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A FLIGHT EXAMINATION OF OPERATING PROBLEMS OF V/STOL AIRCRAFT IN STOL-TYPE LANDING AND APPROACH

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SUMMARY

A flight investigation has been conducted using a large twin-engine cargo aircraft to isolate the problems associated with operating propeller-driven aircraft in the STOL speed range where appreciable engine power is used to augment aerodynamic lift. The problems considered would also be representative of those of a large overloaded VTOL aircraft operating in an STOL manner with comparable thrust-to-weight ratios.

The study showed that operation at low approach speeds was compromised by the necessity of maintaining high thrust to generate high lift and yet achieving the low lift-drag ratios needed for steep descents. The useable range of airspeed and flight path angle was limited by the pilot's demand for a positive climb margin at the approach speed, a suitable stall margin, and a control and/or performance margin for one engine inoperative. The optimum approach angle over an obstacle was found to be a compromise between obtaining the shortest air distance and the lowest touchdown velocity. In order to realize the greatest low-speed potential from STOL designs, the stability and control characteristics must be satisfactory.

INTRODUCTION

Considerable effort has been expended in the past, both in this country and abroad, to develop conventional type aircraft with short-take-off-and-landing performance. A number of these airplanes have utilized high thrust-to-weight ratios to achieve good take-off performance but have relied on low wing loadings and conventional high-lift devices to obtain short landing distances. Although these aircraft can be designed to meet specific requirements in regard to take-off and landing performance, they are relatively inefficient in high-speed cruise flight and derive few benefits from the large amount of power available to them during the landing approach. In fact, for these vehicles to achieve the shortest landing distance over a given obstacle the approach must be conducted at idle power. This deprives the pilot of much of his ability to adjust the touchdown point during the approach and places considerable reliance on his judgment of when and where the approach should be commenced. Although this type of operation has often been referred to as STOL, it does not meet the definition used in reference 1, which refers to STOL operation in terms of a specific operational flight regime rather than in terms of the performance capabilities of a particular airplane.

Recent studies conducted by the NASA as well as by individual aircraft companies have been directed toward harnessing a portion of available engine power to use in augmenting aerodynamic lift during the landing approach as well as during take-off. Both two-propeller and four-propeller models have been tested in the Ames 40- by 80-Foot Wind Tunnel with various forms of boundary-layer control (BLC) applied to both the highly deflected trailing-edge flaps and the drooped ailerons. The aerodynamic characteristics have been reported in references 2, 3, and 4. At the Ames Research Center, STOL operational flight experience has, for the most part, been obtained on a Stroukoff YC-134A airplane obtained from the U.S. Air Force. All of these vehicles utilize propeller slipstream effects in conjunction with BLC to develop high lift coefficients. In addition to determining the feasibility of STOL operation of large airplanes having a gross weight up to 50,000 pounds, it was desired to find out the problem areas that may result by flying at relatively low speeds with considerable power being applied. Although the test vehicle represented a conventional transport-type airplane, the results of the tests are also felt to be applicable to a VTOL vehicle operating in an overload condition or at a thrust-to-weight ratio of less than 1, such as might occur with a partial power loss.

It is the purpose of this report to review the results that have been obtained to date, to point out the limitations, and to show how some of these limitations can be coped with to obtain further improvements.

NOTATION

b wing span, ft

BLC boundary-layer control

C_L lift coefficient

$C_{L_{max}}$ maximum lift coefficient

C_D drag coefficient

$C_{1/2}$ cycles required for lateral-directional oscillation to damp to half amplitude.

C_2 cycles required for lateral oscillation to double amplitude

C_w wing chord

F control force, lb

R_{p_e}	empirical pilot rating
R_{p_o}	observed pilot rating
T_c'	thrust coefficient
$T_{1/2}$	time required for lateral oscillations to damp to half amplitude
T_2	time required for lateral oscillation to double amplitude
ΔV_f	change in speed during landing flare, knots
V	airspeed, knots
α	fuselage angle of attack, deg
β	angle of sideslip, deg
γ	flight-path angle, deg
δ	control angle, deg
φ	bank angle, deg
$\ddot{\varphi}$	roll acceleration, radians/sec^2
$\frac{\lvert\varphi\rvert}{\lvert v_e\rvert}$	amplitude ratio of the angle of bank to equivalent side velocity in the oscillatory mode, deg/ft/sec

Subscripts

App	approach
a	aileron
c	calibrated
e	elevator
f	flap
r	rudder
s	stall
TD	touchdown

EQUIPMENT AND TEST AIRPLANE

A YC-134A airplane was used as the flight vehicle for this investigation. A two-view sketch of the airplane is shown in figure 1 and a photograph of the airplane is shown in figure 2. Table I presents the geometric data for the airplane.

The airplane was designed and built by the Stroukoff Aircraft Corporation under Air Force contract. Propulsion was provided by two R-3350-89A reciprocating engines (3250 HP max - sea level to 3500 ft) turning Aeroproducts A644FN-C2 four-bladed 15-foot diameter propellers. The airplane was equipped with area-suction boundary-layer control applied to both the trailing-edge flaps and the drooped ailerons. Suction for the boundary-layer control system was provided by a J-30 turbojet engine mounted in the fuselage. Although the jet engine speed was controllable for these tests, the engine was run at maximum speed to insure maximum boundary-layer control and lift augmentation. When the ailerons were drooped, the lateral control was augmented by spoilers, located on the upper surface of the wing ahead of the flaps (see fig. 1). The trailing-edge flaps and the ailerons were of the slotted type hinged on the lower surface. Figure 3 is a sketch of a typical cross section of the flap or aileron showing pertinent dimensions. The porous area was composed of perforated aluminum alloy with a porosity, hole size, and spacing as given in table II. The chordwise porous opening and position were determined from reference 2, and the location of the porous area is shown in figure 3. The internal volume in front of the spar of the flap or aileron acted as the plenum chamber and the BLC air duct. A rotating seal at the hinge line connected the BLC ducts at the aileron-flap and the flap-fuselage junctures. The trailing-edge flap had a maximum deflection of 60° and the aileron droop was 30°. In the drooped configuration, the aileron travel was between 0° and 50° deflection. Further details on characteristics of the airplane are given in the appendix.

INSTRUMENTATION AND TEST

Standard NASA recording instruments were used to record airspeed, altitude, accelerations, and angular velocities. A photo panel was used to record angles of attack and yaw, control positions and forces, and engine torque and speed. The angles of attack and yaw vanes along with the free-stream total pressure probe, and static orifices were mounted on a one-chord-length wing-tip boom. The airspeed static pressure was calibrated over the speed range by the trailing bomb method and the angle of attack was calibrated, using sensitive accelerometers and a statoscope to determine changes in altitude.

The flight tests to document and evaluate handling qualities and stall characteristics were conducted between 5,000 and 10,000 feet altitude. The landing approach evaluation was made at the Naval Auxiliary Landing Facility, Crows Landing, California, elevation 165 feet. The landing approaches included a range of approach angles from 1° to 10°. The angles and air distances were measured by a Fairchild flight analyzer and were corrected to eliminate the effect of wind. The tests were, for the most part, made with the trailing-edge flaps deflected 60° and the ailerons drooped 30° with full BLC on both flaps and ailerons. Only a limited amount of testing was done with other flap deflections, with undrooped ailerons, or with BLC off. Engine power was varied from idle to 70 percent of the maximum attainable at sea level. The average wing loading was 45.0 pounds per square foot (gross weight of 55,500 lb). The center of gravity at this weight was 26.2-percent mean aerodynamic chord.

RESULTS AND DISCUSSION

In the discussion, only those results obtained from the flight tests of the YC-134A that apply directly to general STOL operating problems are discussed. Other results, peculiar only to the test vehicle but which, nevertheless, are considered of interest are contained in the appendix.

STOL Operating Characteristics

Operating envelope.- A generalized plot of the STOL operating envelope of the test aircraft which derives a portion of its lift capabilities from engine power is presented in figure 4. (Additional information on the lift characteristics of the YC-134A is presented in the appendix.) In figure 4, steady-state flight-path angle is plotted as a function of velocity for various values of engine power in terms of the percentage of total power available. In this particular example, maximum power represents a thrust-to-weight ratio of about 0.3. The broken lines on the figure indicate the angle of attack that corresponds with each combination of power and airspeed in steady nonaccelerated flight. This envelope which is bounded on three sides by the aerodynamic and performance capabilities of the airplane illustrates the basic problem in obtaining STOL performance; namely, use of high engine power to obtain high lift for low airspeeds in a sinking approach. For the YC-134A the difference in $C_{L_{max}}$ between idle and 70-percent maximum power corresponds to a reduction in stall speed of about 20 knots. However, at low airspeed and only 0.3 maximum power, the effective lift-drag ratio is still too high to produce a flight-path angle much steeper than 4°. The boundary on the lower left represents the stalling speed and illustrates its variation with engine power for this particular vehicle. The maximum steady-state glide angle, the bottom boundary, is of course limited by the aerodynamic lift-to-drag ratio of the airplane at idle power. The upper line represents the maximum attainable climb angle in this configuration with full power.

Piloting technique.- It is important to point out the control technique required of the pilot when he is operating in this STOL flight region. Changes in angle of attack have, at best, little effect on flight-path angle. In fact, it can be seen from figure 4 that the steady-state flight-path angle resulting from changes in angle of attack may be in the opposite direction from that to which the pilot is accustomed. In this flight region, using the elevator to control flight-path angle can lead to a rapid divergence in speed; therefore, the pilot tries to maintain a relatively constant angle of attack and controls his approach-path angle by changing the power. This method of control is not difficult; however, it requires the pilot to keep one hand on the throttles while controlling attitude and angle of attack with the other. It is thus felt that the flight-control systems of STOL aircraft should be designed for one-hand operation. In addition, the thrust response to throttle movement should be smooth and rapid. It should be pointed out that with the YC-134A there was considerable lag between the application of power and the resulting change in flight-path angle. In order to obtain the desired response, and to avoid overcontrolling, the throttles were moved in a stepwise fashion to anticipate a desired flight-path-angle correction while the elevator was used to make short-term adjustments about the desired path. Of equal importance is the transient effect on flight-path angle which occurs before the velocity stabilizes in response to an angle-of-attack change. The pilot must be aware of these effects in order to anticipate the desired flight-path corrections. Because of this method of control, it was considered impractical to divide the responsibility of control applications between two pilots, as is sometimes done in a more conventional type of approach.

During the steep approaches made with idle power, there was little or no means available with which to adjust touchdown point once the approach was commenced. If the approach were short, power could be added, resulting in a shallower approach angle; however, if the approach were long, since power could not be reduced, the only way to increase flight-path angle was by nosing over. This, of course, resulted in excess air-speed which had to be dissipated before touchdown. The only alternative was to land long or wave-off.

Operating limitations.- In addition to these aerodynamic and performance boundaries, there are certain limitations imposed by the pilot in order that the approach may be conducted in what he considers a safe manner. The areas that are avoided are indicated in figure 5 by the shaded region superimposed on the STOL envelope.

The first of these limitations is represented by the vertical line in the upper left-hand portion of the figure. This is the minimum air-speed at which it is possible to perform a satisfactory wave-off. Current Civil Air Regulations specify that a 1.8° climb gradient must be available in this configuration with all engines operating. It was found that under ideal conditions, with a clear unobstructed path available for climbout, Ames research pilots have considered a climb gradient of less than 1° to be acceptable; however, this would be considered acceptable only for an emergency situation. Perhaps a more practical solution to the question of satisfactory wave-off performance should consider any obstacles which would have to be cleared during climbout.

The second limitation is imposed by the proximity to the stall. This is represented by the diagonal line which runs roughly parallel to the stall boundary. The stall in this case is considered to be defined by either a sudden loss of lift or a rapid deterioration of stability or control characteristics. Previous research at Ames on jet fighter-type airplanes indicated that the pilots were willing to approach at speeds as low as 1.1 times the power-on stall speed (ref. 5); however, when the stall speed was less than 100 knots, it was found that a fixed margin, rather than a fixed percentage above the stall, is desirable. This provides protection against finite variations in approach speed due to pilot distractions or disturbances such as gusts. If the stall speed remained constant as power was varied, a margin of 10 knots above the stall would represent a realistic minimum. However, when the lift coefficient and hence stall speed vary greatly with engine power, as is the case with these vehicles, an airspeed margin becomes less useful during the approach. The pilot must turn to something more consistent to protect against inadvertent stall. Reference to the angle-of-attack indicator in the YC-134A proved to be most satisfactory for this purpose since the pilot could maneuver or manipulate the throttles as much as he wished and still be assured that he was maintaining a safe margin from the stall. During the landing evaluation of the YC-134A, the pilots chose to approach at an angle of attack which corresponded to about a 10-knot margin above the stall speed for any desired power setting.

Another limitation which occurs as the approach angle becomes steeper concerns the pilot's ability to flare the aircraft at constant power. In executing this flare it has been found from the YC-134A tests that the pilot will not normally use more than 85 percent of the maximum lift coefficient that is available. The assumption that the flare is made at constant power is based on the current design and locations of the engine control system, which has rendered the addition of power during the flare impractical.

In the discussion of steep approaches, the question quite naturally arises as to what is the maximum rate of descent that the pilot will tolerate prior to the flare. Most certainly as sink rate increases in magnitude, the errors associated with estimating it and in estimating the ability to arrest it become greater. These errors, of course, detract from the safety of the operation, and, if large enough, can lead to disaster. There is little quantitative data on the ability of the pilot to arrest these high sink rates. It is of interest to note that during the steepest approaches that were conducted with the YC-134A, which were about 10° with 1700 feet per minute rate of descent, the ability to flare was considered marginal.

A remaining limitation not indicated in figure 5 is a demand for ability to control flight-path angle. Since power is being used as the primary flight-path control, the pilot desires a portion of it to be held in reserve; therefore, he will not consciously choose to approach in a condition where he does not have this reserve. Again previous research (ref. 5) involving jet fighter airplanes has indicated a minimum available thrust-to-weight ratio of about 0.1 to be limiting. Additional research is necessary, however, to determine whether this value is applicable to this type of aircraft.

