9. STUDY OF LOW-SPEED FLYING QUALITIES OF VERY LARGE AIRPLANES BY MEANS OF AN IN-FLIGHT SIMULATOR

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SUMMARY

Very large jet transports such as the supersonic transport (SST) and the C-5 type airplanes now being considered introduce geometric and design features which can be expected to affect low-speed handling qualities adversely. As a result, the Langley and Ames Research Centers have recently conducted flight programs in which a large jet transport was used as an in-flight SST simulator to study the low-speed handling qualities of the SST and the C-5 type configurations.

Pilots found the initial pitch response to be sluggish, and they considered it a problem. Undesirable transient response characteristics were created by the low frequencies of the longitudinal short-period motion. For the configurations tested, it appears that some sort of stability augmentation will be necessary to correct the sluggish initial pitch response and the undesirable transient response caused by the low frequency of the longitudinal short-period motion. For the delta-type SST configuration, the speed-thrust instability did not present any appreciable problem for the particular pilot evaluation tasks used in these tests. However, more throttle activity and pilot workload were required to perform the same evaluation tasks. Roll-to-yaw coupling did not cause noticeable problems for the configurations and parameters tested. However, the C-5 type airplane may require some form of lateral-directional stability augmentation.

INTRODUCTION

Some of the future very large jet transports such as the SST's and the C-5's have mass and dimensional characteristics that are considerably different from those of present jet transports. A comparison of some of the mass characteristics of present jet transports with those of several generalized future large jet-transport configurations is shown in table I. The future large jet transports are a delta type SST, a variable-geometry type SST, and a C-5 type transport. The data presented represent parameter ratios of future jet transports to present jet transports, and the ratios of the weights are indicative of the large differences in size. It can be seen from the data that the pitch moments of inertia of future transports are at least three to six times those of current jets and that the periods of the longitudinal short-period motion and Dutch roll motion are considerably longer.

These different characteristics tend to cause problems, particularly in low-speed flight. Some of the possible problems related to the size of these aircraft are: sluggish or low initial aerodynamic pitch response resulting from high pitch inertias; unusual dynamic or transient characteristics resulting from low frequencies of the longitudinal short-period and Dutch roll motions; and roll-to-yaw coupling resulting from unusual mass and aerodynamic characteristics.

There are other possible problems related to specific operating conditions for these types of very large jet transports. For example, operation with speed-thrust instability (or operation on the back side of the thrust-required curve) may cause a problem for the delta type SST configurations; these configurations operate in this condition because of the target approach speed recommended by the Federal Aviation Agency.

Since the geometric and design features of these very large jet transports appear to introduce characteristics which can adversely affect the low-speed flying qualities, an exploratory investigation of the possible problem areas was made to obtain some preliminary indications of criteria and requirements for this type of airplane. The best method to study these potential low-speed problems would be with an in-flight simulator; therefore, a contract was negotiated with the Boeing Company to modify a jet transport for in-flight simulation.

Presented in this report are the results of two flight-test programs in which the modified jet-transport airplane was used: tests conducted at the Langley Research Center of two simulated SST type configurations and tests conducted at the Ames Research Center of some parametric variations related to the C-5 type airplane. Because of the basic difference in the setup of the parameters of these two programs, the results will be discussed separately. However, the same general trends were noted in both sets of tests.

SYMBOLS

δ_c deflection of control column, in.

δ_w deflection of control wheel, deg

ζ damping ratio

$\zeta\omega_n$ Dutch roll damping parameter, 1/sec

$\ddot{\theta}$ pitching acceleration, rad/sec

$\ddot{\theta}/\delta_c$ longitudinal control sensitivity parameter, $\frac{\text{rad/sec}^2}{\text{in.}}$

$\dot{\phi}$	rolling velocity, deg/sec
$\dot{\phi}/\delta_w$	lateral control sensitivity parameter, 1/sec
ω_n	undamped natural frequency, rad/sec
ω_n^2	longitudinal short-period stability parameter, $(rad/sec)^2$

APPARATUS AND EQUIPMENT

The airplane that was used as an in-flight simulator is shown in figure 1; it is the Boeing 707 prototype (the 367-80 airplane). The nose boom shown in the figure has a vane at the forward end for sensing the angles of attack and sideslip.

Details of the method of simulation are described in reference 1, and the functions used are indicated in table II. As may be noted, the desired pitching, rolling, and yawing motions were obtained by conventional inputs to the elevator, lateral control, and rudder, respectively. The unique features of the system are the simulation of the lift and drag characteristics by modulating the spoilers and thrust reversers. Although the simulation of nonlinear ground effects by use of height information from the radar altimeter is another of the unique features of this system, ground-effect results will not be discussed in this paper.

TEST PROCEDURES

For each of the tests, the low-speed flight characteristics were evaluated by using the simulated Instrument Flight Rules (IFR) approach illustrated in figure 2 as the basic evaluation task. The airplane intercepted the localizer at approximately 8 miles from the runway at an altitude of 1500 feet. At the intercept of the glide slope, approximately 5 miles from the runway, the pilot initiated the descent and attempted to fly the prescribed flight path as closely as possible down to approximately 200 feet and, if conditions were favorable, to continue visually to touchdown. The lateral-directional tests were made with the localizer offset 200 feet from the runway center line. After the simulated IFR breakout occurred at an altitude of 200 feet, the pilot performed a visual sidestep maneuver to line up with the runway.

