subsonic jet transports are compared with the requirements of figure 5-11. The pilot evaluations for the various supersonic transport configurations appear to be in good agreement with the boundaries shown in the figure. All but two of the supersonic transport configurations had the low ratios of roll to side velocity representative of the current jet transports; the degraded fixed geometry and variable-geometry (emergency landing) configurations have higher values and the corresponding ratios of roll to sideslip angle $\left(\frac{\phi}{\beta} = 1.6 \text{ and } 2.5\text{, respectively}\right)$ are above the value of 1.5 suggested as acceptable for the landing approach in reference 6.

Variation of Dutch roll frequency with damping ratio.- The Dutch roll damping and frequency characteristics of the configurations tested are compared in figure 5-12 with the lateral oscillation criteria proposed as a revision to the existing specifications of reference 5. Although the results of the flight tests for the fixed-geometry configurations generally are in agreement with the criteria of figure 5-12, the results for variable-geometry configurations are not consistent with the criteria.

The basic and augmented variable-geometry configurations were found to have good handling qualities (pilot evaluation ratings of 2.4 and 2.1, respectively, based on Dutch roll characteristics) but are located in the unacceptable region shown in figure 5-12. It is evident that the low frequencies of the lateral oscillations rather than the damping ratios are responsible for their locations with respect to the boundaries.

Variation of pilot rating with damping.- Pilot rating has recently been related to the damping parameter $\zeta\omega_d$ in several papers. (For example, see refs. 7 to 9.) The characteristics of the test configurations of this investigation are compared with data from references 7 and 8 in figure 5-13. The test points agree with the reference data except for the variable-geometry (emergency landing) configuration.

Several factors may have contributed to the rather poor pilot rating for this configuration. First, the Dutch roll oscillation always seemed to be present because it was excited by almost any control input as well as by external disturbances and, because of the relatively short period, there was a tendency for the pilot to sustain the oscillation rather than damp it. Second, the high ratio of roll to sideslip of the Dutch roll oscillation made it more objectionable. Finally, this configuration had several poor stability and control characteristics; thus it was the most difficult configuration in which to evaluate the Dutch roll independently of the other lateral-directional characteristics.

Spiral stability characteristics.- The only requirement given in the existing military specifications of reference 5 for the power-approach condition is that if the spiral motion is divergent, the rate of divergence shall not be so great that after a small disturbance in bank with controls fixed, the bank angle is doubled in less than 20 seconds in the power-approach condition. The calculated data of table 5-2 show that all the supersonic transport configurations met the requirement. The fixed-geometry configuration was actually slightly convergent and, as such, it would be considered to be satisfactory according to the military specifications.

The calculated values of the spiral damping are compared with the boundaries taken from reference 10 and presented in figure 5-14. All the configurations are shown to be satisfactory according to the boundaries of figure 5-14. With one exception, the variable-geometry (emergency landing) configuration, the spiral stability characteristics were found to be satisfactory by the evaluation pilots; the strong spiral stability of the variable-geometry (emergency landing) configuration, resulting from the high effective dihedral, caused poor lateral control characteristics in that bank angle could not be maintained without holding continuous, or even increasing, wheel displacement. Reference 10, however, suggests that $T_{1/2}$ or T_2 should be greater than 14 seconds for satisfactory spiral stability characteristics; if this recommendation is applied to the variable-geometry (emergency landing) configuration $\left(T_{1/2} = 12 \text{ seconds}\right)$, it would only be considered acceptable.

Cross-coupling characteristics.- Figure 5-15 is taken from reference 7 and relates pilot rating with the aileron yaw parameter ω_{ϕ}/ω_{d}. Values for ω_{ϕ}/ω_{d} shown in figure 5-15 were calculated by using the derivatives given in reference 2 and table 2-2 and the approximate expressions presented in the appendix of reference 11.

The characteristics of these three basic configurations are in good agreement with the variation shown by the band representing the results of previous investigations. All configurations had values less than 1.0 and thus had unfavorable yaw due to aileron since all had positive effective dihedral. (See ref. 12.) In spite of the large increases in yaw-to-roll moments of inertia (3 to 4 times) of the supersonic transport compared with the subsonic transports, no unusual roll-yaw coupling effects were noticed for the supersonic transport configurations at the approach speeds of these tests.

Reference 12 relates pilot opinion to the aileron coupling parameter $N'_{\delta a}$ and the Dutch roll damping ratio ζ as shown in figure 5-16. The configurations of the present investigation shown in the figure agree fairly well with the data of reference 12. Again, all the values of the aileron coupling parameter $N'_{\delta a}$ are positive and indicate adverse aileron yaw.

Roll-response characteristics.- The variation of pilot rating with roll-time constant as shown in reference 4 is presented in figure 5-10 and compared with the corresponding characteristics for the supersonic transport configuration of this investigation. The two curves in figure 5-10 represent fairings of test points from several investigations using ground-based simulators and from flight tests. Although the curves represent results for fighter and reentry vehicles, the data of this investigation are generally in agreement with the trends of figure 5-10. The pilot evaluation-rating number for the variable-geometry (emergency landing) configuration appears to be high according to the criteria suggested by the reference curves, but the evaluation was influenced not only by the long roll-time constant but also by the low roll power, as previously discussed, and by the adverse aileron yaw characteristics indicated in figures 5-15 and 5-16.

The roll-response characteristics of both the basic fixed-geometry and variable-geometry configurations were considered to be good and typical roll-response records are shown in figure 5-17. The variable-geometry curve was taken directly from test records and the fixed-geometry curve was extrapolated from flight records of a response to a 10° wheel input because the simulation for this case was only valid up to wheel displacements of 15°. Examination of the roll responses of these configurations shows that the roll performance of these configurations exceeded the minimums indicated in reference 4 from an analysis of available data for large airplanes in approach conditions. The two criteria offered are: (1) the time to bank to 30° of about 3.5 seconds seems to be the maximum acceptable and values below about 3.0 seconds are considered satisfactory; and (2) that the minimum acceptable roll rate can apparently be as low as 12° per second. The basic variable-geometry configuration should be considered satisfactory since it reached a bank angle of 30° in 3.0 seconds. The basic fixed-geometry configuration required a little longer, 3.2 seconds, to reach a bank angle of 30° and would be acceptable and also not far from satisfactory. The roll rates of 13° per second for the variable-geometry configuration and 20° per second for the fixed-geometry configuration shown in figure 5-17 are both above the minimum acceptable rate of 12° per second and it should be pointed out that the actual supersonic transport airplane will probably have more control power available than that provided by the 30° wheel deflection used to determine the roll rates for the simulated airplanes.

CONCLUDING REMARKS

The lateral-directional results of the investigation of the low-speed handling qualities of three supersonic transport configurations are summarized by configuration.

Variable-Geometry Configuration

The lateral-directional characteristics of the basic variable-geometry configuration were good and were characterized by adequate Dutch roll damping, good directional stability, positive effective dihedral, good roll response, roll damping, heading-change precision, and low workload; the relatively long period of the Dutch roll oscillation did not appear to be objectionable to the pilots. The basic variable-geometry configuration was given an average Cooper pilot opinion rating of 3.0.

The lateral-directional characteristics of the variable-geometry configuration were degraded to determine the effect of such characteristics on the handling qualities of airplanes the size of these supersonic transport configurations. The characteristics were degraded by reducing the Dutch roll damping ratio from 0.18 for the basic configuration to 0.05 and increasing the adverse yaw due to rolling velocity. The principal results of the degraded characteristics were a moderate increase in workload, especially near touchdown, and a reduction in heading-change precision. This configuration was given an average Cooper rating of 4.5 compared with 3.0 for the basic configuration.

Variable-Geometry (Emergency Landing) Configuration

The lateral-directional characteristics of the variable-geometry (emergency landing) configuration were unsatisfactory because of weak roll control, large positive dihedral effect, and low Dutch roll damping. This configuration was, however, considered to be acceptable for emergency operation and was given a Cooper rating of 5.5.

Fixed-Geometry Configuration

The lateral-directional characteristics of the basic fixed-geometry configuration were good and were characterized by good Dutch roll damping, good directional stability, positive effective dihedral, and low workload in the approach although the damping in roll was low and a little extra care was required to make precise heading changes. This configuration was given an average Cooper rating of 3.5.

The lateral-directional augmentation consisted of a 50-percent increase in the damping-in-roll parameter $C_{l_{\dot{\phi}}}$ to eliminate the tendency to overshoot or undershoot in turn maneuvers. The augmented fixed-geometry configuration was given an average Cooper rating of 2.8 on the basis of reduction in effort required to make precise heading changes.

The lateral-directional characteristics of the fixed-geometry configuration were degraded in the same way and to the same degree as were those of the variable-geometry configuration with essentially the same effect on the handling qualities, namely, a moderate increase in workload over the basic configuration and a reduction in heading-change precision. This configuration was given an average Cooper rating of 4.5 compared with 3.5 for the basic fixed-geometry configuration.

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TABLE 5-1.- SUMMARY OF FLIGHT-TEST CONFIGURATIONS AND RESULTS

Parameters varied	Pilot	Lateral-directional pilot ratings (Cooper scale)		Pilot's comments
		Overall	Dutch roll	
				Variable-geometry configuration; $\zeta = 0.18$
$C_{n_{\dot{\beta}}} = 0$ $C_{n_{\dot{\phi}}} = -0.022$	A	3.0	2.5	Stability: (a) Dutch roll oscillation seems to be mostly in yaw with little noticeable roll; appeared to damp in 1 to $1\frac{1}{2}$ cycles. No tendency to be excited in normal maneuvers. (b) Spiral stability seemed neutral. (c) Positive directional stability. Maneuverability: (a) Roll response is excellent. Roll damping high. (b) Heading-change precision within about 1°. Slight heading lag at low rates of roll became noticeably large at high rates of roll. Work level in the approach and flare is low.
	B	3.0	2.0 to 2.5	Stability: (a) Dutch roll damping is very good, appears to be almost all yaw and little roll, $\beta/\phi = 3$ to 4; damped in 1 to $1\frac{1}{2}$ cycles. No tendency to be excited in normal maneuvers. (b) Spiral stability was neutral or slightly divergent. (c) Very good directional stability and positive effective dihedral. Maneuverability: (a) Roll rate very good; maximum wheel not used because rates available with small inputs were adequate. Roll damping quite acceptable. (b) Heading-change precision acceptable, about 1° to 2°. Slight heading lag noted. High adverse sideslip noted in turns. Work level in the approach and flare is minor.
	C	2.0	--------	Stability: (a) Dutch roll damping very good; rolling is the predominant motion but is not excessive. Tendency toward excitation in normal maneuvers is very small. (b) Spiral stability not noted. (c) Good directional stability and effective dihedral appeared positive and normal; not easy to keep wings level with rudder alone because of long response time. Maneuverability: (a) Roll response appears to be good with no detectable adverse yaw but some adverse sideslip; however, the behavior of the airplane following development of sideslip was good. Roll damping appeared to be good. (b) Heading-change precision was good; the adverse sideslip was no problem. Work level in the approach and flare low.

TABLE 5-1.- SUMMARY OF FLIGHT-TEST CONFIGURATIONS AND RESULTS – Continued

Parameters varied	Pilot	Lateral-directional pilot ratings (Cooper scale)		Pilot's comments
		Overall	Dutch roll	
				Variable-geometry configuration; $\zeta = 0.18$
$C_{n_{\dot{\beta}}} = 0$ $C_{n_{\dot{\phi}}} = -0.022$	D	3.0	--------	Stability: (a) Dutch roll damping appeared to be marginal because, although the oscillation damps to less than one-half amplitude in 1 cycle, the period was relatively long (10 seconds) so the time to damp was longer than desired. The motion was predominantly yawing. There was a tendency to excite an oscillation but the pilot was relatively unconscious of it because of the long period and lack of any side force in the cockpit. (b) Directional stability was satisfactory and the effective dihedral was mildly positive and satisfactory. Maneuverability: (a) Roll response: initial response was satisfactory and rate of roll was good. Roll damping was satisfactory. (b) Heading-change precision was good; no appreciable heading lag although there was a definite tendency to sideslip in maneuvers. Work level in approach and flare was low.
	E	3.0	--------	Stability: (a) Dutch roll damping was good with a sideslip-to-roll ratio of about 2. There was no tendency to excite the oscillation in normal maneuvers. (b) Spiral stability was neutral. (c) Directional stability was fair to good and the effective dihedral was positive. Maneuverability: (a) Roll response: initial response was good and rate of roll satisfactory. Roll damping was fair to good. (b) Heading-change precision was within about $1\frac{1}{2}^{\circ}$. There appears to be no adverse heading change on the turn indicator but adverse sideslip noted on sideslip indicator. Work level in the approach and flare was normal.
	F	3.0	--------	Stability: (a) Dutch roll damping was almost deadbeat, damping completely in less than 1 cycle. The sideslip-to-roll ratio was about 1 and the roll lagged the yaw by 2 to 3 seconds. No tendency to excite the oscillation in the very smooth air encountered on this flight. (b) Directional stability: returned from 10° to trim properly; dihedral effects were positive to 10° of sideslip but preferred less dihedral than airplane had. Maneuverability: (a) Roll response: initial response was 6° to 7° in the first second and the rate of roll seemed to be at least 20° to 25° per second. Roll damping permitted roll to precise bank angles. (b) Heading-change precision was satisfactory; tendency to sideslip was relatively large but rudder response was so slow that no rudder given to coordinate turns. Slightly objectionable but did not seem to interfere with other tasks. Work level in the approach and flare was very low laterally and none on the rudder.

TABLE 5-1.- SUMMARY OF FLIGHT-TEST CONFIGURATIONS AND RESULTS – Continued

Parameters varied	Pilot	Lateral-directional pilot ratings (Cooper scale)		Pilot's comments
		Overall	Dutch roll	
				Variable-geometry configuration; $\zeta = 0.18$
$C_{n_{\dot{\beta}}} = 0$ $C_{n_{\dot{\phi}}} = -0.022$	G	3.0	--------	Stability: (a) Dutch roll damping was very good, 2 cycles to damp to zero roll rate. Perceptible motion is primarily rolling and sideslip noted from sideslip indicator only. The tendency to excite the oscillation in normal maneuvers was very slight. (b) Directional stability was low and the effective dihedral was satisfactory. Maneuverability: (a) Roll response felt to be too high initially (roll control forces are a little low and the roll acceleration was too high for small aileron inputs). Care required to fly the airplane smoothly on turn entries. Some tendency to sideslip in maneuvers. Roll damping was good. (b) Heading-change precision: overshoot or undershoot was the order of 1°, 2°, or 3° depending on the turn entry rate and roll out rate as a result of the sideslip generated. Work level is normal in the approach but fairly high in the flare because of the high wheel activity resulting from overcontrolling.
				Augmented variable-geometry configuration; improved Dutch roll damping: $\zeta = 0.28$
$C_{n_{\dot{\beta}}} = 0.086$ $C_{n_{\dot{\phi}}} = -0.022$	A	3.5	2.0	Stability: (a) Dutch roll damping was very high, oscillation disappeared in 1 cycle. The motion appears to be mostly yawing. No apparent tendency to excite the oscillation in normal maneuvers. (b) Spiral stability was neutral. (c) Directional stability apparently lower than for basic configuration because of rather sluggish return from steady sideslip. Dihedral effect was positive. Maneuverability: (a) Roll response was quick with a high initial rate and good roll damping. (b) Heading changes are slower than for the basic configuration because of larger initial adverse sideslip and heading lag. Precision was good. Trace of adverse lateral acceleration in turn entries. Work level was low with no appreciable difference from the unaugmented configuration. Lift-drag controllability has been downgraded because of the increased sideslip on turn entries and trace of adverse lateral acceleration. Tendency to fly sideslipped several degrees.
	B	3.0	2.0 to 2.5	Could not tell any appreciable difference between this configuration and the basic configuration; especially during approach could not tell any difference.
	C	2.5	--------	Stability: (a) Dutch roll damping was very good with the same roll-to-yaw ratio as for the basic configuration (predominantly roll). Tendency to excite the oscillation in normal maneuvers is very little. (b) Directional stability and effective dihedral were both good; comment on holding wings level with rudder alone same as for 20° basic configuration. Maneuverability: (a) Roll response was good both initial rate and maximum rate. The roll damping was good. (b) Heading-change response was good but not quite as good as for the basic configuration because there was a little tendency toward motions of the airplane in terms of residual oscillation. The work level in the approach was low.

TABLE 5-1.- SUMMARY OF FLIGHT-TEST CONFIGURATIONS AND RESULTS – Continued

Parameters varied	Pilot	Lateral-directional pilot ratings (Cooper scale)		Pilot's comments
		Overall	Dutch roll	
		Degraded variable-geometry configuration; low Dutch roll damping and higher adverse yaw; $\zeta = 0.05$		
$C_{n_{\dot{\beta}}} = -0.120$ $C_{n_{\dot{\phi}}} = -0.076$	A	4.0 to 4.5	4.0	Stability: (a) Dutch roll damping was very low or neutral; oscillation appeared to have no damping; the rolling motion could be damped in about $1\frac{1}{2}$ cycles with lateral control and the yawing motion would damp in about 2 cycles more with control fixed. Initially, the roll-to-yaw ratio was about 2:1 or 3:1 decreasing to about 1:1 after 3 cycles. The oscillation was excited by any abrupt wheel input or by any wheel input of greater than 5°. (b) Spiral stability appeared to be neutral. (c) Directional stability was somewhat masked by the Dutch roll oscillation but appeared to be not as stable as basic configuration. Dihedral effect was positive. Maneuverability: (a) Roll response: initial rate is adequate with no apparent lag in buildup of roll rate and apparent small time constant. A very pronounced heading lag noted. The maximum roll rate oscillates because of the sideslip and dihedral effect. (b) Heading changes are difficult to make because of the heading lag (about 2 seconds) and the precision is only about 3° to 4°. Difficult to coordinate with rudder, also. Work level not found to be high in the approach, although not as low as for basic variable-sweep configuration.
	B	4.5	4.5 to 5.0	Stability: (a) Dutch roll damping noted to be low but stable, with a roll-to-yaw ratio of about 2:1. The oscillation was easily excited in normal maneuvers and seemed to be present almost all the time. (b) Spiral stability seemed to be neutral. (c) It was fairly difficult to hold steady sideslip because of the Dutch roll oscillation. The dihedral effect seemed quite positive. Maneuverability: (a) Roll response: the initial rate seemed to lag a bit; 20° wheel gives all the roll rate required. Slight adverse yaw but quite a bit of adverse sideslip. (b) Heading changes were very difficult to make more precisely than 3° to 5° in a rapid turn; rudder was used but was difficult to coordinate. Work level is very low at the start of the approach letting the airplane oscillate until close to the ground to go VFR. Work load increases accordingly and is greater than for the basic configuration.

TABLE 5-1.- SUMMARY OF FLIGHT-TEST CONFIGURATIONS AND RESULTS – Continued

Parameters varied	Pilot	Lateral-directional pilot ratings (Cooper scale)		Pilot's comments
		Overall	Dutch roll	
				Variable-geometry configuration (emergency landing); $\zeta = 0.17$
	A	5.5	4.5	Stability: (a) Dutch roll damping was low and the period was short enough for a tendency to sustain the oscillation rather than damp it. It is chiefly a rolling oscillation which is excited by almost any external disturbance or control input. Hard to estimate roll damping because of Dutch roll presence all the time. (b) The spiral mode was extremely stable and because of this there was no divergence as the roll angle was always around zero in spite of the low Dutch roll damping. (c) Directional stability seemed fairly high and there was a large positive dihedral effect. Maneuverability: (a) Roll response to wheel was sluggish and oscillatory because of the influence of the Dutch roll and because the strong spiral stability arrested the roll rate; continuous wheel was required to maintain a desired bank angle. (b) Heading response: some heading lag noted the precision low because Dutch roll so easily excited and limits accuracy to 2° to 3°. The time for completion of a turn is longer than that for the basic variable-geometry configuration but not unacceptable. (c) Because of the high effective dihedral, rudder generated a high roll rate which could be extremely dangerous near the ground in decrabbing from sideslip in a cross-wind landing. Work level was high.
				Fixed-geometry configuration; $\zeta = 0.38$
$C_{l_{\dot{\phi}}} = -0.044$ $C_{n_{\dot{\phi}}} = -0.005$ $C_{n_{\dot{\beta}}} = 0$	A	3.5	2.5	Stability: (a) Dutch roll was well damped with a roll-to-yaw ratio of about 2:1 and no apparent tendency to be excited in normal maneuvers. (b) Spiral stability was positive. (c) Directional stability and dihedral effect are positive. Maneuverability: (a) Roll response: initial response is high, almost too sensitive in roll response; roll control power also is high. Roll damping is low and requires some attention to control; tendency to overshoot. (b) Heading changes: small adverse sideslip. Work level is low in the approach.
	B	3.5	2.5 to 3.0	Stability: (a) Dutch roll damping did not seem as high as for the basic variable-geometry configuration. The roll-to-yaw ratio was about 1:1. There was a tendency toward excitation of the oscillation in normal maneuvers. (b) Spiral mode seemed to be neutral or slightly divergent. (c) Directional stability and effective dihedral were positive. Maneuverability: (a) Roll response: initial response was good but roll damping was low. (b) Heading changes: small adverse yaw in turn entries. Work level is low in the approach.

TABLE 5-1.- SUMMARY OF FLIGHT-TEST CONFIGURATIONS AND RESULTS – Continued

Parameters varied	Pilot	Lateral-directional pilot ratings (Cooper scale)		Pilot's comments
		Overall	Dutch roll	
				Fixed-geometry configuration; $\zeta = 0.38$
$C_{l_{\dot{\phi}}} = -0.044$ $C_{n_{\dot{\phi}}} = -0.005$ $C_{n_{\dot{\beta}}} = 0$	C	3.5	--------	Stability: (a) Dutch roll damping was good with a fairly high roll-to-yaw ratio. Some tendency to over-control in roll on turn entries and recoveries. (b) Spiral stability was positive and good. (c) Directional stability seemed good and dihedral was positive to extent that it was difficult to prevent an oscillation using rudder alone to keep wings level. Maneuverability: (a) Roll response: initial response was adequate and maximum rate seemed higher than needed, but not objectionable. Roll damping seemed a little low. (b) Heading change: adverse sideslip caused heading lag following bank but could be coordinated with a little rudder. Precision downrated a little because of tendency to overshoot or under-shoot in roll. Work level was moderate in the approach.
	D	3.5	--------	Stability: (a) Dutch roll damping was good. Initially the motion is yawing and the roll-to-yaw ratio appears to be low. The rolling motion lags the yawing motion. There was a minor tendency to excite the Dutch roll in normal maneuvers. (b) Directional stability was good and the effective dihedral positive and higher than desired. Maneuverability: (a) Roll response: initial response was very good but sensitivity was too high. The rate of roll was very good but the roll damping was lower than desirable, but did not seem to cause any real problem. There was a mild adverse yaw. (b) Heading-change response appeared satisfactory although the high lateral sensitivity was adverse. Some oscillatory tendencies during rapid entries and in roll-outs, probably due to high lateral sensitivity and high dihedral effect. Work level in approach estimated to be satisfactory but no landings actually made because of high level of turbulence.
	E	3.5	--------	Stability: (a) Dutch roll damping was fair and seemed to damp to 3 to 4 cycles; roll displacement is more apparent than sideslip, particularly in cross-wind landing, with a tendency to set up pilot-induced oscillation. (b) Spiral stability was neutral and that was desirable. (c) Directional stability was very good and the effective dihedral was positive. Maneuverability: (a) Roll response: initial response was rapid and roll rate was excellent. Also noted that the roll-generating capability using rudder was good. (b) Heading changes: a definite heading lag was noted – sizable roll angle established before airplane starts turning. A large longitudinal deceleration noted in turns. Work level was less under the hood than visual, probably because of greater attention to the instruments.

TABLE 5-1.- SUMMARY OF FLIGHT-TEST CONFIGURATIONS AND RESULTS – Continued

Parameters varied	Pilot	Lateral-directional pilot ratings (Cooper scale) Overall	Dutch roll	Pilot's comments
				Fixed-geometry configuration; $\zeta = 0.38$
$C_{l_{\dot{\phi}}} = -0.044$ $C_{n_{\dot{\phi}}} = -0.005$ $C_{n_{\dot{\beta}}} = 0$	F	3.0	--------	Stability: (a) Dutch roll damping appears to be deadbeat with a roll-to-yaw ratio of 1.5:1 and did not notice very much lag between roll and yaw as had for the basic variable sweep. No tendency to excite Dutch roll oscillation in normal maneuvers. (b) Spiral stability was neutral in one direction and positive in the other indicating slightly positive. (c) Directional stability was good and dihedral effect was positive. Maneuverability: (a) Roll response: initial response was quite satisfactory and the roll rate seemed to be above 20° per second. (b) Heading response was good in turn entries with no oscillatory tendency in turns. Work level was low, all on wheel and none on rudder.
	G	4.0	--------	Stability: (a) Dutch roll damping - no comment because of computer malfunction at the time this was being evaluated without pilot realizing that the simulation was in error. (b) Spiral stability was positive but neutral preferred. (c) Directional stability seemed low and the dihedral was moderate. Maneuverability: (a) Roll response: extremely responsive initially. The roll accelerations were excessive and the rate of roll was too high for normal control inputs. Roll damping was fair. (b) Heading changes: some lag in heading response on turn entry and exit and too much sideslip generated in steady turns. No oscillatory tendency noticed. Felt that precision might be poor in rough air due to overshoot and undershoot or springback in heading after turn. Because of very gusty air near the ground, no landings were made; one simulated VFR approach was made from 3,000 feet to 1,500 feet altitude.
				Fixed-geometry augmented configuration; increased damping in roll; $\zeta = 0.38$
$C_{l_{\dot{\phi}}} = -0.070$ $C_{n_{\dot{\phi}}} = -0.015$ $C_{n_{\dot{\beta}}} = 0$	A	3.0	2.5	Stability: (a) Dutch roll oscillation was well damped with a roll-to-yaw ratio of about 1:1. The oscillation was not excited by normal controls. (b) Spiral stability was positive with a very slow convergence rate. (c) Directional stability is high and the effective dihedral is positive. Maneuverability: (a) Roll response was good and roll damping was high. (b) Heading changes: there was a smaller heading lag than for the basic configuration. The precision was good, within 1° and there was no noticeable overshoot or undershoot. Work level was low.

