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MEMORANDUM

FLIGHT STUDIES OF PROBLEMS PERTINENT TO LOW-SPEED

OPERATION OF JET TRANSPORTS

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SUMMARY

Flight studies have been made of the low-speed operational regime of jet transports in order to assess potential operating problems. The study was performed utilizing a large multiengine jet airplane having geometric characteristics fairly representative of the jet transports; however, to insure general applicability of the results, the aerodynamic characteristics of the test airplane were varied to simulate a variety of jet-transport airplanes.

The specific areas investigated include those of the take-off and landing, and the relation of these maneuvers to the 1 g stall speed and stalling characteristics. The take-off studies included evaluation of the factors affecting the take-off speed and attitude, including the effects of premature rotation and of over-rotation on ground run required. The approach and landing studies pertained to such factors as: desirable lateral-directional damping characteristics; lateral-control requirements; space-positioning limitations during approach under VFR or IFR conditions and requirements for glide-path controls; and evaluation of factors affecting the pilot's choice of landing speeds.

Specific recommendations and some indication of desirable characteristics for the jet transports are advanced to alleviate possible operational difficulties or to improve operational performance in the low-speed range.

INTRODUCTION

There has been considerable speculation on the feasibility of extending current piston-engine transport operating techniques to the jet transport, both in the low- and the high-speed range. An investigation of the high-speed flight regime is reported in reference 1. In the low-speed flight regime, the specific areas of interest have pertained to take-off and landing, as outlined in table I. With regard to the first item listed, some questions have been raised concerning the magnitude of take-off speed as related to the stall speed, the length of take-off run normally required for various loading conditions, and the effects of early rotation or over-rotation on the take-off run. The questions regarding the second item listed, airplane approach and landing characteristics, involve several factors pertaining to aircraft requirements and limitations, such as: lateral-directional damping requirements; lateral-control requirements; limitations on space-positioning during the landing approach under either VFR (visual flight rules) or IFR (instrument flight rules) conditions; requirements for use of glide-path controls; approach and landing speeds, and the factors affecting the pilot's choice of these speeds.

To investigate these aspects of take-off and landing, a flight study was performed at the NASA High-Speed Flight Station, utilizing a large multiengine jet airplane having geometric characteristics fairly representative of the jet transports. The test airplane had 35° swept wings of aspect ratio 7.1 and swept tail surfaces (fig. 1). For test purposes the airplane was equipped with a nose boom to measure airspeed, altitude, and directional flow angles. To simulate the aerodynamic characteristics of a variety of jet transport airplanes, various amounts of lateral-control power, glide-path control, and lateral-directional damping were utilized under conditions that might be encountered during transport operation in the low-speed flight regime.

SYMBOLS

a_n	normal acceleration, g units
b	wing span, ft
C_D	drag coefficient
C_m	pitching-moment coefficient
C_N	normal-force coefficient, $a_n W/qS$
F_a	lateral-control force, lb
F_e	longitudinal-control force, lb
F_r	rudder-pedal force, lb

Δh	height above runway, ft
h_p	pressure altitude, ft
i_t	stabilizer deflection, deg
P	period of lateral-directional oscillation, sec
p	roll rate, deg/sec or radians/sec
$pb/2V$	wing-tip helix angle, or lateral-control parameter, radians
q	dynamic pressure, lb/sq ft; pitching velocity, radians/sec
r	yawing velocity, radians/sec
S	airplane wing area, sq ft
$T_{1/2}$	time for lateral-directional oscillation to damp to 1/2 amplitude, sec
T_2	time for lateral-directional oscillation to double amplitude, sec
$T_{\phi=10^{\circ}}$	time to change bank angle 10°, sec
V	true velocity (except in ratio V/V_s), ft/sec
V_i	indicated calibrated airspeed, knots
V_s	indicated stall speed (from manufacturer's flight handbook), knots
V/V_s	ratio of indicated airspeed to indicated stall speed
W	airplane weight, lb
Y'	lateral displacement of airplane from runway center line extended, ft
α_i	indicated angle of attack, deg
β_i	indicated angle of sideslip, deg
δ_e	elevator deflection, deg

δ_{a_t} total aileron deflection, deg

δ_f flap deflection, deg

δ_r rudder deflection, deg

DISCUSSION

Basic Aerodynamic and Stalling Characteristics

In the landing or take-off maneuver, the imminence of heavy buffeting, stalling, or other deleterious characteristics will require operational limitations to avert possible hazardous regimes or will impose additional requirements for safety of operation. Inasmuch as both landing and take-off speeds have been related to the 1g stall speed and stall characteristics of the unswept-wing piston-engine transports, the stall characteristics of the jet transports should be examined in the same light. Figures 2 and 3 illustrate the stalling and flight-determined aerodynamic characteristics of the test airplane in the take-off or approach configuration with a 30° flap deflection for a normal mid-center-of-gravity position and a wing loading of 68 pounds per square foot. Initial buffet occurred very near the peak value of normal-force coefficient attainable. This was followed by a mild pitch-up, as shown by the appreciable increase in angle of attack with no additional control input and even with a reversal of control force and deflection. Increased buffeting accompanied this phenomenon. It can be seen that the pitching-moment-coefficient curve approaches neutral stability in the pitch-up region; however, the pitching rates experienced during pitch-up were quite mild, and there was no tendency to roll off on one wing. Recovery was easily accomplished by applying power and relaxing the back pressure on the control column. As would be expected for any swept-wing configuration, the drag coefficient increased rapidly with increase in angle of attack; the magnitude of drag at $\alpha_i = 10^{\circ}$ to 12° was almost double that at $\alpha_i = 0^{\circ}$ to 2°.