RESULTS AND DISCUSSION

Longitudinal Aerodynamic Characteristics

Results of Langley Research Center tests.- Some of the more pertinent results of the Langley Research Center studies of the longitudinal aerodynamic characteristics of generalized configurations of a delta type and a variable-geometry type SST in which the in-flight simulator was used are summarized in figures 3 to 7.

Because of the large values of the moment of inertia, the SST configurations exhibited sluggish initial pitch response, as illustrated in figure 3. In this figure, the changes in glide-path angle and pitching velocity with a step elevator input are compared for the two SST configurations and the present jet transport. Compared with present jet transports, the supersonic transport has a rather low and sluggish initial pitch response (or velocity). This response, along with the greater lift losses due to control for the short-coupled SST airplane, resulted in considerably longer times being required for small glide-path changes. These longer times made it difficult for the pilot to make quick and precise glide-path corrections and resulted in a higher pilot workload. The data of figure 3 show, however, that after this initial period the SST configurations had higher maximum pitching velocities than the present jet transport.

One method of relieving this sluggish-initial-response problem is the use of high initial control gearing fed through a stability-augmentation system. Shown in figure 4 are the variations of elevator deflection, pitching velocity, and change in angle of attack with time for the basic airplane and the airplane with such a stability-augmentation system. The curves for the basic airplane represent the response of a conventional airplane to a step elevator input.

The operation of the stability-augmentation system on the airplane is as follows: The high initial control gearing causes an increased pitch rate and angle-of-attack response, as shown in the figure; but, as both pitch rate and angle of attack build up, the augmentation system, which is also sensitive to these parameters, washes out the increased elevator gearing. As a result, the initial response is considerably improved without the already adequate steady-state response becoming overly sensitive.

Another problem encountered during the flight program, which the pilots called apparent low damping, is illustrated in figure 5. This figure, which is an illustrative example and not flight data, shows a comparison of the resulting pitching velocity following a step elevator input for present jet transports and for very large future jet transports. The solid curves illustrate the oscillatory motion, and the dashed curves illustrate the resulting motion with no oscillation. Both the oscillatory-motion curves have the same cycles to damp to half amplitude. Cycles to damp to half amplitude is normally used by the pilot as an indication of the damping. In this illustrative example, the SST period is double that of the present jet; therefore, the motion takes twice as long to damp. When the pilot applies control, the present jet transports generally respond as shown on the left side of the figure. However, for the SST (right side of fig. 5), the oscillatory motion continues into the part of the maneuver where it should have died out. This type of operation leads to problems in precision maneuvering. For example, when maneuvering the SST type configurations, the pilots would first apply more pitching moment or control than normally required in an effort to obtain better initial pitch response; this procedure was then followed by a control reversal to minimize the large overshoot (apparent low damping) and still maintain the desired steady-state pitching velocity.

Shown in figure 6 is the evaluation of a stability-augmentation system that was used to correct this maneuvering problem. Plotted in the figure is the undamped natural frequency of the longitudinal short-period oscillation ω_n as a function of the damping ratio ζ for the basic and augmented SST type airplanes. The letters "P.R." next to the symbols indicate the average Cooper pilot ratings of two pilots for each condition. This numerical pilot rating system (ref. 2) is shown in table III. These numerical ratings suggest relative flight difficulties; for example, ratings of $3\frac{1}{2}$ or less are satisfactory, ratings between $3\frac{1}{2}$ and $6\frac{1}{2}$ are unsatisfactory, and ratings above $6\frac{1}{2}$ are unacceptable to catastrophic.

The data of figure 6 show that use of the final satisfactory stability-augmentation system in both configurations resulted in an increase in the natural frequency with essentially no change in the damping ratio. In order to determine the effect of increasing both the damping and the frequency, some flight-test data for an increased damping ratio of 0.94 with a moderate increase in frequency are also plotted in this figure. Although this change improved the basic condition, the pilots still were not entirely satisfied with the apparent damping characteristics of the airplane as shown by the poorer average pilot rating of $3\frac{1}{2}$ as compared with a rating of 3 for the final stability-augmentation system.

A specific SST problem that was associated with the generalized delta configuration during the landing approach was operation of the aircraft on the back side of the thrust-required curve or with speed-thrust instability where increased power is required to fly slower. Illustrated in figure 7 are the effects of back side operation; two typical simulated IFR approaches are shown. The desired glide slopes with vertical offsets are indicated by the two sets of parallel lines. The vertical offsets were put into the glide slopes for these tests to establish an additional pilot task that would help evaluate the speed-thrust instability. The figure shows comparison data for a delta type SST with a value of speed-thrust instability (thrust weight ratio divided by velocity) of -0.0024 and a normal value of speed-thrust stability of 0.0005. For the airplane with speed-thrust stability, the airspeed that has decreased while the pilot restabilizes on the new glide slope starts to return to the original value; however, for the airplane with speed-thrust instability, the airspeed tends to decrease steadily until the pilot is required to use the throttle to prevent stalling. Even though the pilot, in this instance, was only attempting to evaluate the effects of back side operation with minimum use of throttles, it is apparent that his ability to change the glide slope was not appreciably affected by the speed-thrust instability for the particular evaluation tasks used in this investigation.

