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

by Robert C. Innis and Curt A. Holzhauser

Ames Research Center

INTRODUCTION

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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 that is available to them during the landing approach. In fact, in order to achieve the shortest landing distance over a given obstacle with these vehicles, 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 herein 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 towards harnessing a portion of this available power to use in augmenting lift during the landing approach as well as during take-off. These are exemplified by the models and aircraft shown in figure 1. Both the two-propeller and four-propeller models shown on the left have been tested in the Ames 40- by 80-foot 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 1, 2, and 3. The airplane at the upper right, the Stroukoff YC-134A, has been flight tested at the Ames Research Center. At the lower right is the BLC version of the Lockheed C-130B which has been flight tested by Lockheed Aircraft Corporation. All of these vehicles utilize propeller slipstream effects in conjunction with BLC to develop high lift coefficients. In addition to determining the

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feasibility of STOL operation of these large airplanes having a gross weight of 50,000 to 100,000 pounds, it was desired to find out the problem areas that may result by flying at the relatively low speeds with considerable power being applied. Although the test vehicles represent conventional transport-type airplanes, the results of the tests are also felt to be applicable to the 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 paper 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.

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RESULTS AND DISCUSSION

A generalized plot of the STOL operating envelope of an aircraft which derives a portion of its lift capabilities from engine power is presented in figure 2. These characteristics are quite similar to those of the aircraft in figure 1. In figure 2, steady-state flight-path angle is plotted as a function of velocity for various values of engine power. This is represented on the figure by the series of solid lines, each of which is labeled with its corresponding amount of power in terms of the percentage of total power available. In this particular example, 100-percent power represents a thrust-to-weight ratio of about 0.4. 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 is bounded on three sides by the aerodynamic and performance capabilities of the airplane. 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.

It is important to point out the control technique that is 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 the figure 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. This is known as a "region of reversed command" or the "back side of the drag curve." Attempting to control flight-path angle by use of the elevator while in this region can lead to a rapid divergence in speed; therefore, the pilot tries to maintain a relatively constant angle of attack while he controls his approach-path angle by use of power changes. This method of control is not difficult; however, it requires that the pilot keep one hand on the throttles while controlling attitude and angle of attack with the other. Because of this, it is 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.

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 3 by the shaded region superimposed on the STOL envelope.

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The first of these limitations is represented by the vertical line in the upper left-hand portion of the figure. This is the minimum airspeed 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 has indicated that the pilots were willing to approach at speeds as low as 1.1 times the power-on stall speed; however, when the stall speed is less than 100 knots, it has been 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 are greatly affected by engine power, as is the case with these vehicles, use of airspeed during the approach becomes less useful. The pilot must turn to something more consistent to protect against inadvertent stall. Reference to the angle-of-attack indicator in the Stroukoff YC-134A proved to be most satisfactory for this purpose as 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 occurs as the approach angle becomes steeper, the pilot's ability to flare the aircraft at constant power. In executing this flare it has been found 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 practice of designing and locating the engine control system, which has rendered the addition of power during the approach 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/minute rate of descent, the ability to flare was considered marginal.

The remaining area which is indicated as being avoided by the pilot reflects his 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 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 programed in order 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.

Using the limitations indicated in figure 3 as a guide, minimum approach and touchdown speeds can be predicted for an STOL vehicle at various values of approach angle. 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. By combining the air distance required for the approach and flare with the ground roll resulting from the corresponding touchdown speed, the total distance can be calculated. Figure 4 presents the results obtained with the YC-134A for the landing distance over a 50-foot obstacle. The solid curve indicates 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 method outlined in reference 4. The circled points are values obtained from flight tests by a Fairchild Flight Analyzer from three representative approaches. It is of interest to note that the flight approach speeds corresponding to the various glide angles shown in figure 4 were 84 knots for 5.6° and 97.5 knots for 8.7° and 9.5°. To obtain the total distance, the calculated ground roll has been added assuming two different values of braking coefficient. The short-dashed curve on the right corresponds to the ground roll that might be obtained if wheel brakes only were used for deceleration. The long-dashed curve is representative of the use of reverse thrust in addition to wheel braking. 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.