The combination of all these limitations can rather severely limit the scope of the STOL operating envelope. It is of interest, therefore, to see if this envelope can be expanded by deviating from the current operating techniques. For example, an aircraft that is limited by the ability to wave-off could be improved if the pilot were willing to accept a configuration change such as reduced flap deflection in order to accomplish a wave-off. Such a change, however, would have to be carefully programmed to avoid undesirable trim changes or a loss of lift. Another way in which the envelope could be expanded is the use of power to assist in flaring the airplane during steep approaches. This would not only eliminate the excess speed required during the approach for the flare, but would also reduce the stalling speed as the flare was accomplished. Such a technique has been used quite successfully on a jet fighter-type airplane which incorporated boundary-layer control on a highly deflected trailing-edge flap (ref. 6).

Another problem that must be given serious attention is that of losing an engine. The minimum control speed of STOL aircraft must be examined in the approach configuration as well as the take-off condition. Figure 6 illustrates the severe reduction to the STOL operating envelope that can occur unless the pilot chooses to ignore the minimum control speed. This is indicative of results obtained with the YC-134A. The shaded area above the one-engine inoperative line is unusable to the pilot partly because he is unable to maintain control. The loss of control may result from a lack of lateral control power, as well as direction control power, because of the reduced lift on the side with the inoperative engine. This implies that if an engine were lost on the YC-134A during an approach that was shallower than about 5° there would be no alternative but to land short, unless sufficient altitude remained to make a configuration change. If the approach were planned for a flight path steeper than 5°, sufficient power could be added on the good engine to reach the intended touchdown spot. Although the use of boundary-layer control on both lateral and directional control surfaces can increase their effectiveness and thereby reduce the minimum control speed, the landing problem is not completely alleviated. Loss of an engine will reduce the upper boundary of the STOL envelope by the percentage of power represented by the inoperative engine; therefore, the pilot may still be forced to accept the fact that he is committed to land because of the inability to wave-off. The use of interconnected propellers would, of course, improve the situation considerably since directional asymmetry would be avoided and performance might be somewhat better than that obtained with 50-percent power due to the propellers sharing the load from the operative engine.

Selection of approach speeds.- Two of the Ames research pilots conducted evaluations of the landing approach characteristics of the YC-134A airplane, and minimum confortable approach speeds for various approach angles. The results are presented in figure 4 where the approach speeds selected are plotted against the flight-path angle which was determined by the approximate power used during the approach. The primary factor which influenced the choice of approach speed at the intermediate angles was proximity to the power-on stall. During shallow approaches of approximately 1°, which incidentally the pilots considered to be essentially flat, certain objectionable stability and control characteristics could not be ignored and were considered at least partially a limiting factor. High control forces and, in particular, an undesirable lateral control sensitivity contributed considerably to the pilot workload during the approach. The effort required to maintain straight wings-level flight prior to touchdown detracted from the pilot's ability to control longitudinal flight-path angle. At idle power, the minimum approach speed was determined by the amount of excess speed required to execute an aerodynamic flare. These approaches were not considered by the pilots to be STOL but were included because they provided a practical limit to the maximum flight-path angle attainable.

Optimum approach angle.- The limitations indicated in figure 5 can be used as a guide to predict minimum approach and touchdown speeds for the YC-134A at various approach angles. Figure 7(a) presents the computed approach and touchdown speed variation with approach angle. Included also are measured values for comparison purposes. It is obvious that for a vehicle of this type, the lowest touchdown velocity and consequently the shortest ground roll will be achieved from an essentially flat approach where maximum advantage is taken of the lift augmentation to reduce the stalling speed. Unfortunately, however, consideration must be given to obstacles which have to be cleared in the approach path; therefore, a realistic value for the landing distance of an STOL airplane must take into account the air distance required to clear such an obstacle. This air distance, of course, becomes smaller as the approach path is steepened. However, the reduced power required for a steep descent results in a higher stall speed and consequently a higher touchdown speed which increases the ground roll. It therefore appears desirable to determine if an optimum approach angle exists which will result in the shortest total distance over a given obstacle. If the air distance required for the approach and flare is combined with the ground roll resulting from the corresponding touchdown speed, the total distance can be calculated. Figure 7(b) presents the results obtained with the YC-134A for the landing distance over a 50-foot obstacle. The solid curves indicate the calculated variation in the air distance required for the approach and flare as the approach angle is steepened. The calculations are based on the methods outlined in references 7 and 8. The circled points are values obtained from flight tests from three representative approaches. To obtain the total distance, the calculated ground roll has been added assuming two different values of braking coefficient. It can be seen that an optimum angle does exist and also that this angle shifts to a steeper value if the greater braking coefficient is assumed. It is important to note, however, that relatively small gains were realized with the YC-134A at approach angles greater than about 4°. To the pilot, this means that he can approach at a reasonably shallow angle with a moderate rate of descent and still obtain near maximum performance. This shallower approach affords much better control of both sink rate and touchdown point.

Effect of Basic Airplane Configuration on STOL Operation

In the remainder of the discussion some problems are considered which are associated with STOL operation of relatively conventional aircraft not possessing features required by true VTOL aircraft. It is important to point out that the limitations which were outlined previously are approached only if the aircraft possesses satisfactory handling qualities. Experience with the YC-134A has tended to emphasize increasing importance of certain stability and control characteristics in STOL operation as opposed to conventional landings.

Longitudinal stability and control.- As the speed is reduced and the thrust coefficient is increased, the longitudinal stability in pitch may be reduced because of the change in downwash characteristics at the horizontal tail (ref. 4). The importance of maintaining a constant angle of attack during STOL approaches has been pointed out previously. This is particularly true if the approach is being conducted on the back side of the drag curve. Any reduction in the tendency of the airplane to return to trim angle of attack following disturbance could greatly complicate the pilot's control task and should be avoided if at all possible. The trim change that occurs with power must also be examined in this light. Both of these stability parameters are influenced by the location of propellers as well as by the position of the horizontal tail. If good stability cannot be obtained by a judicious choice of airplane geometry, stability augmentation should be considered in the design of the vehicle.

Side-force characteristics.- All conventional aircraft with propellers of like rotation exhibit increasing left sideslip as speed is reduced. During the flight tests of the YC-134A (see fig. 8), it was noted that with high power as the stall was approached in straight wings-level flight nearly full lateral and directional control was required. Banking the airplane slightly to the right greatly reduced these control requirements. Unpublished wind-tunnel tests indicate that these side forces do not result from inplane propeller forces or from air-flow separation, but rather from the flow field produced by corotating propellers. The use of four rather than two propellers did not reduce the severity of this problem. The problem would be alleviated, of course, by use of propellers of opposite rotation.

Lateral-directional and control characteristics.- It was found in flight at low airspeeds that the lateral-directional damping may decrease to unacceptable values. The YC-134A airplane, for example, was easily disturbed directionally by either gusts or lateral control inputs and the resulting yawing motions were quite uncomfortable. Because of the long period (5.4 sec) and the poor directional control system characteristics, such as high friction and inertia forces, considerable time and effort were required by the pilot to damp these oscillations. The pilots rated the lateral-directional damping of the airplane using the rating scale indicated in table III. Figure 9(a) compares the results with the recommended boundaries for V/STOL aircraft (ref. 1). The fact that the damping of the YC-134A satisfies these requirements questions their validity when oscillations of a long period are concerned. Reference 9, as well as reference 1, suggests that the parameter $1/T_{1/2}$ might be a better measure of damping criteria. Figure 9(b) indicates the pilot opinion of the YC-134A and agrees well with an extension of the recommended boundaries of reference 9 expressed in terms of $1/T_{1/2}$. It is quite possible that STOL aircraft may require the use of a yaw damper at low airspeeds to obtain satisfactory directional behavior.

Directional control in the landing approach also may become more of a problem as speed is reduced. For the YC-134A the directional control was rated poor and inadequate. The response to rudder deflection was quite sluggish. This in conjunction with the high forces and easily excited directional oscillations rendered the precise control of sideslip virtually impossible. Sideslip characteristics for the YC-134A are discussed further in the appendix.

It is obvious that as speed is reduced, the control power afforded by aerodynamic surfaces deteriorates rapidly. This situation can be alleviated to some extent by the application of BLC to the surfaces. Figure 10 shows the maximum rolling acceleration obtained with the YC-134A using drooped ailerons with area suction, and when complemented by spoilers. These accelerations are compared with the value required to obtain a bank angle of 15° at the end of 1 second (see ref. 1). The use of drooped ailerons plus spoilers resulted in sufficient control power down to about 80 knots, whereas the drooped ailerons without spoilers were unsatisfactory at the same speed. It is felt that an increase in effectiveness such as could be obtained with a more effective BLC system (such as blowing BLC) should be sufficient to provide satisfactory control for maneuvering at a somewhat lower airspeed. However, to obtain further increases in control power, it would be necessary to immerse the ailerons or spoilers in the propeller slipstream or to use differential propeller thrust. Further consideration of the lateral control characteristics of the YC-134A can be found in the appendix.

CONCLUSIONS

The following conclusions have been drawn from a flight investigation of the problems involved in operating a large twin-engined propeller-driven aircraft in the STOL speed range where appreciable engine power is used to augment aerodynamic lift.

1. Operation at low airspeeds in the landing approach was compromised by the necessity of maintaining high thrust to generate high lift and yet of achieving the low effective L/D needed for steep descents. For the YC-134A airplane to achieve a flight-path angle steeper than 4°, engine power had to be reduced below 0.3 maximum power.

2. Landing approaches were made more easily and safely when engine power was used to adjust flight-path angle and elevator control was used to maintain a constant angle of attack. For this method of control the control forces had to be small enough to permit one-hand operation.

3. The usable range of airspeed and flight-path angle was limited by the pilot's demand for a positive climb margin at the chosen approach speed, a margin from the stall (expressed in terms of angle of attack), an acceptable rate of descent, an engine power range for adjusting flight-path angle, and a control and/or performance margin with one engine inoperative.

4. The optimum approach angle resulting in the shortest total landing distance over a given height obstacle was found to be a compromise between obtaining the shortest air distance and the lowest touchdown velocity. For the YC-134A airplane, approach angles steeper than 4° reduced the total distance only slightly, and increased the difficulty of hitting a prescribed touchdown point.

5. To realize the greatest low-speed potential from STOL designs, the aircraft must have stability and control characteristics which possess positive-angle-of-attack stability, no variation of side force with airspeed (control fixed), satisfactory lateral-directional damping, and adequate directional and lateral control.

6. For further significant performance gains beyond those representative of the aircraft tested, the installed thrust-to-weight ratio would have to be increased appreciably. This, in turn, might require interconnected propulsion systems with propellers of opposite rotation to eliminate the possibility of asymmetrical flight conditions.

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APPENDIX

LIFT AND DRAG CHARACTERISTICS

The lift and drag data for the YC-134A airplane with 40° and 60° flap deflections with and without aileron droop, and with boundary-layer control on and off, are shown in figure 11(a). These data show that compared to the 40° flap configuration without BLC the flap lift was increased about 65 percent at 0° angle of attack due to boundary-layer control and drooped aileron at the thrust coefficient for these tests.

The effect of engine power on the lift and drag characteristics is shown in figure 11(b) for the configuration with 60° flap, 30° drooped aileron, and BLC on. These data emphasize the large contribution of engine power, as defined by the thrust coefficient (T_c'), on the maximum lift as well as on the flap lift. In figure 11(c), the values of $C_{L_{max}}$ and α for $C_{L_{max}}$ at two T_c' values are compared with results obtained in a full-scale wind-tunnel investigation (ref. 2) on a similar model. (The main difference between the model and the airplane was the position of the engines on the wing.) The data show good correlation for α for $C_{L_{max}}$ but the $C_{L_{max}}$ values themselves are lower for the airplane. This reduction is probably due to the engine nacelle that extended over the flaps on the airplane (see fig. 1) reducing the flap effectiveness. The $C_{L_{max}}$ that could be realized with the airplane was limited by the T_c' available. The maximum T_c' (0.75) is based on maximum continuous engine power; slightly higher T_c' would be obtained with maximum power (available for take-off).

MECHANICAL CHARACTERISTICS OF THE FLIGHT CONTROL SYSTEM

The mechanical characteristics of the flight control system of the YC-134A airplane are indicated in figure 12. Friction in the aileron system was excessive, requiring about 20 pounds force to move the control. This is considerably greater than the 5 pounds maximum specified in reference 1 and prevented the lateral control system from centering. The ailerons were augmented by a spoiler system which began to operate at about 20° deflection of the control wheel, as shown in figure 12(b). Actuation of the spoilers involved an additional breakout force of about 10 pounds which was considered very objectionable. To obtain full deflection of the lateral control system required about 120° of rotation of the control wheel. The rotation required was considered excessive since it severely limited the pilot's ability to obtain full deflection with one hand. The high friction forces present in the longitudinal and directional control systems were also objectionable. In addition, the inertia of these systems was so large that it was difficult to make rapid, precise control motions. Although the mechanical characteristics of the engine throttles were not measured, they were considered unsatisfactory since they did not allow small precise power changes to be made in the range used during the approach.

LONGITUDINAL STABILITY AND CONTROL

Both the elevator-fixed and elevator-free static stability of the YC-134A airplane are presented in figure 13. The stability was measured at three different power conditions in order to adequately cover the range of lift coefficient available with the airplane. For all the conditions examined, static longitudinal stability, with the elevator both fixed and free, was positive and considered satisfactory.

Longitudinal control effectiveness was satisfactory, and the response to elevator inputs seemed adequate; however, the maneuvering control force gradient at 80 knots was 96 pounds per g, which was considered too high and not in keeping with the concept of one-hand operation. The force required to flare the aircraft in steep approaches was excessive (approximately 90 lb). This was due in part to the high friction and inertia present in the longitudinal control system. The short period undamped natural frequency was 1.57 radians per second and was well damped (damping ratio = 1.55) at the approach speed (V_c = 80).