If the throttle had been used to compensate for changes in airspeed during these approaches, both sets of data would have shown improvements, particularly in airspeed accuracy, and the pilot's ability to fly the configuration would have been essentially the same for the speed-thrust instability and speed-thrust stability conditions, except that more throttle activity and pilot workload would be required for the speed-thrust condition. Several pilots mentioned, however, that large values of speed-thrust instability did cause rapid speed bleed off or loss of altitude in turn maneuvers. Thus a fair amount of pilot attention was required to prevent high rates of descent from building up.

Results of Ames Research Center tests.- Some of the more pertinent results of the Ames parametric studies of the generalized C-5 type airplane are given in figures 8 and 9. The same in-flight simulator that was used in the SST studies at the Langley Research Center was employed for these tests. Data are presented for both ground-based and in-flight simulator results.

In figure 8, Cooper pilot rating is plotted as a function of the longitudinal stability parameter ω_n^2. The term ω_n^2 is the square of the undamped natural frequency of the short-period oscillation. These data are for a limited variation of control sensitivity, that is, for values of pitching acceleration divided by column deflection $\ddot{\theta}/\delta_c$ from 0.03 to 0.07. The damping ratio ζ was 0.6 to 0.9, and the phugoid stability was positive. Reasonably fair agreement is obtained between the ground-based simulator results and the in-flight simulator results. The ground-based simulator is a moving-base simulator which used pitch and roll attitude cues during the tests. The satisfactory and unsatisfactory boundaries are related to the pilot rating scale. (See table III.) The trends of the data in figure 8 show that the pilot ratings are sensitive to variations in the longitudinal stability parameter for values less than about 1.2; however, the pilot ratings are relatively insensitive to variations for higher values of the parameter. The data also show that values of ω_n^2 less than about 0.8 appear to be unsatisfactory. The value of ω_n^2 for the generalized C-5 type airplane is approximately 0.5 and the value for present jet transports is approximately 1.4. The relatively low value of the parameter for the C-5 type airplane is caused by the high moments of inertia and low approach speeds.

Longitudinal control sensitivity is also an important parameter, as illustrated in figure 9. Pilot rating is plotted as a function of the control sensitivity parameter $\ddot{\theta}/\delta_c$ (pitching acceleration divided by column deflection) for a restricted range of the longitudinal stability parameter ω_n^2 from 0.75 to 0.85 and for a minimum column deflection (required for maximum moment) of approximately 5 inches. The damping ratio and phugoid stability were the same as for figure 8. There is fair agreement between ground-based and in-flight data with the flight values having poorer pilot ratings. As would normally be expected, variations in the control sensitivity in the lower range cause large changes in pilot rating. It can be seen that values of $\ddot{\theta}/\delta_c$ less than 0.02 are generally undesirable. Inasmuch as the values of this parameter for the C-5 type airplane fall in this general area, this airplane may encounter longitudinal control problems.

Lateral-Directional Aerodynamic Characteristics

Results of Langley Research Center tests.- The lateral-directional characteristics of the generalized SST type configurations investigated at the Langley

Research Center were satisfactory, and the effects of the different inertia ratios were not noticeable in the roll-to-yaw coupling of the Dutch roll motions at the approach speeds used.

The unaugmented Dutch roll characteristics of these airplanes are shown in figure 10. Shown in the figure are data for the marginally satisfactory, unaugmented present jet transports $\left(\text{pilot rating } 3\frac{1}{2} \text{ to } 4\frac{1}{2}\right)$ and the unaugmented variable-geometry and delta type SST airplanes $\left(\text{pilot ratings of } 3 \text{ and } 3\frac{1}{2}, \text{respectively}\right)$. The fact that the frequencies of the SST's are somewhat lower than those of the present jets indicates that the SST's would normally be given poorer pilot ratings. However, the increased damping ratio for the supersonic transports results in the satisfactory pilot ratings of 3 and $3\frac{1}{2}$. The delta type configuration was not rated higher than $3\frac{1}{2}$ because the low damping characteristics of the rolling mode tended to cause the pilots to overshoot the desired roll angles when giving roll control.

Results of Ames Research Center tests.- Some of the Ames Research Center results related to lateral-directional parameters are given in figures 11 and 12. Figure 11 shows the variation of pilot rating with the Dutch roll damping parameter. The Dutch roll damping parameter $(\zeta\omega_n)$ is the damping ratio multiplied by the undamped natural frequency. There is good agreement between ground-based and in-flight simulator data. These data indicate that damping and frequency are important, particularly in the lower ranges where the pilot rating changes markedly for small changes in the damping parameter. The generalized C-5 type airplane and present jet transports both have Dutch roll damping parameters of approximately 0.1, and thus they would be in an area where Dutch roll problems could occur. As a result, augmentation may be required to improve the flight characteristics of the C-5 type airplane.