Comparing the total landing distances over the range of approach angles provides a convenient method of evaluating STOL operation and the relative merits of various high-lift devices. Using the foregoing discussion as a guide, the reductions in landing distances indicated to be possible were examined. The results calculated from the wind-tunnel tests are summarized in figure 5. The curve on the right represents the total landing distance of the vehicles with two propellers assuming that the approach is conducted in a conventional manner at 1.3 times the power-off stall speed. The improvement that is made possible by adopting the STOL technique (i.e., using power to augment lift) is apparent. The effect of increasing the trailing-edge flap effectiveness to provide more lift augmentation was also examined. Increasing the trailing-edge flap effectiveness by applying BLC produces higher power-off lift coefficients. Increased lift coefficients result in larger induced-drag coefficients which necessitate more thrust for a given glide angle. This in turn provides a larger benefit from the slipstream. With BLC applied to the trailing-edge flap and aileron, the maximum lift coefficient is limited by airflow separation from the leading edge of the wing, even on the 17-percent-thick wing used in the tests. Tests in the wind tunnel have demonstrated that the leading-edge stall can be delayed by the use of a plain nose flap. The improvements that would be expected from adding a leading-edge nose flap with blowing are also shown in figure 5. The calculations presented in figure 5 were based on a conventional transport-type airplane having a wing loading of 45 pounds per square foot and a thrust-to-weight ratio of about 0.4. It was shown that by applying STOL techniques to this airplane and utilizing the lift augmentation obtained from the propeller slipstream effect on a highly effective flap, the total landing distance can be reduced by more than half. Improvements of this order can be expected for similar aircraft having wing loadings ranging from 30 to 60 pounds per square foot. The curve on the left of figure 5 (BLC on the leading edge and the trailing edge) represents what is felt to be about the minimum attainable landing distance for a vehicle of this type without resorting to much of the complexity and expense associated with the true VTOL vehicle. In order to obtain further significant gains, the installed thrust-to-weight ratio would have to be increased significantly. This in turn would lead to the requirement of interconnected propulsion systems with propellers of opposite rotation. The low approach speeds involved would rule out the use of aerodynamic control surfaces and a more sophisticated control system would have to be included.

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. For example, as the speed is reduced and the thrust coefficient is increased, the longitudinal stability in pitch of the airplane is reduced because of the change in downwash characteristics at the horizontal tail. 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.

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During the flight tests of the YC-134A, it was noted that with high power a buildup in sideslip occurred as the stall was approached and straight wing level flight was maintained. This required nearly full lateral and directional control and of course was objectionable. By banking the airplane slightly to the right these control requirements were greatly reduced. The wind-tunnel tests indicate that these side forces do not result from inplane propeller forces or from airflow 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.

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. With one engine out the area above the line is unusable to the pilot because he is unable to maintain control. The loss of control may result from a lack of lateral control power, as well as directional 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 6° 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 6°, sufficient power could be added on the good engine to reach the intended touchdown spot. If reverse thrust is not considered for deceleration, there would be little reduction in landing performance. 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.

It has been found that reducing speed by the use of high thrust coefficient will also decrease directional stability. The low directional stability in combination with the low airspeed results in a lateral directional oscillation that is easily excited and has quite a long period. Its presence in the YC-134A was quite objectionable even though the damping of the oscillation meets the current military specification in cycles to damp to half amplitude. This suggests that the parameter time to damp to half amplitude might be a better criterion when oscillations of long period are involved. It is quite possible that STOL aircraft may require the use of a yaw damper at low speed in order to obtain satisfactory lateral directional characteristics.

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 7 shows the maximum rolling acceleration obtained with the YC-134A by 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. 5.) The drooped ailerons plus spoilers were considered satisfactory by the pilots down to about 80 knots, whereas the drooped ailerons without spoilers were unsatisfactory at the same speed. Also shown in this figure is the rolling acceleration that would be expected with blowing applied to the ailerons. It is felt that the increase in effectiveness should be sufficient to provide satisfactory control for maneuvering down to a somewhat lower airspeed. However, in order 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.