Reference 5 indicates the importance of minimizing the longitudinal trim changes due to power especially when power is used as a primary control of flight-path angle. With the YC-134A, angle of attack rather than airspeed was maintained relatively constant during the approach in order to provide an adequate margin from the stall. Therefore, the longitudinal trim change was evaluated in the power approach configuration at 0° angle of attack which was approximately that used during the approaches. The results are presented in figure 14 which indicate that there is essentially no trim change present except at very low power settings. Although power adjustments are not normally made in the region where the trim change occurred, the presence of a trim change was considered unsatisfactory because of the high force required to prevent a hard landing if power were reduced to idle prior to touchdown. Reference 1 suggests that the trim change due to power should not exceed 10 pounds. This value may be too large for vehicles designed for STOL operation.

LATERAL-DIRECTIONAL CHARACTERISTICS

The dihedral effect or roll due to sideslip was essentially zero in the approach configuration as indicated in figure 15 by the aileron position required to balance during steady-state sideslips. This was considered to be unsatisfactory by the pilots. Reference 10 indicates the desirability of being able to use the rudder to raise a wing during the approach. Of perhaps equal or greater importance is the cue that a sideslip condition exists afforded to the pilot by the lateral control force required to maintain wings level. A negative dihedral effect could easily create a tendency to apply rudder in the wrong direction to correct sideslip.

Adverse yaw due to aileron deflection was excessive, especially for small deflections. At large deflections (beyond 10°), when the spoilers became effective, adverse yaw was alleviated somewhat; however, normal use of the lateral control during the approach seldom actuated the spoilers; therefore, adverse yaw was considered unsatisfactory.

The airplane exhibited unsatisfactory spiral divergence characteristics in the landing approach. It required only 4 seconds to double bank amplitude while reference 1 specifies a minimum of 20 seconds for this configuration. This rapid divergence was considered unsatisfactory because too much attention was required of the pilot to maintain the desired bank angle during the approach.

Static directional stability is indicated in figure 15 where control position and force are plotted against angle of sideslip. The nonlinearity of rudder position and the lightening of rudder force which occurred in right sideslip were considered unsatisfactory beyond 10° sideslip.

The lateral control system characteristics of the YC-134A in the approach configuration were considered unsatisfactory. In addition to the high forces and lack of centering previously mentioned, control sensitivity left much to be desired. The nonlinearity of roll acceleration as a function of lateral control deflection shown in figure 16 was most disconcerting. Because of these nonlinear characteristics the majority of the the control applications made during the approaches were within the region of reduced slope (±10° aileron deflection) which occurred prior to spoiler actuation. Control power in this region was too low. When larger lateral control deflections were made, considerable overcontrolling resulted. This increase in roll acceleration which was associated with the actuation of the spoilers occurred after about 5° of aileron deflection beyond the point where the breakout force of the spoilers was encountered.

STALL CHARACTERISTICS

With flaps and ailerons deflected, BLC on, the stall consisted of a slow but uncontrollable roll off to the left which occurred without warning either with power on or off. This roll off, which often exceeded 60° bank angle, was accompanied by a build-up in sideslip in the same direction. Reference to the cockpit-mounted angle of sideslip indicator was essential to determine the magnitude and direction of sideslip. Recovery from the stall involved a considerable altitude loss and heading change. Both the stall and lack of stall warning were unsatisfactory.

To determine the effect of losing boundary-layer control during an approach, the BLC system was turned off abruptly at high power and low airspeed (0.7 maximum power at 75 knots). The effect was negligible with no appreciable roll-off or settling. It should be pointed out, however, that the BLC system of this particular airplane was not considered very effective at the minimum approach speed.

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TABLE I.- GEOMETRIC DATA

Wing	
Total area, sq ft	1234.9
Span, ft	110.0
Airfoil section	MS-016.64
Mean aerodynamic chord, ft	11.66
Taper ratio	.513
Aspect ratio	9.8
Sweep (leading edge), deg	2.1
Dihedral (lower surface), deg	1.3
Angle of incidence, deg	
Root	8.0
Tip	4.0
Aileron	
Area (aft of hinge), sq ft	88.4
Span (each side), ft	19.3
Chord (percent wing chord)	25.0
Droop, deg	30.0
Travel	
Normal, deg	
Up	20.0
Down	-15.0
Drooped, deg	
Up	0
Down	-50.0
Flap	
Area (aft of hinge), sq ft	164.4
Span (each side), ft	26.8
Chord (percent wing chord)	25.0
Deflection (maximum), deg	60.0
Spoilers	
Area, sq ft	24.2
Span (each side), ft	14.05
Chord, ft	.93
Travel, deg up	80.0
Horizontal tail	
Stabilizer area, sq ft	219.6
Elevator area, sq ft	126.4
Span, ft	39.3
Aspect ratio	4.4
Elevator travel, deg	
Up	30.0
Down	20.0
Stabilizer incidences (variable), deg	-1.0, +3.0

TABLE I.- GEOMETRIC DATA - Concluded

Vertical tail	
Center fin area (including dorsal), sq ft	203.1
Center rudder area, sq ft	64.4
Outboard fin area (each), sq ft	25.7
Outboard rudder area (each), sq ft	16.1
Span, center, ft	17.0
Span, outboard, ft	8.3
Rudder travel (center and outboard), deg	±30

TABLE II.- POROUS MATERIAL DATA

	Flap				Aileron			
Wing station, in.	84-210	210-265	265-346	346-417	417-472	472-529	529-579	579-644
Percent open area	3.9	3.9	4.9	5.8	9.5	10.8	13.0	14.6
Hole diameter, in.	.060	.060	.067	.073	.094	.100	.109	.116
Chordwise spacing of holes, in.	0.289							
Spanwise spacing of holes, in.	0.250							

TABLE III.- PILOT OPINION RATING SYSTEM

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	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 operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[1]Failure of a stability augmenter

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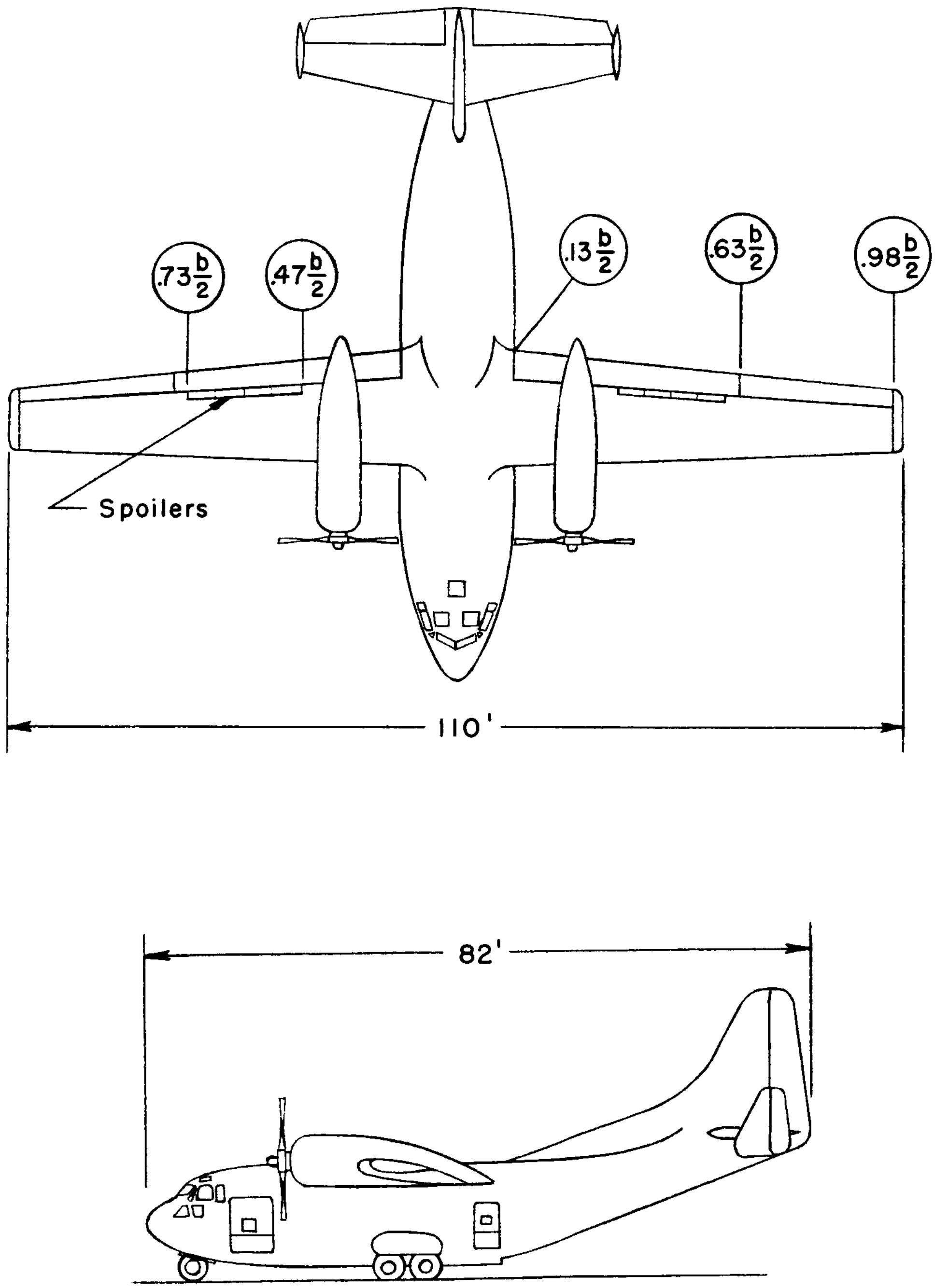

Figure 1.- Two-view drawing of test airplane.

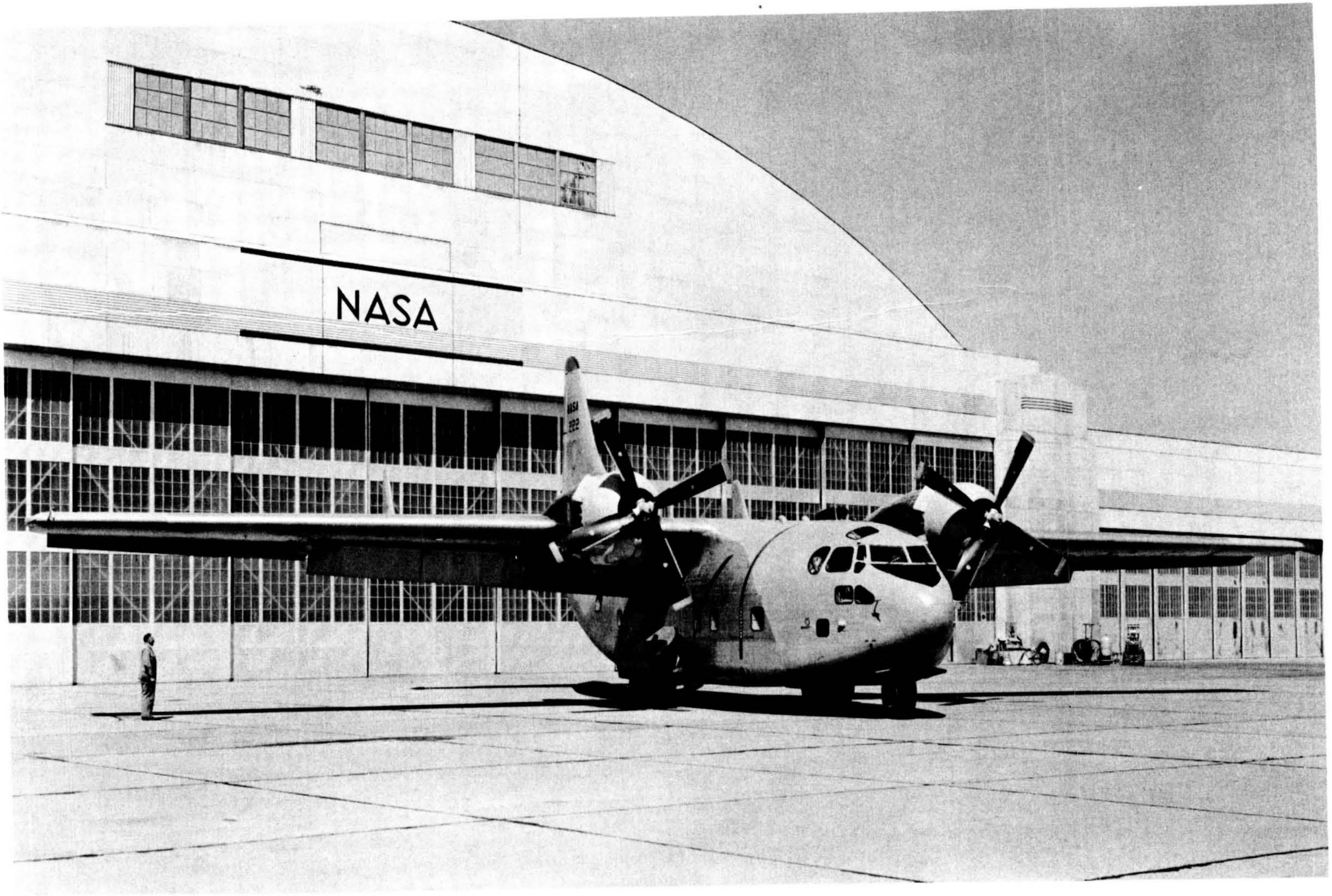

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Figure 2.- Photograph of test airplane.