The effect of the variation of the lateral control sensitivity parameter $\dot{\phi}/\delta_w$ (rolling velocity divided by wheel deflection) is shown in figure 12. In this figure, the pilot rating is plotted as a function of this parameter for configurations with good turn coordination and Dutch roll damping. For these data, roll-time constants from 0.5 to 0.75 were used, and the tests only considered wheel deflections required for a maximum rolling moment of between 30° and 90°. The sluggish and too-sensitive areas shown in the figure were established from ground-based simulator studies. Agreement between ground-based and in-flight simulator studies is good. The small crosshatched area in the lower right-hand side of the figure shows a single ground-based-simulator condition plotted to indicate what happens to pilot rating as lateral control becomes too sensitive. These data indicate that a value of the roll control sensitivity parameter $\dot{\phi}/\delta_w$ between 0.6 and 0.7 would apparently be the optimum setting for aircraft of this size. The generalized C-5 type airplane is located on the lower side of this range, having a value of $\dot{\phi}/\delta_w$ of approximately 0.4. For these tests, in which parameter variations were being studied, lateral-directional augmentation was used. The C-5 type airplane may also require some form of augmentation because of the roll-to-yaw coupling at the low approach speeds. Results of tests related to this roll-to-yaw coupling problem are discussed in references 3 and 4.

In addition to the requirement for a minimum value of $\dot{\phi}/\delta_W$, the initial rolling response is important. Pilot opinion of initial roll response in terms of bank angle attained 1 second after control initiation is given in reference 5.

CONCLUDING REMARKS

The results of the in-flight simulation tests of very large jet transports can be summarized as follows:

1. Sluggish initial pitch response was apparent and was considered a problem by the pilots.

2. Undesirable transient response characteristics were created by the low frequencies of the longitudinal short-period motion.

3. For the configurations tested, it appears that some sort of stability-augmentation system will be necessary to correct the sluggish initial pitch response and the undesirable transient response caused by the low frequency of the longitudinal short-period motion.

4. For the delta type SST configuration, the speed-thrust instability did not present any appreciable problem for the particular pilot evaluation tasks used in these tests. However, more throttle activity and pilot workload were required to perform the same evaluation tasks.

5. In the tests of the C-5 type airplane conducted at the Ames Research Center, there was reasonable agreement between the ground-based and in-flight simulator studies.

6. Roll-to-yaw coupling did not cause any noticeable problems for the configurations and parameters tested. However, the C-5 type airplane may require some form of lateral-directional stability augmentation.

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3. Quigley, Hervey C.; Vomaske, Richard F.; and Innis, Robert C.: Lateral-Directional Augmentation Criteria for Jet Swept-Wing Transport Airplanes Operating at STOL Airspeeds. Conference on V/STOL and STOL Aircraft, NASA SP-116, 1966, pp. 295-310.

4. McNeill, Walter E.; and Innis, Robert C.: The Effect of Yaw Coupling in Turning Maneuvers of Large Transport Aircraft. Conference on Aircraft Operating Problems, NASA SP-83, 1965, pp. 203-213.

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TABLE I

LARGE JET-TRANSPORT CHARACTERISTICS

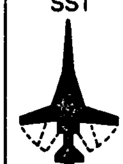
FUTURE JET TRANSPORTS	DELTA TYPE SST 	VARIABLE-GEOM.TYPE SST 	C-5 TYPE TRANSPORT 
PARAMETER	FUTURE JET TRANSPORT / PRESENT JET TRANSPORT		
LANDING WEIGHT	1.8	1.8	2.5
MOMENT OF INERTIA:			
PITCH	3.6	3.5	6.0
ROLL	.6	.8	4.9
YAW	2.4	2.4	5.3
DAMPED PERIOD:			
LONG. SHORT PERIOD	2.3	1.3	1.3
DUTCH ROLL MOTION	1.2	1.5	1.4

TABLE II

SST SIMULATION FUNCTIONS

FUNCTION	SYSTEM USED
PITCH AXIS	LONGITUDINAL CONTROL
ROLL AXIS	LATERAL CONTROL
YAW AXIS	DIRECTIONAL CONTROL
LIFT	MODULATED SPOILERS
DRAG	MODULATED THRUST REVERSERS
GROUND EFFECTS	RADAR ALTIMETER

TABLE III

COOPER PILOT RATING SYSTEM

OPER. COND.	ADJECTIVE RATING	NUMER. RATING	DESCRIPTION	PRIMARY MISSION ACCOMP.	CAN BE LANDED?
NORMAL OPER.	SATIS-FACTORY	1	EXCEL., INCLUDES OPT.	YES	YES
		2	GOOD, PLEASANT TO FLY	YES	YES
		3	SAT., BUT WITH SOME MILDLY UNPLEASANT CHARACTERISTICS	YES	YES
EMERG OPER.	UNSATIS-FACTORY	4	ACCEPTABLE, BUT WITH UNPLEASANT CHARAC-TERISTICS	YES	YES
		5	UNACCEPTABLE FOR NORMAL OPERATION	DOUBTFUL	YES
		6	ACCEPTABLE FOR EMERG. CONDITION ONLY*	DOUBTFUL	YES
NO OPER.	UNACCEPT-ABLE	7	UNACCEPTABLE EVEN FOR EMERG. COND.	NO	DOUBTFUL
		8	UNACCEPTABLE-DANGER-OUS	NO	NO
		9	UNACCEPTABLE-UNCON-TROLLABLE	NO	NO
	CATA-STROPHIC	10	MOTIONS POSSIBLY VIO-LENT ENOUGH TO PRE-VENT ESCAPE	NO	NO

* FAILURE OF A STABILITY AUGMENTER.