TABLE 5-1.- SUMMARY OF FLIGHT-TEST CONFIGURATIONS AND RESULTS – Continued

Parameters varied	Pilot	Lateral-directional pilot ratings (Cooper scale) Overall	Dutch roll	Pilot's comments
Fixed-geometry augmented configuration; increased damping in roll; $\zeta = 0.38$				
$C_{l_{\dot{\phi}}} = -0.070$ $C_{n_{\dot{\phi}}} = -0.015$ $C_{n_{\dot{\beta}}} = 0$	B	2.5	2.0 to 2.5	Stability: (a) Dutch roll damping was good with a roll-to-yaw ratio of 3 or 4:1. No tendency noticed to exciting the oscillation by normal maneuvering control inputs. (b) Spiral stability seemed to be slightly positive. (c) Directional stability was good and the effective dihedral was high. Maneuverability: (a) Roll response: initial response was good and roll rate was much more than adequate. The roll damping was good. (b) Heading changes could be made rapidly and with good precision. Work level was very low.
	C	3.5	--------	Stability: (a) Dutch roll damping was good with a high roll to yaw ratio. There was little tendency to excite the oscillation by normal use of controls except moderate sideslip is developed. (b) Spiral stability was positive and good. (c) Directional stability was same as for basic configuration - good and the effective dihedral positive. Maneuverability: (a) Roll rate: initial rate was good; maximum rate was good; roll response seems less than for the basic configuration. Roll damping was somewhat low. (b) Heading changes were found to be slow developing because of the adverse yaw and adverse sideslip but did not pose much of a problem. Small heading changes rated good but larger changes degraded some due to adverse yaw and tendency toward roll overshoot; requires normal use of rudder. Work level is just moderate, use of rudder for coordination required.

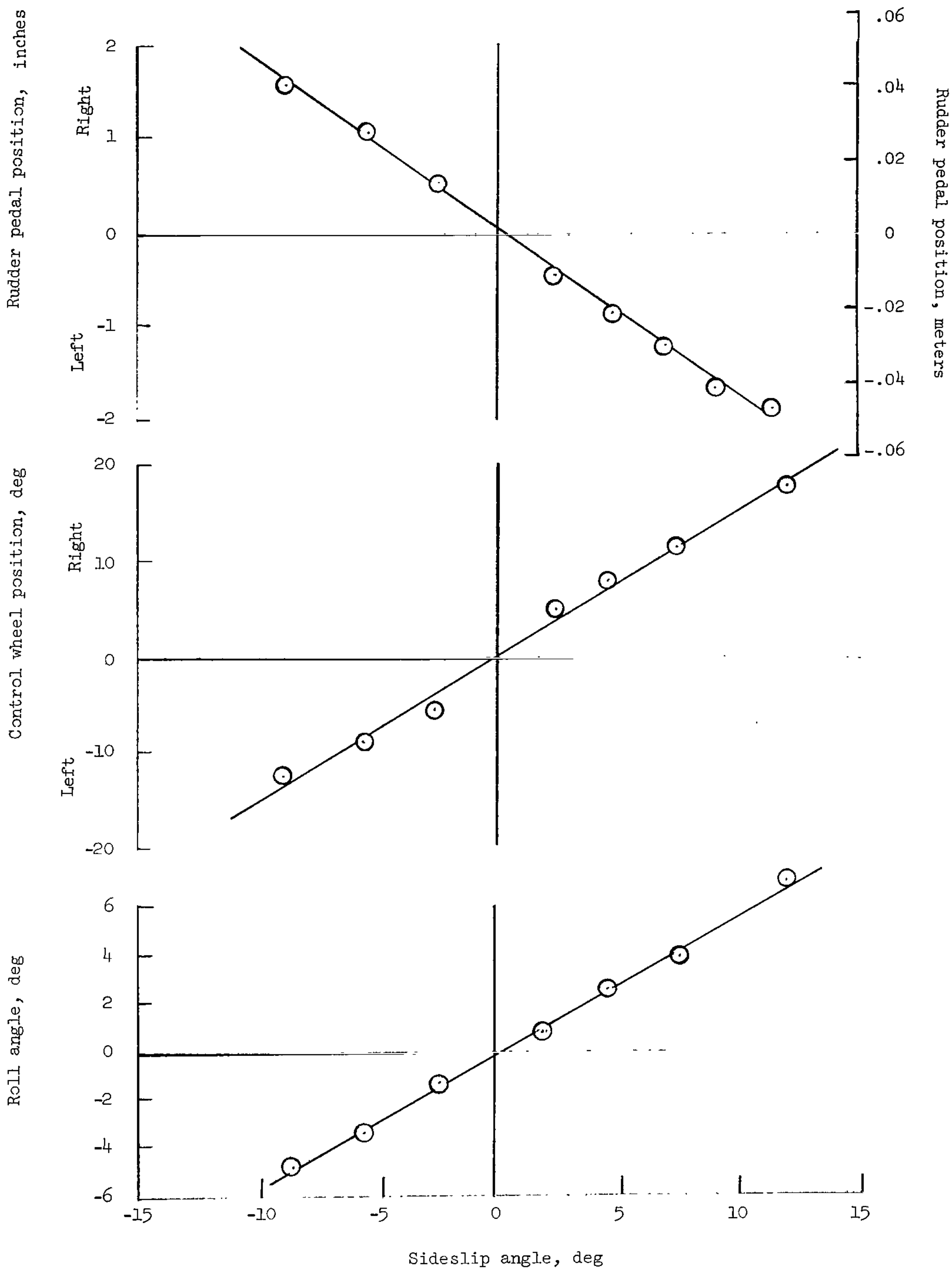
TABLE 5-1.- SUMMARY OF FLIGHT-TEST CONFIGURATIONS AND RESULTS – Concluded

Parameters varied	Pilot	Lateral-directional pilot ratings (Cooper scale)		Pilot's comments
		Overall	Dutch roll	
Fixed-geometry degraded configuration; lower Dutch roll damping and higher adverse yaw; $\zeta = 0.05$				
$C_{l_{\dot{\phi}}} = -0.044$ $C_{n_{\dot{\phi}}} = -0.035$ $C_{n_{\dot{\beta}}} = -0.138$	A	4.5 to 5.0	4.0	Stability: (a) Dutch roll damping obviously lower than for the basic configuration but can be damped by wheel control with low level of work. No tendency for pilot-induced or sustained oscillation in approach. (b) No spiral divergence noted. (c) No change in directional stability or effective dihedral noted from basic configuration. Maneuverability: (a) Low roll damping apparent in tendency to bobble about a selected bank angle. (b) Heading-change precision is about $\pm 2^{\circ}$ because of the slight oscillation in heading on roll-outs.
	B	4.25 to 4.5	5.0	Stability: (a) Dutch roll damping is low, converging at the rate of about 1° per cycle. The oscillation seemed to be predominantly yawing. There was a tendency to excite the oscillation in rapid wheel inputs but for small gradual inputs it was not bothersome. (b) Spiral stability - appeared to be slightly divergent; only checked for a few seconds. (c) Directional stability about the same as for the basic configuration and the effective dihedral was positive. Maneuverability: (a) Roll rate: initial rate was very good and the maximum rate was not used but was obviously much more than required for normal maneuvering. Roll damping appeared to be lower than for the basic configuration making it difficult to roll rapidly and stabilize on a desired bank angle of roll rate. (b) Heading changes: despite difficulty in making precise heading changes at altitude, it was not very bothersome in the approaches. On rapid heading changes appreciable adverse yaw was noted. Work level in the approach was a little higher than for the basic configuration but as the airplane approaches the ground the peripheral cues increase and the control task becomes easier.

TABLE 5-2.- SUMMARY OF THE LATERAL DIRECTIONAL STABILITY OF TEST CONFIGURATIONS AND OF THE CURRENT LARGE SUBSONIC JET TRANSPORTS

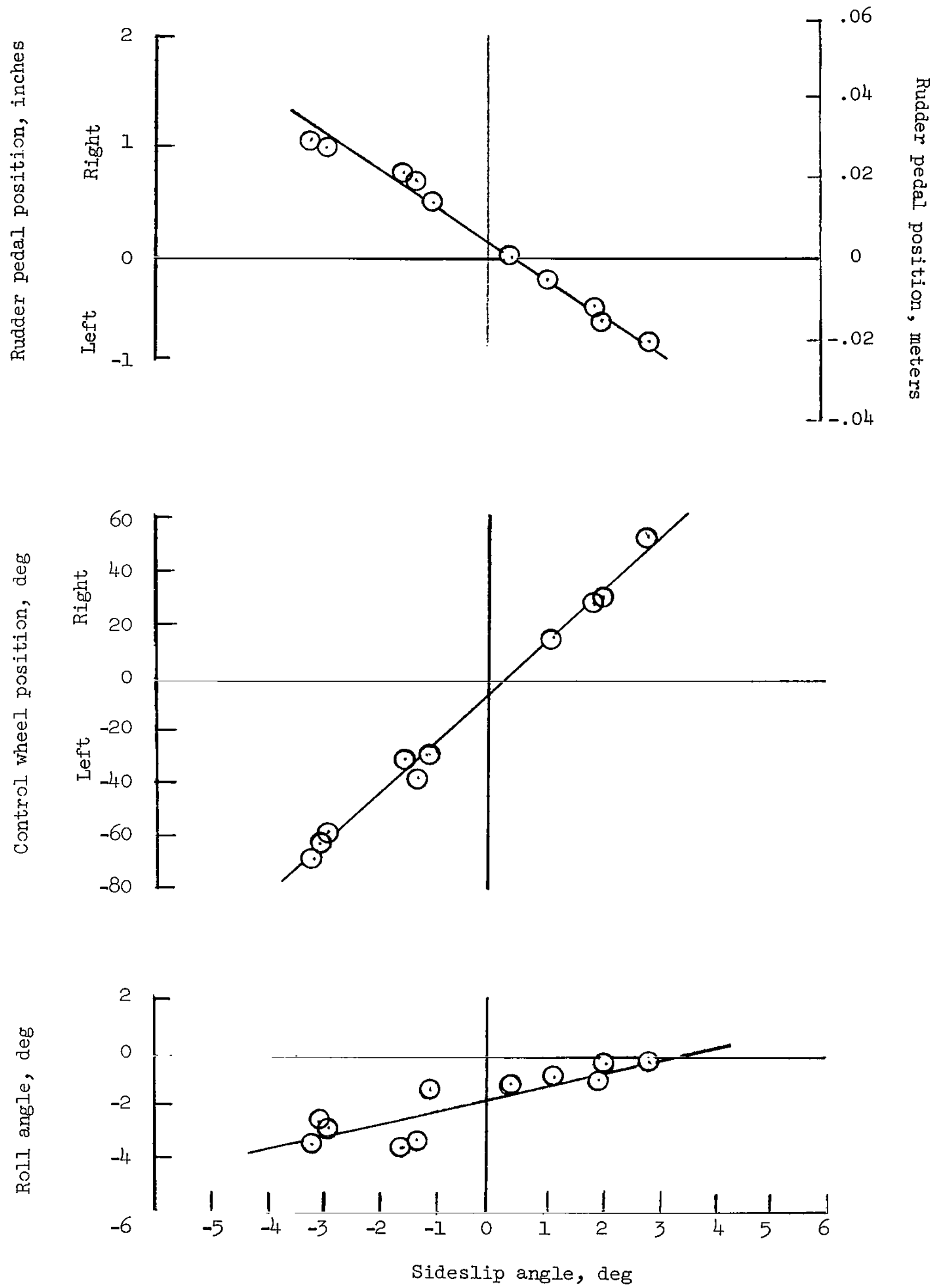
Configuration	Dutch roll oscillation										Spiral mode	Roll mode
	ω_d, rad/sec		ζ		P, sec		$T_{1/2}$, sec		$1/C_{1/2}$		T_2, sec	T_R, sec
	Measured	Calculated	Measured	Calculated	Measured	Calculated	Measured	Calculated	Measured	Calculated	Calculated	Calculated
Variable geometry	0.657	0.628	0.18	0.186	9.6	10.18	5.88	5.93	1.63	1.72	241.3	0.48
Variable geometry, augmented	.622	.621	.28	.282	10.5	10.54	3.98	3.96	2.64	2.66	238.3	.48
Variable geometry, degraded	.675	.692	.05	.051	9.3	9.08	20.6	19.63	.45	.46	275.2	.49
Fixed geometry	.995	.811	.40	.381	7.0	8.37	1.74	2.24	4.02	3.74	51.9	.80
Fixed geometry, augmented	.855	.829	.345	.379	7.5	8.18	2.42	2.21	3.10	3.70	75.8	.57
Fixed geometry, degraded	.983	.982	.05	.050	6.4	6.40	14.1	14.14	.45	.453	67.3	.89
Variable geometry (emergency landing)	1.40	1.24	.09	.172	4.5	5.15	5.5	3.25	.82	1.58	-12.3	1.7
Current jet transport A[a]	(b)	1.03	(b)	.07	(b)	6.1	(b)	9.6	(b)	.635	(b)	(b)
Current jet transport B[a]	(b)	.80	(b)	.06	(b)	7.6	(b)	14.5	(b)	.525	(b)	(b)

[a]Unaugmented.
[b]Not available.



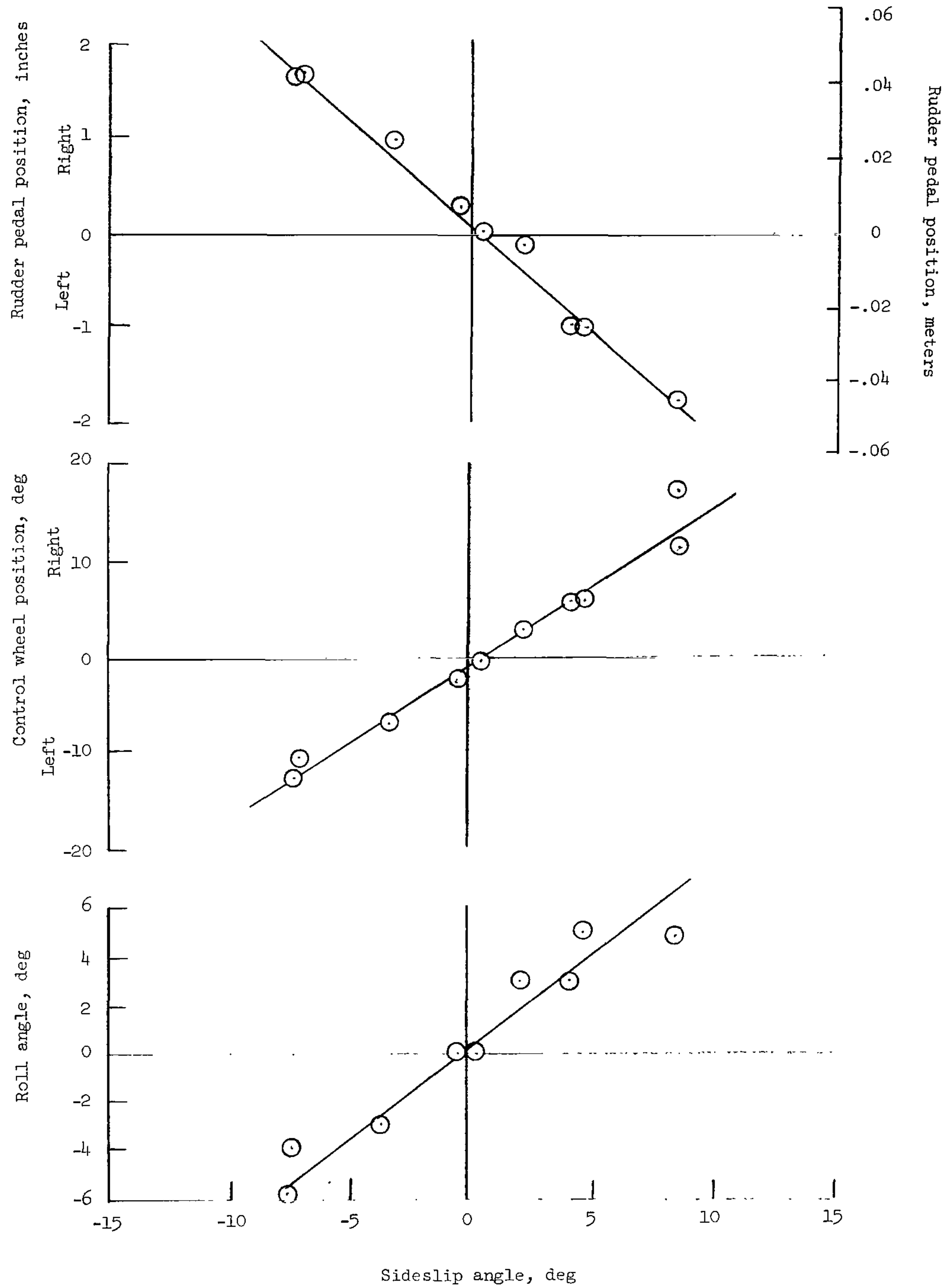
(a) Variable-geometry configuration.

Figure 5-1.- Static lateral-directional stability characteristics of test configurations.



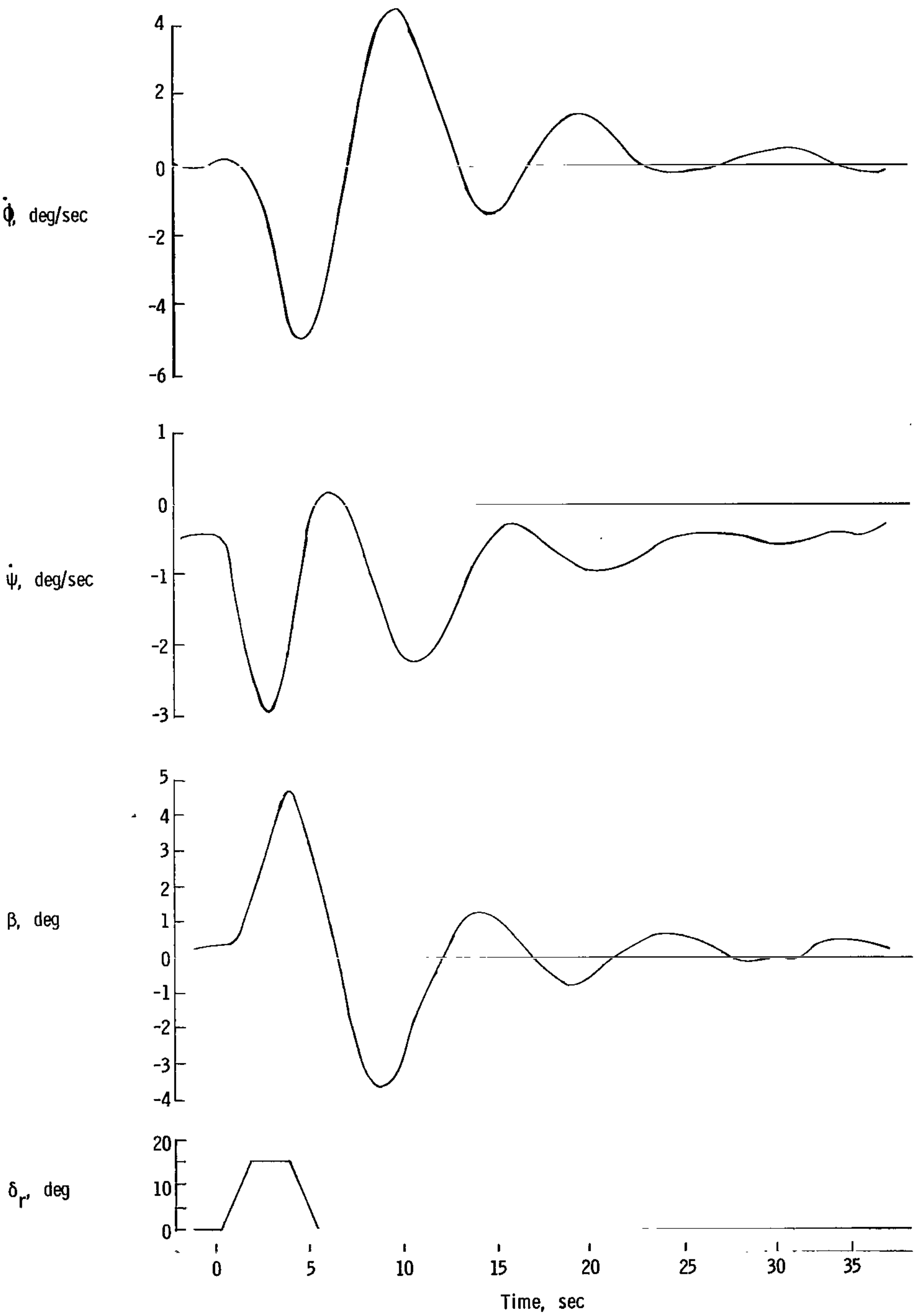
(b) Variable-geometry (emergency landing) configuration.

Figure 5-1.- Continued.



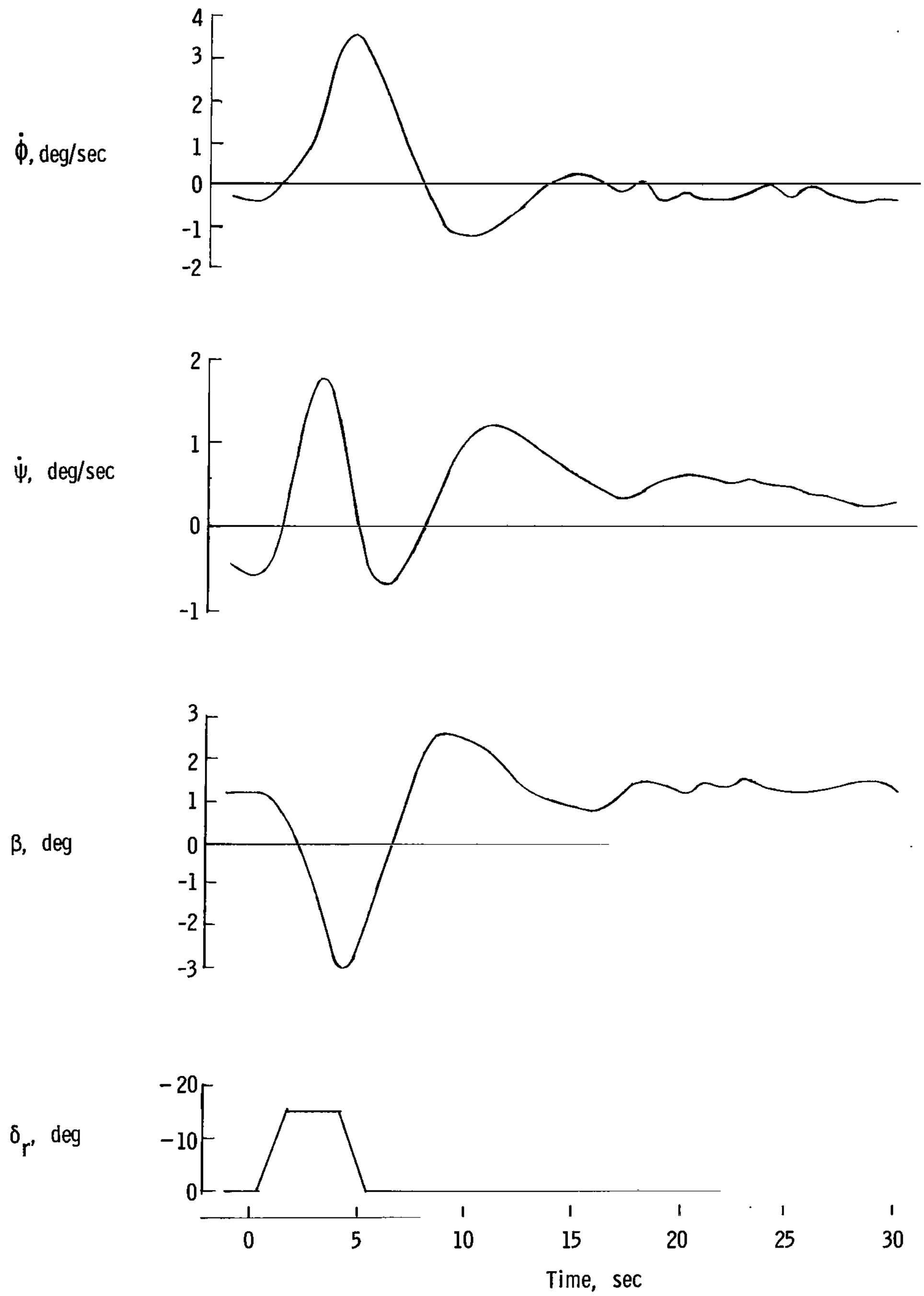
(c) Fixed-geometry configuration.

Figure 5-1.- Concluded.