A significant item to be noted from the data presented in figures 2 and 3 is the determination of the stall speed - defined by the occurrence of maximum airplane normal-force coefficient at a 1g condition - which occurred at an indicated speed of 123 knots and at a moderate angle of attack. A lower, but unusable, speed - approximately 114 knots - was attained in this maneuver by increasing the angle of attack beyond that for wing flow separation in the region where drag increased rapidly despite the decrease in wing lift and the airplane was at a condition of less than 1g and losing altitude. To illustrate, the sink rate attained in this maneuver at the minimum speed point was of the order of 2,500 feet per minute. Therefore, it is recommended that the stall speed for the jet transports be based on maximum normal force or maximum lift as defined by wing stall, inasmuch as lower speeds attainable beyond this point are not usable close to the ground.

It should be noted that the stall speed as defined by this criterion is significantly higher than that specified in the manufacturer's flight handbook ($V_S \approx 103$ knots for the conditions specified in figs. 2 and 3). However, in order to discuss the take-off and landing evaluation on a basis compatible with existing and more familiar criteria, manufacturer's flight handbook values of stall speed are used as a reference in the remainder of this paper.

Factors Affecting Take-Off

In evaluating the factors affecting the take-off problem, items of primary concern are the length of runway required and the ratio of take-off to stall speed for the diverse loadings and operating conditions to be encountered in normal airline operation. Although the present study did not encompass all the conditions encountered in airline operation, several pertinent factors were evaluated. Figure 4 illustrates two take-offs of the test aircraft at essentially the same loading conditions. The solid lines show a normal take-off in which the nose wheel was lifted clear of the ground at about 5 knots below take-off speed. Subsequent to lifting of the nose wheel, the angle of attack increased rapidly and the airplane lifted off the ground. The dashed lines illustrate an early-rotation take-off, wherein the airplane was rotated at about the handbook stall speed V_S and an appreciable angle of attack was attained. After a few seconds the decrease in acceleration resulting from the increase in drag was quite noticeable to the pilot, so he relaxed his pull on the control column and the angle of attack decreased to allow improved acceleration. Several knots below the take-off speed, the aircraft was again rotated and it became airborne at a moderate angle of attack. In both instances, the angles of attack attained were below that for wing-flow separation. It is obvious that the take-off involving early rotation required more time and involved a greater take-off distance than a normal take-off. In contrast to the present piston-engine transports, which almost fly themselves off the ground with little rotation, it was found that swept-wing aircraft required rotation to become airborne.

A summary of the effects of early rotation during several take-off runs is shown in figure 5 as the variation of nose-wheel lift-off speed and airplane take-off speed, expressed as a fraction of V_S, plotted against take-off distance for a wing loading of 86 pounds per square foot. Each rectangular area shown here represents a grouping of several test points. It will be noted that normal nose-wheel lift-off occurred near $1.2V_s$, with airplane lift-off occurring at a slightly higher speed after a take-off run of about 6,800 feet. By contrast, early nose-wheel lift-off occurred below $1.0V_s$, with airplane lift-off occurring near $1.3V_s$ after a much longer take-off run of about 9,000 feet. One point to note is the magnitude of the take-off distances recorded as compared with the length of existing runways at major airports throughout the United States (shown by the cross-hatched area at the bottom of fig. 5). For the early-rotation take-offs discussed, it is obvious that the airplane would not have become airborne before running off the end of the runway at several of these airports. No attempt was made to determine minimum take-off speed or distance; however, it was ascertained that take-off at a slightly higher speed than normally used facilitated a more rapid rate of climb and an impression of better handling characteristics, but required longer take-off distances.

The effect on take-off ground run of over-rotating the airplane even during a normal-type take-off can also be serious because of the excessive drag accompanying the use of large angles of attack. This effect is illustrated in figure 6 for $W/S = 111$ pounds per square foot and $\delta_f = 40^\circ$. The open circle shows where the airplane lifted off after a normal-type take-off at 9,500 feet For the solid circle, take-off speed was attained at the same point as for normal rotation, but due to an over-rotation of about 2° to 3°, and after essentially maintaining this attitude, the airplane became airborne at a slightly higher speed and after an additional 3,500 feet of ground run.

Inasmuch as the pilot does not have a sufficiently accurate indication of airplane attitude once the nose wheel is off the ground, an angle-of-attack indicator was installed in the cockpit and used during some of these tests. The pilot found this indicator to be quite beneficial when coordinated with the other instrumentation, and it enabled him to attain proper take-off attitude at reasonable speeds below his intended take-off speed, and to avoid the large angles of attack that produce major increases in drag. He also found the angle-of-attack indicator useful for maintaining proper attitude for climb-out.