CONCLUDING REMARKS

In this paper the operating envelope of an STOL aircraft has been examined, and limitations have been pointed out which the pilot must consider when choosing his minimum approach speed. Flight and wind-tunnel tests have demonstrated the ability of transport-type airplanes to utilize propeller slipstream effects in conjunction with conventional high-lift devices to obtain short landing distances. These tests indicate that the landing distance can be halved. To realize this reduction a thrust-to-weight ratio of the order of 0.4 will be required. To obtain further significant gains would require much higher thrust-to-weight ratios and would lead to the complexity and expense of the VTOL vehicles. The problems reviewed in the paper would be, in the main, also representative of those of a large overloaded VTOL aircraft operating in an STOL manner with comparable thrust-to-weight ratios.

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REPRESENTATIVE STOL VEHICLES

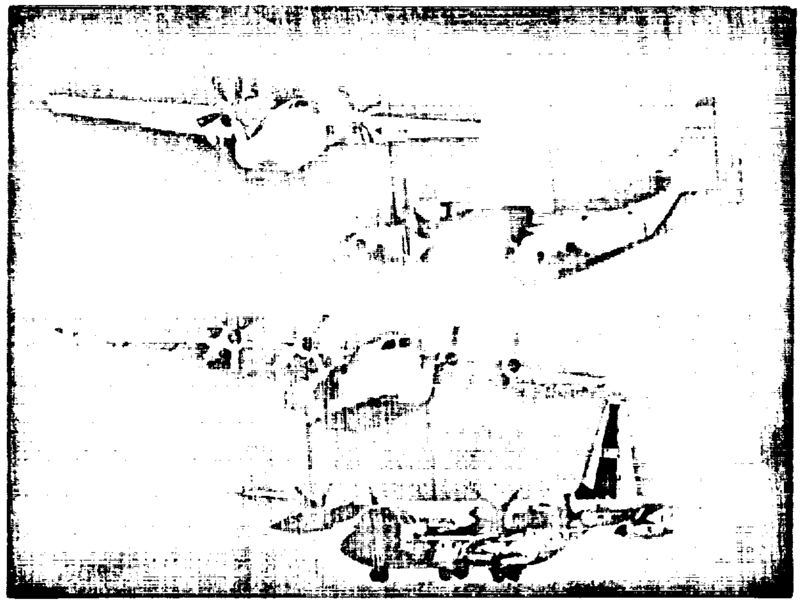

Figure 1

STOL FLIGHT ENVELOPE

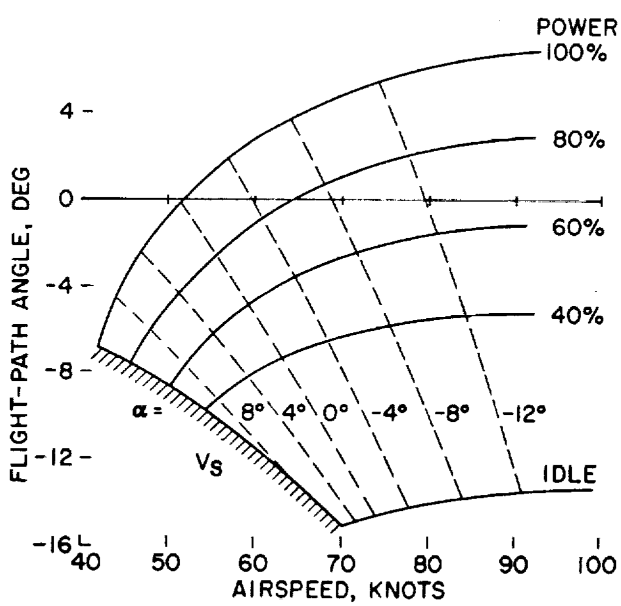