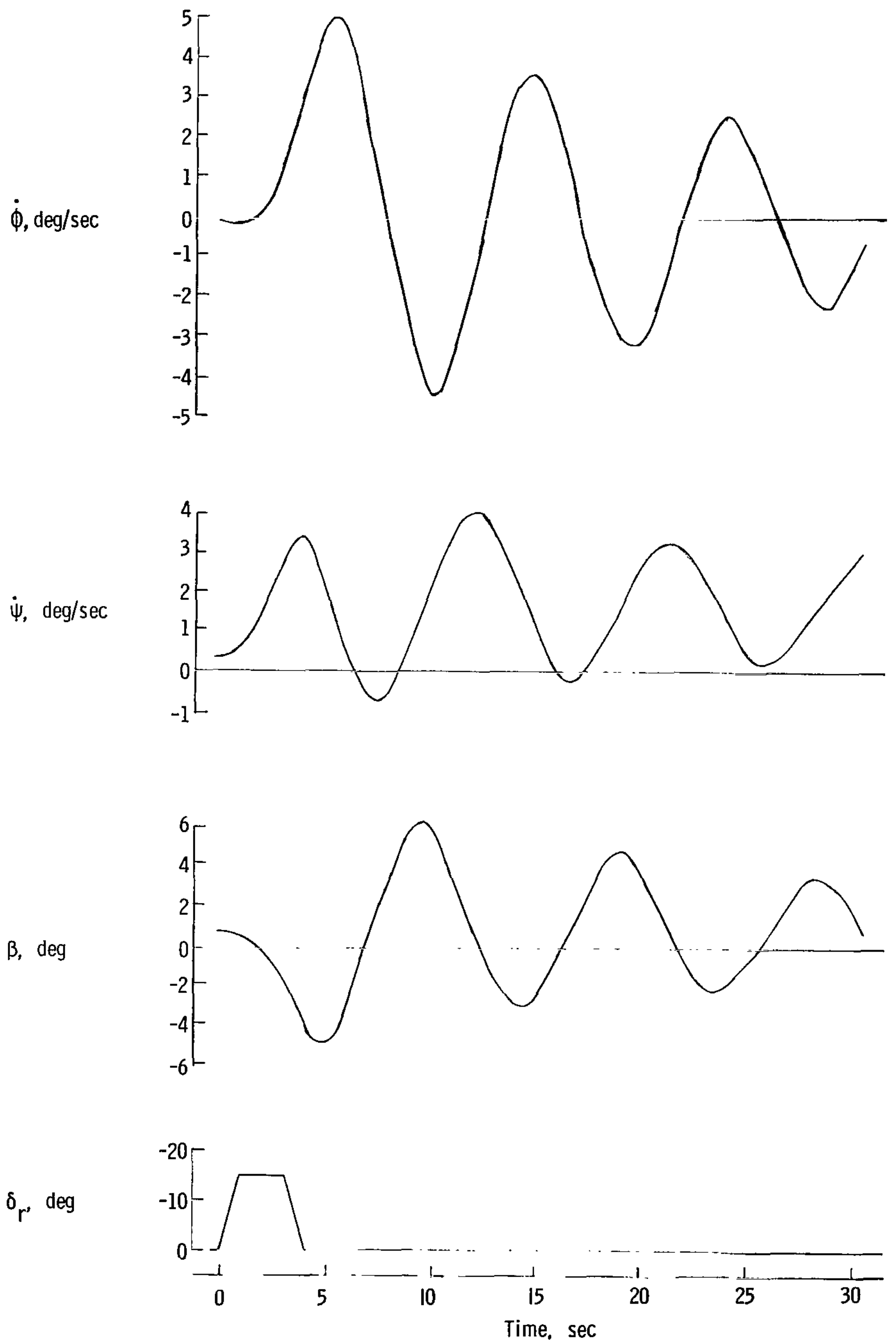
(a) Variable-geometry configuration.

Figure 5-2.- Dutch roll characteristics of test configurations.



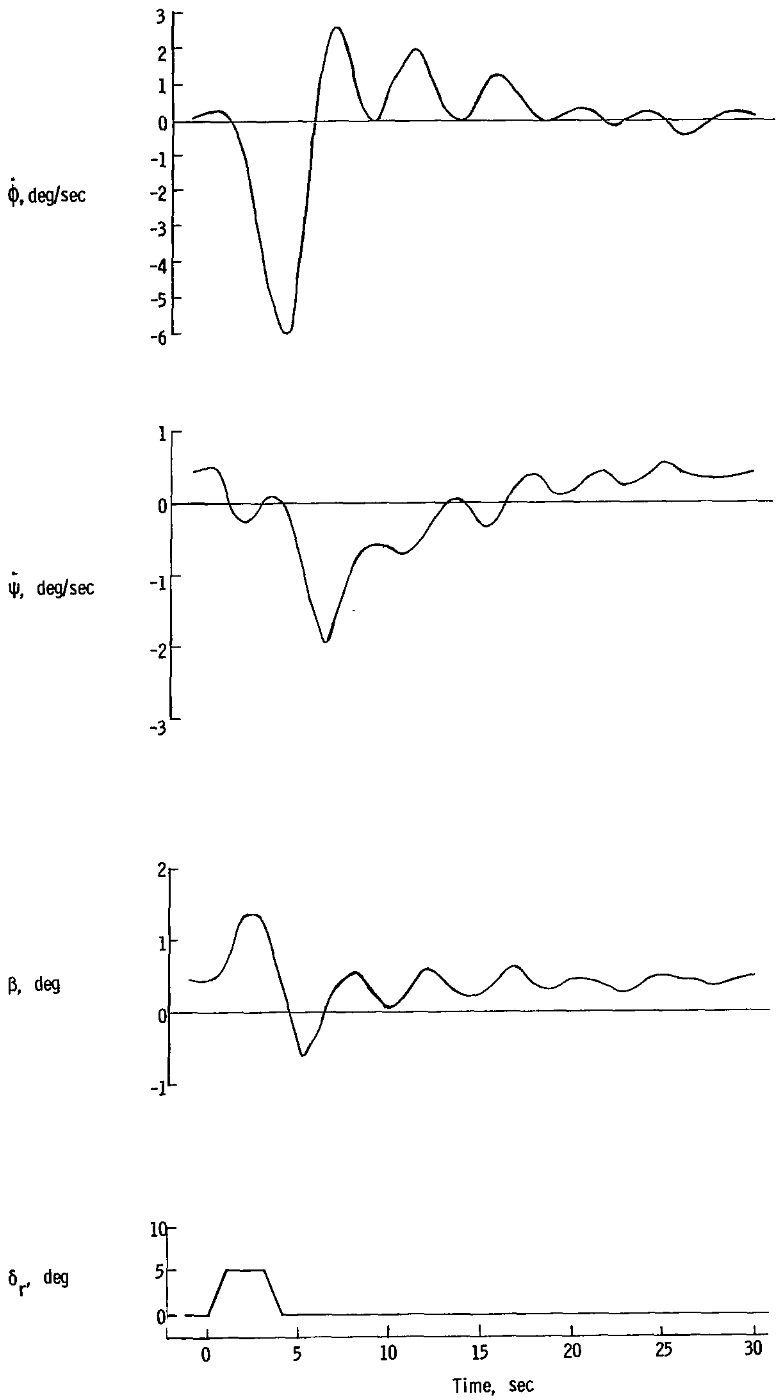
(b) Variable-geometry augmented configuration.

Figure 5-2.- Continued.



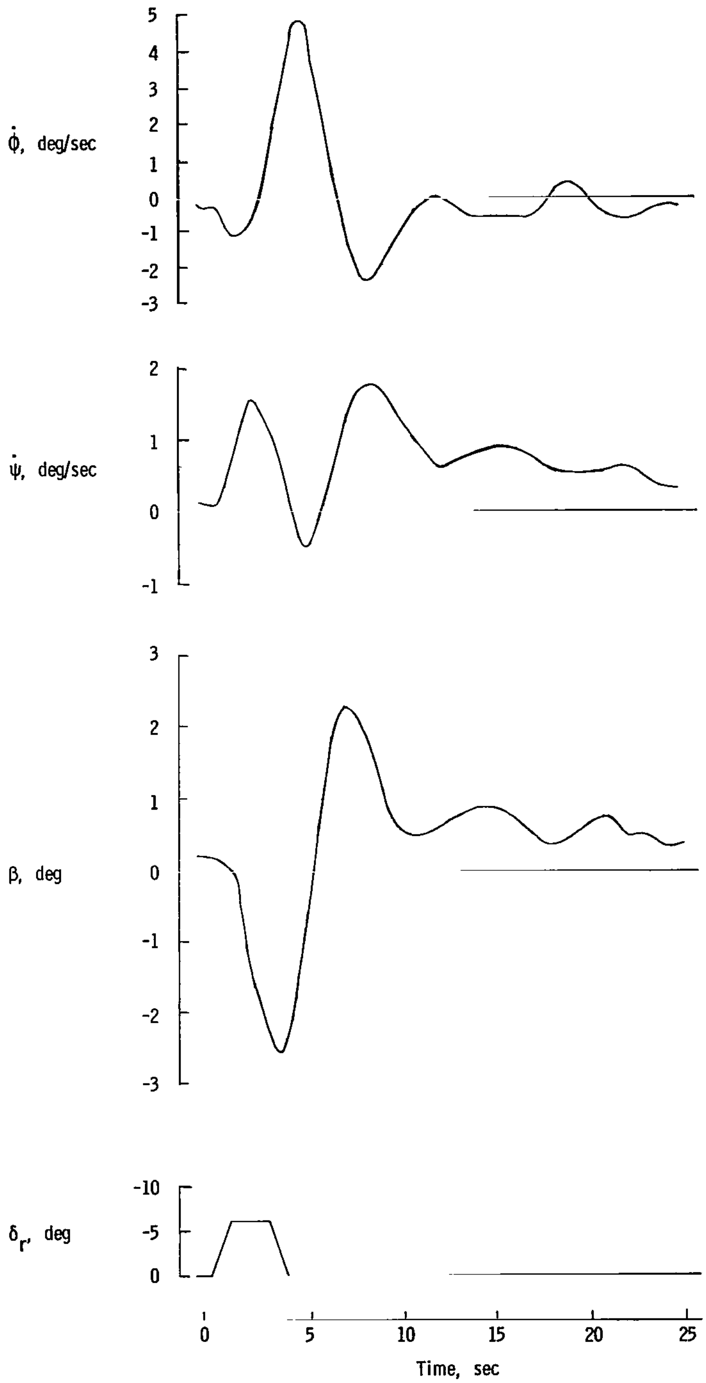
(c) Variable-geometry degraded configuration.

Figure 5-2.- Continued.



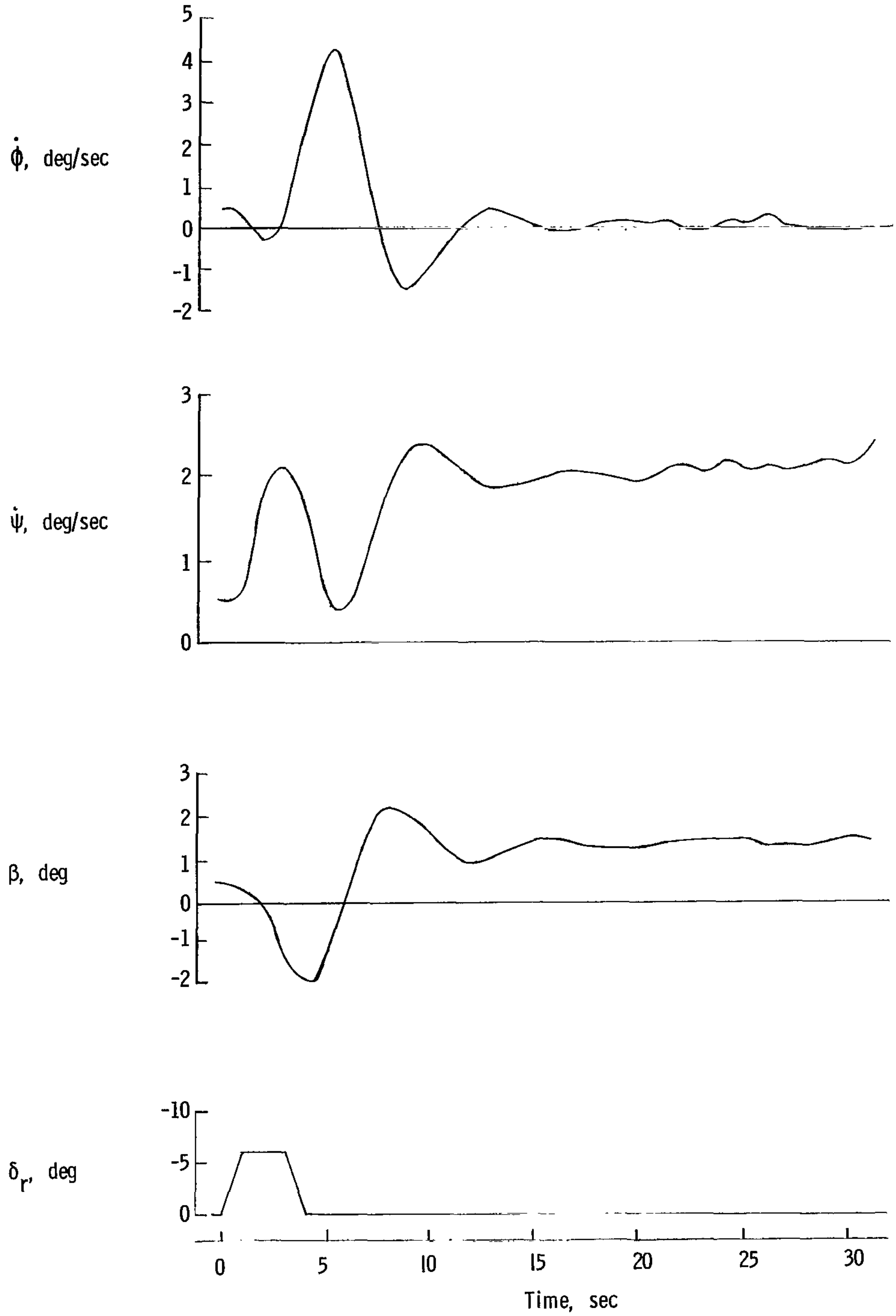
(d) Variable-geometry (emergency landing) configuration.

Figure 5-2.- Continued.



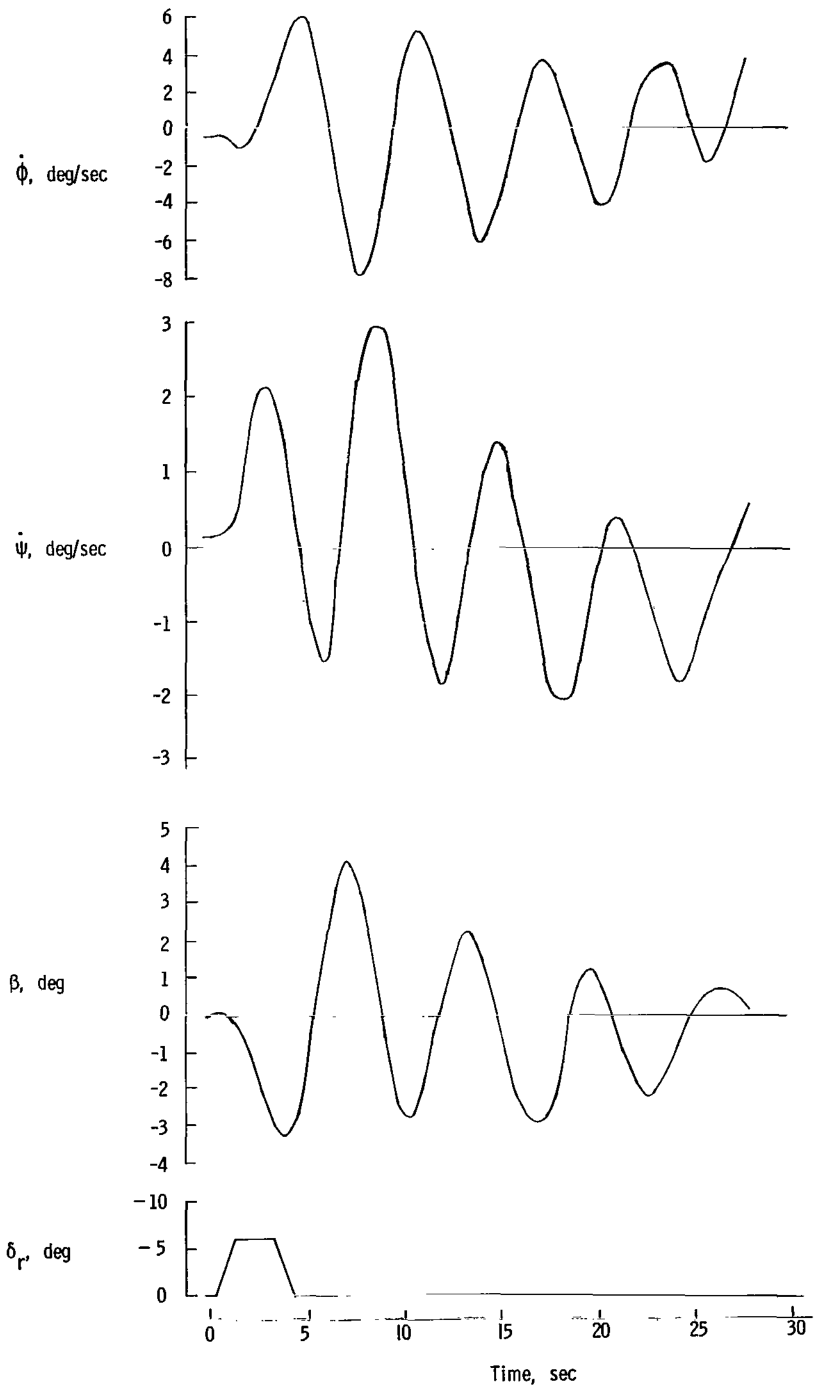
(e) Fixed-geometry configuration.

Figure 5-2.- Continued.



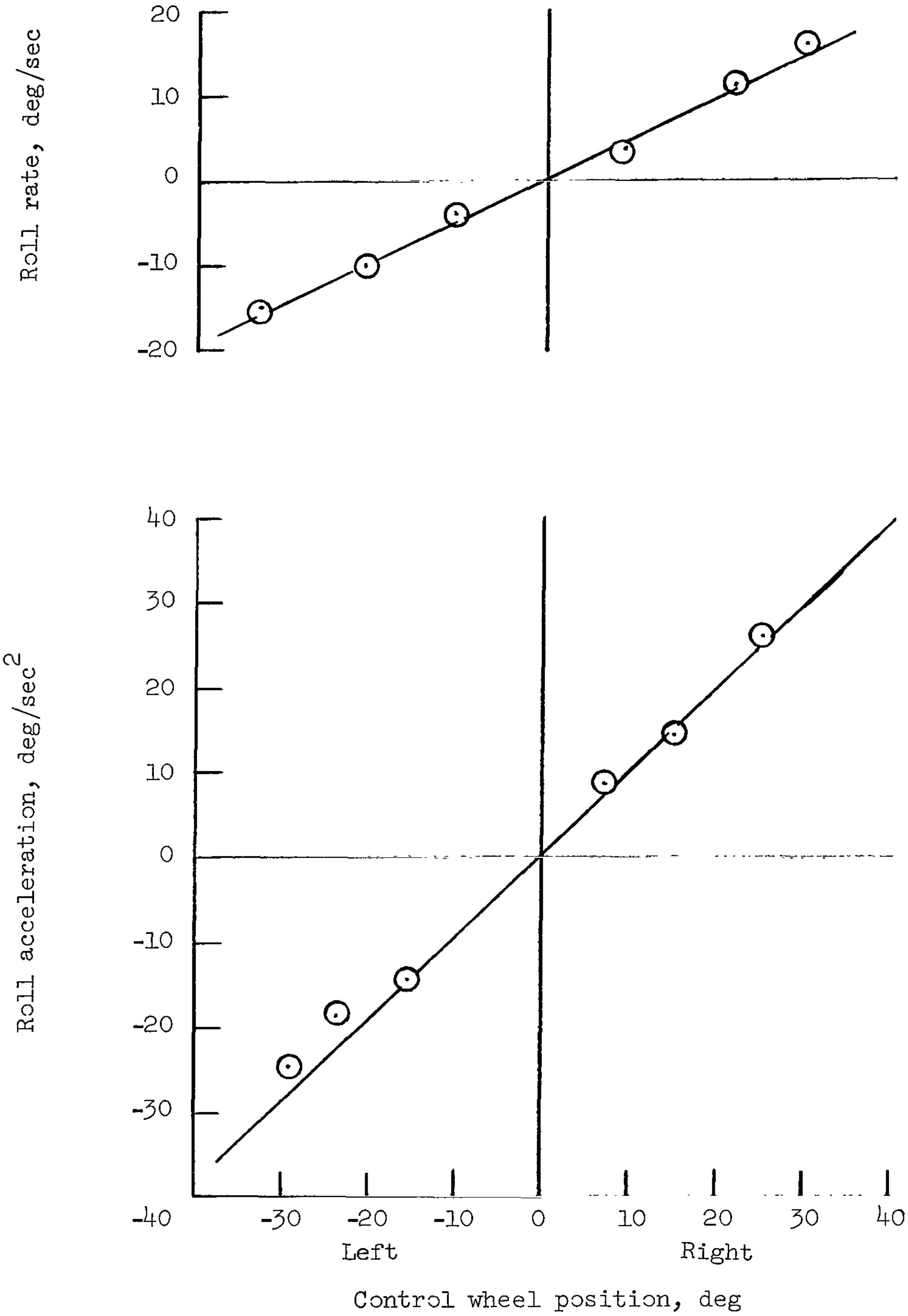
(f) Fixed-geometry augmented configuration.

Figure 5-2.- Continued.



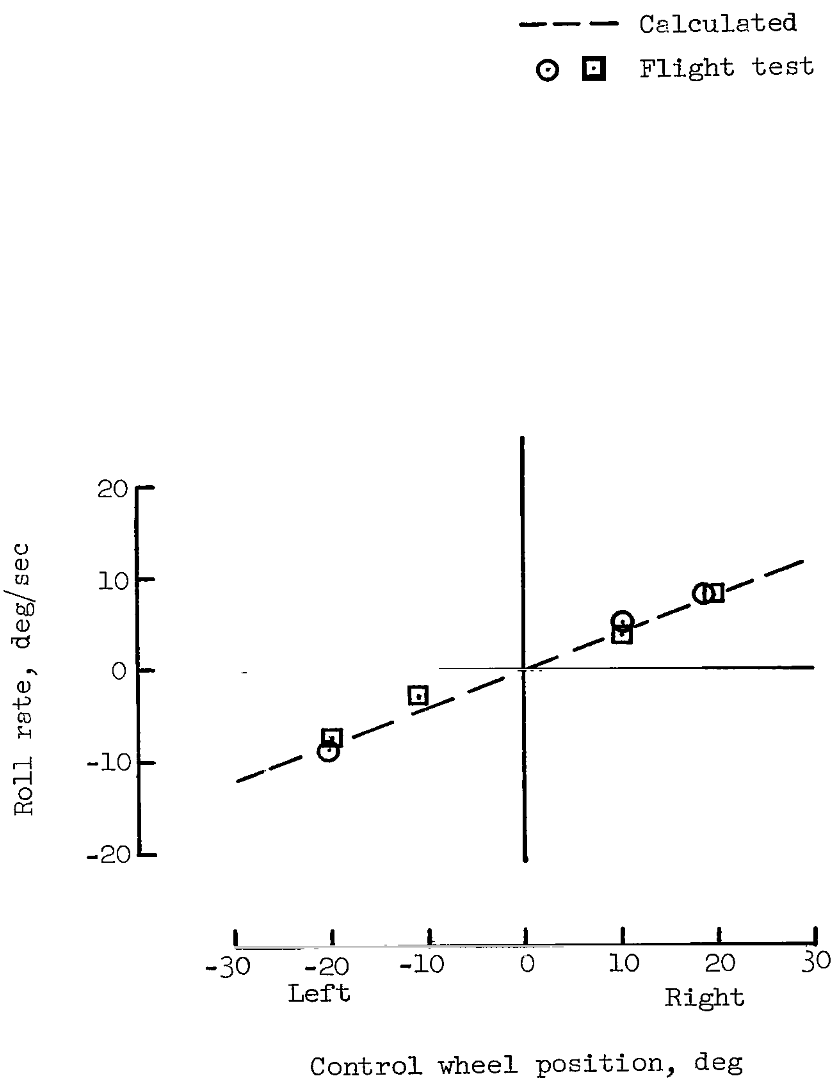
(g) Fixed geometry, degraded configuration.

Figure 5-2.- Concluded.