In general, if early nose-wheel lift-off is effected and the airplane is rotated to an appreciable attitude, a noticeable decrease in longitudinal acceleration is experienced with an attendant increase in the take-off distance; whereas, if the airplane attitude is maintained at a low angle until just a few knots below take-off speed, the acceleration to the take-off point and the take-off distance are not materially affected. However, without the use of some instrument such as an angle-of-attack indicator, the pilot does not have a sufficiently accurate indication of airplane attitude once the nose wheel is off the ground, and significant increases in take-off distance can result from over-rotation.

Approach and Landing Characteristics

Because of the appreciable dihedral effects exhibited by swept-wing aircraft, particularly at low speeds, and the slow rotational speeds encountered in this speed regime, it was felt that the dynamic lateral-directional characteristics and lateral control available would measurably affect the approach and landing characteristics of the swept-wing transports. To determine the desirable or usable levels of lateral control and yaw damping for the approach and landing regime, preliminary studies were made at low altitude to document the control and damping characteristics, and these characteristics were then evaluated in approach and landing maneuvers.

Dynamic lateral-directional characteristics.- In evaluating the lateral-directional characteristics, the test airplane was initially investigated without damper augmentation and with normal damper gain. In order to investigate the handling characteristics with significantly worse damping than that produced by the basic airframe, tests were also made with reversed damper setting. The dynamic lateral-directional characteristics of the test airplane for three yaw-damper gain settings and two flap configurations are shown in figure 7 as variations with indicated airspeed of the period of the oscillation and the time to damp the oscillation to half amplitude or to double the amplitude. It can be seen that the various damper settings had a slight effect on the period of the oscillation at all speeds and thereby slightly affected the apparent stability. Also, the basic aircraft exhibited essentially undamped (or neutrally damped) characteristics after an initial disturbance, whereas the reversed damper setting caused the lateral-directional oscillations to be highly divergent at all speeds. Although use of a dynamically unstable airplane is highly unlikely, reversed damper settings were used to determine minimum levels of stability which could be tolerated in emergency conditions.

In general, the basic airplane performed well in smooth air and did not present a problem from the viewpoint of lateral-directional dynamics. However, the pilots considered use of a yaw damper necessary, particularly after a course correction or in rough air where the high dihedral effect produced an appreciable amount of rolling when a directional oscillation was experienced. Since the period of the oscillation was reasonably long, it was possible to control the airplane in rough air with damper off and with damper reversed; however, with damper reversed much effort and cross-control coordination by the pilot were necessary and would result in considerable discomfort to passengers. For even the most divergent conditions investigated, the aircraft characteristics would not constitute an emergency condition at these low speeds.

Lateral-control characteristics.- Since the requirement for low-speed maneuvering is far more stringent than for high-speed maneuvering, it is felt that the low-speed regime will generally dictate the lateral-control requirements of the jet transport. Inasmuch as civilian requirements are not as specific as military requirements with regard to desirable control levels, it was thought that a measure should be made of lateral-control levels in terms of some criterion. To determine the suitability of various levels of lateral control, the test airplane was evaluated with several combinations of conventional trailing-edge ailerons and either inboard spoilers, outboard spoilers, or both sets of spoilers. Figure 8 presents a summary of the lateral control available with full control deflection for each of two flap configurations with the test airplane, and these results are presented in terms of several possible control criteria. The solid lines represent the rolling power when full ailerons and spoilers are used, and the dashed lines represent the rolling power when ailerons alone are used. With ailerons and either inboard or outboard spoilers available, the rolling characteristics are about midway between the solid and dashed curves shown. Comparative data for the B-47A airplane, which utilizes ailerons and flaperons for control power in the landing configuration, are presented on the right of figure 8. The improved roll performance of the test airplane with the spoiler-aileron combination as compared with that available with ailerons alone is readily apparent, regardless of the roll criteria used. The rolling power available with spoilers and ailerons on the test airplane and with controls on the B-47A, in terms of maximum roll rate and $pb/2V$, appears similar and also exceeds military specifications for such large aircraft, whereas the rolling power of the ailerons alone on the test airplane does not meet military specifications. However, even these high levels of lateral control produced on both airplanes appeared somewhat marginal in rough air during the final phases of landing, where small changes in bank angle are generally required and aircraft response becomes most important. The rolling power of the test airplane was appreciated by the pilot more than that of the B-47A because of its greater roll acceleration, as shown by comparing the plots of time to roll 10°, and also because the control-wheel rotation involved with full control deflection was appreciably less than on the B-47A. For the large transport-type airplane, it is felt that a suitable roll criterion for the landing configuration would be a specification for a given change in bank angle - such as 10° - within a finite time.

Space-positioning studies and evaluation of glide-path controls.- To determine the limits of aircraft controllability for performing the landing approach maneuver, both under VFR and ILS conditions, space-positioning studies were performed with the test airplane, utilizing various control techniques and various aircraft characteristics. Combinations of ailerons and spoilers were used to provide lateral control, the lateral-directional damping was varied by appropriate damper settings, and various amounts of symmetrical spoiler projection were used as speed brakes to provide added control over the glide slope. Figure 9 shows a perspective of the space-positioning and landing-approach area used, extending from the outer marker to the runway, and the relation of this area to the runway. Beginning at the outer marker, which was 5 miles from the end of the runway, VFR approaches were attempted from various lateral displacements up to 6,000 feet from the runway center line extended, and from various vertical displacements up to 3,500 feet above the runway surface. When ILS approaches were evaluated, the lateral displacement limits were only 3,000 feet because this was the limit of the range. For all approaches, the airplane bank angle was limited to a maximum value of 30°.