IN-FLIGHT SIMULATOR

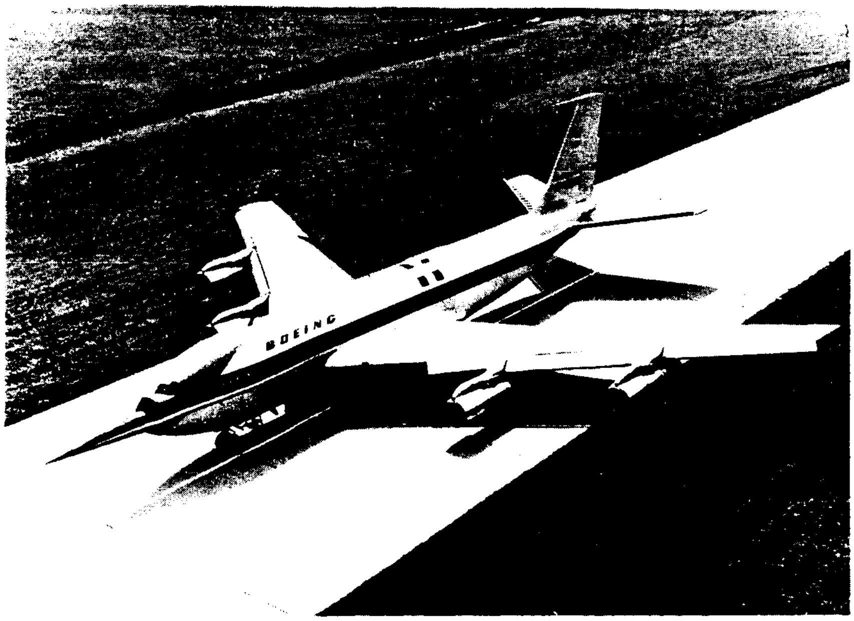


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Figure 1

BASIC EVALUATION TASK

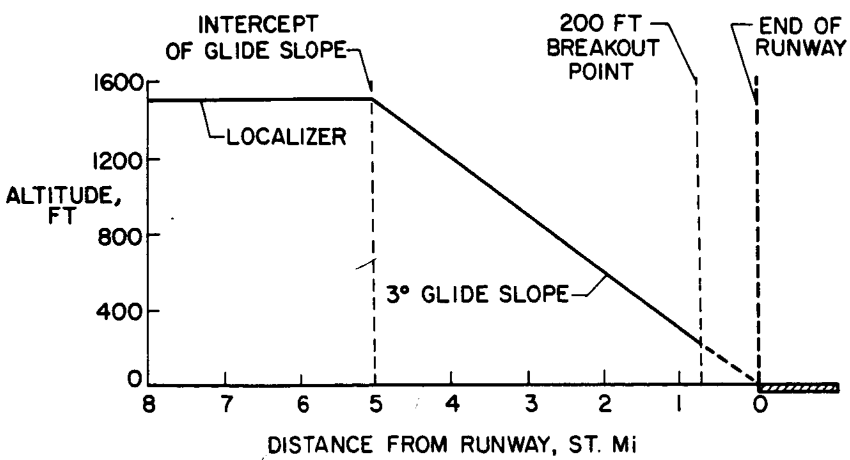

Figure 2