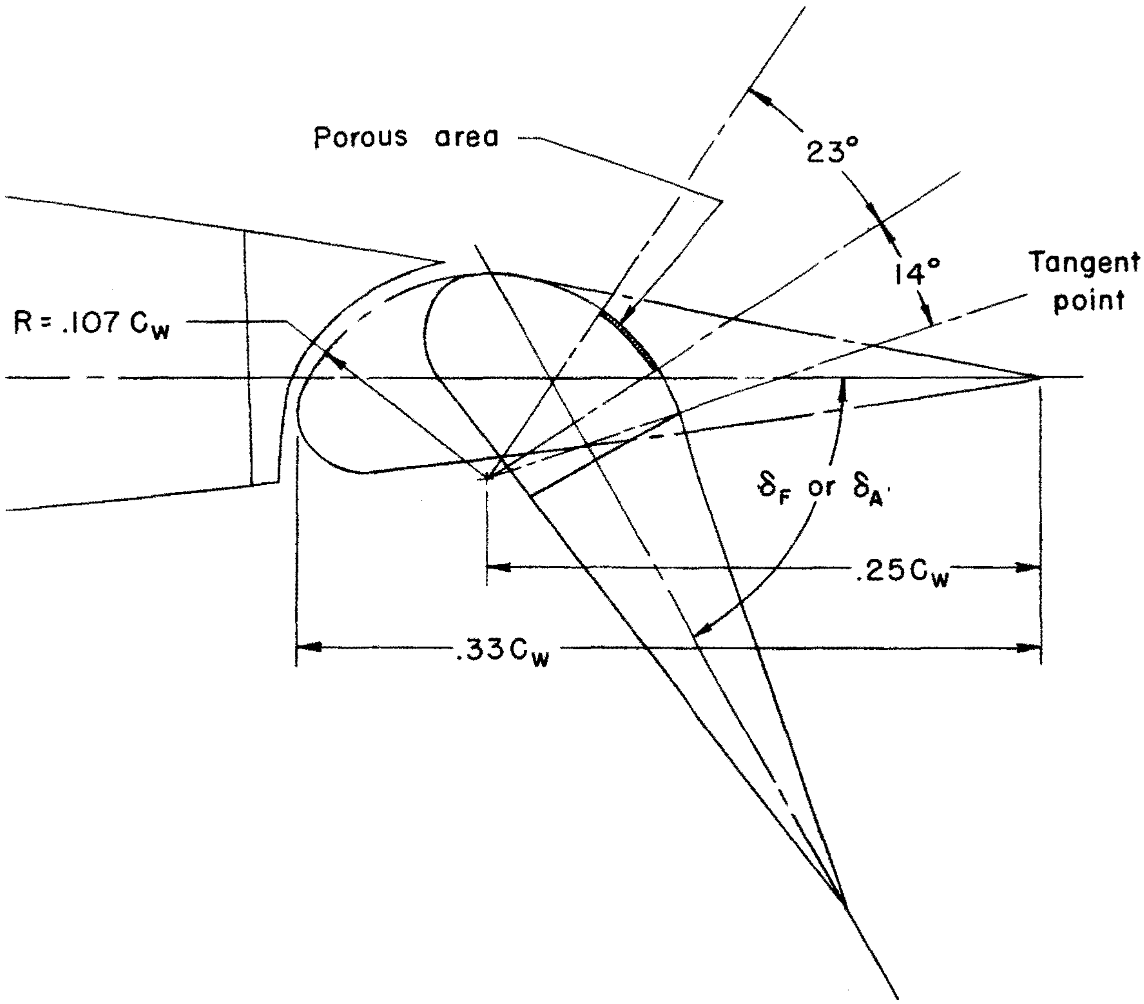


Figure 3.- Cross section of BLC flap or aileron.

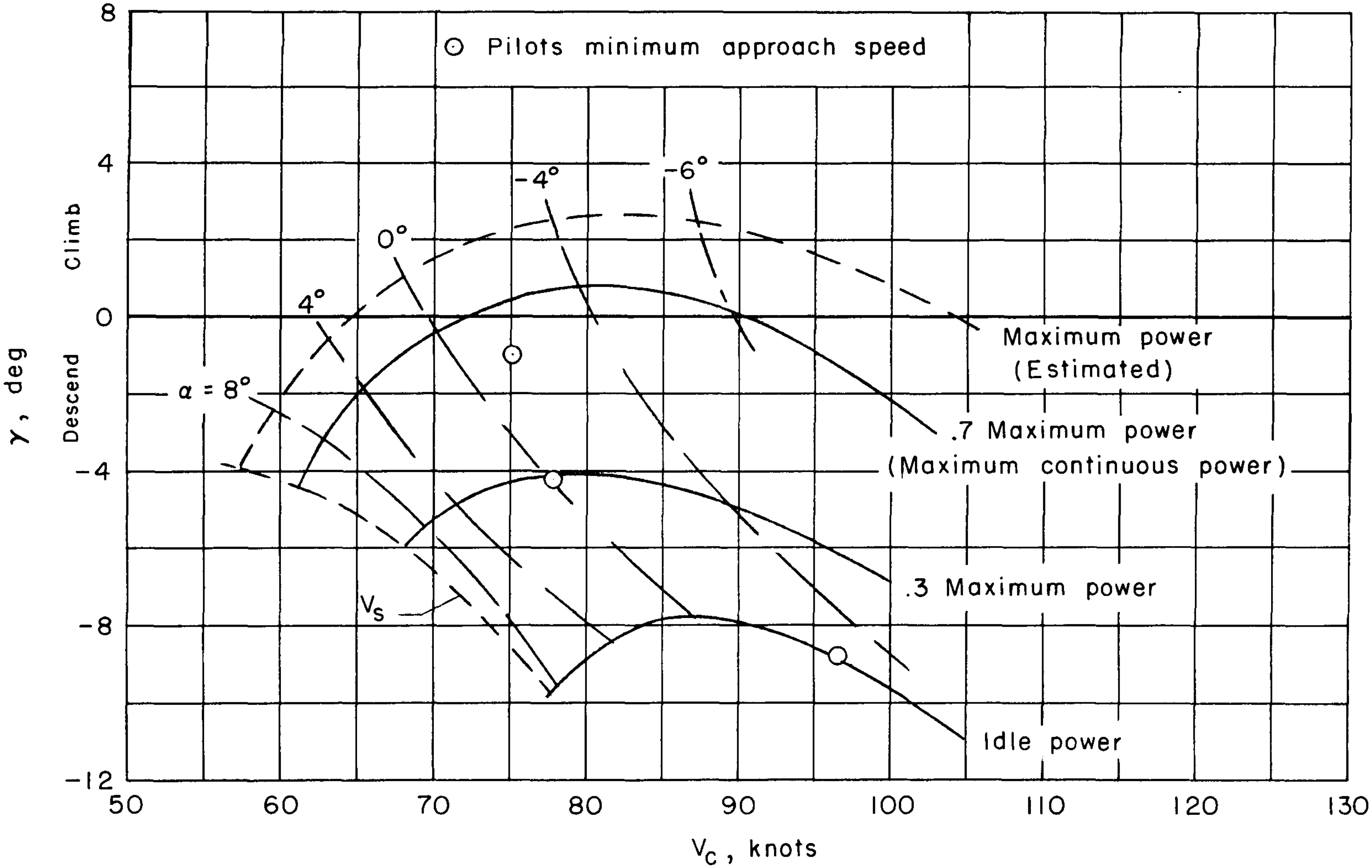


Figure 4.- STOL operational envelope.

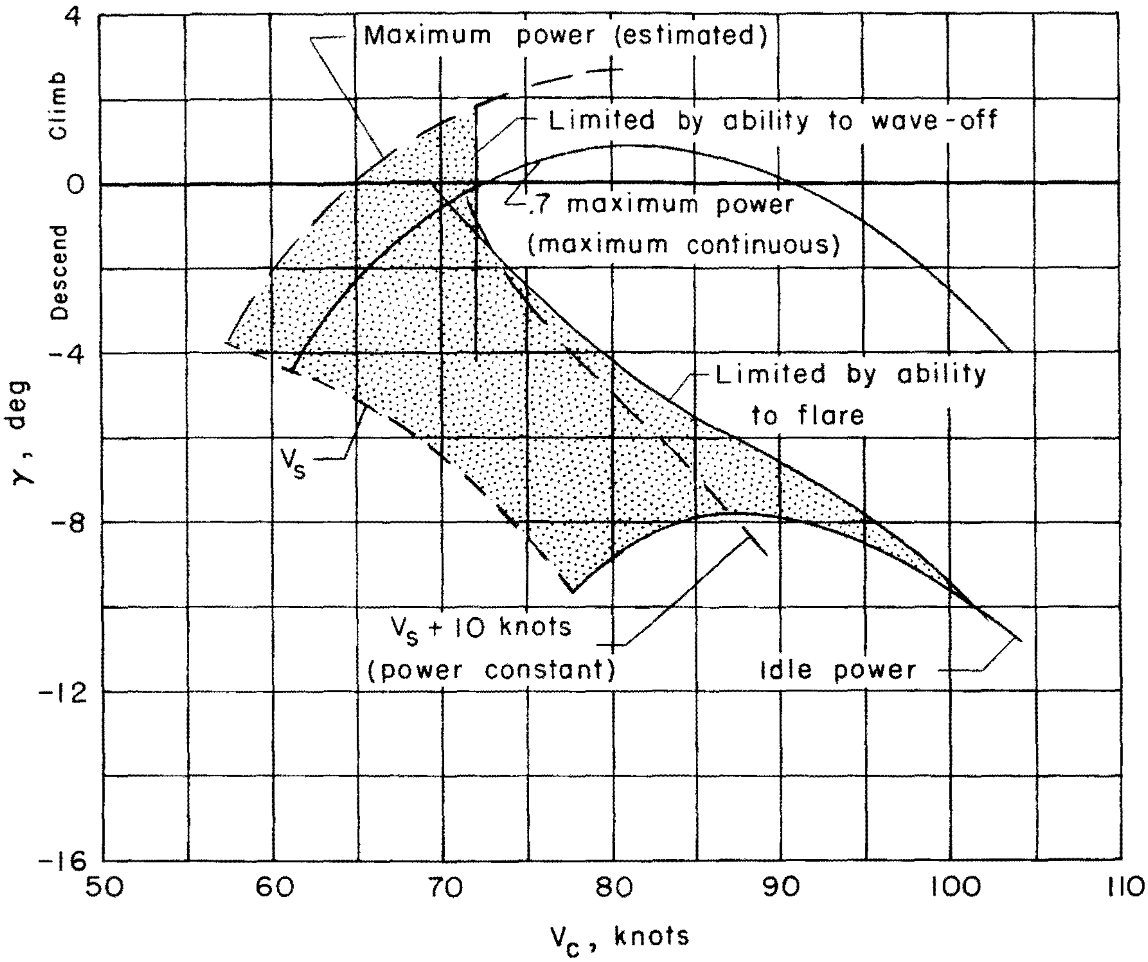


Figure 5.- STOL operational limitations.