For either visual or instrument conditions, the lateral control available with ailerons alone or ailerons and spoilers was adequate to permit normal landing approaches from any laterally displaced position at the outer marker up to the limits tested; however, when the spoilers were not available for use as glide-path controls, vertical displacements up to only about 3,000 feet could be used.

The various magnitudes of lateral-directional damping used had essentially no effect on the space-positioning limitations determined. Essentially similar effects were experienced with the basic and the positively damped airplane; however, pilot effort and control movement - particularly rudder control - exhibited a threefold increase when a reversed damper setting was used. (See figs. 10 and 11.) It is believed that much of this pilot effort and pedal force resulted from rudder-force feedback.

In all cases investigated, the airplane was maneuvered onto the glide slope from various vertical and lateral displacements before it was about 2 to 3 miles from the end of the runway. The use of glide-path controls (spoilers) made this task especially easy, but produced buffet similar to stall buffet at extremely low speeds. From the pilot's viewpoint, the use of glide-path controls in conjunction with higher throttle settings was more desirable for approach control than the technique of lower throttle settings with no glide-path control available. Further study of speed brakes for glide-path control in a penetration-type landing approach revealed that the time required from a 20,000-foot altitude to touchdown could be reduced by approximately 1/3 through the use of glide-path controls. (See fig. 12.)

When performing the landing approaches under ILS conditions, the pilot felt he was using the controls and working to a greater extent than when operating under VFR conditions from comparable positions at the outer marker; however, the flight records did not support this contention. Also, the flight speeds in IFR approaches were more nearly constant but of the same order of magnitude as during VFR approaches.

Final approach and touchdown.- In the final phases of the approach, the piloting technique for control of airspeed and altitude was gradually changed so that the throttle was used for altitude control and the elevator was used for control of airspeed. This technique became mandatory as the touchdown was approached and provided adequate control of the aircraft rate of descent. Although the controllability problem was not evaluated up to the present weather minimums of 200 feet at 1/2 mile from touchdown, the altitude at the 1/2-mile point (which was generally about 12 seconds from touchdown) ranged up to 128 feet with accompanying sink rates up to 1,100 feet per minute. Also, despite the fact that the vertical velocity at touchdown ranged as high as $7\frac{1}{2}$ feet per second, most touchdowns were performed at a rate of descent of less than 3 feet per second. These values of time, vertical velocity, and altitude, near touchdown, emphasize the range of controllability required for such large aircraft. As might be anticipated, the rates of descent and the altitude levels in the approach and landing were considerably lower under ILS flight conditions than under visual approaches.

The level of airspeeds utilized during the approach and touchdown under VFR conditions is shown in figure 13 for a flap deflection of 50°. At the 1/2-mile point, represented by the open symbols, the airspeeds generally were in the range of $1.45V_s$ to $1.55V_s$ because of the improved longitudinal and lateral controllability as compared with lower speeds. At touchdown, represented by the solid symbols, the airspeeds were in the range of $1.27V_s$ to $1.37V_s$ and in the "bucket" of the drag curve where the lift-drag ratio was essentially maximum. The imminence of buffet and more difficult control of sink rate at lower speeds influenced the choice of these touchdown speeds. During ILS approaches, a smaller flap deflection was maintained nearer to touchdown than for VFR conditions. At the 1/2-mile point, the level of airspeed was generally about $1.4V_s$ to $1.45V_s$, and the pilot preferred to maintain the smaller flap deflection and this airspeed until he established visual contact to insure a better go-around capability. Thereafter, additional flap deflection was added and the speed was decreased in the flare.

Although it was possible to perform the approach and landing with a constant stabilizer trim setting without encountering elevator control forces greater than about 20 pounds, the pilot found it more comfortable to use the stabilizer to reduce the control forces, maintaining just sufficient force to provide control feel. Lateral-directional damping had essentially no effect on the pilot's ability to perform the landing maneuver; however, greatly increased effort and concentration were required for the dynamically divergent damper configuration, as previously mentioned. In the final stages of landing, the level of lateral control produced by ailerons alone appeared inadequate because of the requirements for compensating for cross-wind effects. With the lateral control power of the ailerons and spoilers, control was marginal in rough air because of the time required to raise a low wing in the proximity of the runway. With cross winds of the order of 12 to 15 knots, a significant amount of lateral control up to the maximum available was utilized during landing and after touchdown.

In performing landings with appreciable cross winds, a crabbed heading into the wind could be maintained to touchdown, but the pilot found this uncomfortable. Using the crabbed heading up to the 1/2-mile point and then performing a slight sideslip to maintain the flight path to touchdown proved to be a better technique.