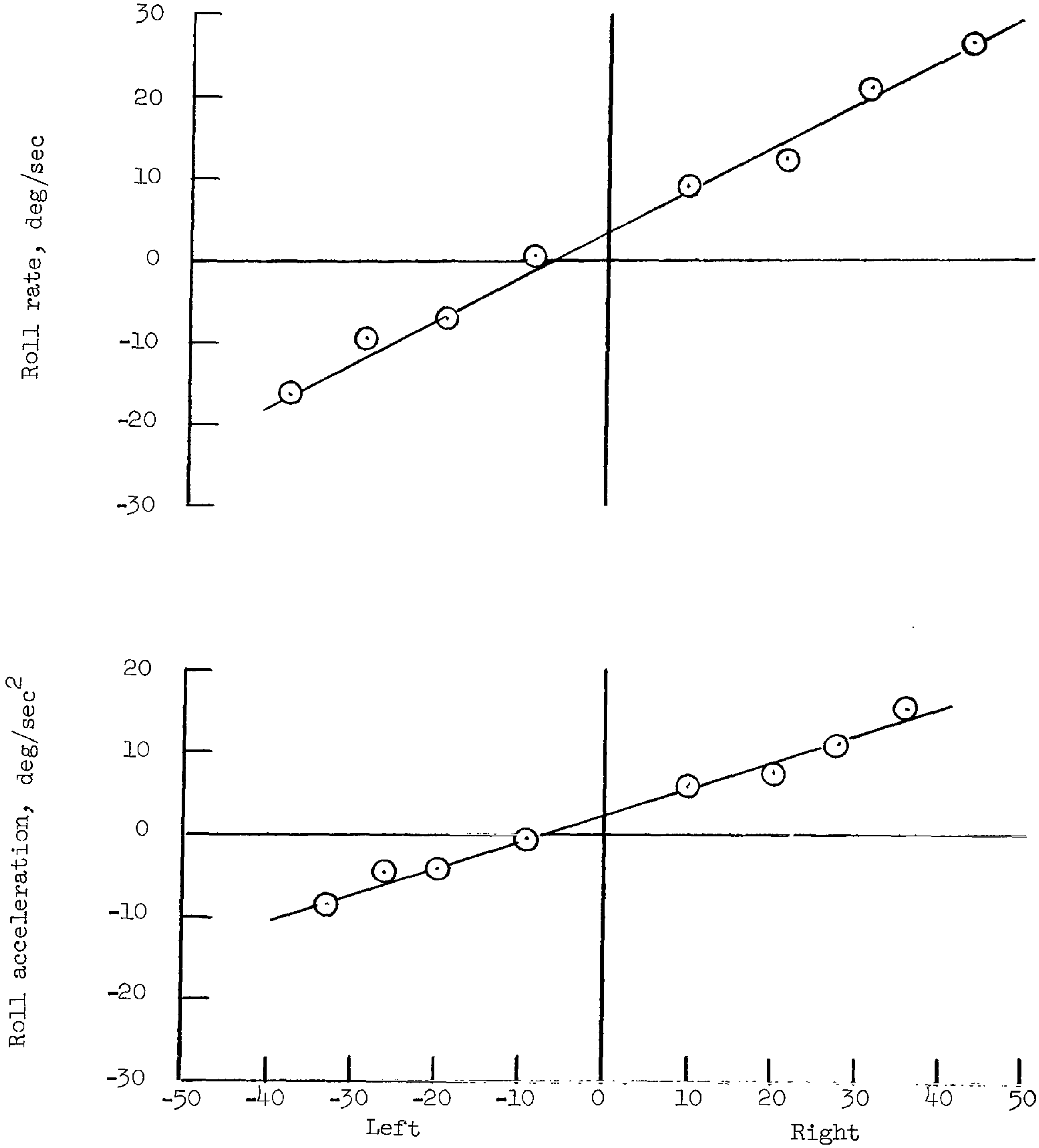
(a) Basic variable-geometry configuration.

Figure 5-3.- Lateral control characteristics of the test configuration.



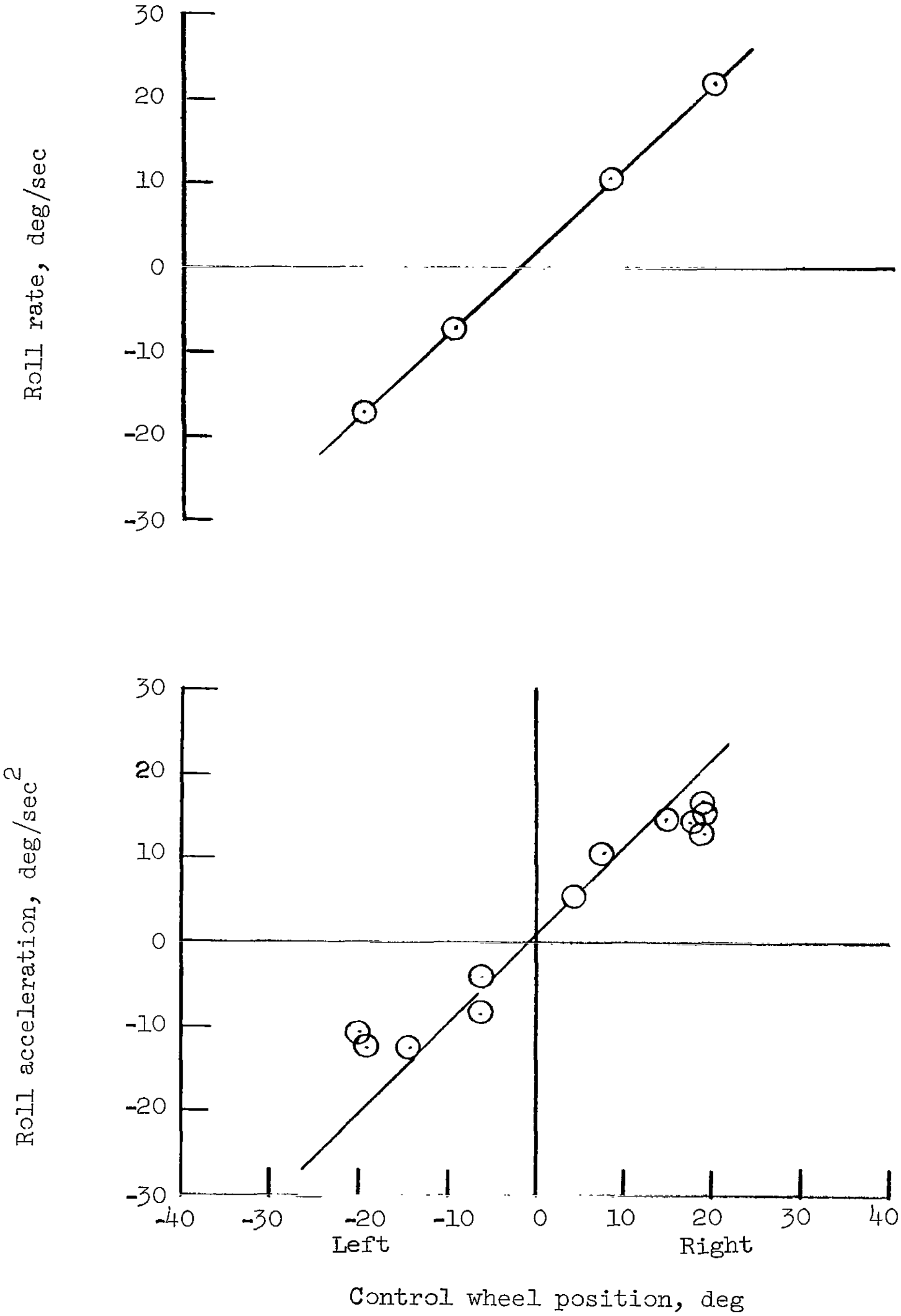
(b) Degraded variable-geometry configuration.

Figure 5-3.- Continued.



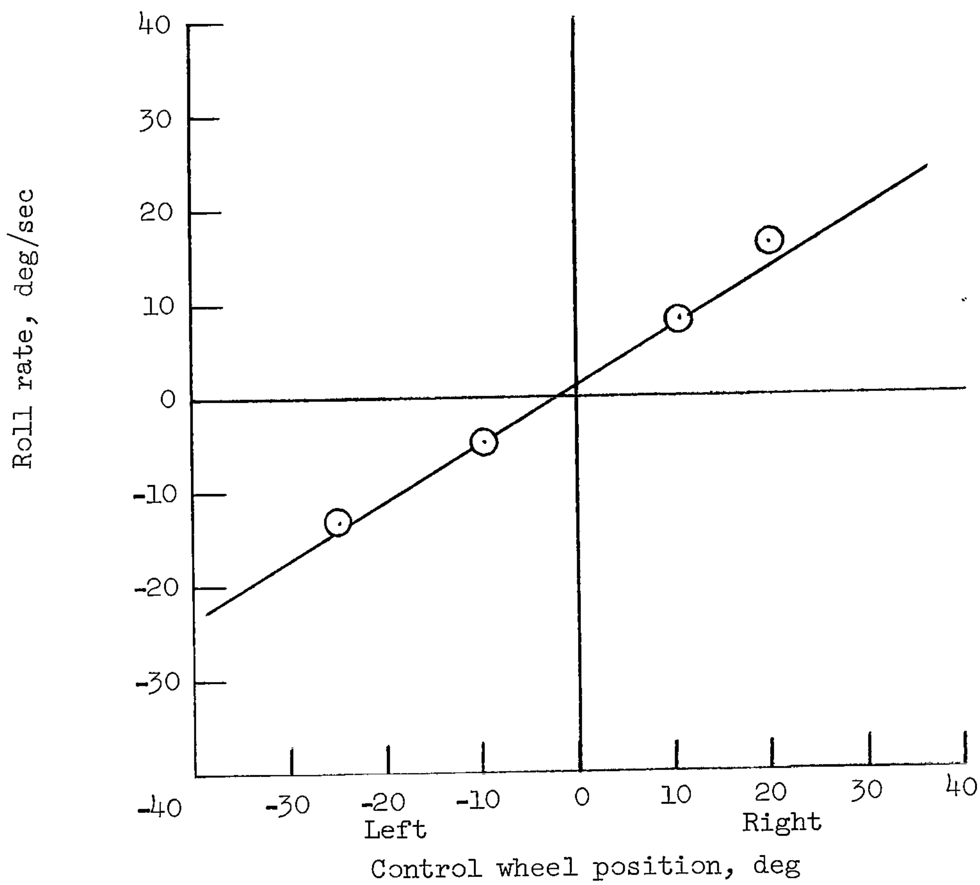
(c) Variable-geometry (emergency landing) configuration.

Figure 5-3.- Continued.



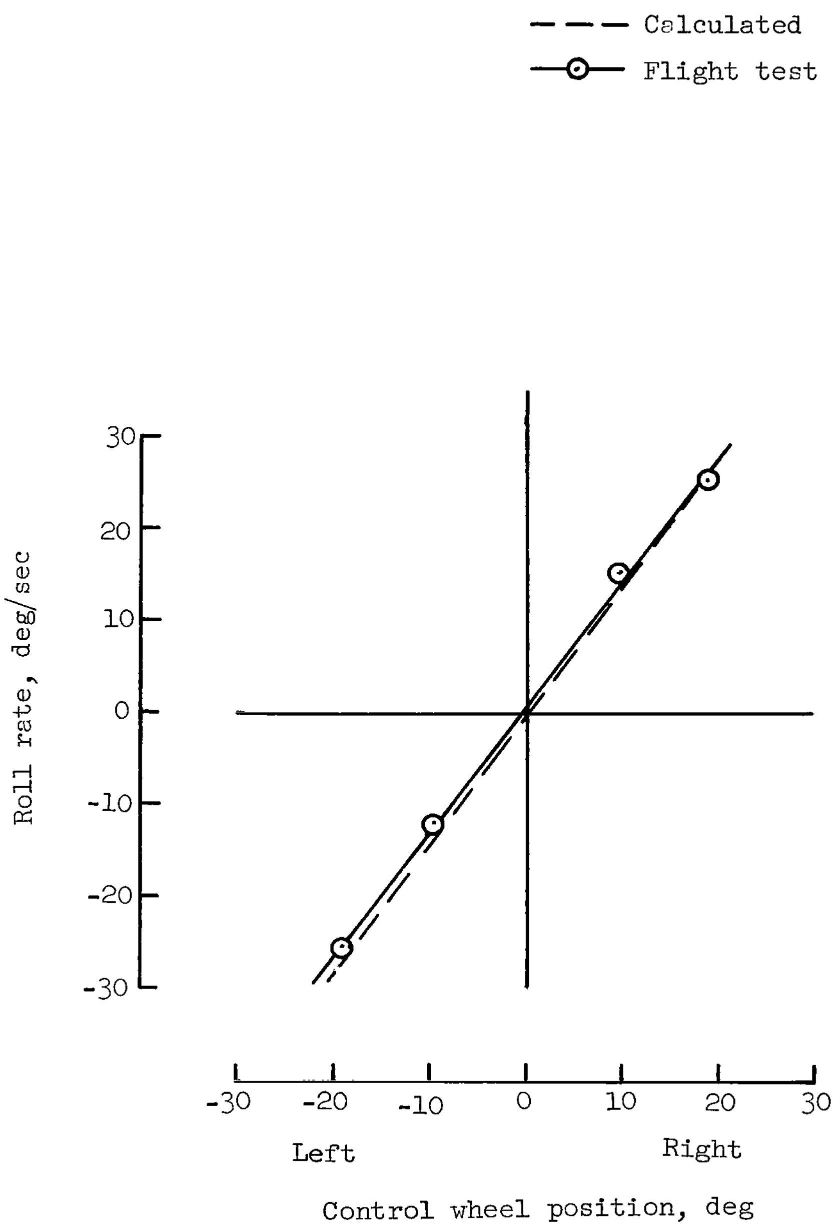
(d) Basic fixed-geometry configuration.

Figure 5-3.- Continued.



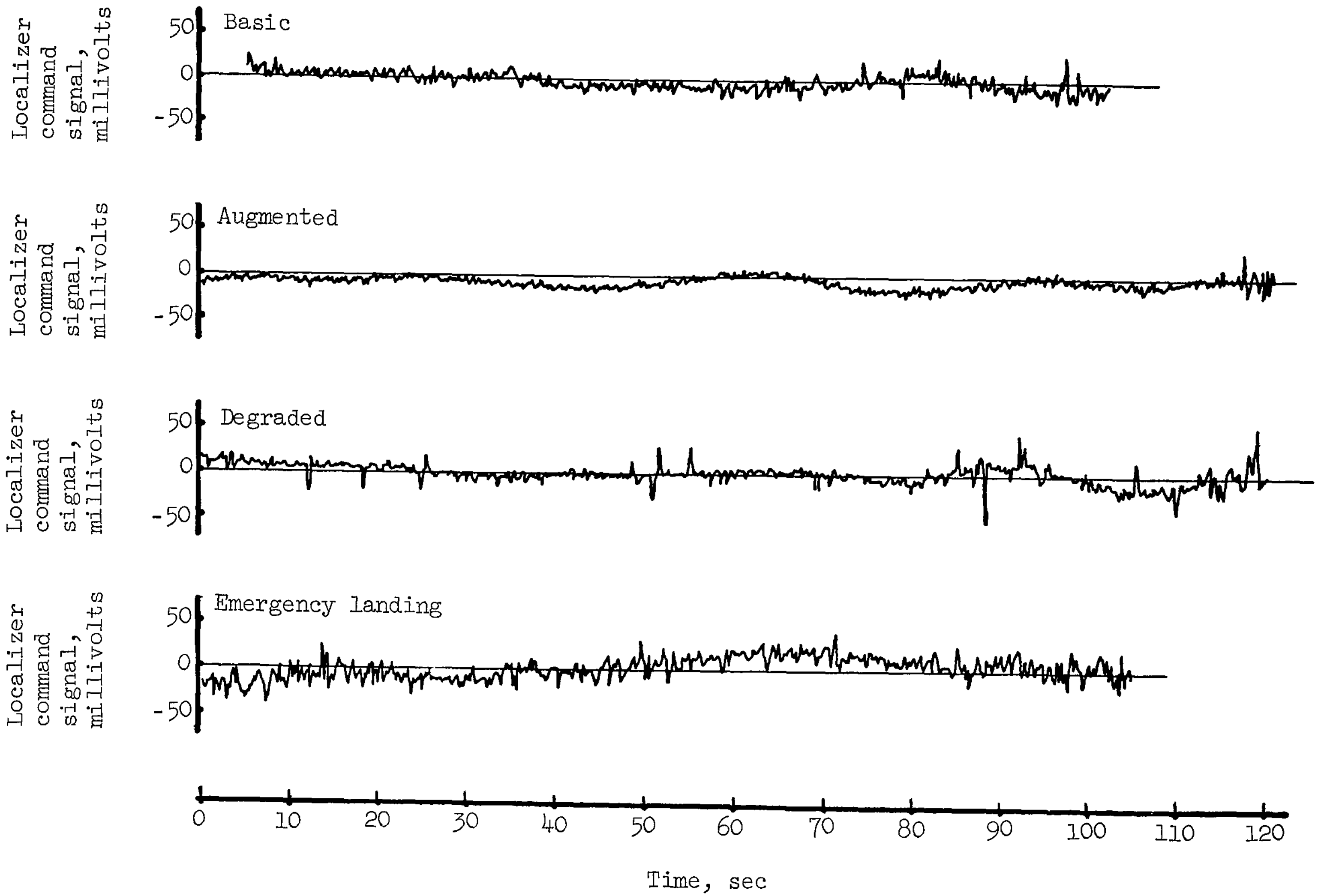
(e) Fixed-geometry augmented configuration.

Figure 5-3.- Continued.



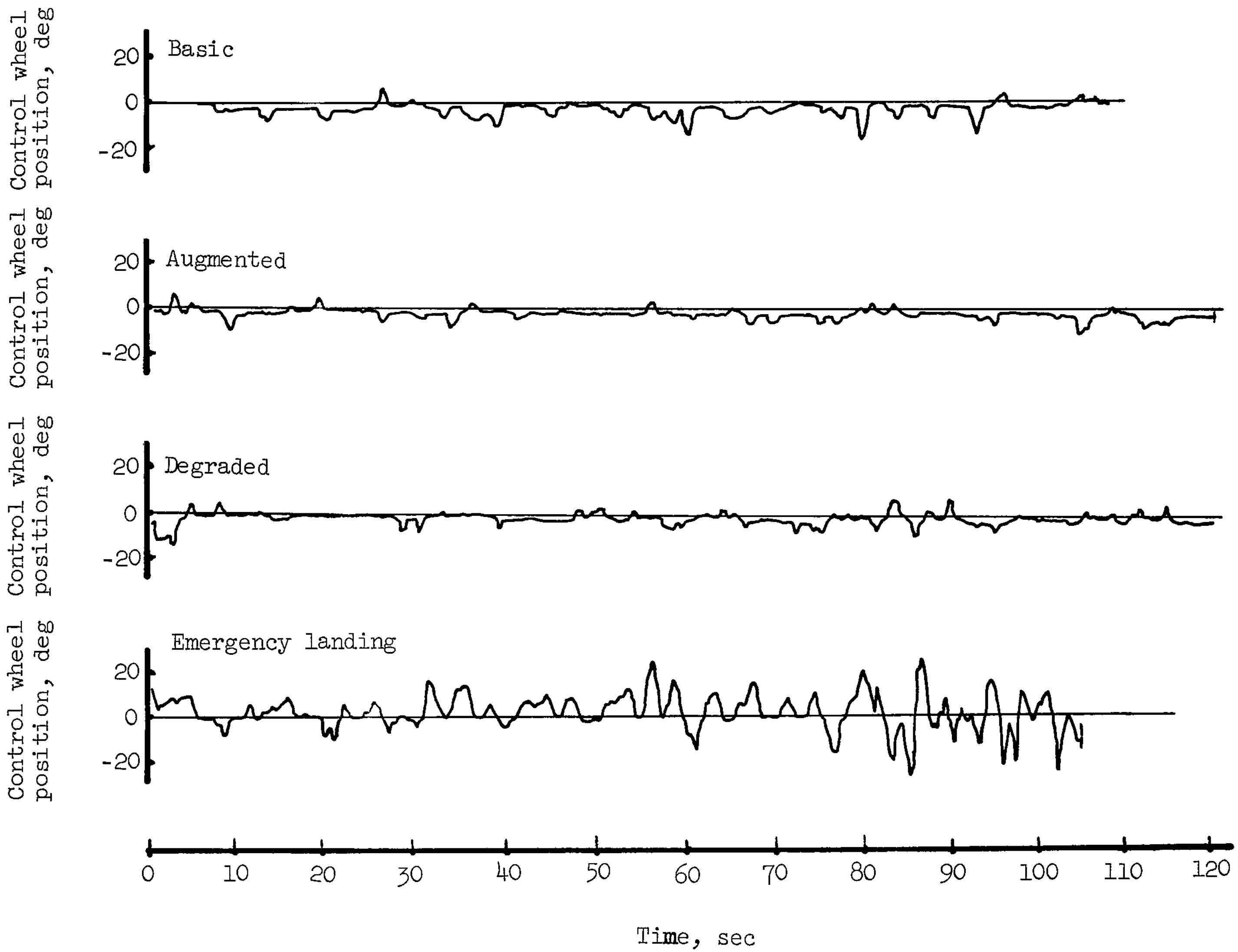
(f) Degraded fixed-geometry configuration.

Figure 5-3.- Concluded.



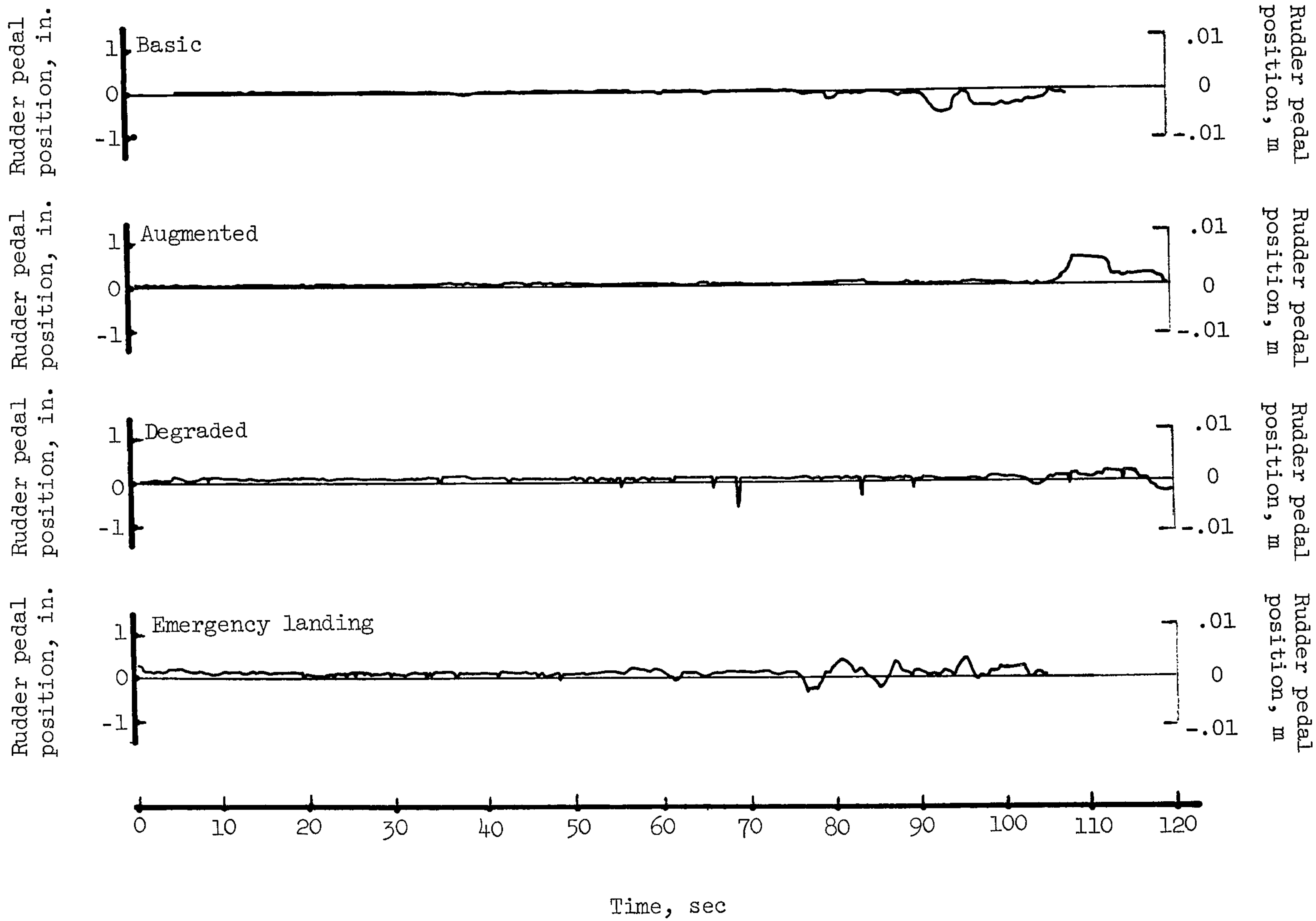
(a) Localizer command signal.

Figure 5-4.- Typical landing-approach time histories of the variable-geometry configurations.