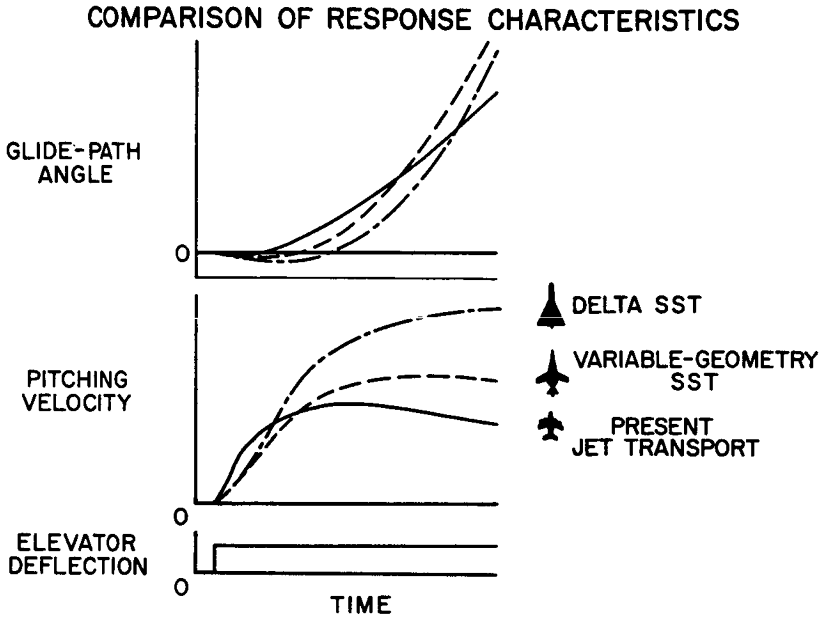

Figure 3

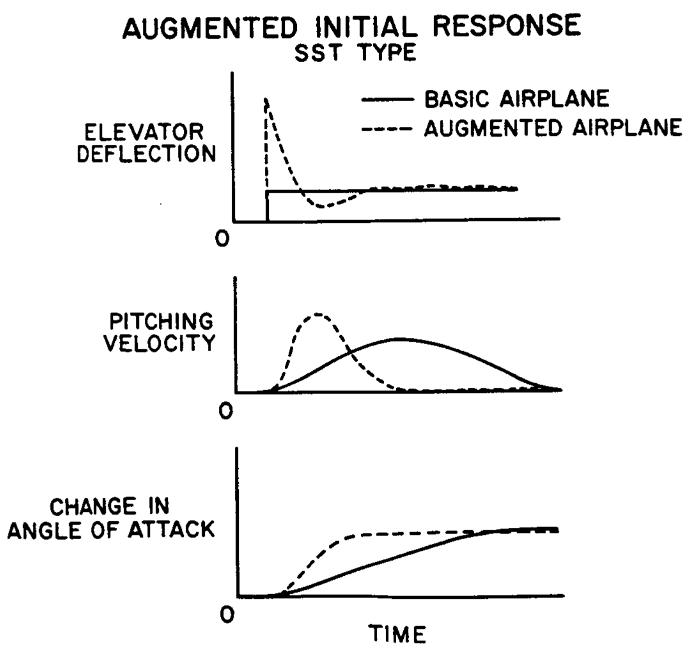

Figure 4

COMPARISON OF TRANSIENT - RESPONSE CHARACTERISTICS

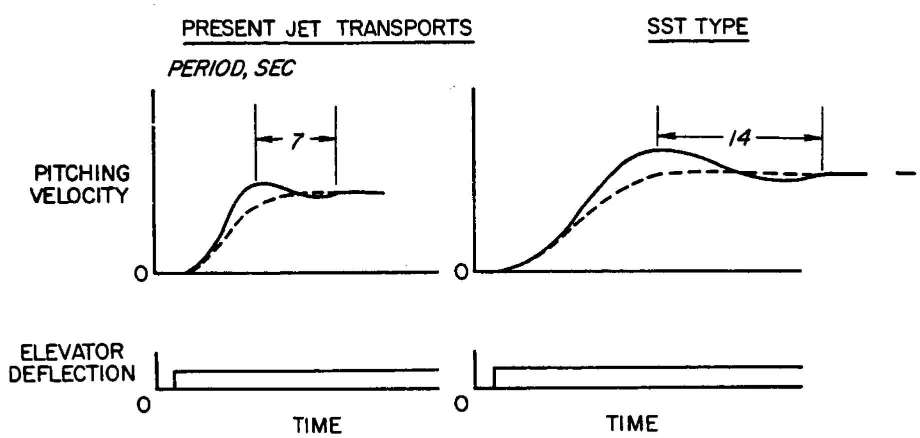

Figure 5