CONCLUSIONS

An investigation of the low-speed operational area of large jet transport airplanes resulted in the following conclusions and recommendations:

1. Stall speed should be based on maximum airplane lift at a 1g condition, inasmuch as minimum speeds attainable only with attendant high sink rates are not realistic.

2. Early nose-wheel lift-off and rotation of the airplane to appreciable values of angle of attack or over-rotation at the proper take-off speed produced increases in take-off distance which could affect the success of the take-off. An angle-of-attack indicator helped the pilot attain proper airplane attitude at take-off speed so that optimum take-off and climb-out could be accomplished and large angles of attack that produce considerable drag could be avoided.

3. Space positioning under VFR conditions from various realistic final-approach positions can be limited by inadequate glide-path control, but was not limited by the minimum levels of lateral-control power and lateral-directional damping of the investigation.

4. Approach speeds at 1/2 mile from touchdown were about $1.45V_s$ to $1.55V_s$ (where V_s is handbook stall speed) because of the improved longitudinal and lateral controllability as compared with lower speeds. Imminence of buffet and more difficult control of sink rate at lower speeds influenced the choice of touchdown speeds; these speeds ranged from $1.27V_s$ to $1.37V_s$, which corresponded to near-maximum lift-drag ratio.

5. Lateral-control power will be dictated by the requirements of the landing maneuver because of the high dihedral effect and low response rates. It is felt that a suitable criterion for adequate lateral control in the landing configuration would be a specification for a given change in bank angle - such as 10° - within a finite time.

6. Although lateral-directional dynamic instability within the limits investigated could be controlled during approach and landing because of the reasonably long period of the oscillation, this condition should be considered for emergency use only, and positive damping is recommended, especially in turbulent air.

High-Speed Flight Station,
National Aeronautics and Space Administration,
Edwards, Calif., November 5, 1958.

REFERENCE

1. Butchart, Stanley P., Fischel, Jack, Tremant, Robert A., and Robinson, Glenn H.: Flight Studies of Problems Pertinent to High-Speed Operation of Jet Transports. NASA MEMO 3-2-59H, 1959.

TABLE I

OUTLINE OF LOW-SPEED JET-TRANSPORT STUDIES

1. FACTORS AFFECTING TAKE-OFF SPEED AND ATTITUDE
2. AIRPLANE APPROACH AND LANDING CHARACTERISTICS
   a. EFFECTS OF YAW DAMPING ON LATERAL-DIRECTIONAL CHARACTERISTICS
   b. LATERAL CONTROL REQUIREMENTS
   c. SPACE POSITIONING DURING LANDING APPROACH, INCLUDING IFR OPERATIONS
   d. EFFECTIVENESS OF GLIDE-PATH AND SPEED CONTROLS
   e. FACTORS AFFECTING CHOICE OF LANDING SPEEDS