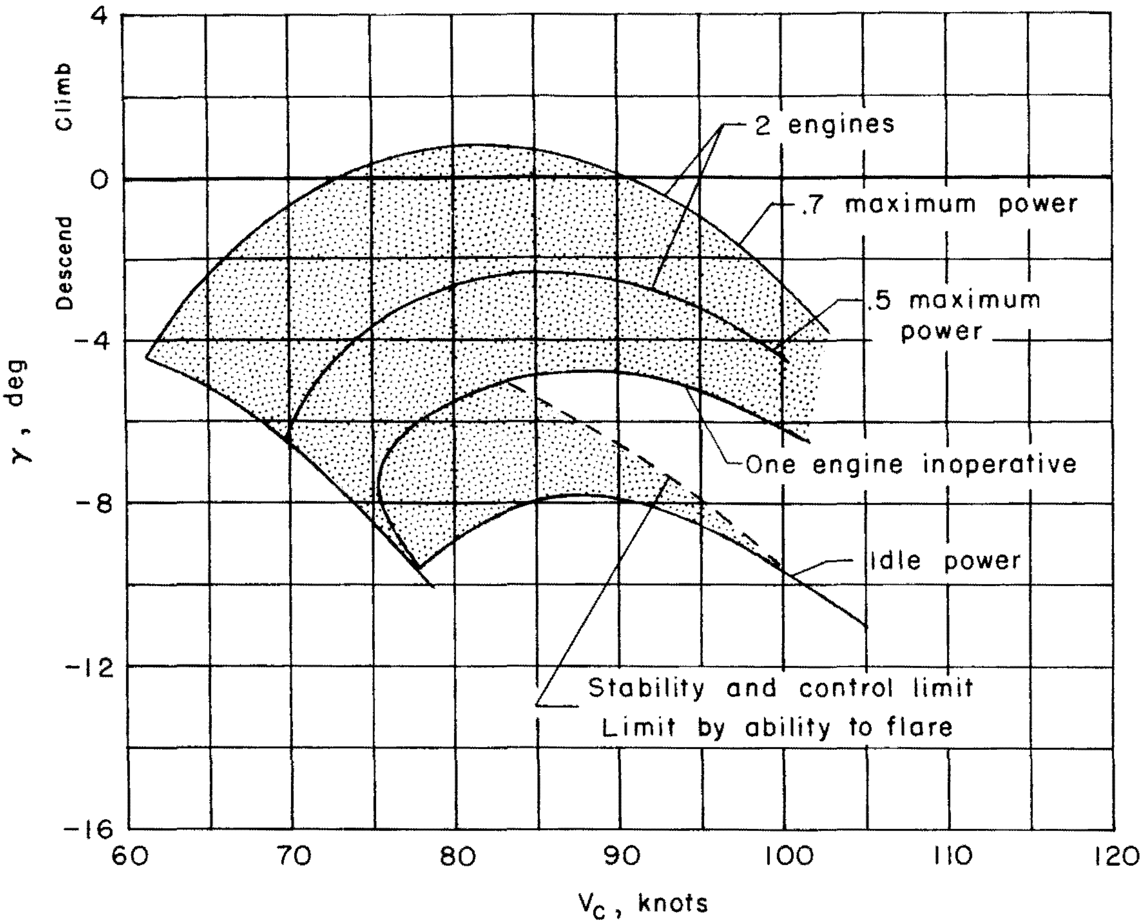
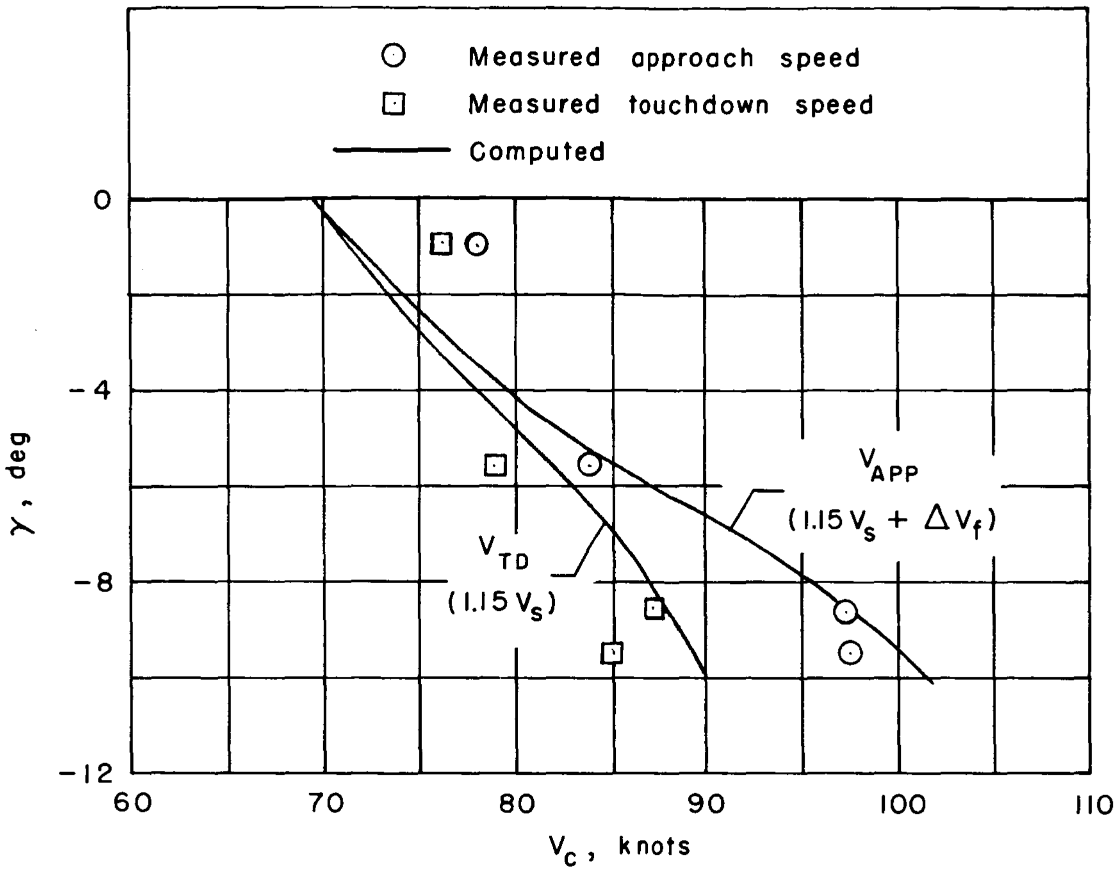
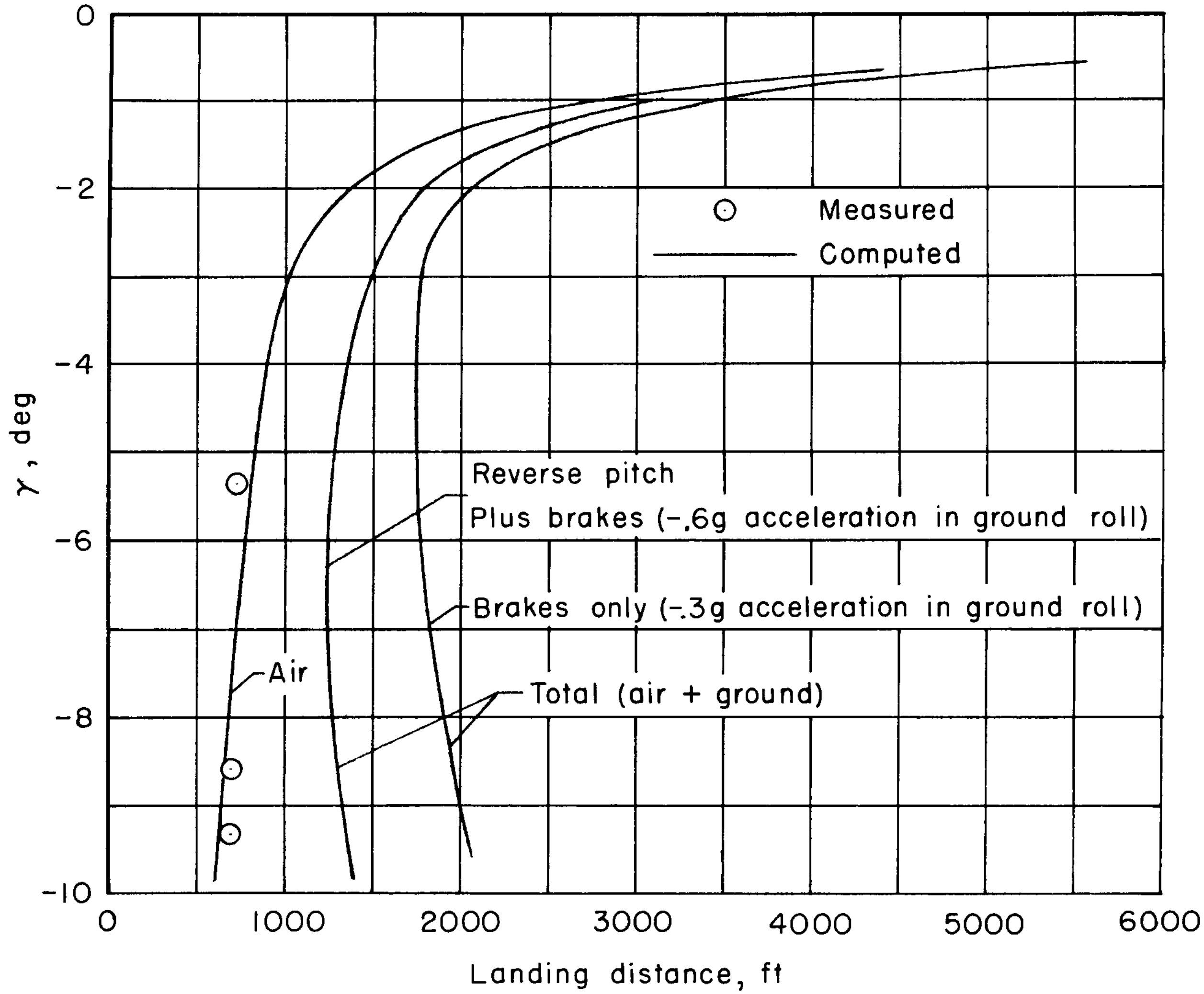


Figure 6.- Flight envelope with one engine inoperative.



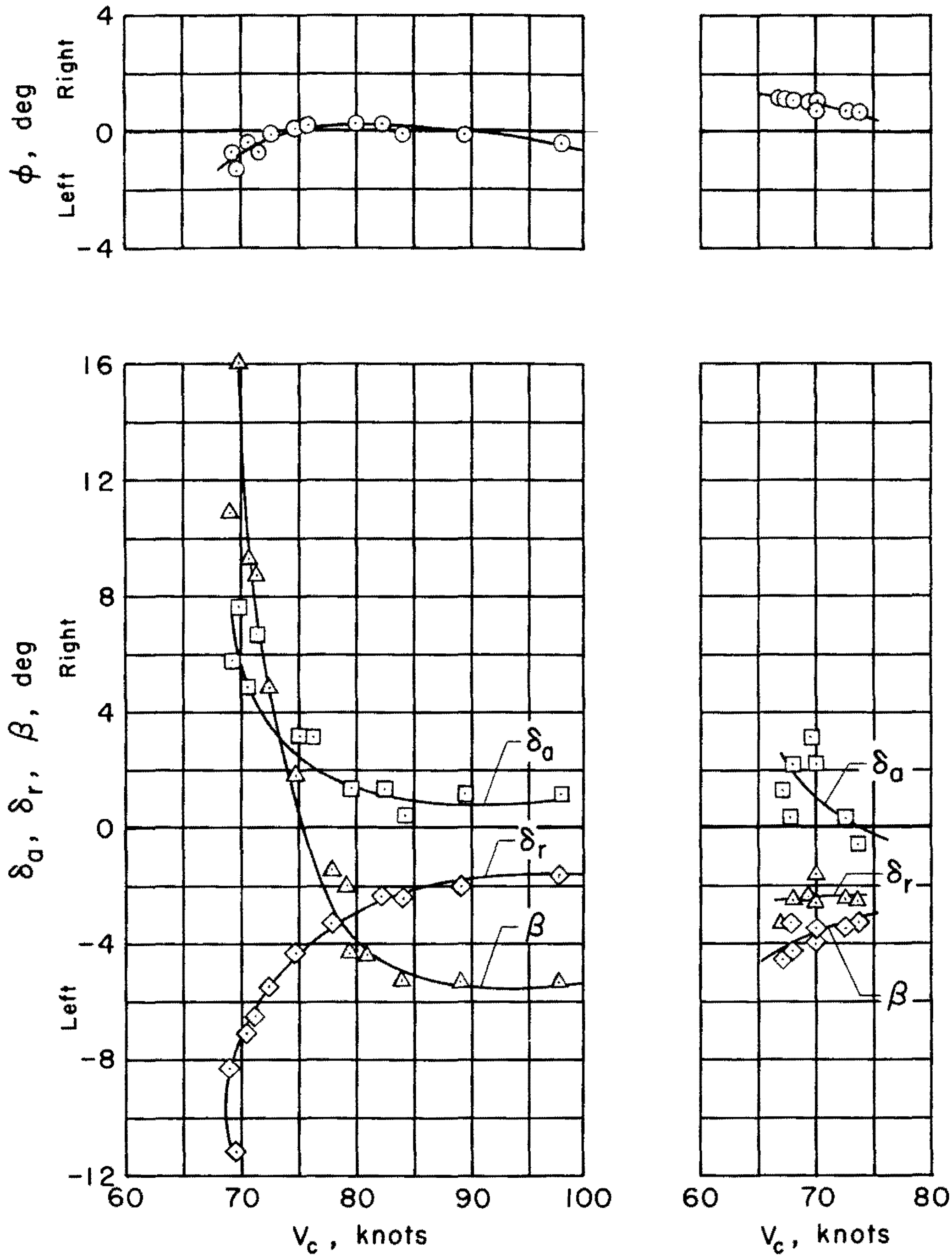
(a) Approach and touchdown speed.

Figure 7.- Variation of approach speed, touchdown speed, and landing distance with approach flight-path angle.



(b) Landing distance over 50 feet.

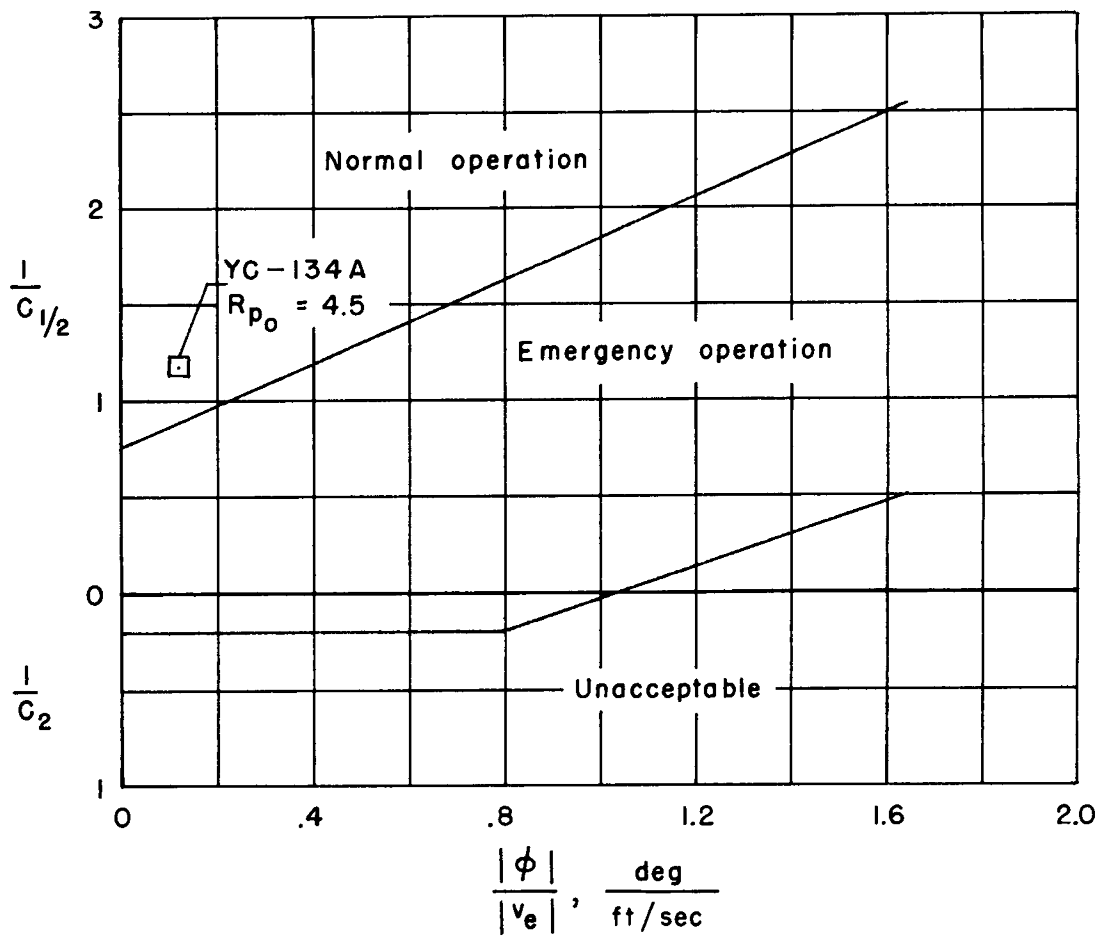
Figure 7.- Concluded.



Wings level (attempted).