Figure 2

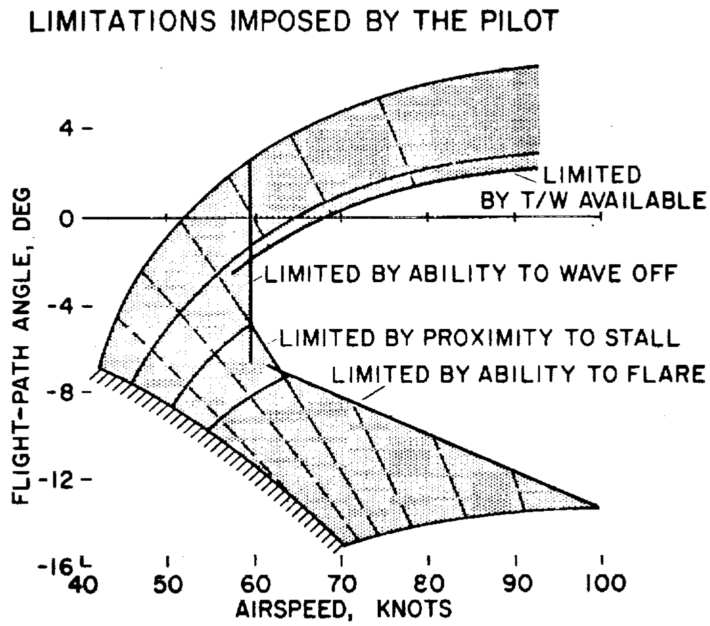

Figure 3

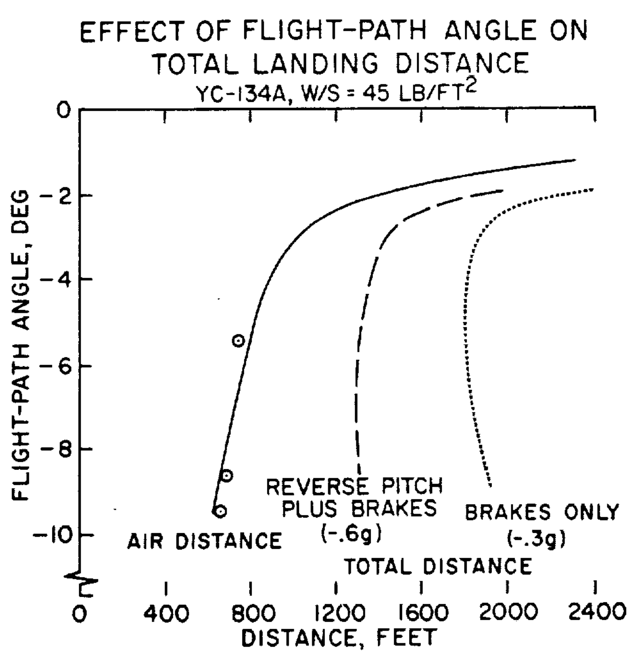

Figure 4

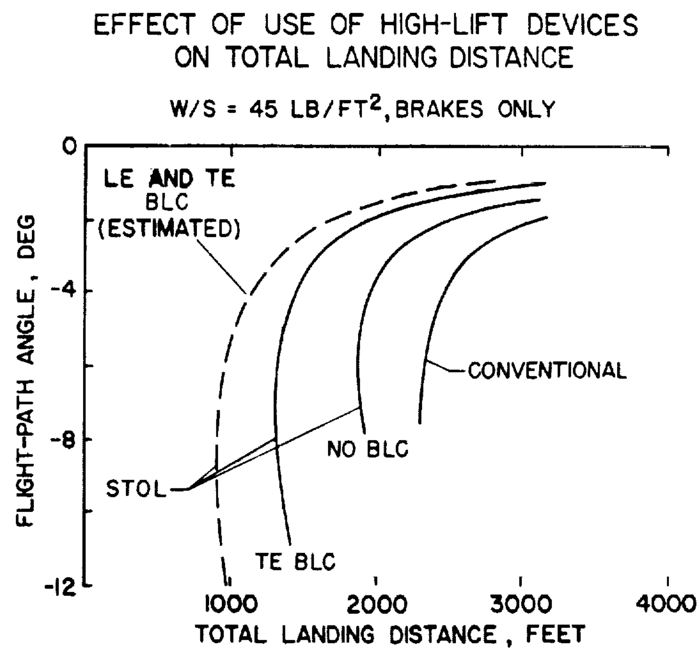

Figure 5

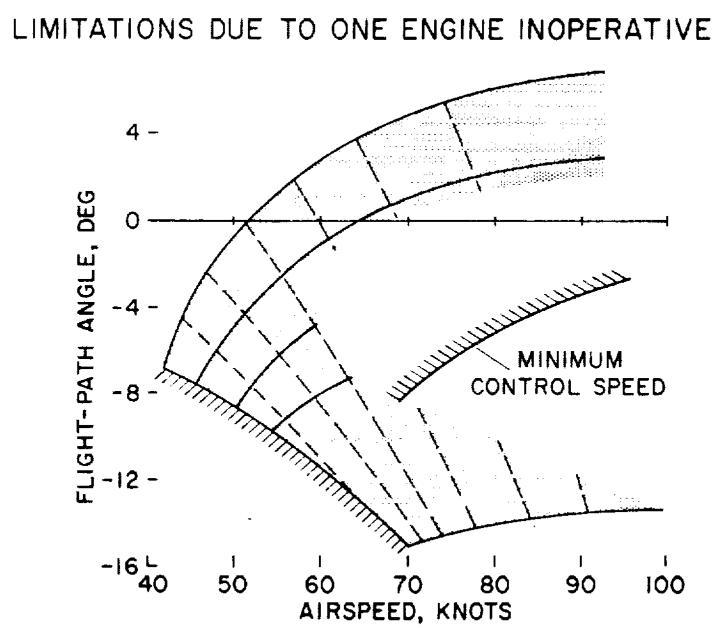

Figure 6

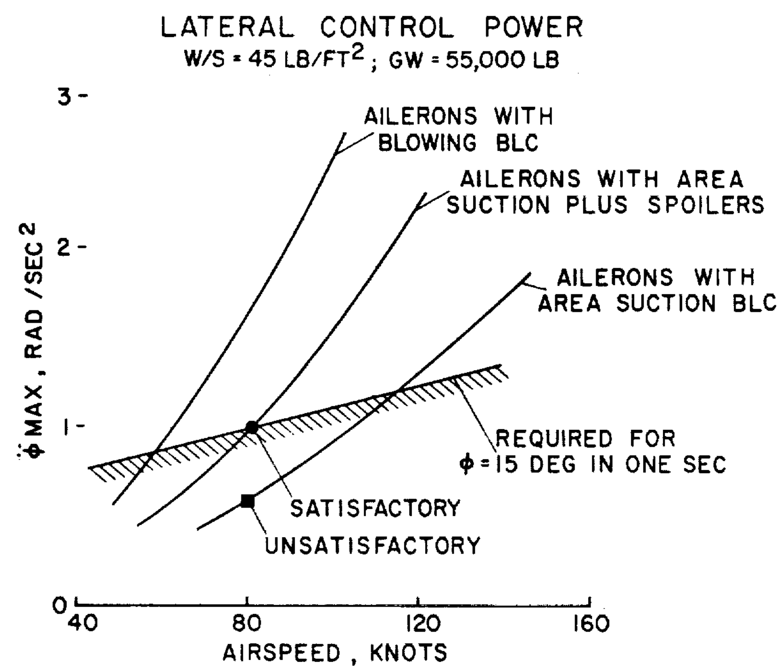
LATERAL CONTROL POWER
W/S = 45 LB/FT^2; GW = 55,000 LB
AILERONS WITH BLOWING BLC
AILERONS WITH AREA SUCTION PLUS SPOILERS
AILERONS WITH AREA SUCTION BLC
REQUIRED FOR ϕ = 15 DEG IN ONE SEC
SATISFACTORY
UNSATISFACTORY
$\ddot{\phi}$ MAX, RAD/SEC^2
0
1
2
3
40
80
120
160
AIRSPEED, KNOTS

Figure 7