TEST AIRPLANE

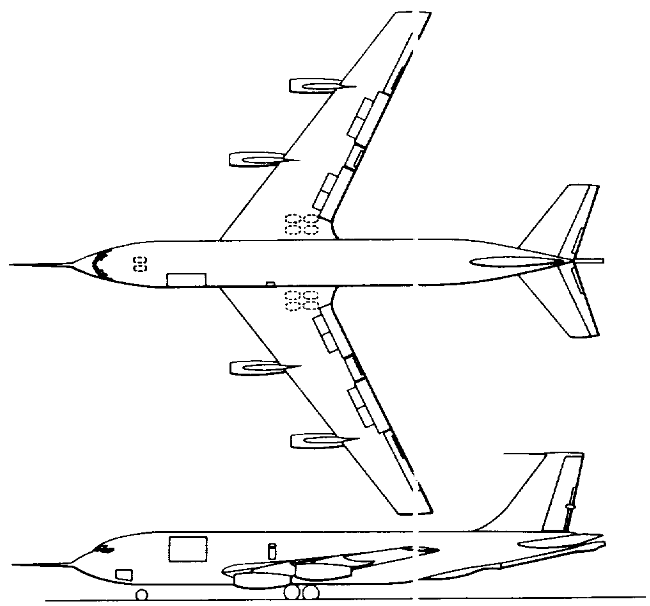

Figure 1

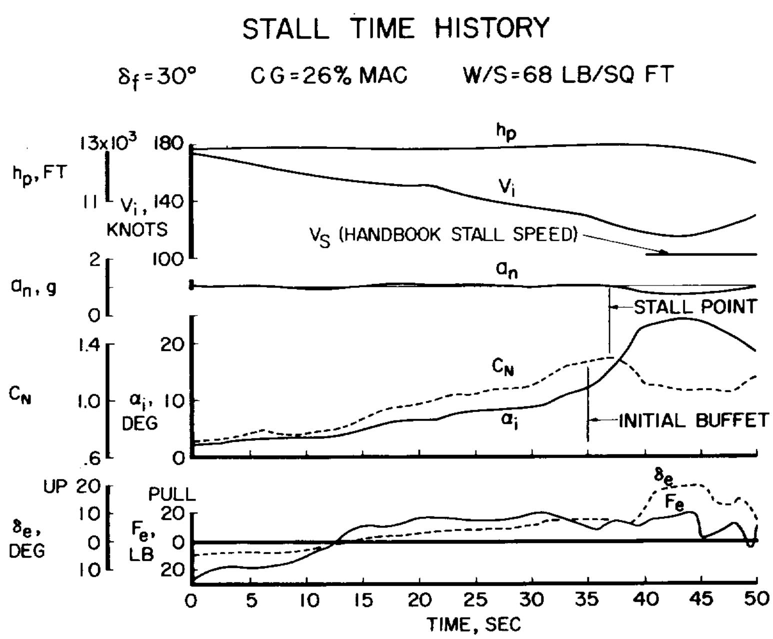

Figure 2

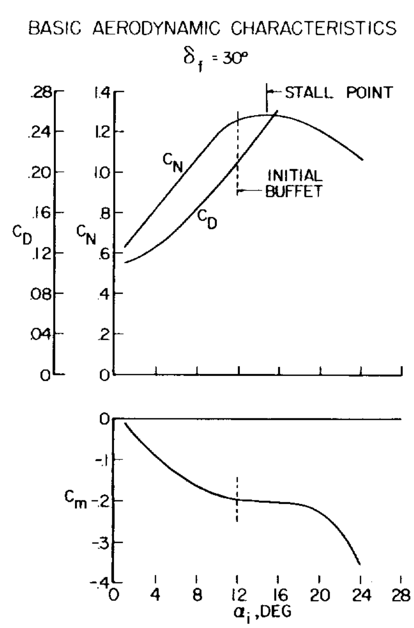

Figure 3

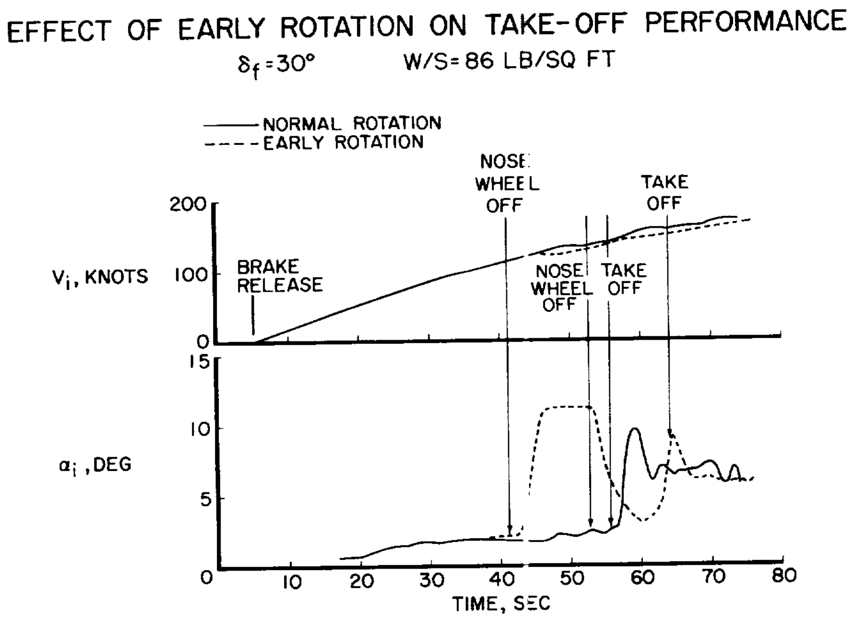

Figure 4

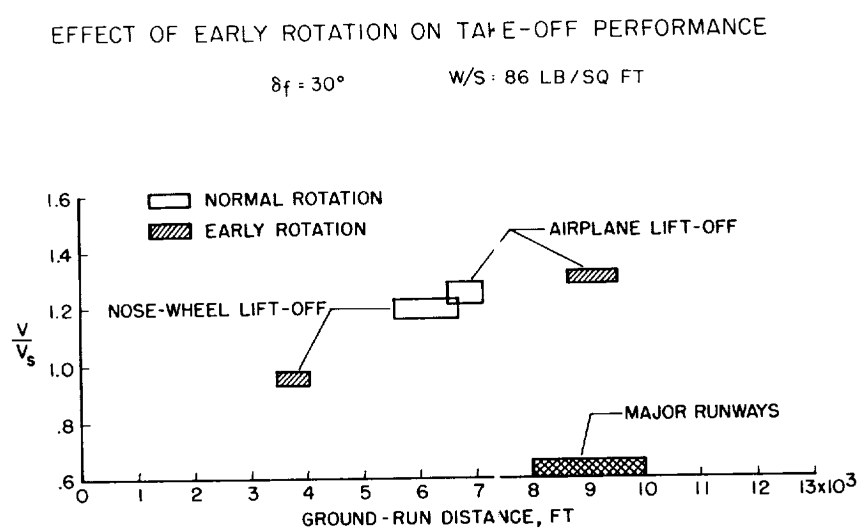

Figure 5

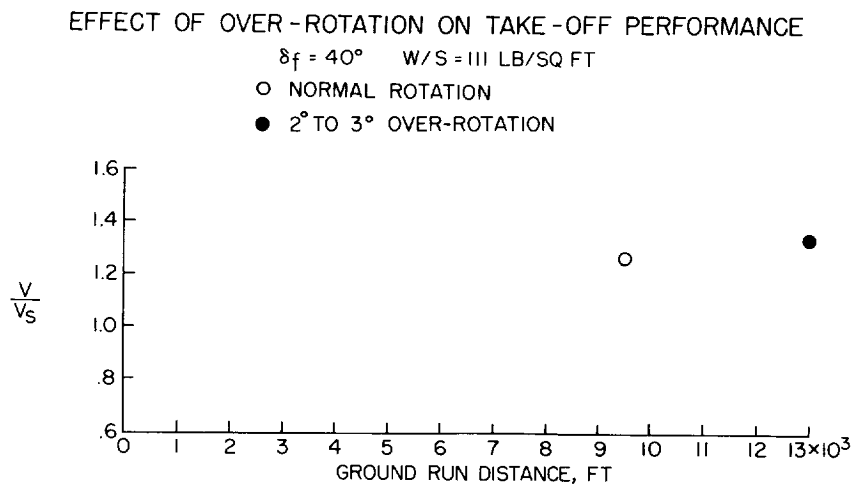

Figure 6

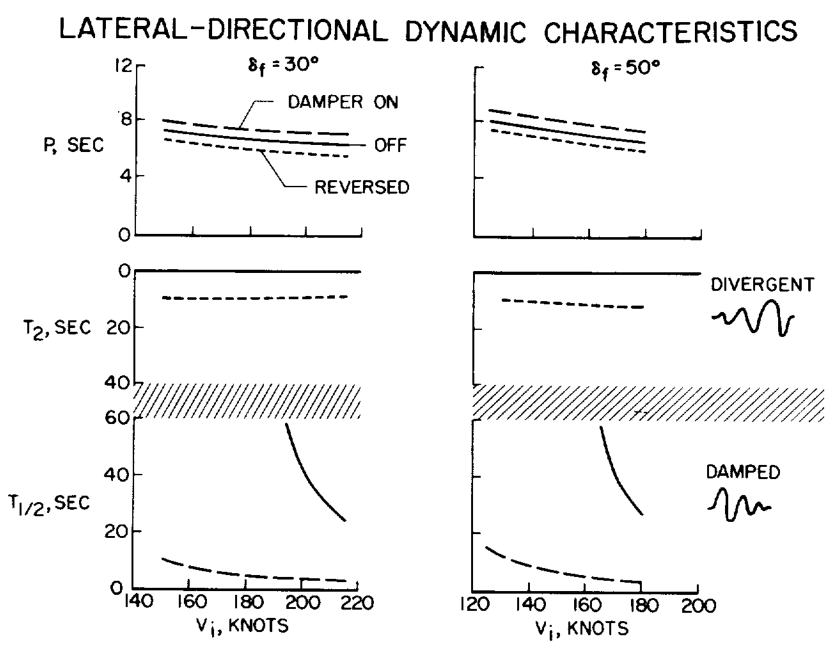