EFFECT OF AUGMENTATION ON LONGITUDINAL SHORT PERIOD
SST TYPE

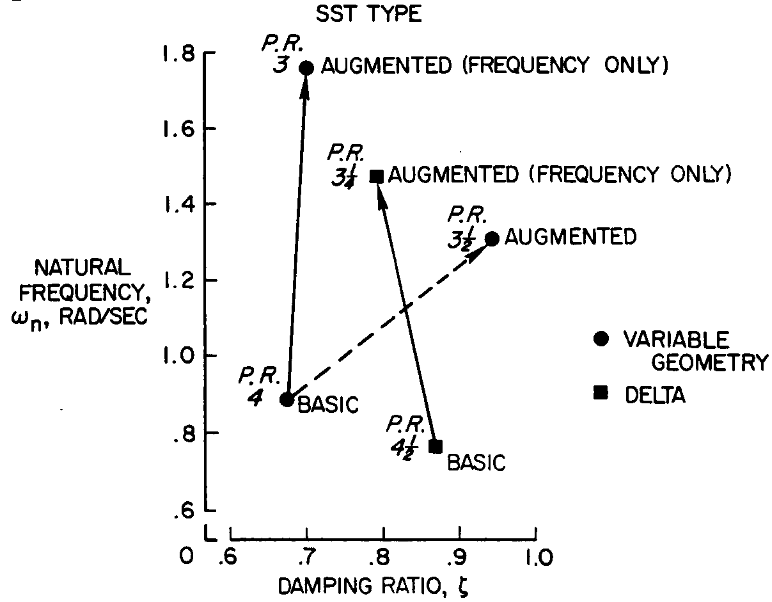

Figure 6

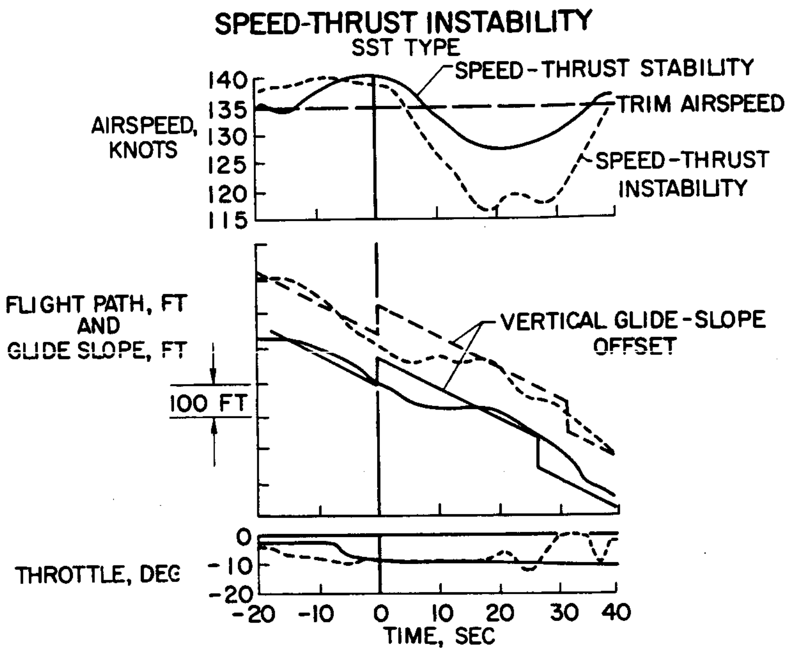

Figure 7

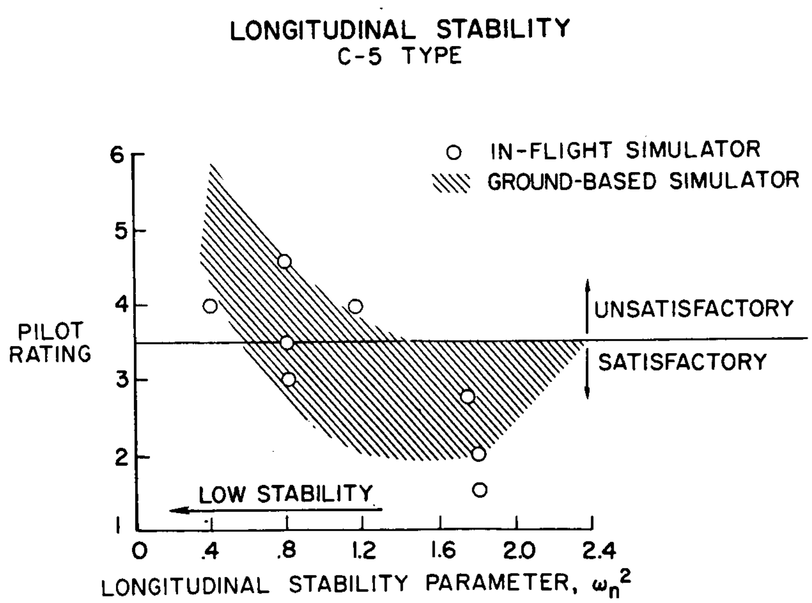

Figure 8