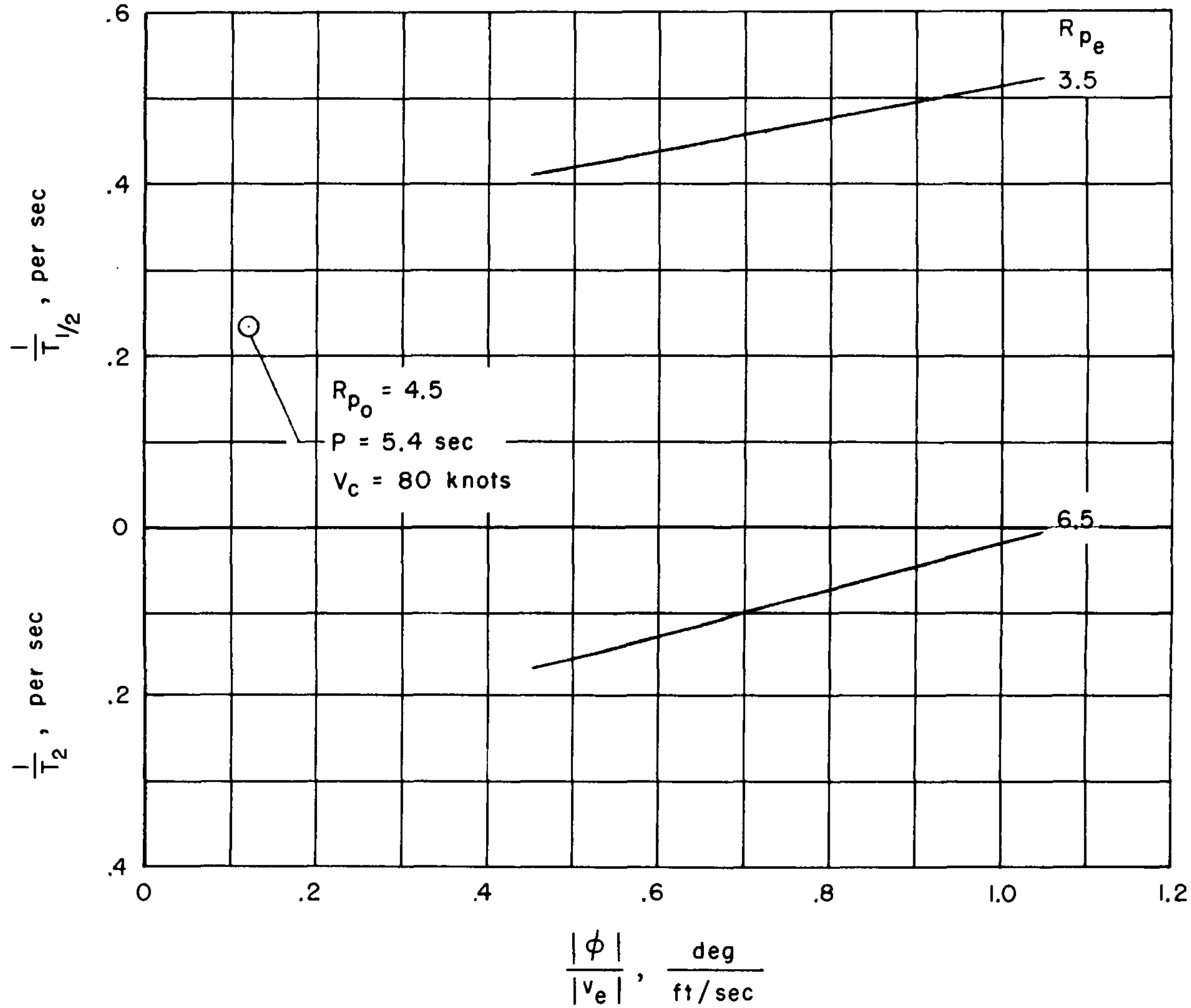
Attempt to minimize trim change by bank angle.

Figure 8.- Lateral and directional control for trim for two approaches to the stall; 0.3 maximum power.



(a) Comparison with boundaries from reference 1.

Figure 9.- Lateral oscillatory characteristics.



(b) Comparison with pilot rating boundaries from reference 9.

Figure 9.- Concluded.

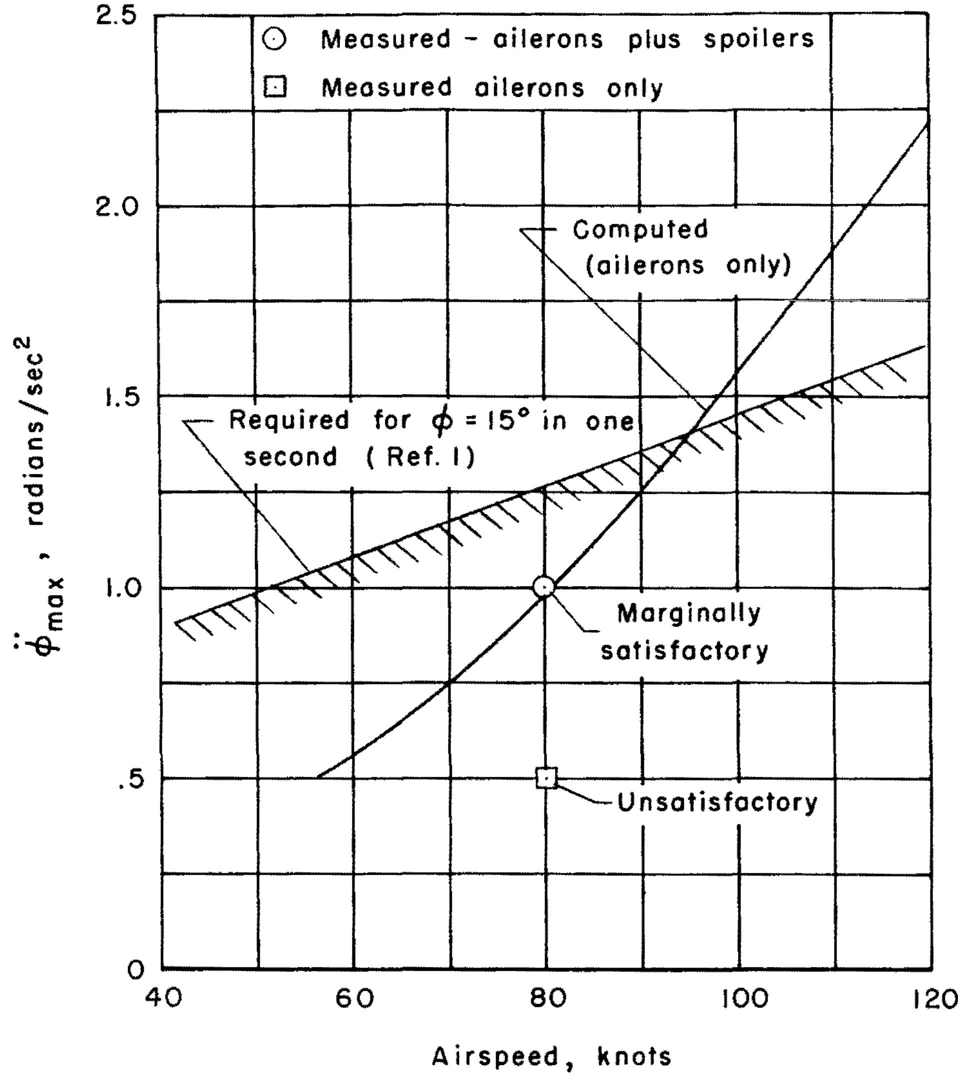
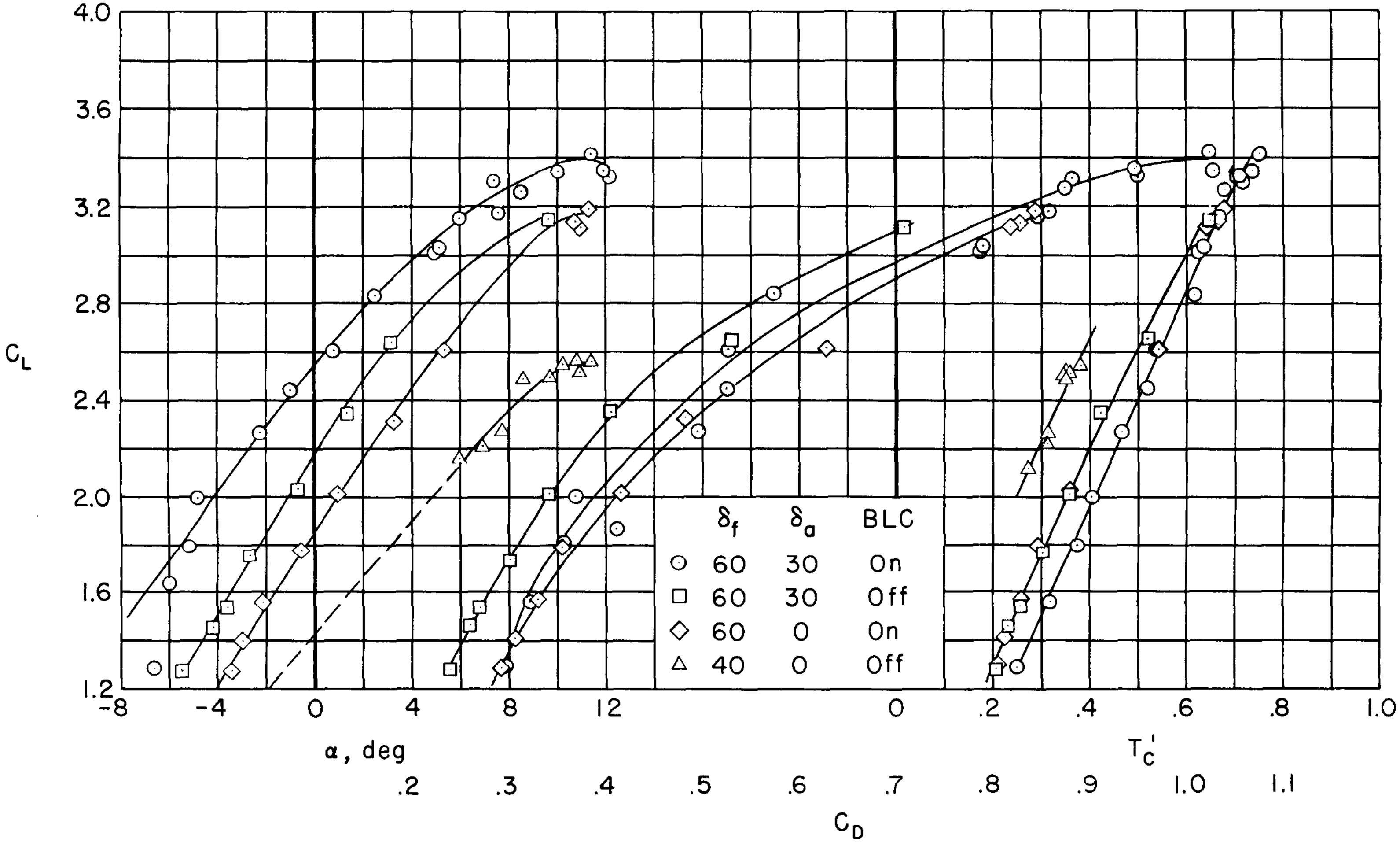
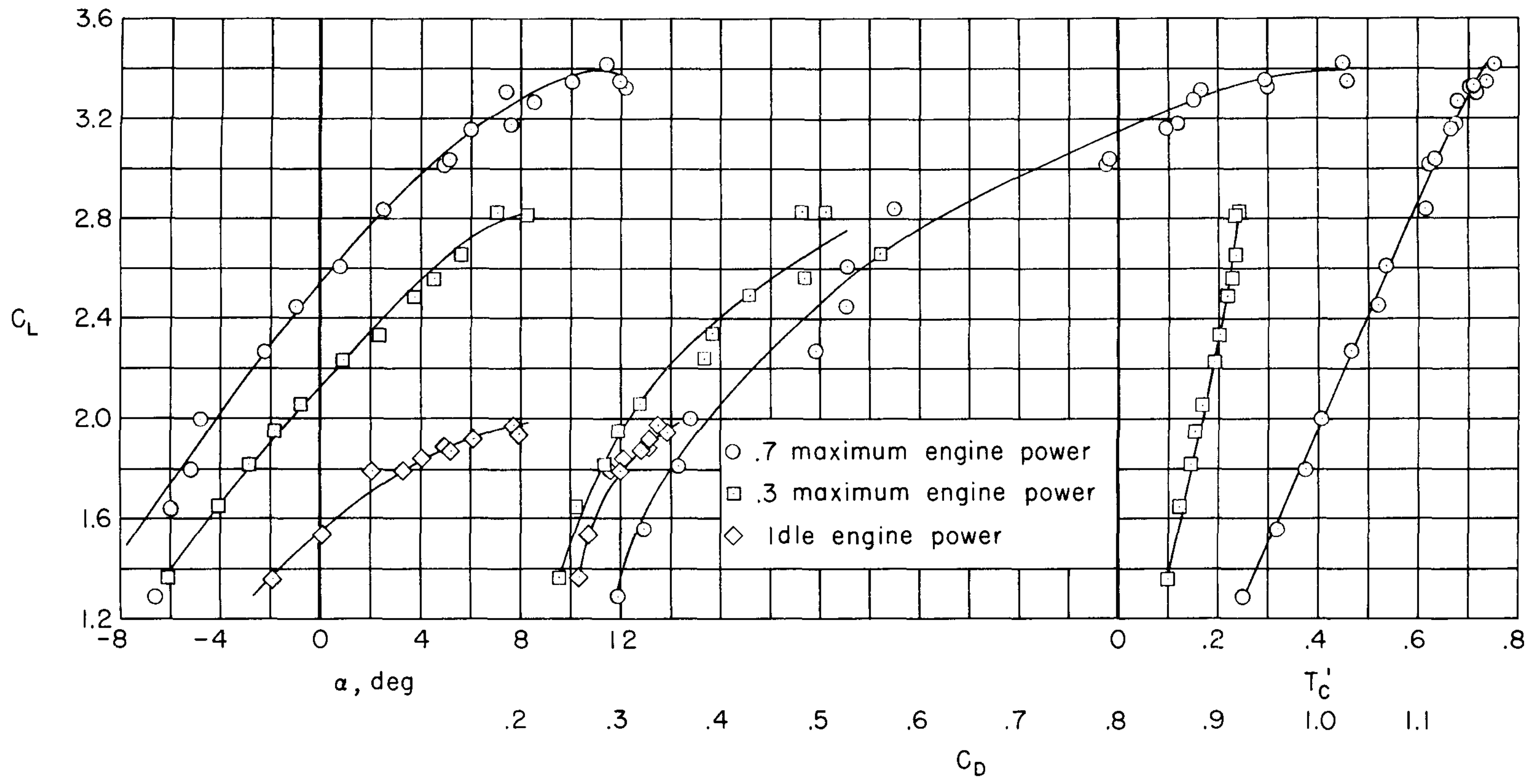


Figure 10.- Variation of maximum control power with airspeed.