Figure 7

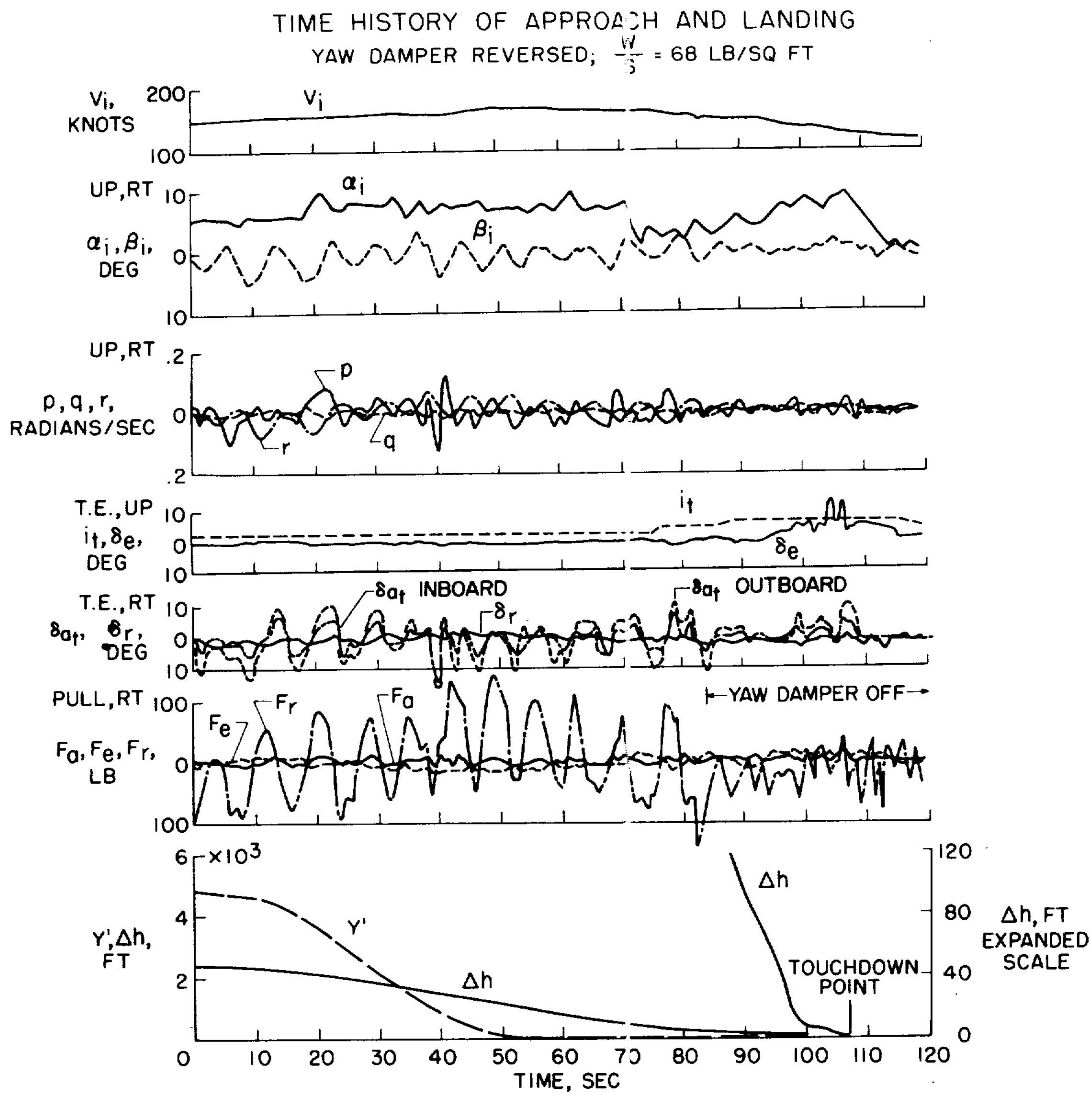
TIME HISTORY OF APPROACH AND LANDING
YAW DAMPER REVERSED; W/S = 68 LB/SQ FT
Vi, KNOTS
UP,RT
αi, βi, DEG
UP,RT
p, q, r, RADIANS/SEC
T.E., UP
it, δe, DEG
T.E., RT
δat, δr, DEG
δat INBOARD
δat OUTBOARD
PULL, RT
Fa, Fe, Fr, LB
YAW DAMPER OFF
Y', Δh, FT
Δh, FT EXPANDED SCALE
TOUCHDOWN POINT
TIME, SEC