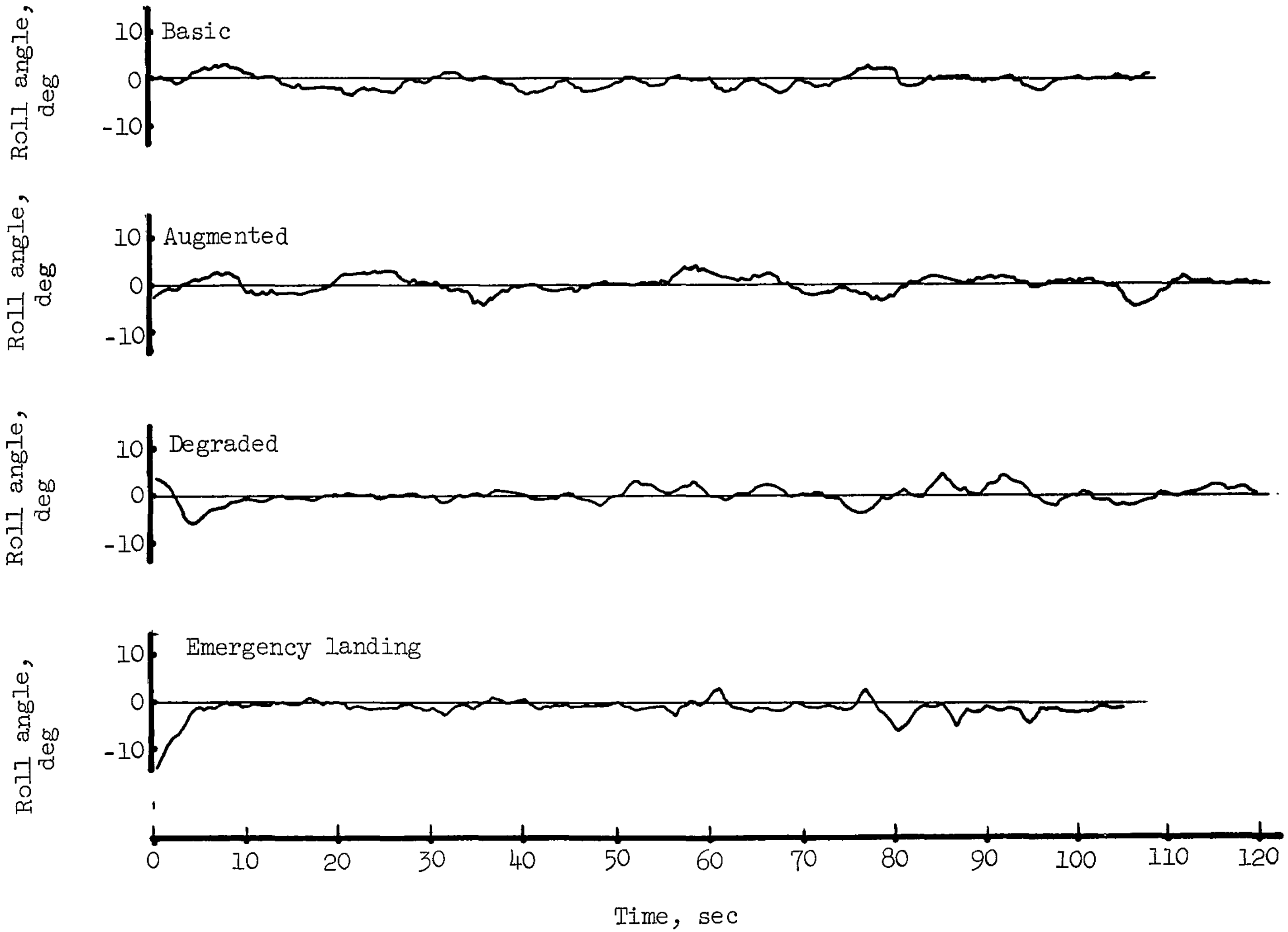
(b) Control wheel position.

Figure 5-4.- Continued.



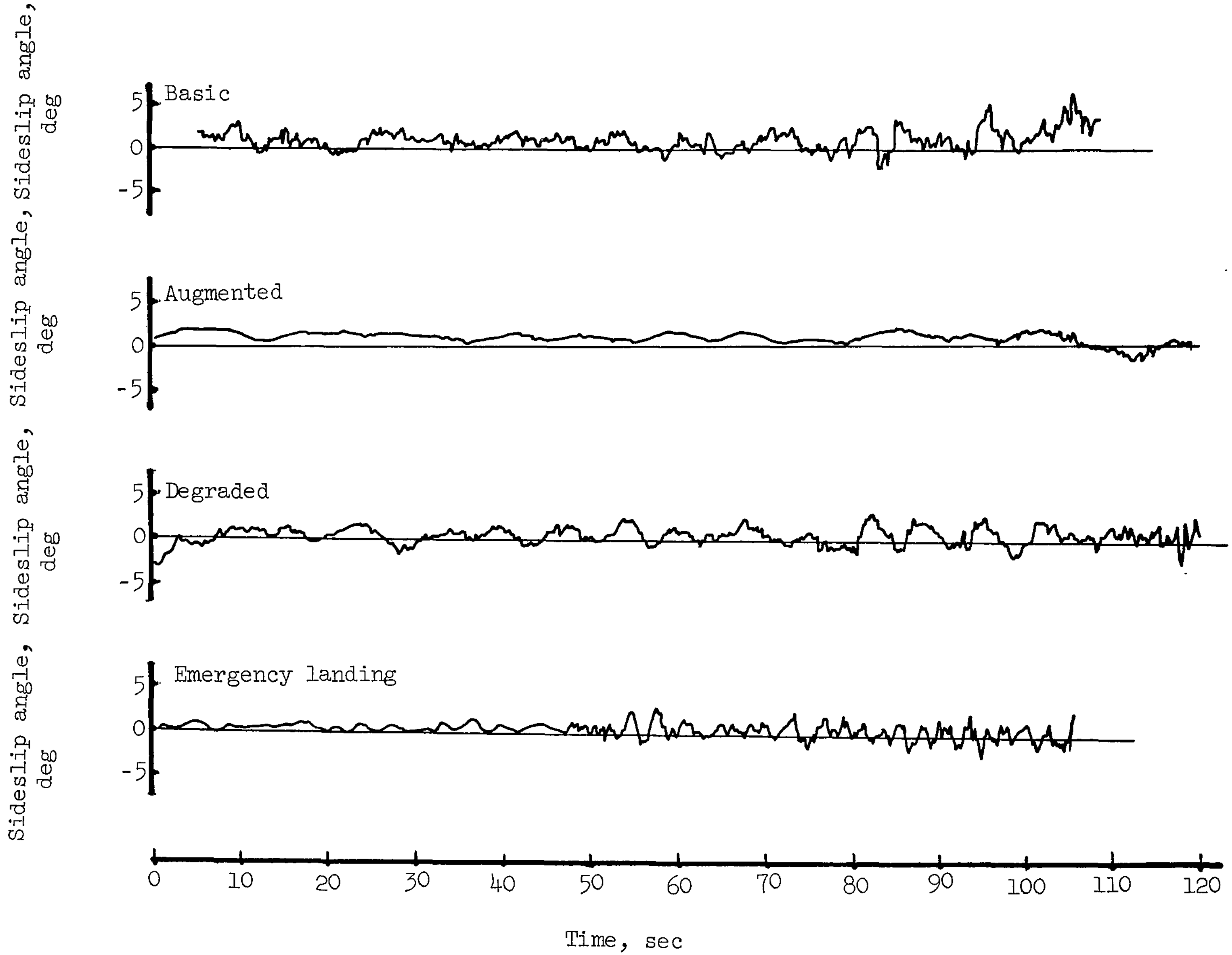
(c) Rudder pedal position.

Figure 5-4.- Continued.



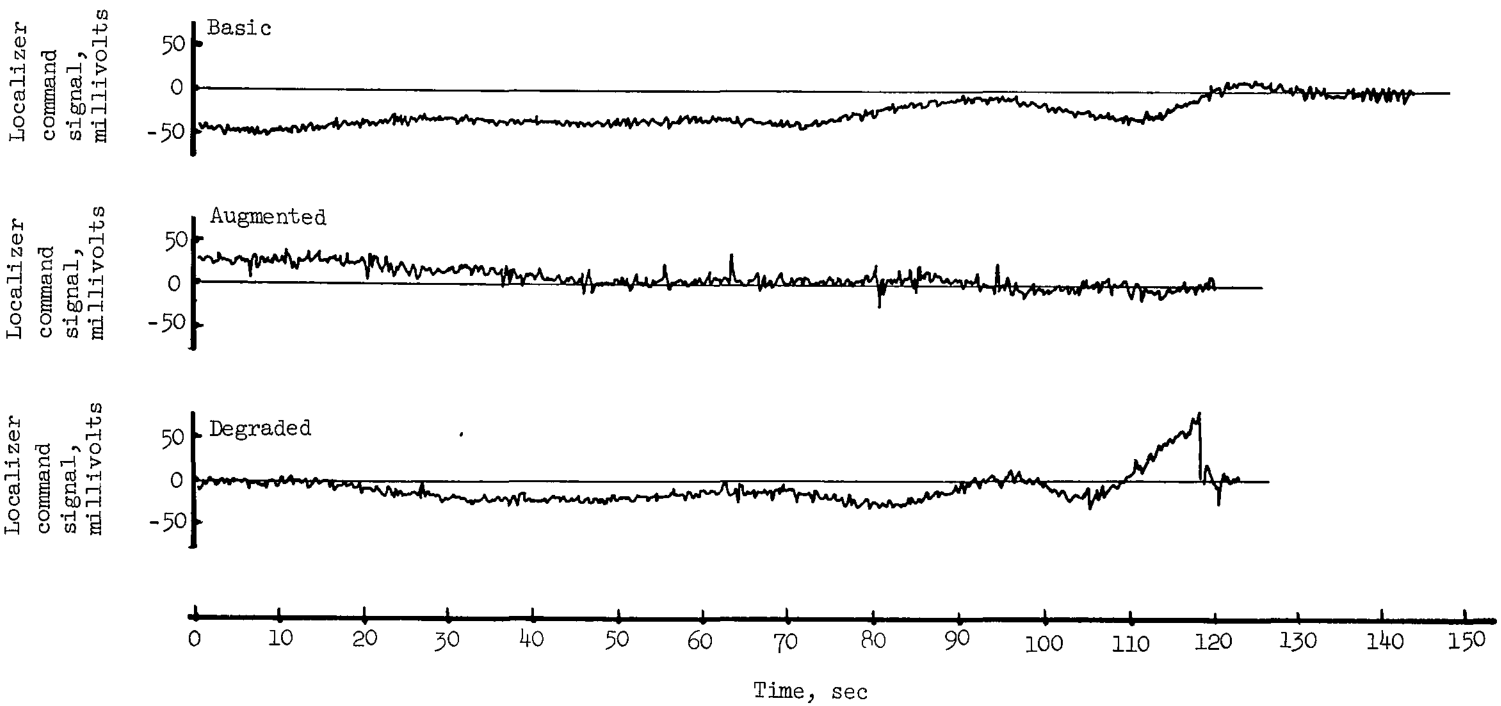
(d) Roll angle.

Figure 5-4.- Continued.



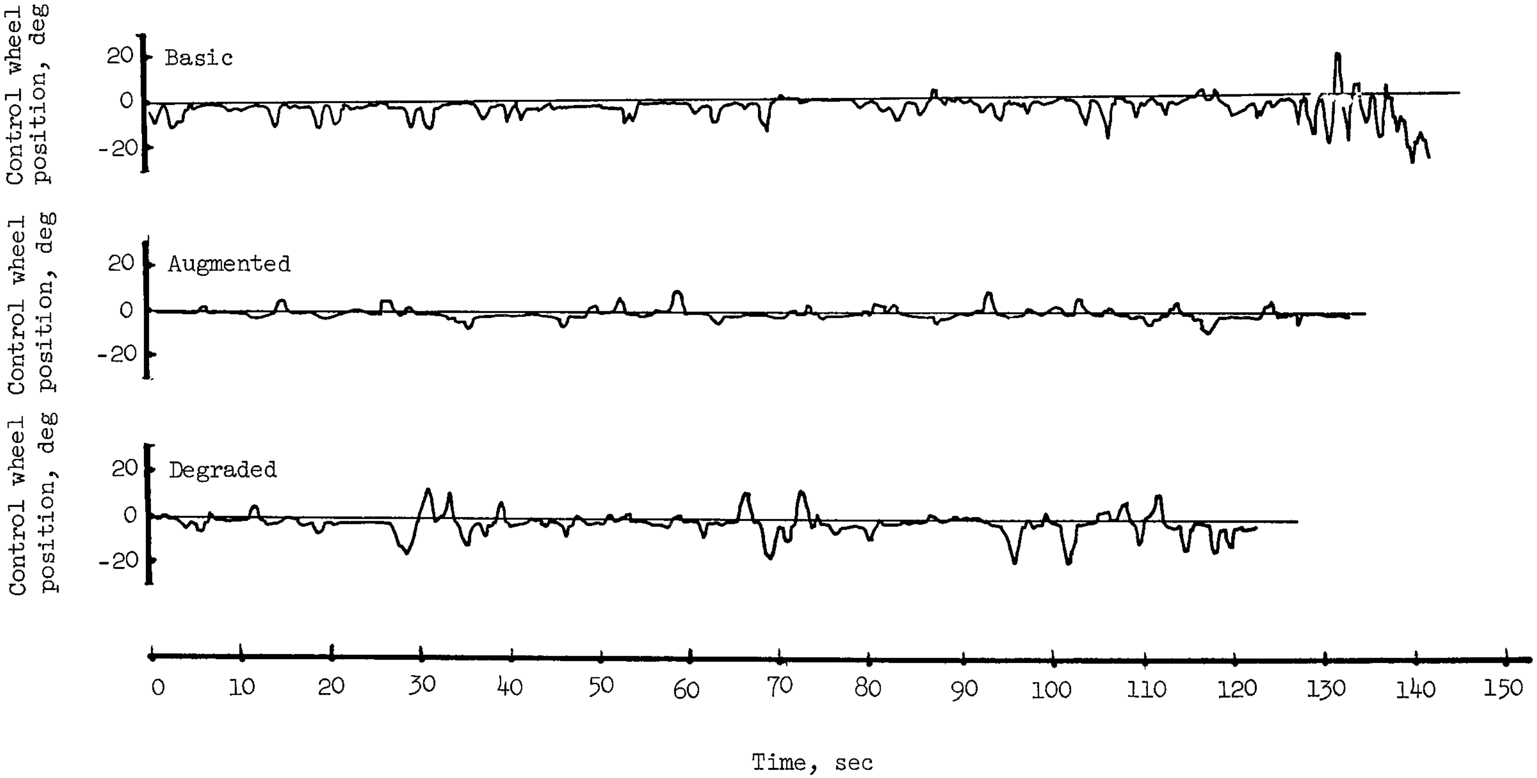
(e) Sideslip angle.

Figure 5-4.- Concluded.



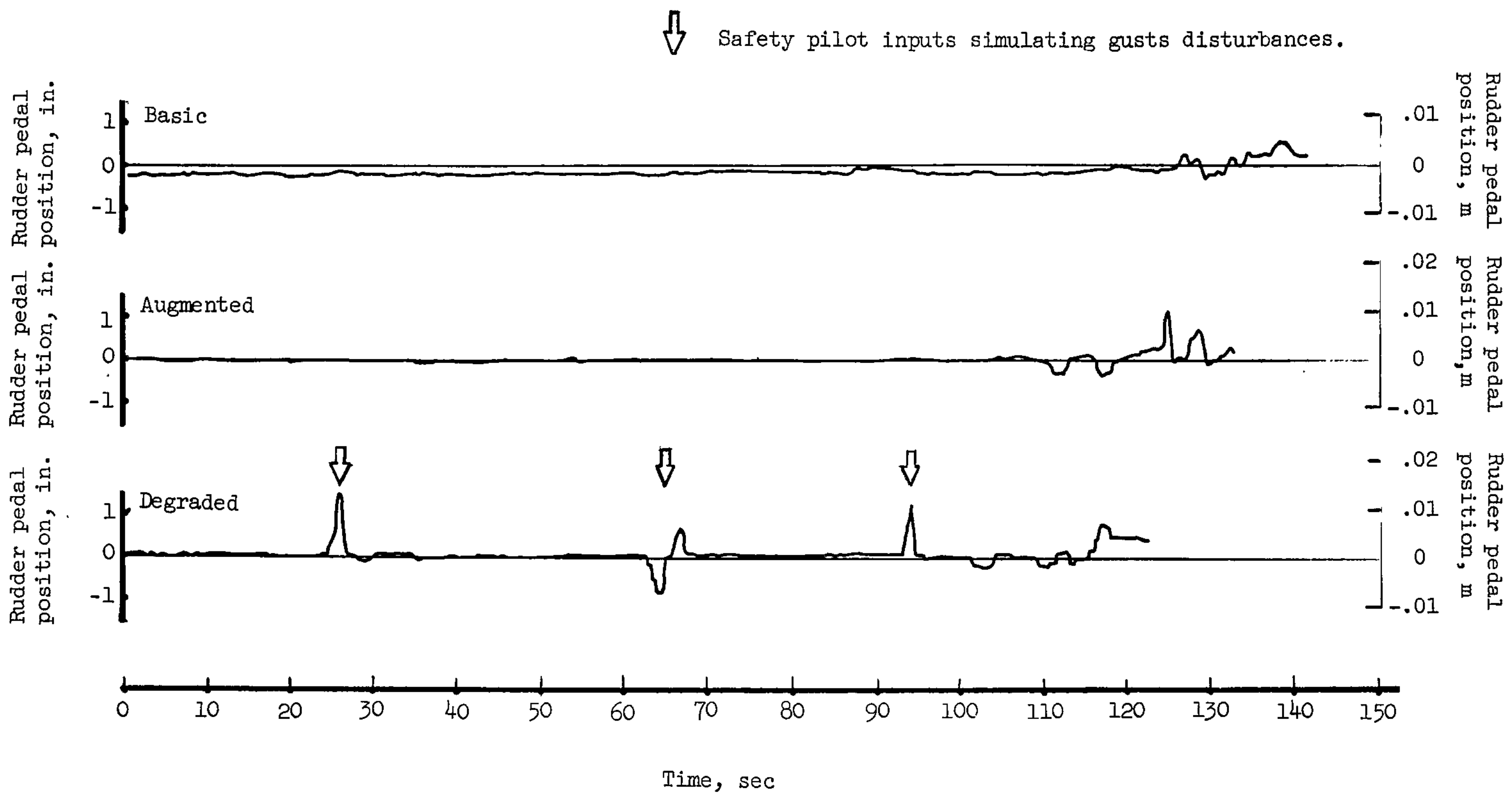
(a) Localizer command signal.

Figure 5-5.- Typical landing-approach time histories of the fixed-geometry configurations.



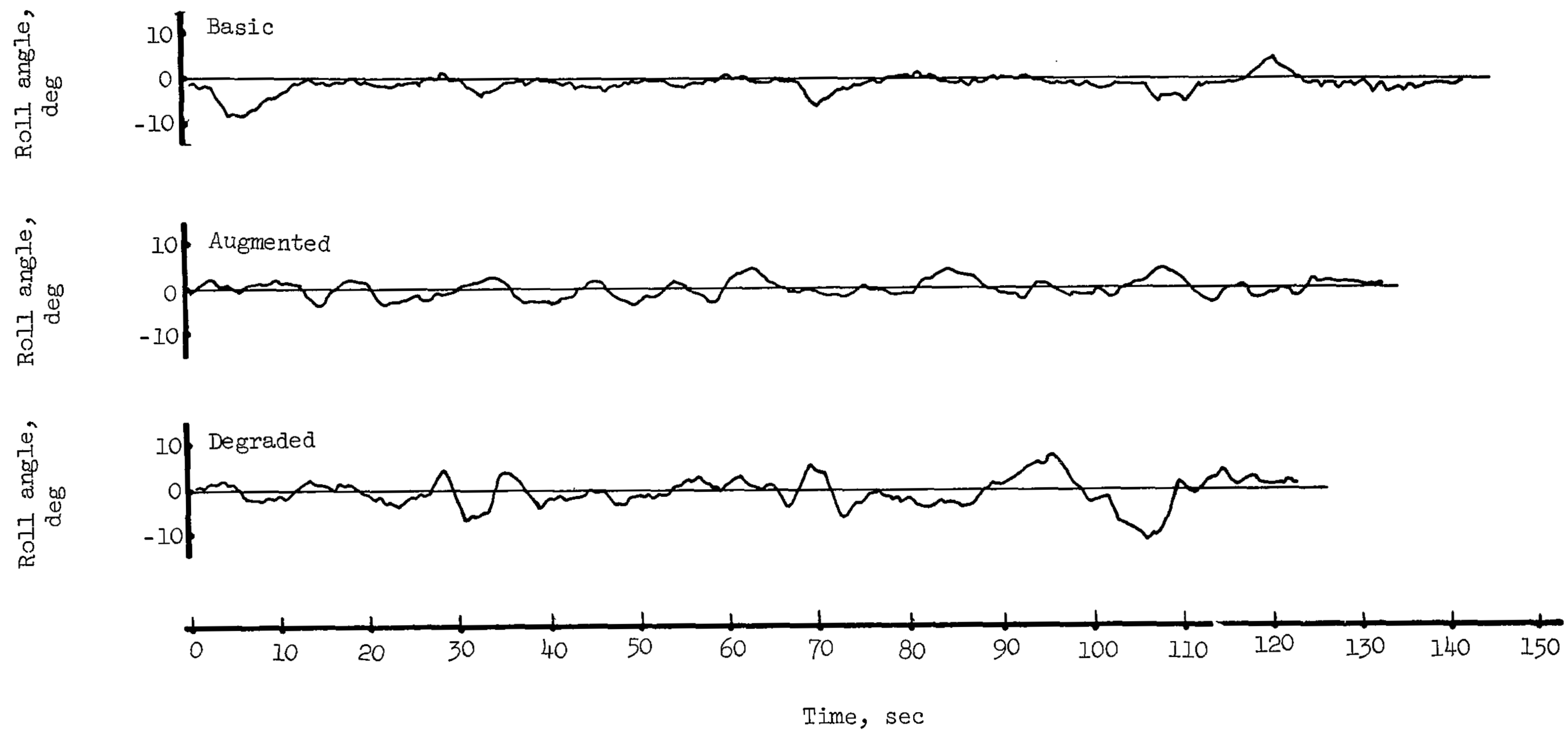
(b) Control wheel position.

Figure 5-5.- Continued.



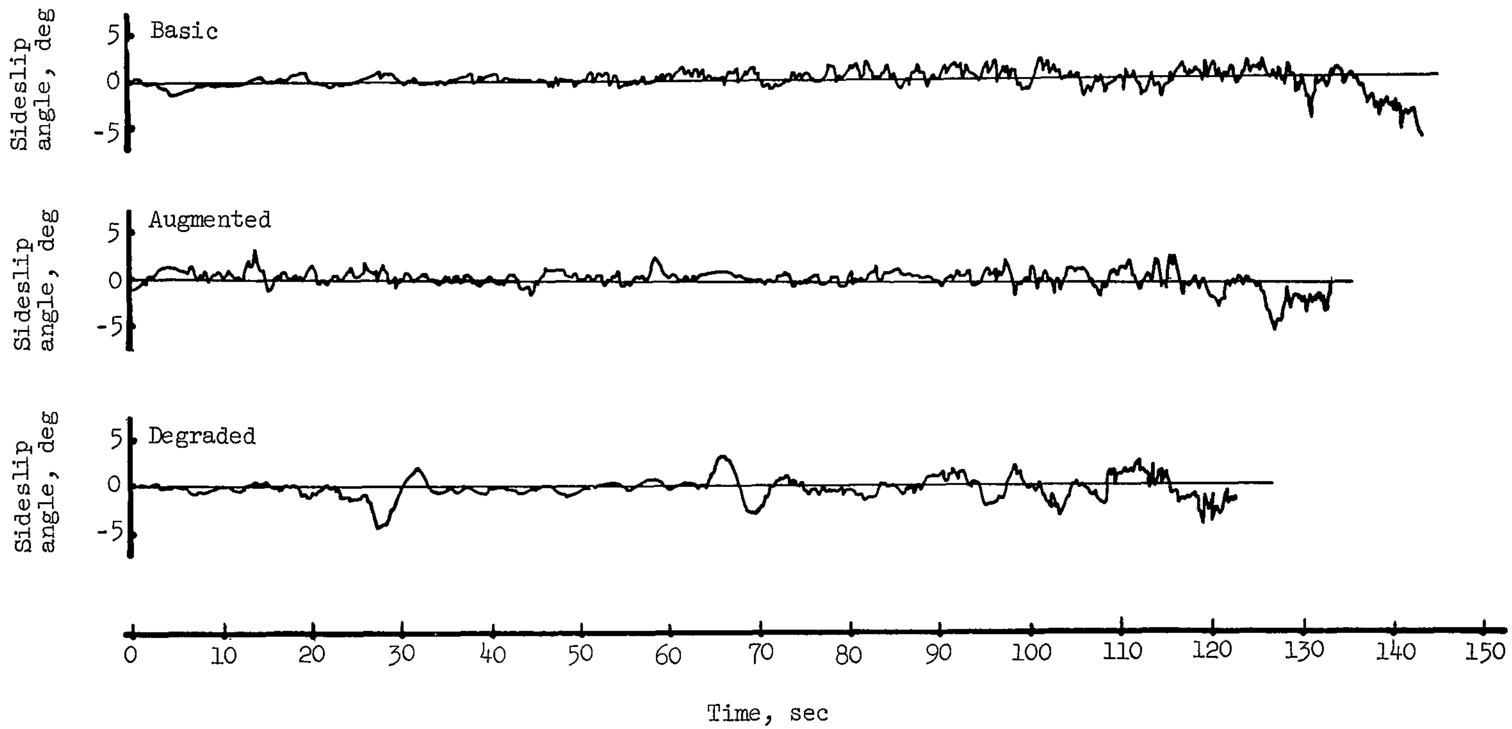
(c) Rudder pedal position.

Figure 5-5.- Continued.



(d) Roll angle.

Figure 5-5.- Continued.



(e) Sideslip angle.

Figure 5-5.- Concluded.