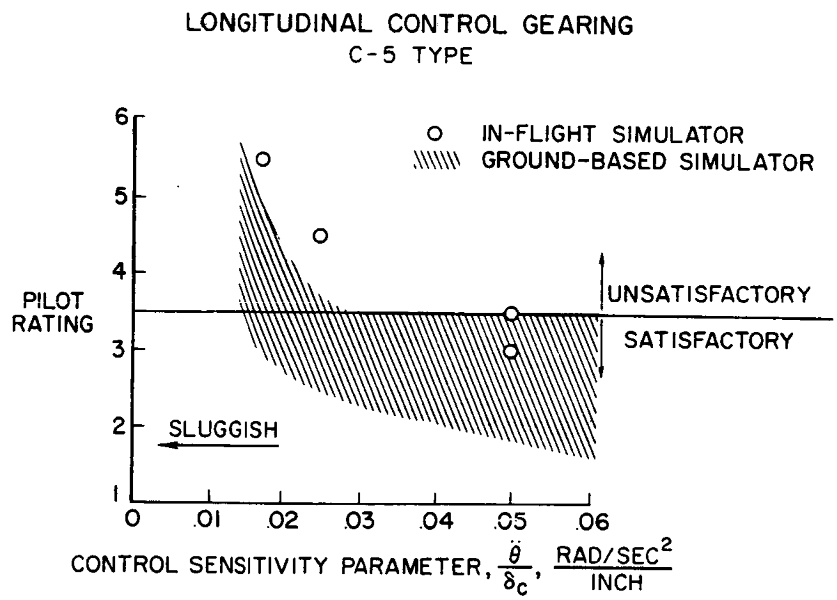

Figure 9

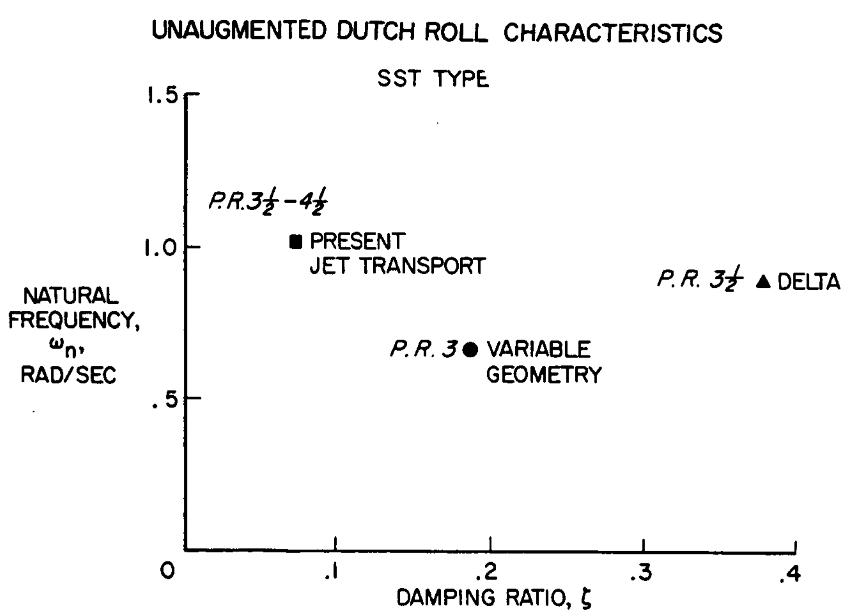

Figure 10

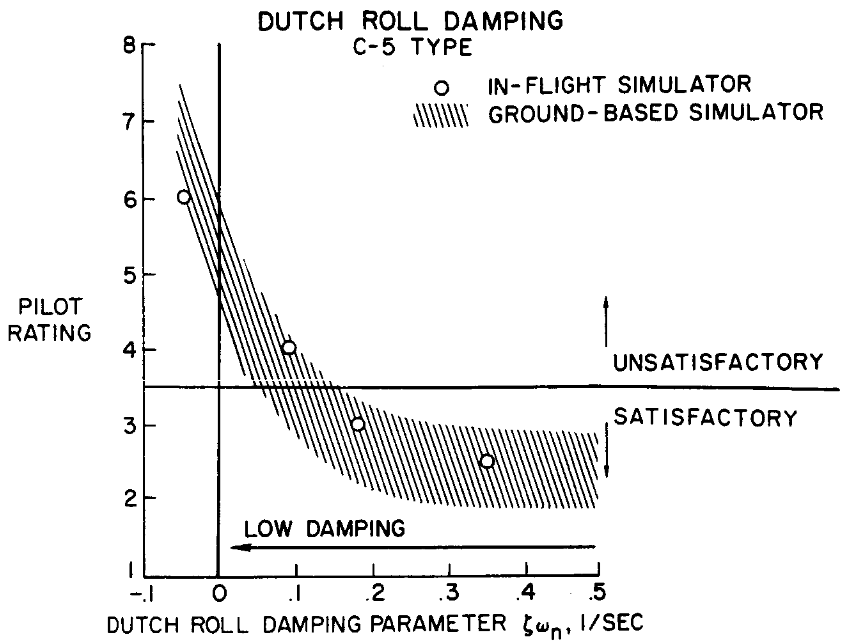

Figure 11

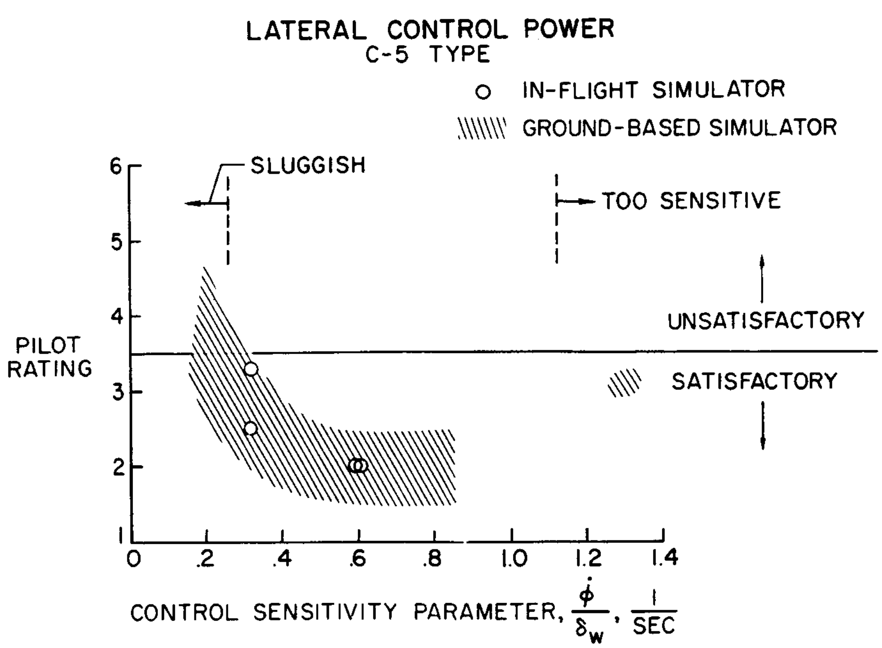

Figure 12