Figure 11

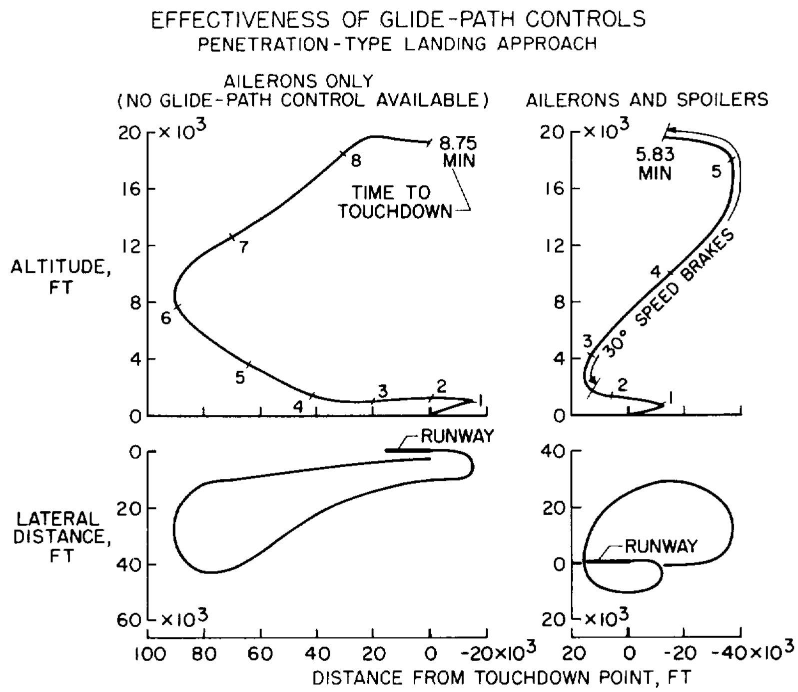

Figure 12

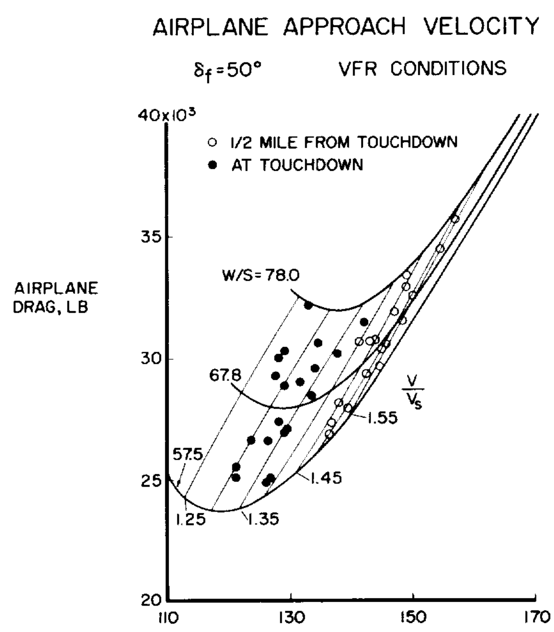

Figure 13