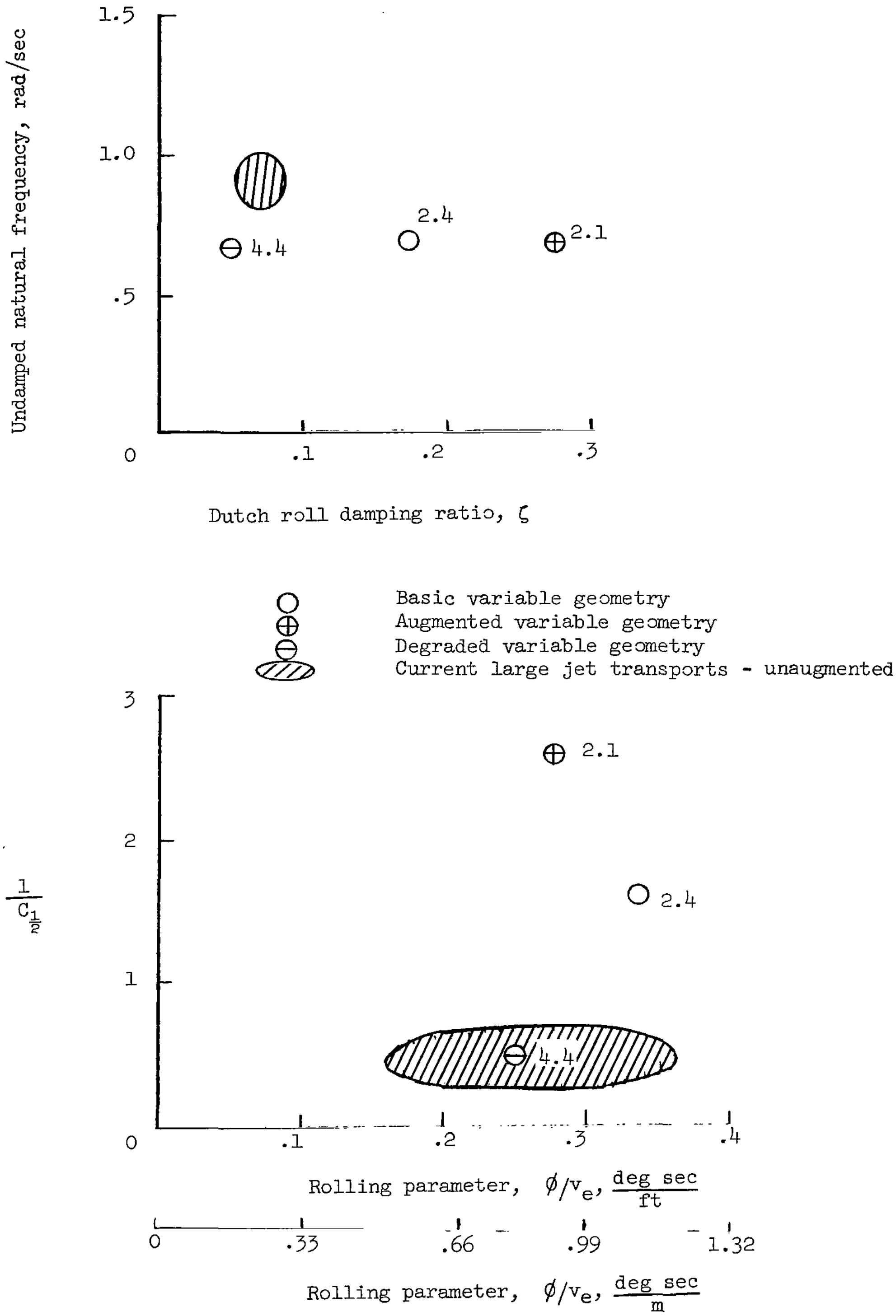


Figure 5-6.- Dutch roll oscillation characteristics of the variable-geometry supersonic transport configurations. Numbers adjacent to symbols are the pilot rating (based on the Dutch roll characteristics) for the particular configuration.

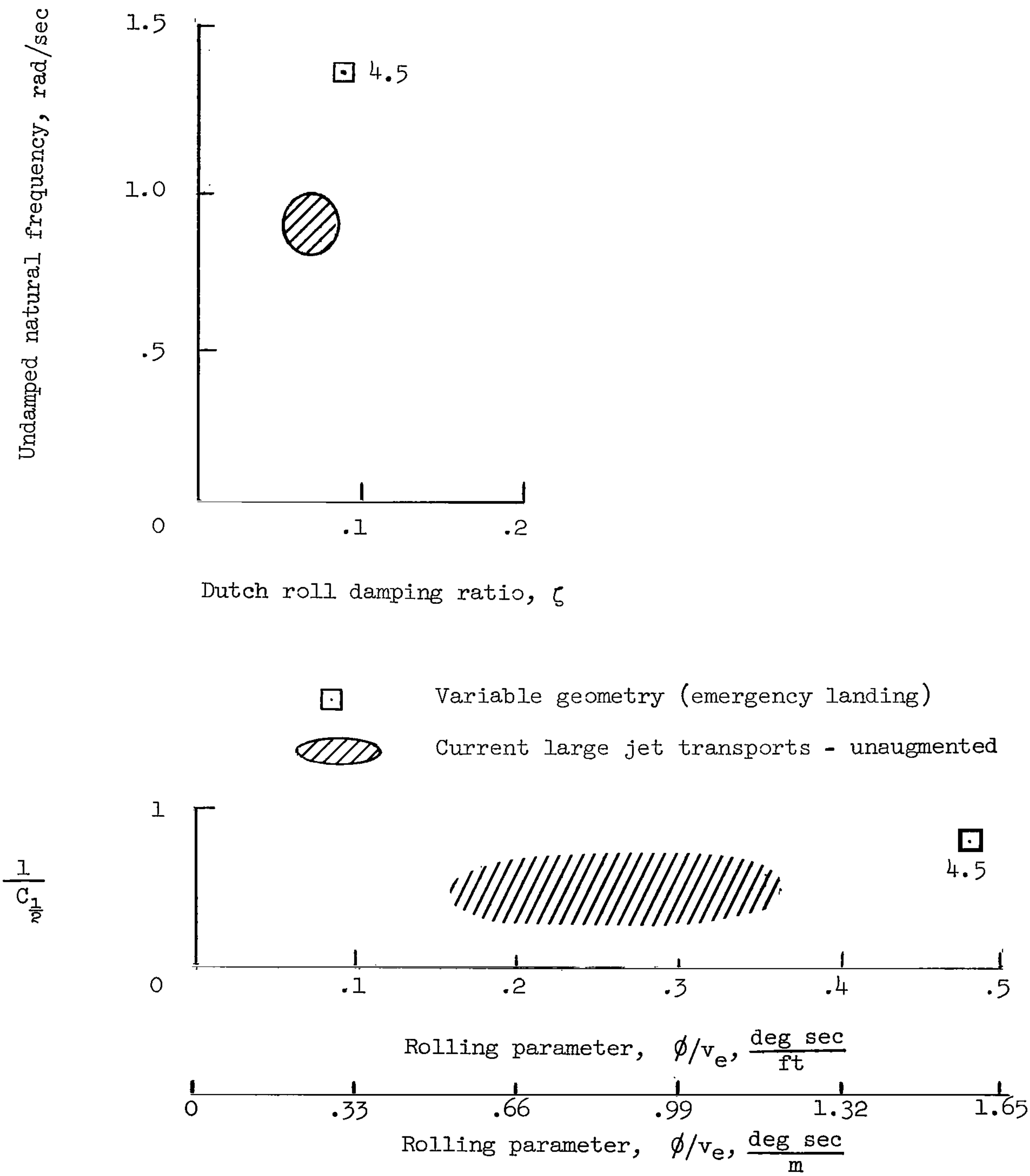
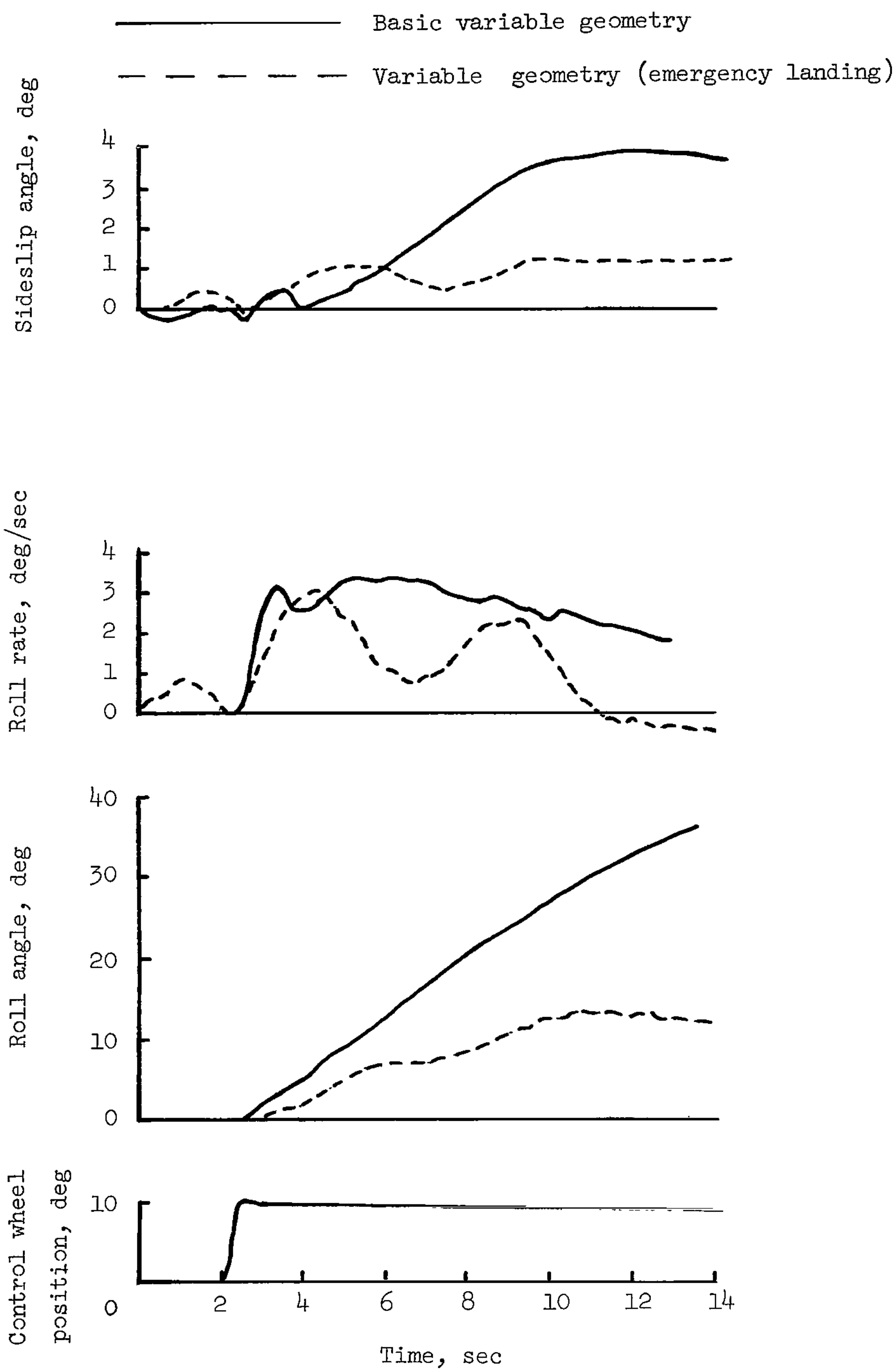
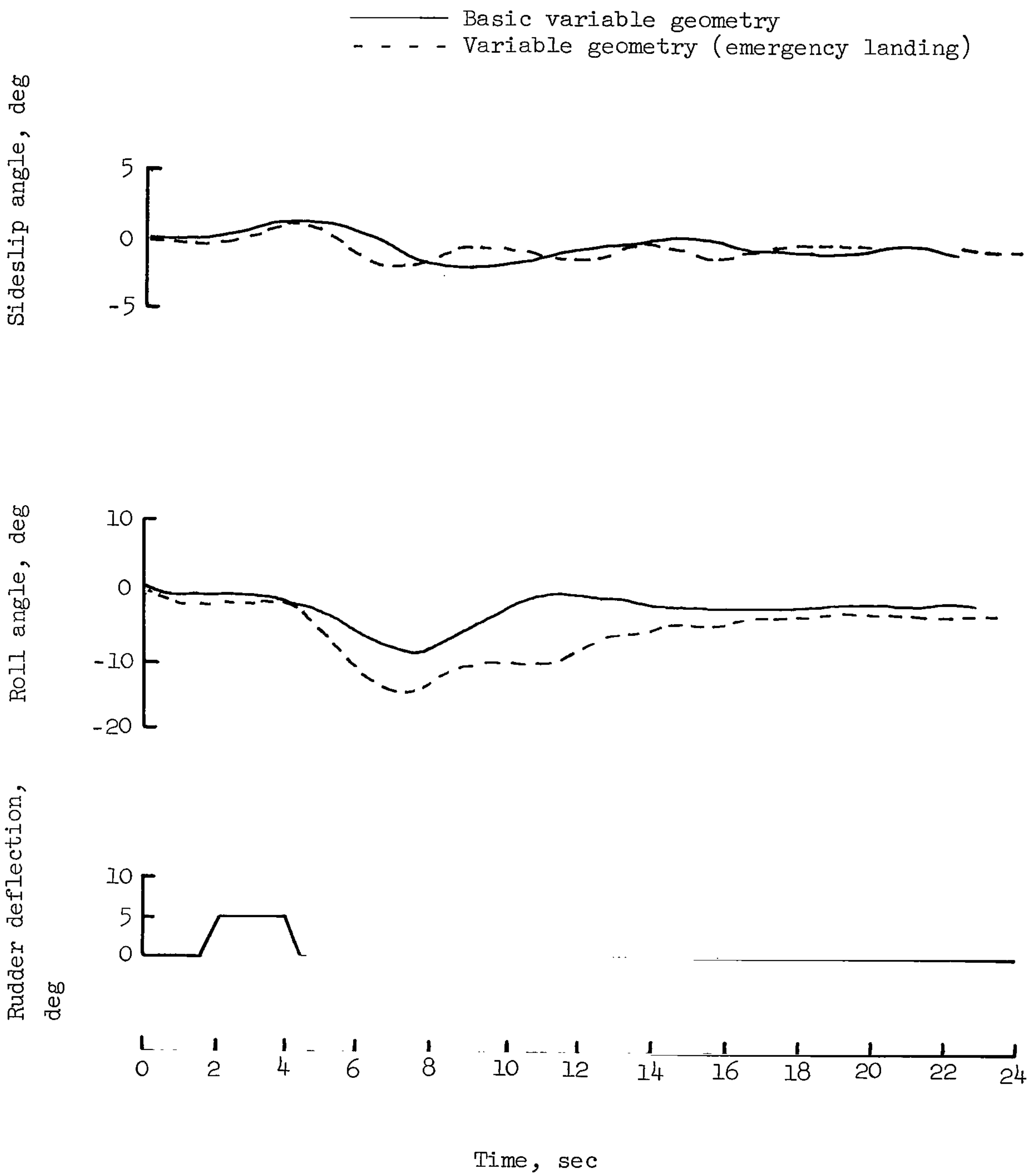


Figure 5-7.- Dutch roll oscillation characteristics of the variable-geometry (emergency landing) configuration. Numbers adjacent to the symbols are the pilot rating (based on the Dutch roll characteristics) for the configuration.



(a) Wheel step.

Figure 5-8.- Comparison of the responses of the basic variable-geometry and of the variable-geometry (emergency landing) configurations to lateral and directional control from flight records.



(b) Rudder pulse.

Figure 5-8.- Concluded.

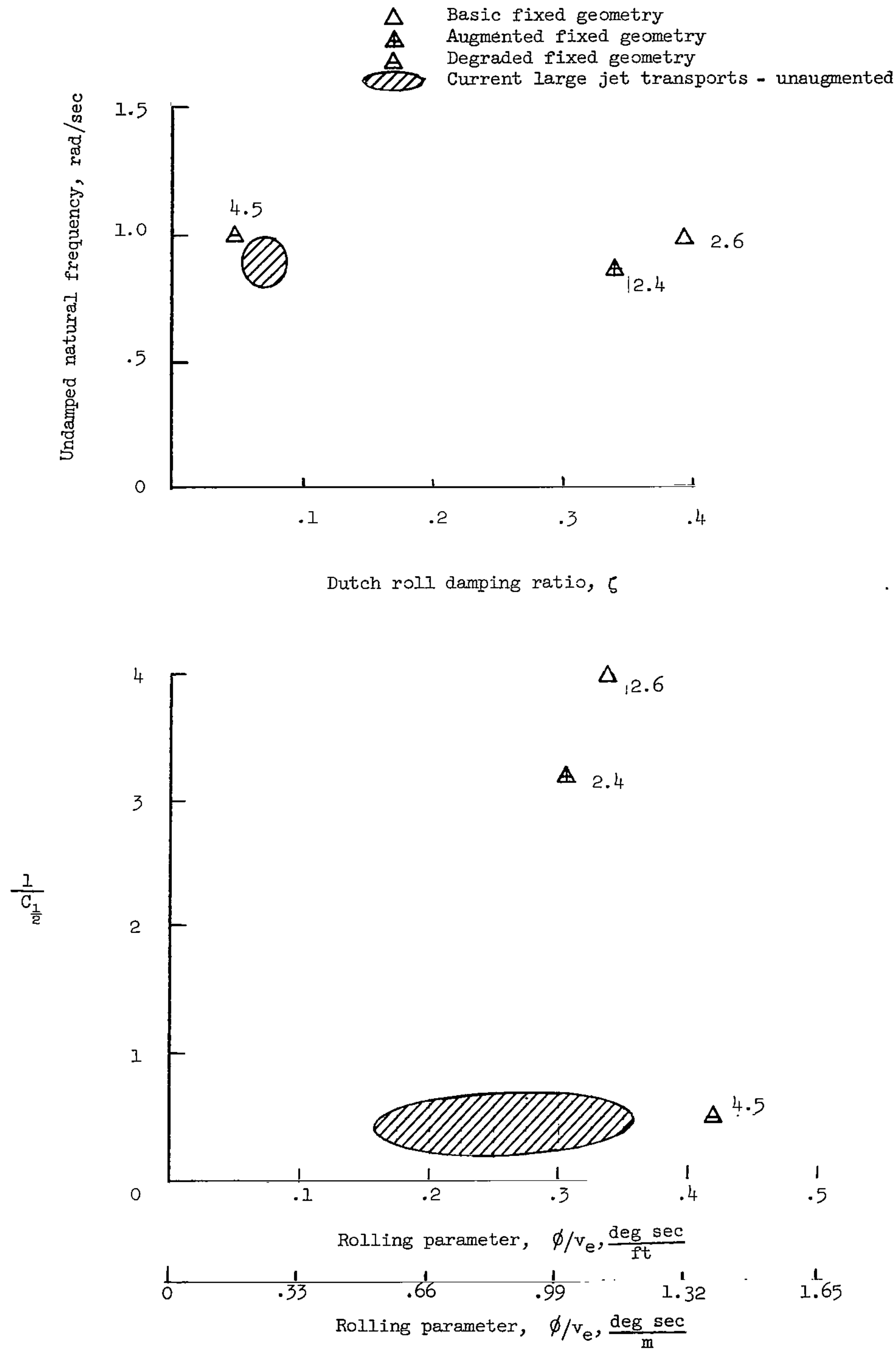


Figure 5-9.- Dutch roll oscillation characteristics of the fixed-geometry configurations. Numbers adjacent to symbols are the pilot rating (based on the Dutch roll characteristics) for the particular configuration.

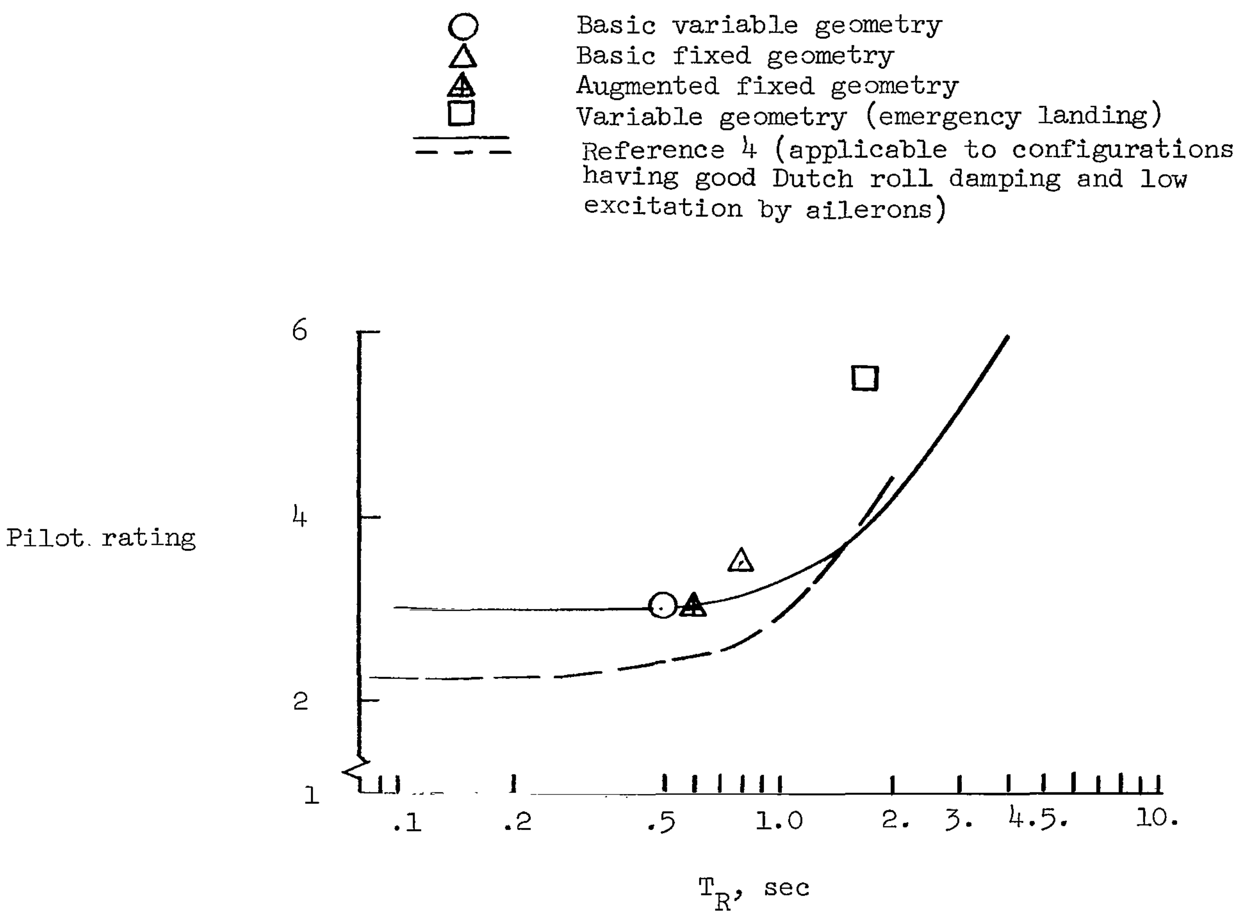


Figure 5-10.- Variation of pilot rating with roll time constant.

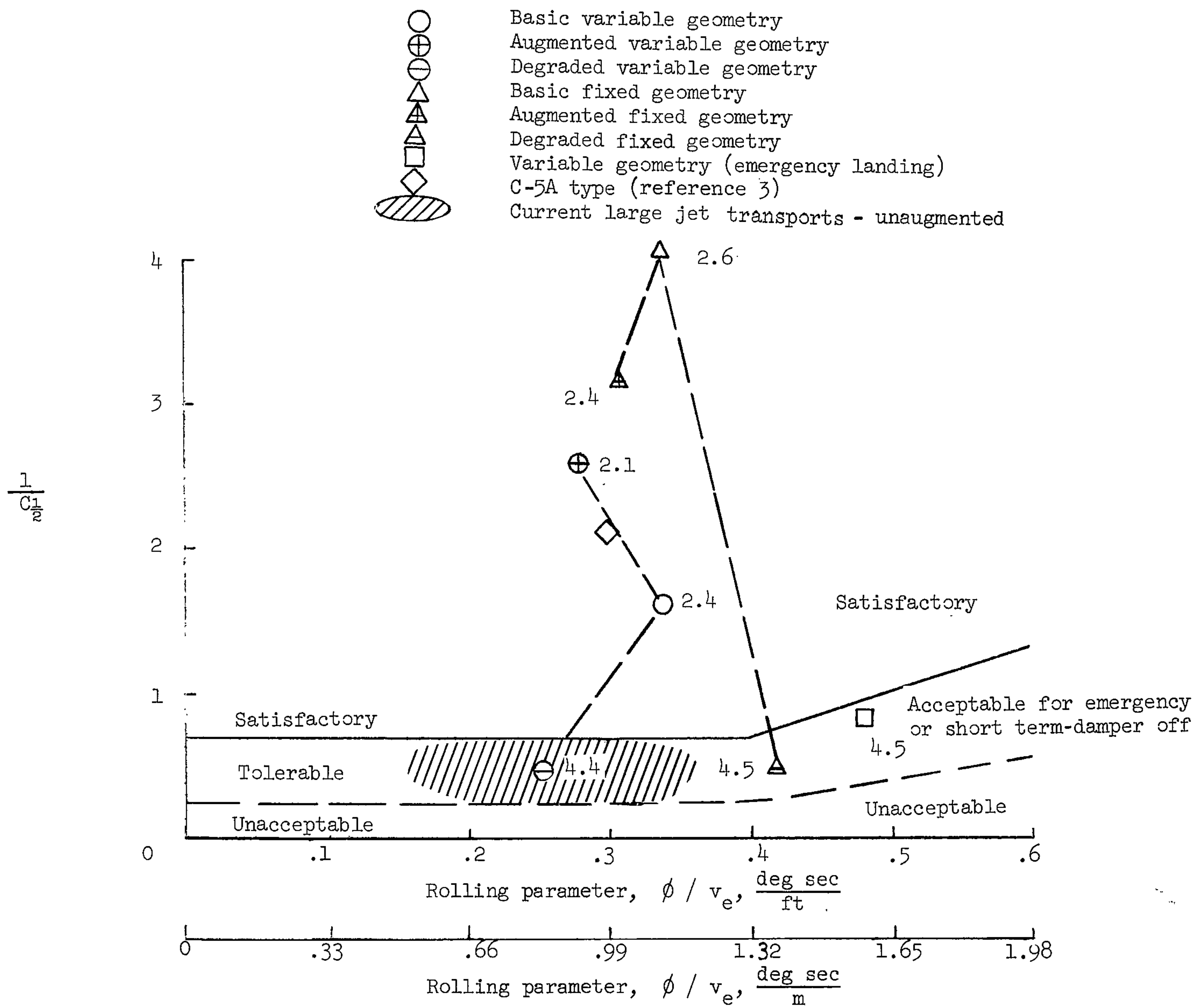


Figure 5-11.- Comparison of the Dutch roll characteristics of the test configurations with the existing military specifications. Numbers adjacent to the symbols refer to the pilot rating (based on the Dutch roll characteristics) for the particular configuration.