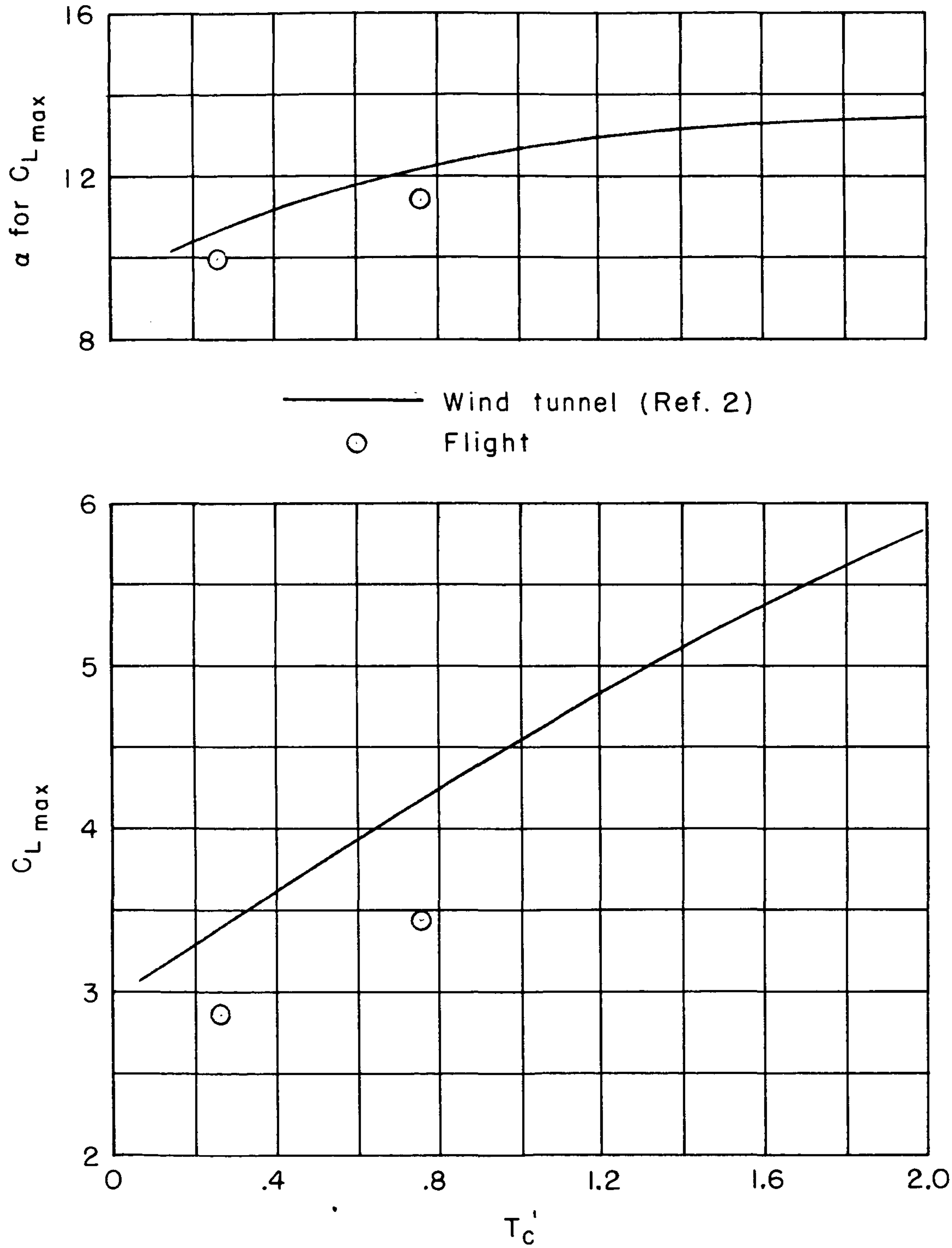
(a) Lift and drag characteristic for various flap configurations.

Figure 11.- Lift and drag characteristics.



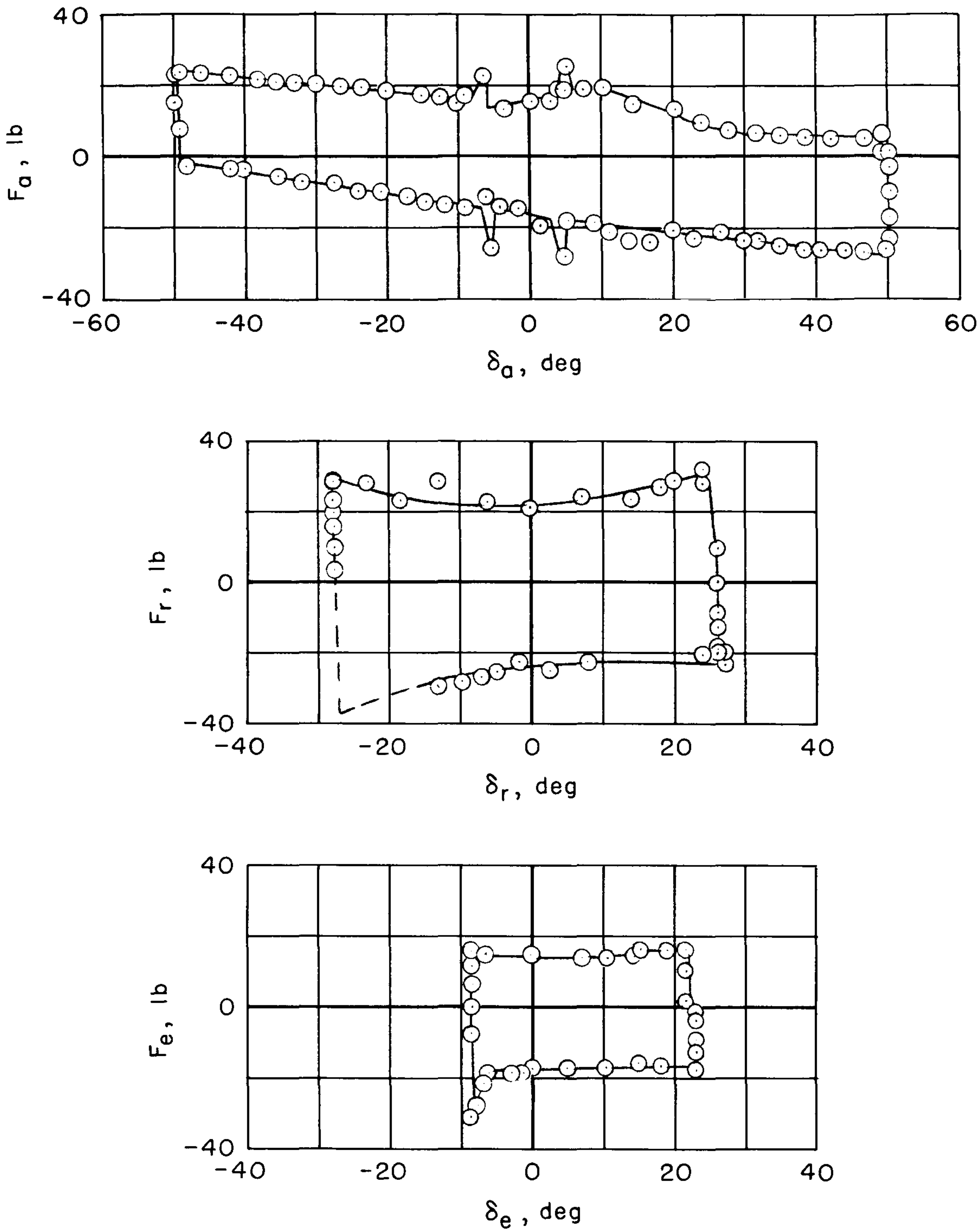
(b) Lift and drag polars for engine powers; $\delta_f = 60^\circ$, $\delta_a = 30^\circ$, BLC on.

Figure 11.- Continued.



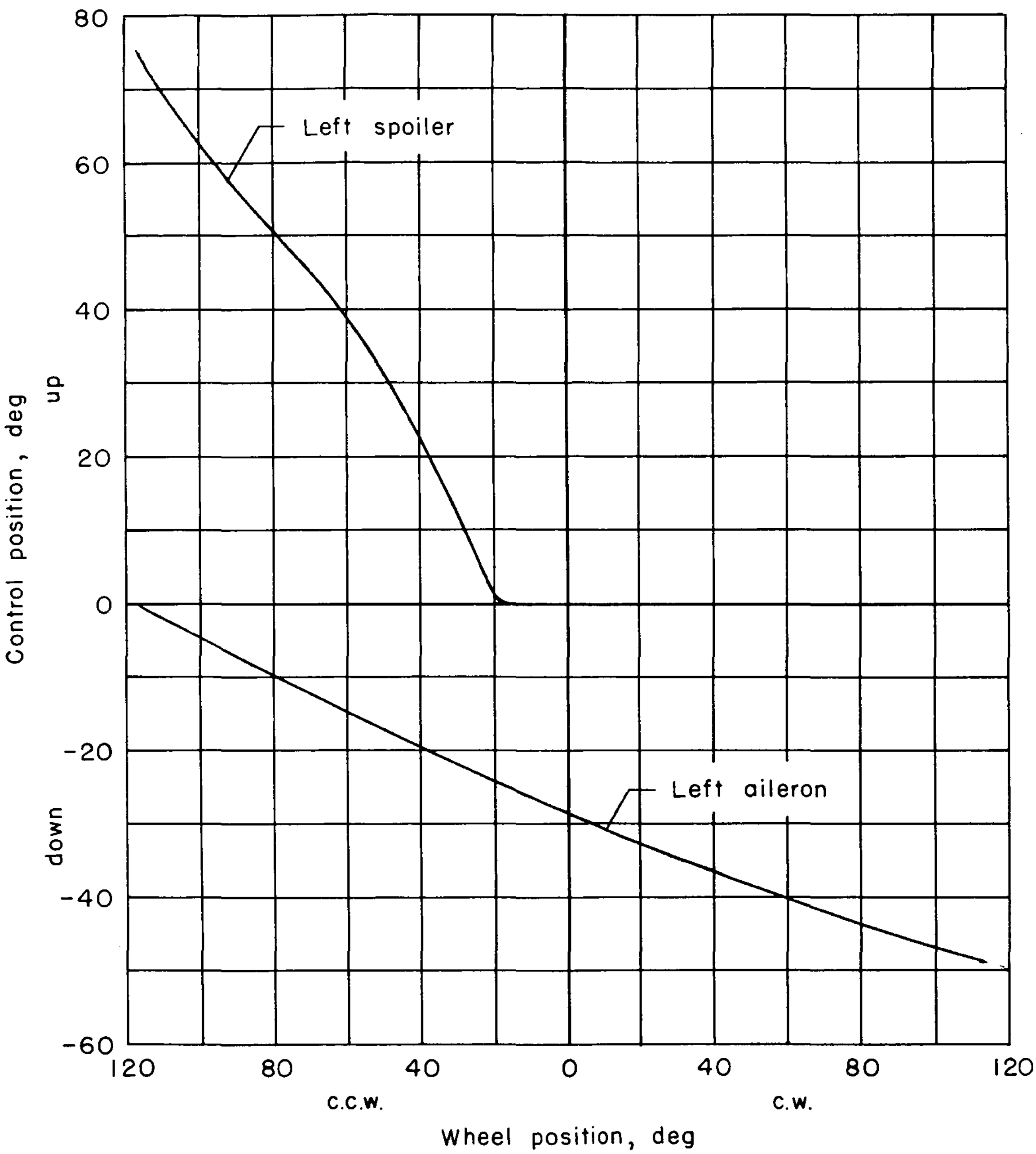
(c) Comparison with wind tunnel.

Figure 11.- Concluded.



(a) Control-system friction.

Figure 12.- Control-system characteristics.



(b) Left aileron and spoiler deflection with wheel position.

Figure 12.- Concluded.