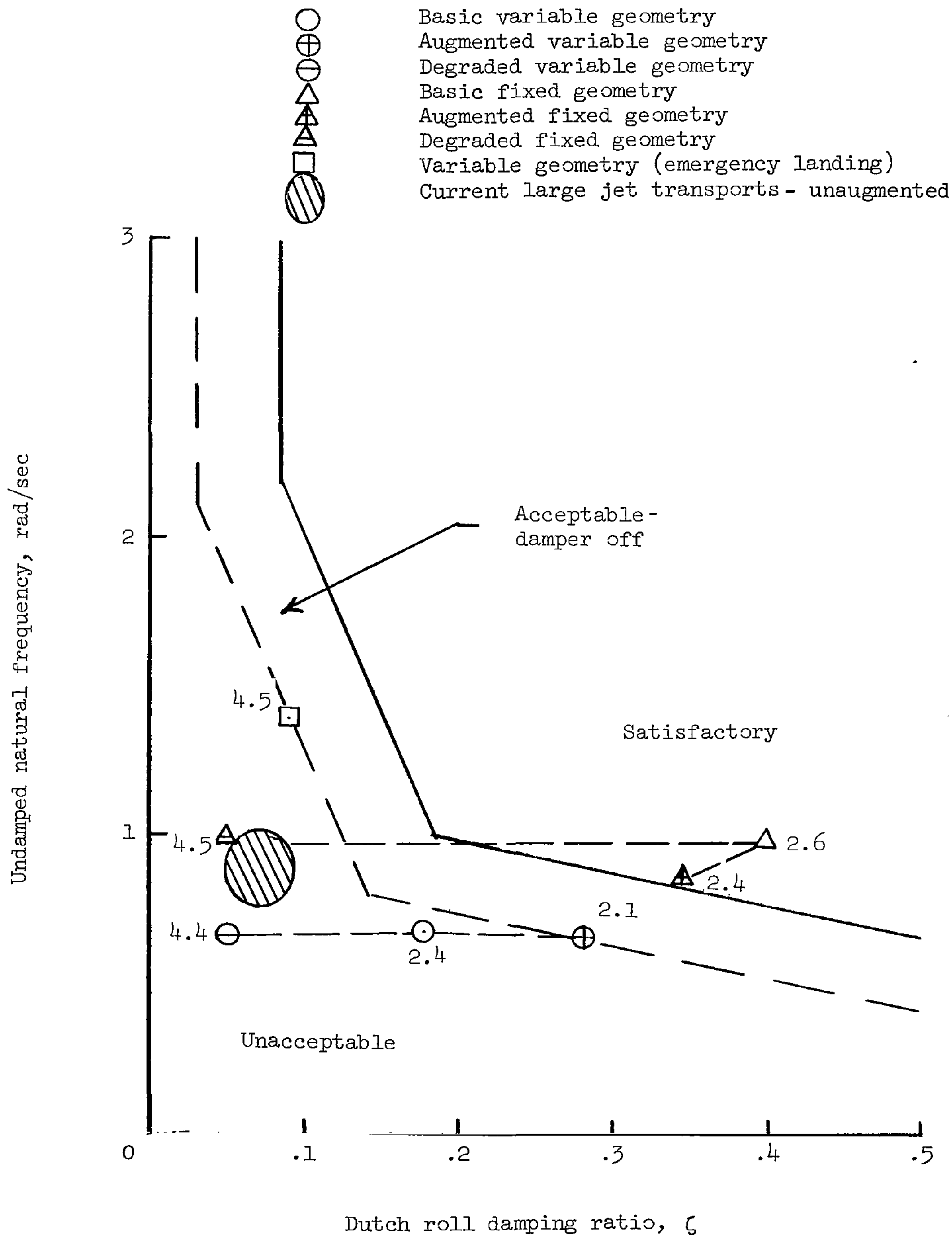


Figure 5-12.- Comparison of the Dutch roll characteristics of the test configurations with the proposed revised military specifications. Numbers adjacent to the symbols refer to the pilot rating (based on the Dutch roll characteristics) for the particular configuration.

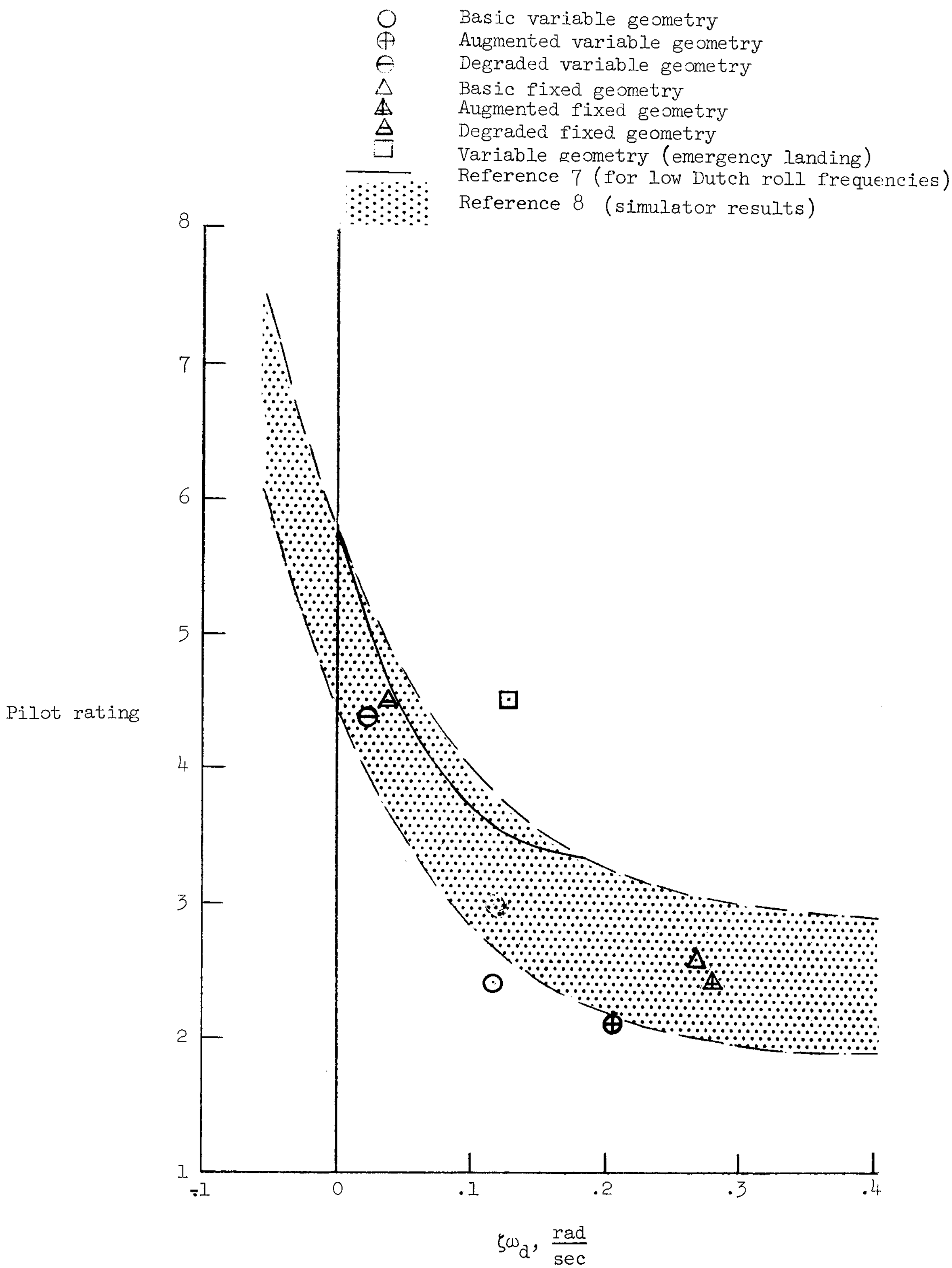


Figure 5-13.- Variation of pilot rating with Dutch roll viscous damping parameter.

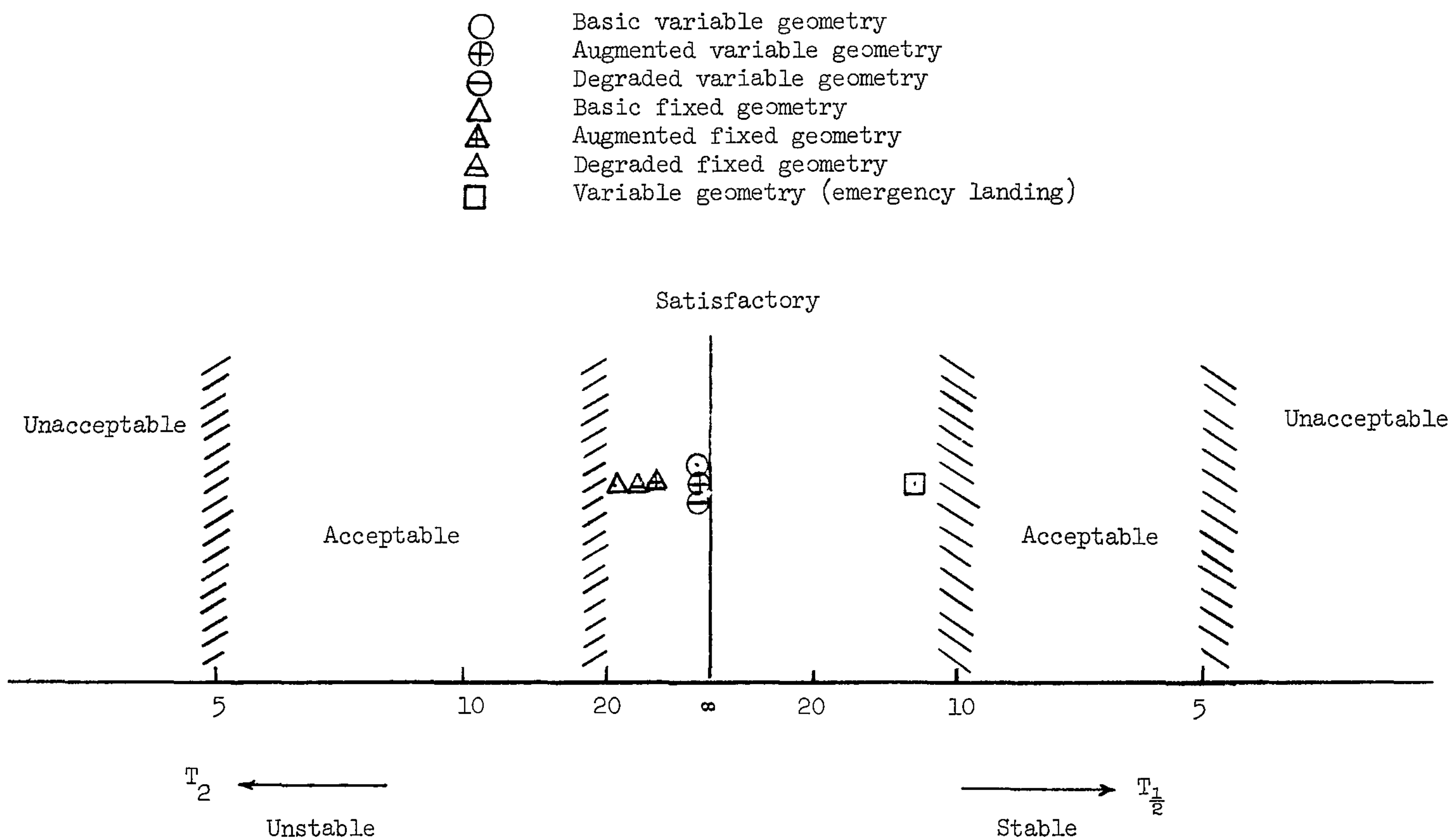


Figure 5-14.- Comparison of the calculated spiral stability characteristics with the criteria presented in reference 10.

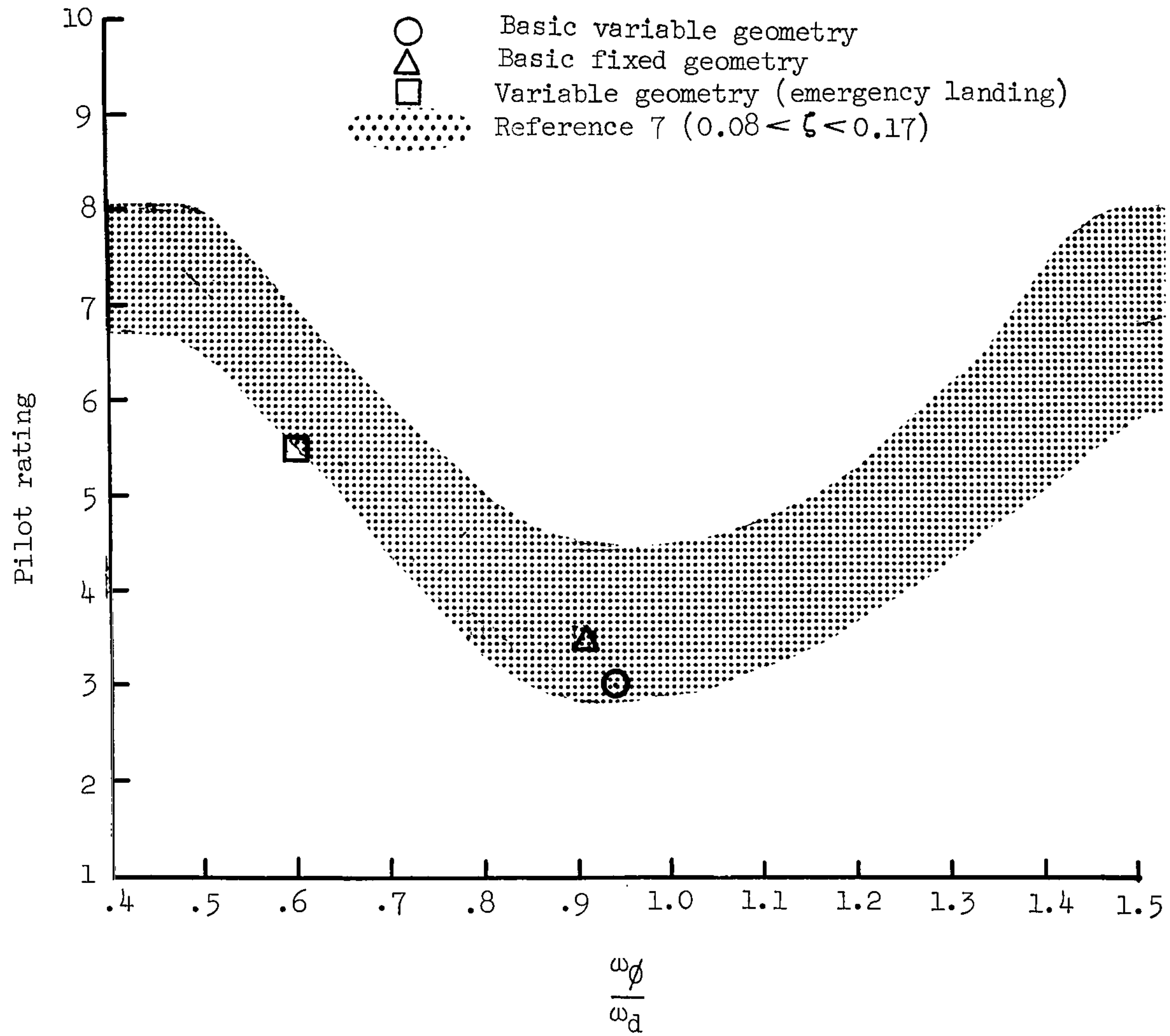


Figure 5-15.- Variation of pilot rating with roll coupling parameter.

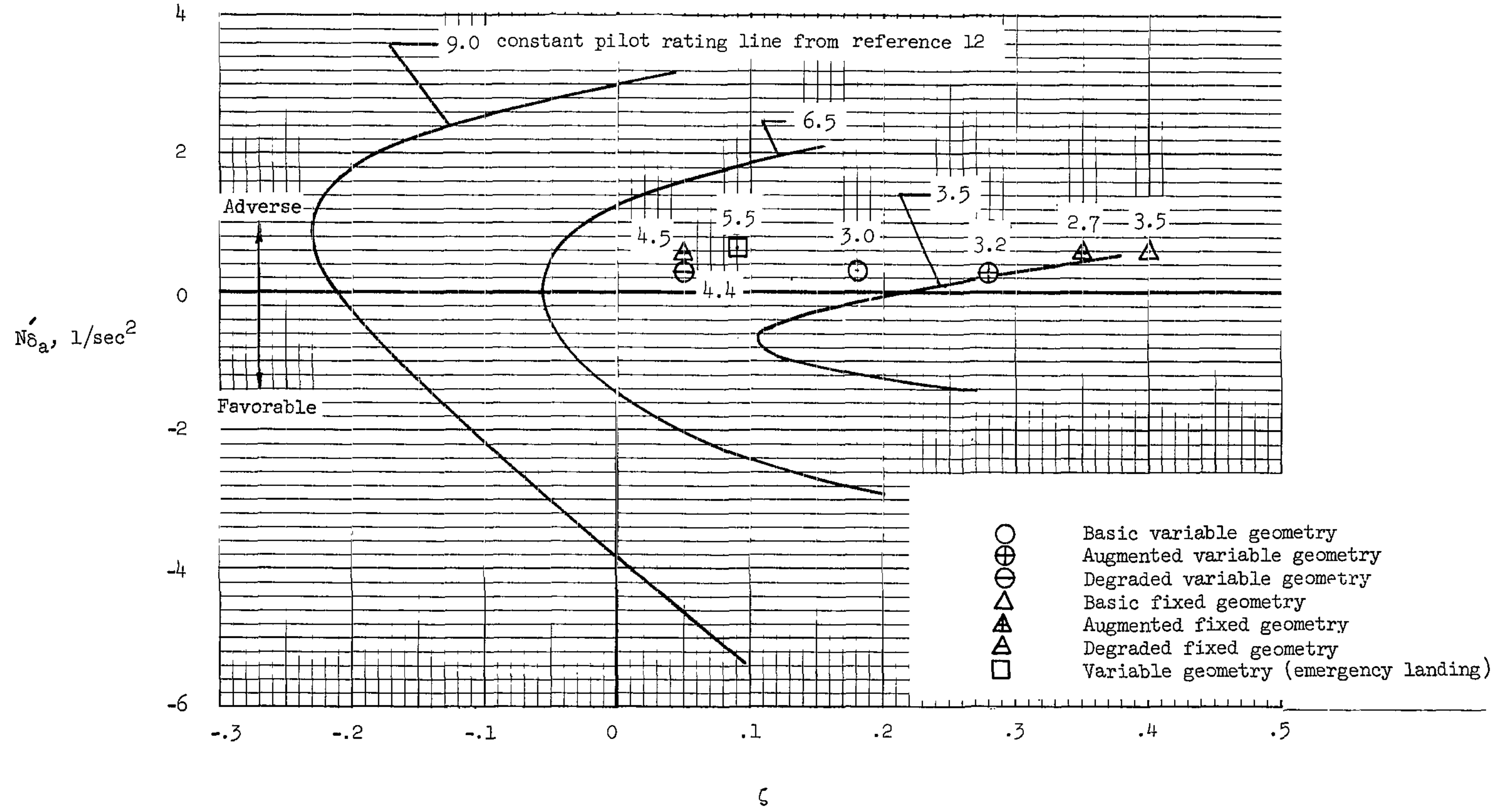


Figure 5-16.- Variation of pilot rating with aileron coupling parameter and Dutch roll damping ratio. Numbers adjacent to symbols refer to pilot rating for the particular configuration.

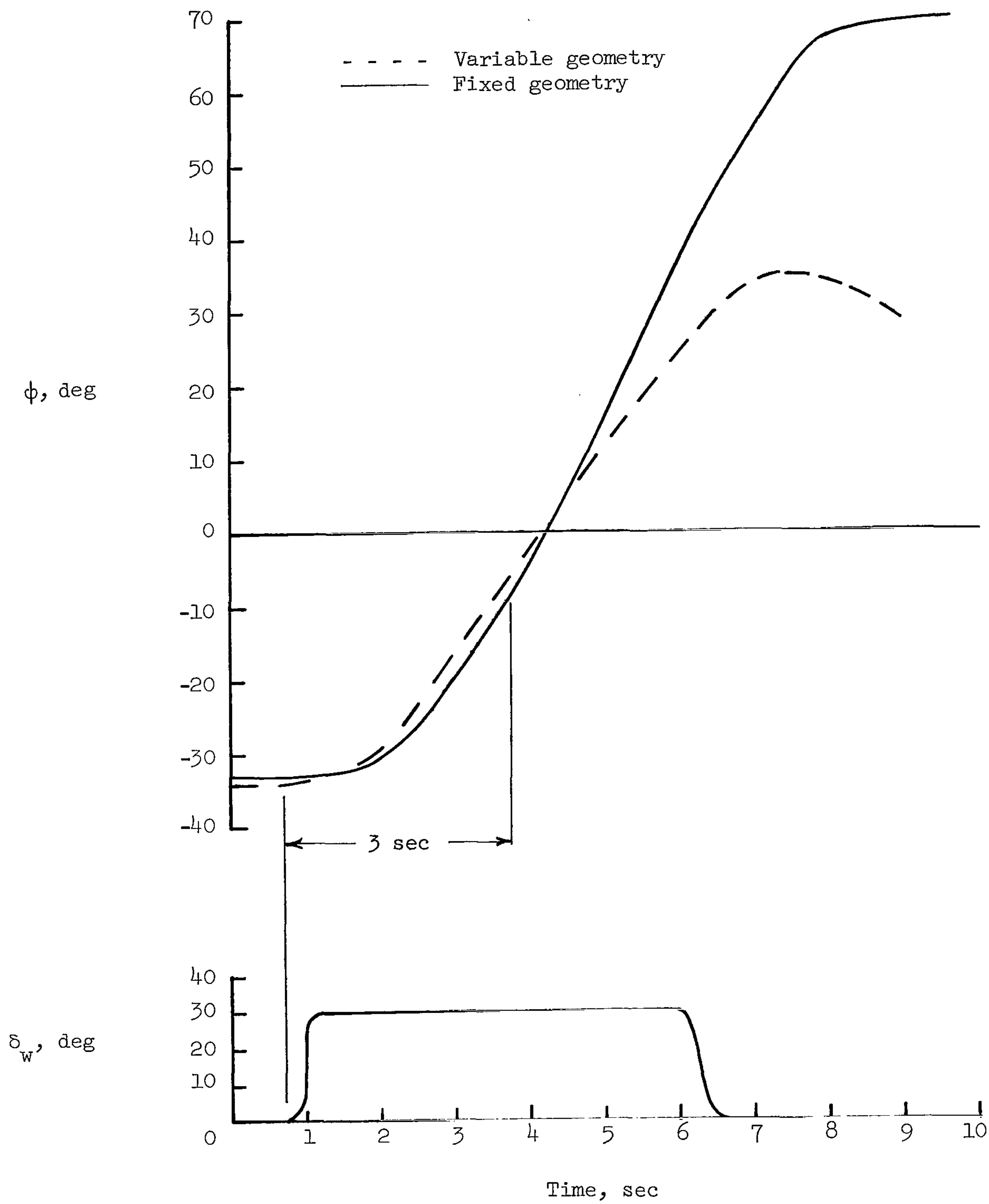


Figure 5-17.- Typical roll responses for basic fixed- and variable-geometry configurations.

6. AN EVALUATION OF PILOT WORKLOAD

By Samuel A. Morello and Albert W. Hall

SUMMARY

Correlation between pilot rating and the physical effort required to control the aircraft during an instrument approach is presented.

The physical effort required to operate the control column was a large enough portion of the total longitudinal workload to be used as documentation of the pilot's rating of the longitudinal characteristics. The wheel and rudder control effort did not correlate with the pilot's opinion of the lateral-directional characteristics.

INTRODUCTION

Quite often in describing various aircraft configurations and flying tasks, the pilot's evaluation is expressed as a pilot rating number, based on a system such as that described in reference 1. The pilot bases this rating on the workload or ease with which the aircraft is controlled, the precision with which the aircraft performs the task or responds to the pilot input, a comparison of these characteristics with those from previous experience, and an extrapolation of the expected aircraft behavior in critical situations.

Pilot ratings are sometimes questioned because pilot opinion varies with the pilot's experience and background and with the evaluation tasks involved. It is believed that there is a need for documentation or verification of pilot opinion, not as a substitute for, but as a supplement to, pilot rating.

In this part is presented the correlation between pilot rating and the physical work required to operate the airplane controls during the instrument approaches. In addition, the variation of flight-path deviations with pilot rating is discussed.

DATA REDUCTION

Pilot Work

For this evaluation, the pilot work was based on the physical definition of work which is $\int F\,ds$ where F is the force and s is the distance through which the force acts. The pilot was assumed to be working only when he moved the controls in opposition to the spring-loaded feel system; therefore, no work was being done when the springs were returning the controls to the center position. The center, or zero force control, position could be adjusted by the pilot through a simulated trim system so that, after the pilot trimmed the airplane for the approach speed, the zero-force-control position was very close to the average position for each approach. The workload was evaluated from the data recorded during the simulated instrument approaches between the time when the airplane was well established on the glide slope and the time for initiation of the landing flare.

In a few approaches the time period during which the work was evaluated varied significantly because the variation of conditions during glide slope capture affected the time required for the airplane to become well established on the glide slope. In order to compare the work data on an equivalent basis, the work determined for each approach was multiplied by the ratio of the time required for a typical approach (126 sec) to the actual time of the particular approach.

Column work.- The column work was determined from the time history of column angular displacement since both the control force and the distance the column traveled at the position of the pilot's hands are functions of control column displacement. For a given control movement, the force was taken to be the average of the control force at the initial position and the force at the final position. The control column forces for the workload computation were based on a breakout force of 4.5 pounds (20.0 newtons) in each direction and a gradient of 4 pounds (17.8 newtons) per degree of column deflection.

A control movement was defined as the motion away from the center position until the direction of motion was reversed towards the center position. After a reversal of control direction, the next motion away from the center position was treated as another control movement. The total column work for an approach was the sum of the work for each control movement.

Wheel work.- Wheel work was determined in a manner similar to the column work from the time history of wheel angular displacement. The wheel forces were based on a breakout force of 2 pounds (8.9 newtons) in each direction and a gradient of 0.16 pound (0.71 newton) per degree of wheel movement.

Rudder pedal work.- Rudder pedal work was determined in the same manner as column and wheel work except that the time history of rudder pedal displacement was expressed in inches (meters) of travel. The rudder pedal forces were based on an 11-pound (49 newton) breakout force and a gradient of 20 pounds per inch (35 newtons per centimeter) of pedal movement.

Throttle work.- Throttle work differed from the work of the other controls in that the force required to move the throttle from any position in either direction was about 1/2 pound (2.2 newtons); therefore, work was required for all throttle movement. The time history of simulated SST throttle motion (in degrees) was used to determine the throttle work. The work was taken to be the product of total throttle movement during an approach and the 1/2-pound (2.2 newton) force.

Flight-Path Deviations

Flight-path deviations were determined from data recorded by the tracking radar unit which provided ILS type of information for the landing approach tests described in part 2 of this paper. The data recording was begun when the airplane first crossed the glide slope and ended when the airplane was about 200 feet (61 meters) above the ground. These data were used to determine the rms deviations from the glide slope for the approaches.

RESULTS AND DISCUSSION

Measurements of control motion and force are relatively easy to obtain during flight investigations. These quantities can be presented in various forms to represent part of the pilot effort required to perform a given task. Reference 2, for example, shows good correlation between pilot rating and total control movement during an instrument approach. Control motion could also be represented as a root-mean-square value. The present investigation combines control motion and control force to give a measure of pilot effort in terms of work in foot-pounds (newton-meters). An indication of the relation between the control column movement and the column work can be seen in figure 6-1 for two instrument approaches. The column work for one approach is almost three times that of the other approach. From inspection of the time histories, the relative control displacements appear to have about the same relationship as the work levels. The control displacement for a given time interval near the end of the approach is much greater than that for the same time interval near the beginning of the approach. A measure of the work as defined here for an approach gives no indication of the variation of work for various portions of the approach.

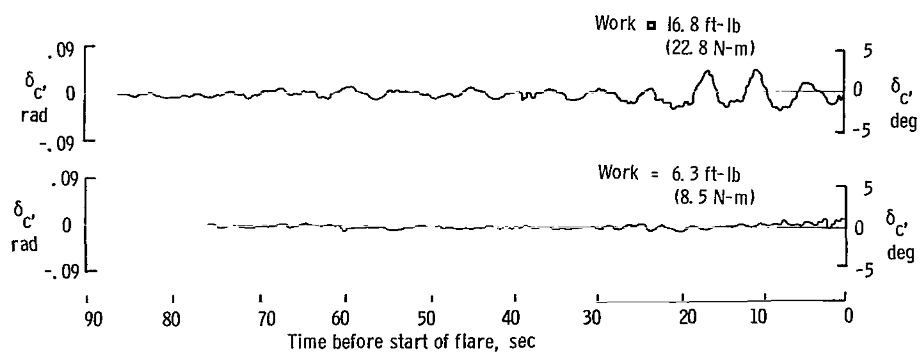


Figure 6-1.- Control column time histories for two instrument approaches.

A summary of the control work and pilot ratings for the instrument approaches made during this investigation is given in table 6-1. The configurations listed in table 6-1 are described in detail in part 2.

Longitudinal Characteristics

Column work.- The variation of pilot rating of the longitudinal characteristics with column work is shown in figure 6-2 for the data of table 6-1. These data show a definite trend of increasing work for increasing pilot rating – that is, the column work for the approaches increases as the airplane characteristics deteriorate. For the basic variable-geometry configuration represented by the circular symbols, the work levels are higher for both pilots than indicated by the general trend of data for other configurations. These data represent the first configuration tested by each pilot and it is possible that the high work levels are representative of the early portion of the "pilot's learning phase." The possibility is indicated here that the measured work could be used to determine when the pilot's learning phase has been completed.

Differences between the two pilots are also indicated by the data shown in figure 6-2. Although the same general trend is shown for each pilot, pilot A generally works harder

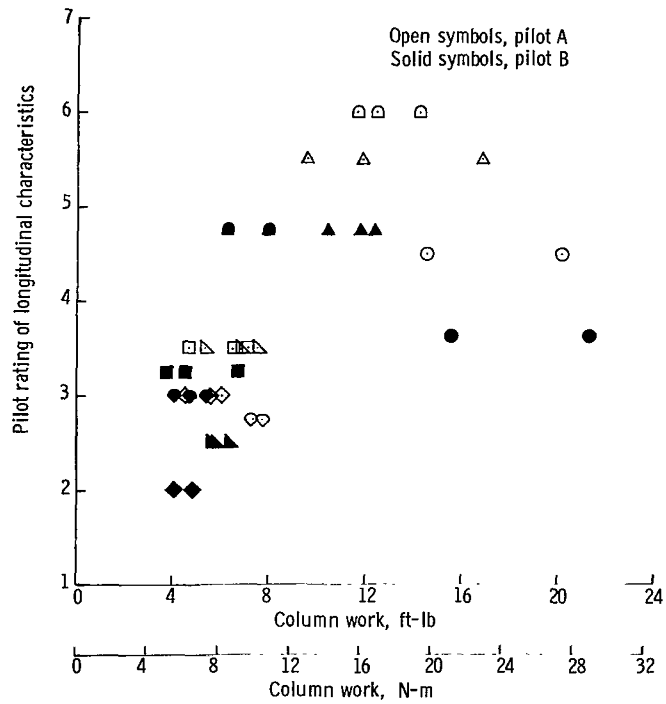


Figure 6-2.- Variation of pilot rating of longitudinal characteristics with column work. Additional symbol identification is given in table 6-1.

and gives a correspondingly higher rating than pilot B for the same configuration. These results indicate that the physical effort required to move the control column during an instrument approach is a sufficiently large portion of the total workload (physical and mental) to be used as documentation of the pilot's rating of the longitudinal characteristics.

Throttle work.- For this study, the throttle motion was expressed as foot-pounds (newton-meters) of work (table 6-1) in an attempt to develop an expression which could be combined directly with column work to give a number representing total longitudinal work. It can be seen in table 6-1 that the numbers for throttle work are an order of magnitude lower than that for the column work. According to the opinion of the pilots, the throttle workload was a much higher percentage of the total longitudinal workload than is indicated in table 6-1. Therefore, the conversion of throttle motion to foot-pounds (newton-meters) of work did not provide a direct comparison with other control workloads having the same units of measurement.

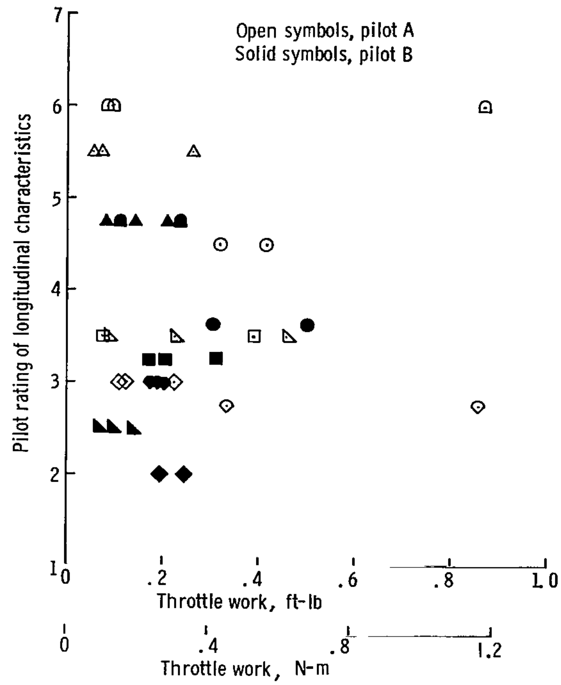


Figure 6-3.- Variation of pilot rating of longitudinal characteristics with throttle work. Additional symbol identification is given in table 6-1.

From figure 6-3 it can be seen that there is no consistent trend between throttle work and pilot rating of the longitudinal characteristics for the various configurations. Other factors, such as mental effort and time required to operate the throttle, apparently are such a large part of the throttle workload that the physical effort required for throttle control is not proportional to the pilot's opinion of either the throttle workload or the rating of the longitudinal characteristics.

Flight-path deviations from glide slope.- The variations of flight path in the vertical plane are given in table 6-1 as root-mean-square deviations from the glide slope for each approach. In order to expedite the presentation of these results, other methods of measuring flight-path performance were not investigated; however, some of these methods could be more suitable than the rms deviations. For example, deviations expressed in terms of percent of glide slope altitude (angular deviation) could be used to indicate the tighter flight-path control required as the airplane nears the ground. (An example of variation of airplane control effort as the airplane nears the ground is illustrated in figure 6-1 by the increased amplitude of control motions.) Another measure of glide-path control would be the error at the conclusion of the approach (point at which the pilot makes transition from instrument to visual flight).

The variation of pilot rating of the longitudinal characteristics with rms deviations of the airplane along the glide slope is given in figure 6-4. The rms deviation from the glide slope has a value between 10 and 30 feet (3.05 and 9.14 meters) for all except four of the approaches shown in figure 6-4. Two approaches having a value outside this boundary were made with the first configuration flown by pilot B. As the longitudinal characteristics of the configurations deteriorate (increased pilot rating), each pilot tends to maintain glide-path control the same as, or better than, that for configurations with better longitudinal characteristics. This result agrees with previous observations that, as the piloting task becomes more difficult, the pilot tends to increase his gain and continues to perform with the same level of accuracy.

This statement indicates that there should be a correlation between work and flight-path accuracy if other variables such as configuration characteristics were held constant. However, during this investigation too few approaches were made with a given configuration to determine the relation between work and flight-path accuracy.

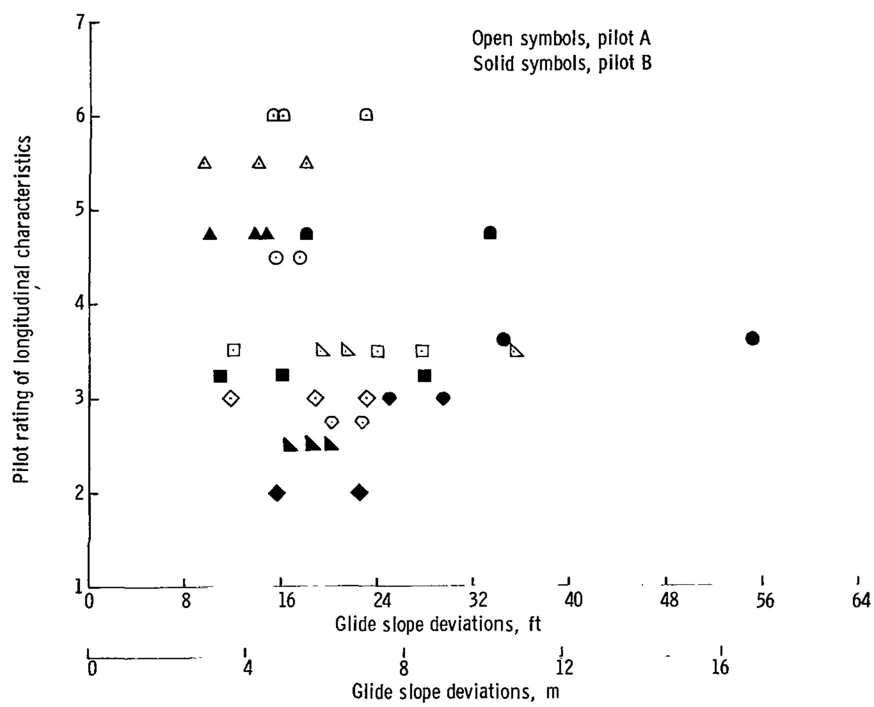


Figure 6-4.- Variation of pilot rating of longitudinal characteristics with rms glide slope deviations during instrument approaches. Additional symbol identification is given in table 6-1.

Lateral-Directional Characteristics

The variation of pilot rating of the lateral-directional characteristics with wheel work is shown in figure 6-5 for the approaches listed in table 6-1. The data indicate that for pilot B the trend is similar to that shown for the longitudinal characteristics (i.e., increased pilot rating is accompanied by increased work). This trend is not as evident for pilot A and in either case the data are rather widely scattered.

The rudder pedal work was added to the wheel work in an attempt to improve the correlation of work with pilot rating of the lateral-directional characteristics (fig. 6-6). The addition of rudder pedal work did not appreciably change the correlation with pilot rating (see figs. 6-5 and 6-6), nor did it reduce the scatter between approaches with the same configuration and pilot. Just as for the throttle work, other factors which are not easily measured apparently constitute a large portion of the pilot's impression of lateral-directional work.

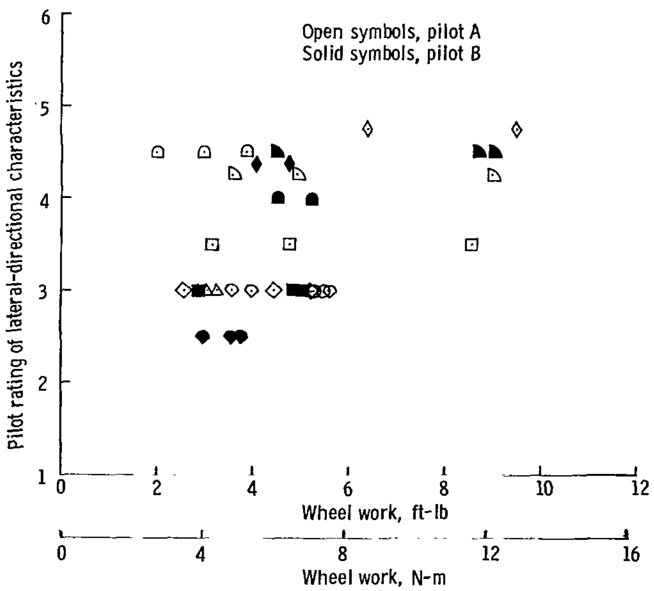


Figure 6-5.- Variation of pilot rating of lateral-directional characteristics with wheel work. Additional symbol identification is given in table 6-1.

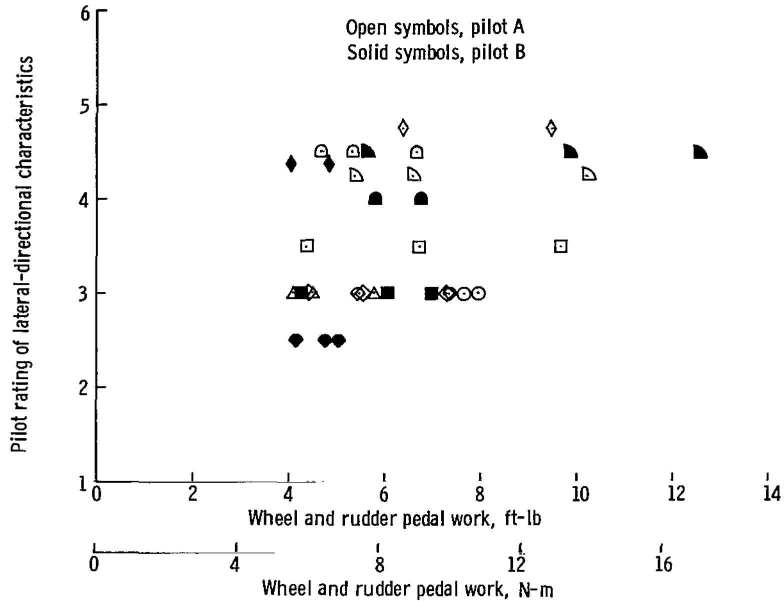


Figure 6-6.- Variation of pilot rating of lateral-directional characteristics with wheel and rudder pedal work. Additional symbol identification is given in table 6-1.

CONCLUDING REMARKS

Part 6 of this publication has presented the results of a method of measuring pilot workload and compares these measurements with pilot opinion. The physical effort exerted by the pilot was expressed in foot-pounds (newton-meters) of work for the control column, wheel, rudder pedals, and throttle for simulated instrument approaches made during the in-flight simulation study of supersonic-transport configurations.

This exploratory study involving only a few approaches for each of several configurations did not furnish enough data to establish any firm conclusions; however, some tentative results and trends were indicated.

The physical effort required to move the control column during an instrument approach appears to be a large enough portion of the total longitudinal workload to be used as documentation of the pilot's rating of the longitudinal characteristics.

The conversion of throttle motion to units of work did not provide a direct comparison with other controls having the same units of measurement nor did the throttle work show any correlation with pilot rating of the longitudinal characteristics.

The physical effort required to move the wheel and rudder pedal controls during these instrument approaches did not correlate with pilot rating of the lateral-directional characteristics.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 26, 1966,
720-04-00-06-23.

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1. Cooper, George E.: Understanding and Interpreting Pilot Opinion. Aeron. Eng. Rev., vol. 16, no. 3, Mar. 1957, pp. 47-51, 56.
2. Klein, Richard H.; Archer, Richard B.; and Lew, Dan W.: Supersonic Transport Handling Characteristics During Approach and Landing Flight Regimes. AFFDL-TR-65-227, U.S. Air Force, Dec. 1965.

TABLE 6-1.- SUMMARY OF DATA FROM INSTRUMENT APPROACHES

Configuration	Pilot	Symbol	rms glide slope deviation, ft	rms glide slope deviation, m	Work: Column, ft-lb	Work: Column, N-m	Work: Wheel, ft-lb	Work: Wheel, N-m	Work: Rudder pedal, ft-lb	Work: Rudder pedal, N-m	Work: Throttle, ft-lb	Work: Throttle, N-m	Pilot rating: Longitudinal characteristics	Pilot rating: Lateral-directional characteristics
Variable geometry (basic)	A	○	15.5	4.72	14.48	19.63	5.26	7.13	2.36	3.20	0.320	0.43	4.5	3.0
			17.5	5.33	20.57	27.89	5.48	7.43	2.47	3.35	.415	.56		
	B	●	54.9	16.73	15.64	21.20	(a)		(a)		.509	.68	3.50 - 3.75	3.0
			34.8	10.61	21.25	28.81	(a)		(a)		.309	.42		
Variable geometry ($\dot{\theta}$ and $\dot{\beta}$ augmented)	A	□	12.1	3.69	6.45	8.74	8.54	11.58	1.09	1.48	0.075	0.10	3.5	3.5
			27.7	8.44	7.06	9.57	4.76	6.45	1.94	2.63	(a)			
			24.0	7.32	4.62	6.26	3.15	4.27	1.19	1.61	.390	.53		
	B	■	11.2	3.41	3.76	5.09	2.86	3.88	1.41	1.91	.017	.02	3.25	3.0
			16.2	4.94	4.51	6.11	4.85	6.58	1.21	1.64	.207	.28		
			28.0	8.53	6.76	9.16	5.07	6.87	1.91	2.59	.310	.42		
Variable geometry (($\dot{\theta} + \Delta\alpha$) and $\dot{\beta}$ augmented)	A	◇	22.9	6.98	4.47	6.06	2.57	3.48	1.69	2.29	0.117	0.16	3.0	3.0
			11.7	3.57	5.51	7.47	4.44	6.02	1.11	1.51	.120	.16		
			18.6	5.67	6.01	8.15	5.26	7.13	2.04	2.76	.225	.31		
	B	◆	15.8	4.82	4.02	5.45	2.00	2.71	1.92	2.60	.195	.26	2.0	(b)
			22.4	6.83	4.83	6.55	3.25	4.77	1.42	1.93	.248	.34		
Variable geometry ($\dot{\beta}$ augmented) with aft c.g.	A	△	14.2	4.33	16.85	22.85	3.25	4.41	2.53	3.43	0.263	0.36	5.5	3.0
			9.6	2.93	9.52	12.91	2.89	3.92	1.49	2.02	.055	.07		
			18.0	5.49	11.89	16.12	3.03	4.12	1.13	1.53	.071	.10		
	B	▲	10.5	3.20	10.36	14.05	3.30	4.47	1.47	1.99	.142	.19	4.5 – 5.0	(b)
			14.5	4.42	12.25	16.61	3.73	5.06	2.57	3.48	.208	.28		
			13.8	4.21	11.77	15.96	4.00	5.42	2.09	2.83	.083	.11		
Variable geometry (($\dot{\theta} + \Delta\alpha$) and $\dot{\beta}$ augmented) with aft c.g.	A	◺	19.2	5.85	7.53	10.21	4.77	6.47	2.63	3.56	0.458	0.62	3.5	(b)
			35.3	10.76	6.83	9.26	5.86	4.94	3.10	4.20	.225	.31		
			21.4	6.52	5.31	7.20	4.71	6.36	5.50	7.46	.083	.11		
	B	◣	18.4	5.61	6.29	8.53	5.17	7.01	1.58	2.14	.067	.09	2.5	(b)
			16.4	4.99	5.58	7.57	4.58	6.21	6.64	9.00	.095	.13		
			20.7	6.31	5.68	7.70	4.31	5.84	1.81	2.45	.133	.18		
Variable geometry with degraded Dutch roll damping and $C_{n_{\dot{\phi}}}$	A	◺	17.7	5.39	4.27	5.79	3.58	4.85	1.74	2.36	0.308	0.42	(b)	4.0 – 4.5
			21.9	6.67	8.47	11.48	4.91	6.66	1.64	2.22	.280	.38		
			14.4	4.39	8.34	11.31	8.97	12.16	1.23	1.67	(a)			
	B	◣	37.0	11.28	7.34	9.95	8.95	12.13	.80	1.08	.416	.56	(b)	4.5
			21.2	6.46	7.27	9.86	8.65	11.73	3.84	5.21	.575	.78		
			20.0	6.10	4.59	6.22	4.45	6.03	1.15	1.56	.200	.27		
Fixed geometry (basic)	A	◠	23.0	7.01	14.16	19.19	2.96	4.01	2.35	3.19	0.868	1.18	6.0	[c]4.5
			16.2	4.94	11.58	15.70	3.86	5.23	2.77	3.76	.084	.11		
			15.4	4.69	12.36	16.76	1.95	2.64	2.67	3.62	.083	.11		
	B	◖	17.7	5.39	6.24	8.46	4.49	6.09	1.30	1.76	.110	.15	4.5 – 5.0	[c]4.0
			35.4	10.79	7.96	10.79	5.20	7.05	1.53	2.07	.237	.32		
Fixed geometry (($\dot{\theta} + \Delta\alpha$) and C_{l_p} augmented)	A	⬭	19.8	6.04	7.29	9.88	5.60	7.59	1.64	2.22	0.325	0.44	2.75	3.0
			22.6	6.89	7.64	10.36	3.98	5.40	1.47	1.99	.860	1.16		
	B	⬬	25.0	7.62	4.65	6.30	3.54	4.80	1.22	1.65	.208	.28	3.0	2.5
			29.6	9.02	4.08	5.53	3.72	5.04	1.31	1.77	.192	.26		
			(a)		5.40	7.32	2.92	3.96	1.22	1.65	.176	.24		
Fixed geometry (($\dot{\theta} + \Delta\alpha$) augmented) with degraded Dutch roll damping and $C_{n_{\dot{\phi}}}$	A	◊	22.5	6.86	5.84	7.92	9.47	12.84	0	0	0.457	0.62	(b)	4.5 - 5.0
			27.0	8.23	5.19	7.04	6.36	8.62	0	0	.600	.81		
	B	⧫	25.6	7.80	6.45	8.74	4.73	6.41	0	0	.360	.49	(b)	4.25 - 4.50
			28.4	8.66	3.52	4.77	4.04	5.47	0	0	.347	.47		

[a]Data not obtained.

[b]Rating not given for this configuration.

[c]These approaches were made with unrealistic adverse yaw. See footnote on page 17.

NASA-Langley, 1967 —— 2 L-5221

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