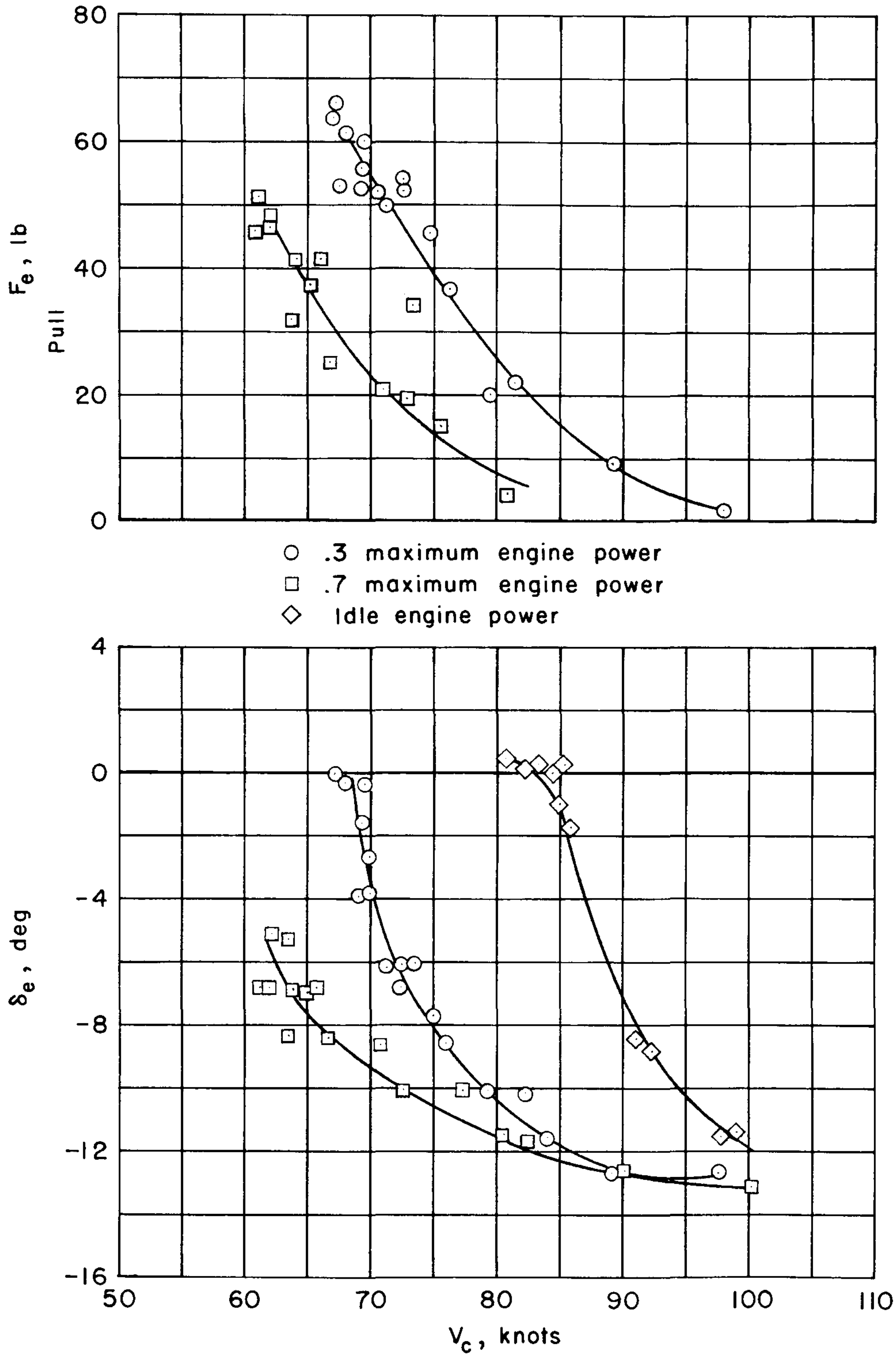


Figure 13.- Static longitudinal stability; flaps 60° - 30°, BLC on.

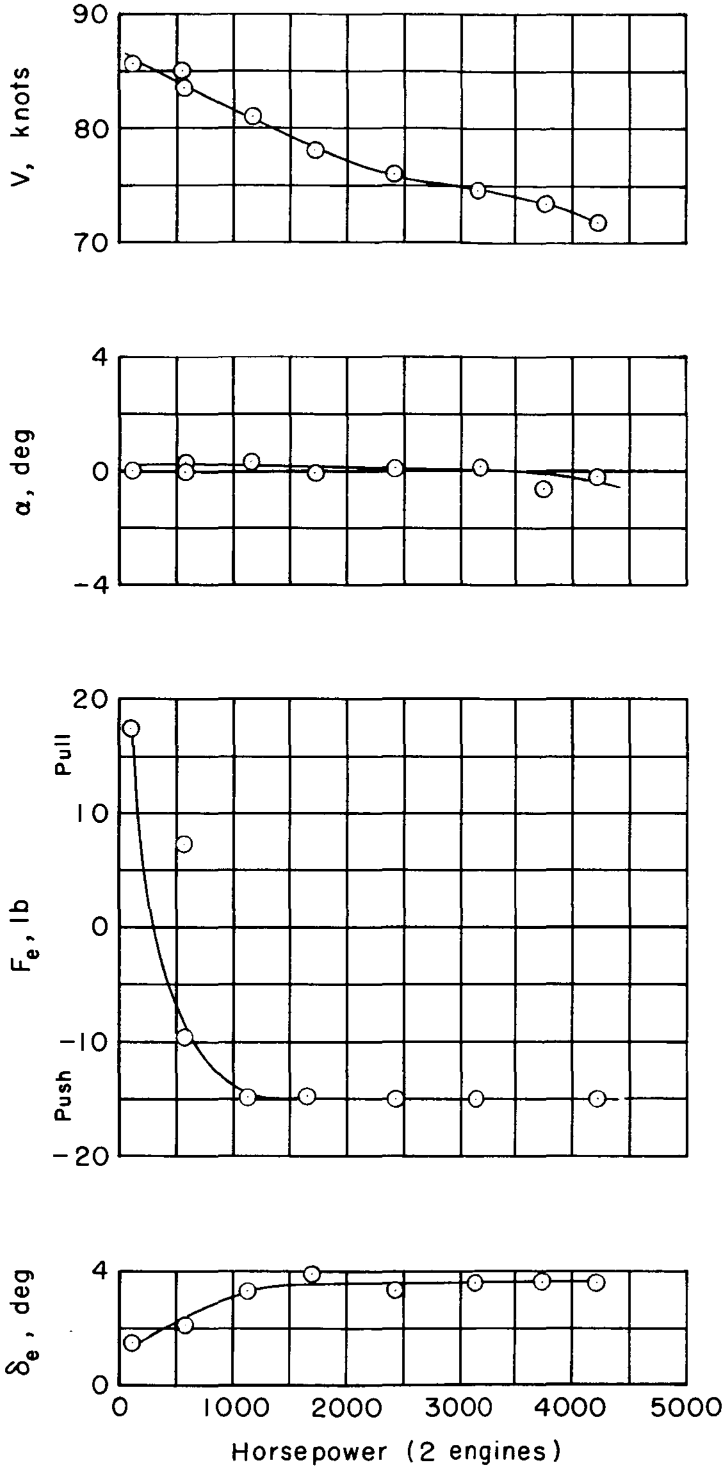


Figure 14.- Variation of elevator position and force with engine power at near constant angle of attack; flaps 60° - 30°, BLC on.

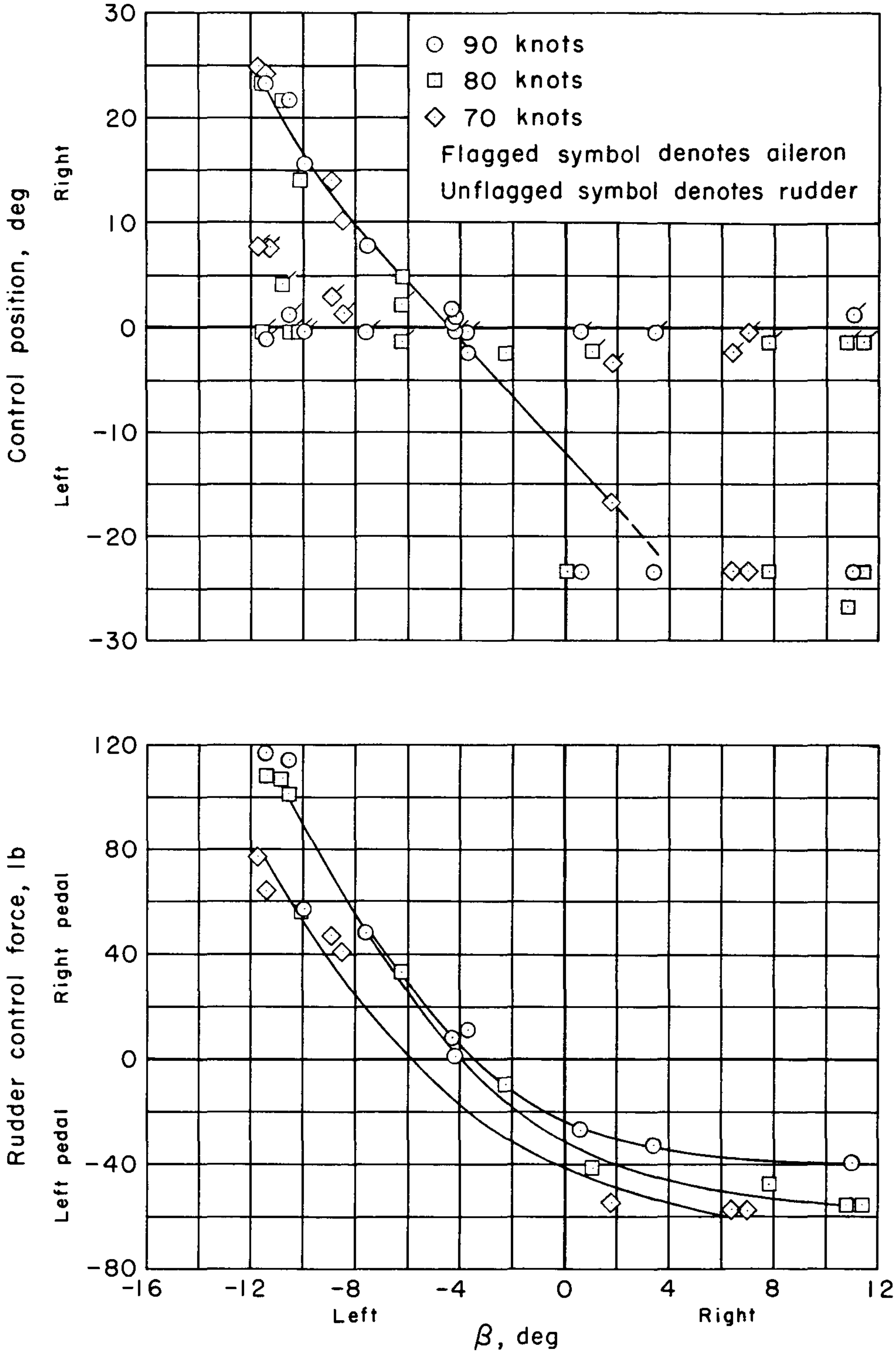


Figure 15.- Aileron and rudder position and rudder force required for steady-state sideslip; flaps 60° - 30°, BLC on.

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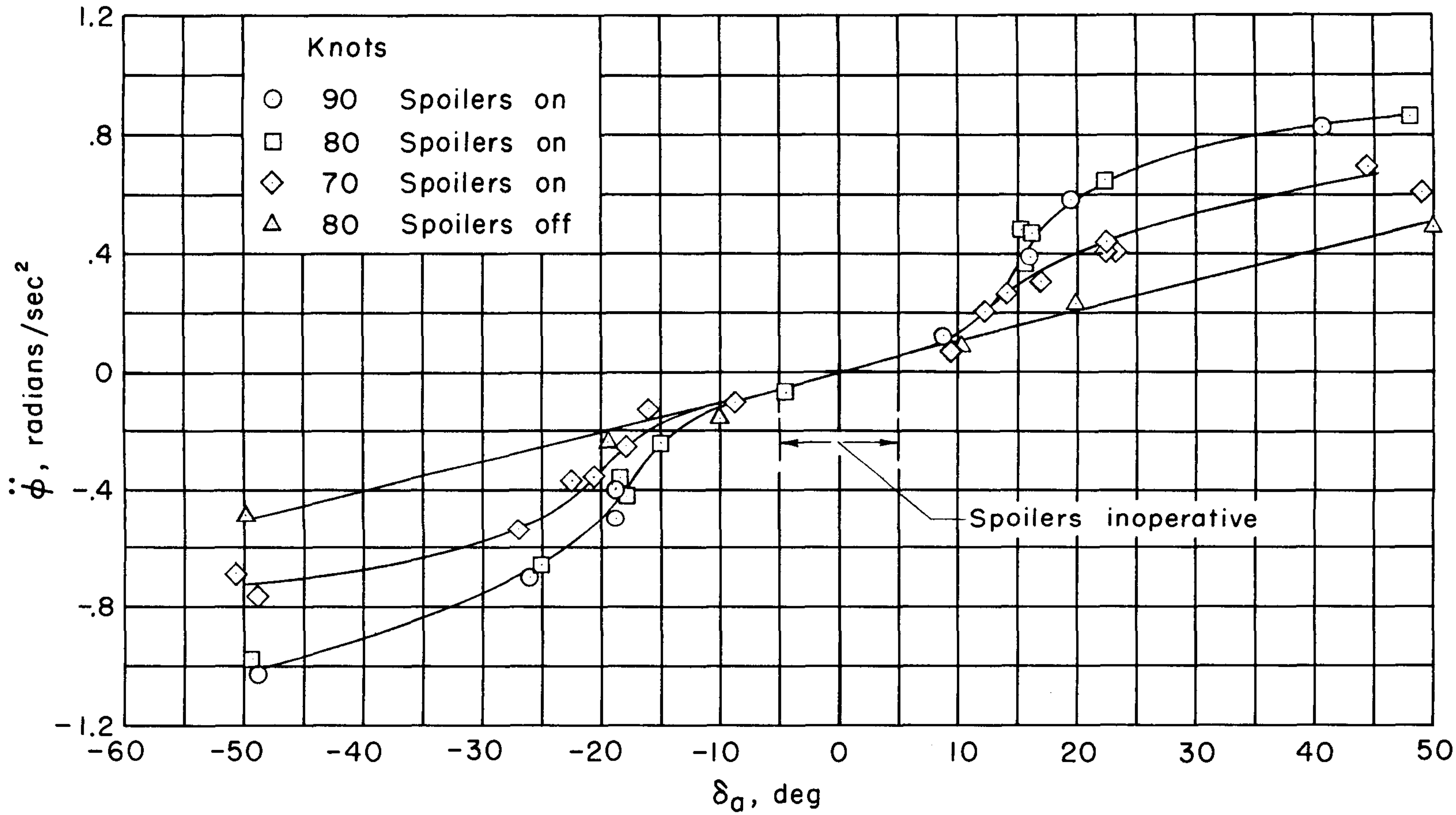

Figure 16.- Roll control power; flaps 60° - 30°, BLC on.