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AERODYNAMICS OF TILTING DUCTED-FAN CONFIGURATIONS

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SUMMARY

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Tests of a full-scale ducted fan have been made at the Ames Research Center. The results of these studies have indicated that the concept of wing-tip-mounted ducted fans has longitudinal problems similar to other V/STOL concepts; however, solution of these problems appears to be possible. An advantage of this concept is the ability to vary the thrust vector independent of the wing angle of attack. Thus, it is possible to keep the wing unstalled, even in descending flight.

INTRODUCTION

The concept of wing-tip-mounted ducted fans for V/STOL aircraft is one which has received less consideration in research programs than other types. As a consequence, only limited information concerning the aerodynamics of such units is available and most of this information was obtained with small-scale models. In order to provide additional information, tests of a full-scale ducted fan have been made at the Ames Research Center.

SYMBOLS

i_t	angle of incidence of horizontal tail, deg
l	moment arm, measured from airplane center of gravity, ft
M	pitching moment, ft-lb
M/I_Y	control power, ft-lb/slug-ft^2
N	normal force, lb
α_w	angle of attack of wing, deg
δ_v	angle of deflection of inlet guide vane, deg

DESCRIPTION OF MODEL

The ducted fan used for these tests was one constructed for use on the Doak VZ-4DA airplane. The fan diameter was 48 inches and the shroud was 33 inches long with a thickness ratio of about 16 percent. Figure 1 is a photograph of the model in the wind tunnel ready for testing. It may be seen that the duct was mounted on a semispan wing. This wing approximated the Doak wing in span and section characteristics.

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TESTS

Primarily, the tests were directed toward determining the variations of the duct angle, the power required, and the pitching moment that would be encountered in steady level flight over a range of airspeeds from hovering to airplane flight. Since the ducted fan and wing used in this investigation were designed for the Doak VZ-4DA airplane, the gross weight of 3,100 pounds and the drag characteristics of that airplane were assumed to apply to the model. Unless otherwise stated, all of the data presented in this paper are for the steady level flight condition.

A brief study of lateral control in hovering and low-speed flight was included in the investigation. These tests included a comparison of two methods of obtaining lateral control; namely, by deflecting radial guide vanes in the duct inlet to control the effective pitch angle of the fan blade and by varying the geometric fan-blade angle.

RESULTS AND DISCUSSION

The variation of duct angle relative to the wing and the variation of shaft horsepower for a transition from hovering to airplane flight are shown in figure 2. The wing angle was held constant at a value of 2°. Also shown on these graphs are points representing the results from flight tests of the Doak airplane during transition at the same wing angle of attack. The agreement indicates that the data obtained by the test procedure were representative of the flight case.

The variation of the distribution of lift between the duct and the wing for this transition is shown in figure 3. The contribution to the lift of each component was determined from tests of each component independent of the other. Of interest is the interaction between the wing and duct; that is, the wing and duct operating together produce a lift larger than the sum of the lifts of each component operating independently and this effect increases in magnitude with airspeed.

Longitudinal Characteristics

The variation of the pitching moment during the transition described
previously is also shown in figure 3. It is seen that the primary source
of the pitching moment is the ducted fan operating at angle of attack to
the airstream when the ducted fan is changing the direction of a large
L mass flow of air. It will be noted that the moment is zero at zero air-
1 speed. The reason for this is that the thrust axis was assumed to be in
4 the plane of the airplane center of gravity at the hovering condition as
1 was the case on the Doak airplane. For this condition, it will be noted
3 that the maximum pitching moment occurs at an airspeed of about 50 knots.
At this speed, the horizontal tail is yet relatively ineffective because
of the low dynamic pressure of the airstream; hence the moment available
for trim is small. However, the problem is further complicated by the
effect of the duct on the downwash at the horizontal tail plane.

The variations of downwash angle with airspeed for several values of wing angle of attack are shown in figure 4. These angles were measured at a location corresponding to the horizontal-tail location on the Doak airplane for steady level flight conditions at the values of constant wing angle of attack which are shown. At each wing angle of attack the variation in downwash is due entirely to the change in duct angle; hence, shifting weight to the wing by increasing wing angle of attack and reducing duct angle results in a lower value of downwash angle at a given airspeed. Figure 4 shows that a fixed tail incidence will produce increasing nose-up moments as speed is reduced, adding to those from the duct shown previously. Any attempt to eliminate the nose-up moments in the critical 50-knot speed range by fixed stabilizer setting will produce large nose-down moments in cruise flight. The desirability of a variable-incidence stabilizer with a large incidence range is evident; in the case of the Doak airplane the variable incidence was required to complete transition.

Although variable incidence reduced the trim problem during transition with the Doak airplane, longitudinal control remained weak, in part because a portion of the reaction control was being used for trim. Rather than add more control, means were sought for a reduction of the pitching moment generated by the ducted fan.

The flow from the duct exit was a continual source of high-energy air regardless of the airspeed and was located behind the duct axis of rotation. Therefore, a deflected vane in this flow would produce a moment counteracting the moment of the duct alone. The vane configuration installed for a study of this effect is shown in figure 5. The vane was two-piece and had a 25-percent-chord flap. A representative setting of the vane and flap is shown in the sketch. As may be seen in figure 6, the exit vane was effective in reducing the maximum duct pitching moment in steady level flight, and thereby the required trimming moment. No attempt was made to determine the optimum setting from this study but simply to demonstrate the effectiveness of this modification; the most effective setting tested was with the vane at 10° and the flap at 20°. At this setting, the maximum pitching moment was reduced by nearly one-half. The effect of the vane on the power required was to increase the power by less than 3 percent.

Figure 6 shows that a fixed vane angle would produce nose-down moments at hover and high speed; programing the vane angle to vary with duct angle would eliminate this problem. The moment variation resulting from a programing based on the data obtained with the vane is compared with that for the duct with no vane in figure 7. It will be noted that with this particular programing, a speed range in which there is no change in trim requirement is realized. Further, since the vane would be undeflected at hover, there would be no increase in the hovering power requirement. The program of vane angle used here is not considered to be optimum because of the limited extent of the vane study. The results of a more optimum study of the exit vanes could show a larger reduction in the moment.

It is of interest to examine these balance-moment requirements of the wing-duct combination in terms of the handling-qualities requirements. For this purpose a hypothetical airplane which possesses only the balance-moment requirements and the tail length of the Doak airplane will be considered. The balance-moment-required curves from figure 7 are repeated in figure 8, but are plotted in terms of control power. Unlike the Doak airplane, it is assumed that the hypothetical airplane has a reaction control power equal to that specified for control in hover in the VTOL handling-qualities criteria (ref. 1). This power is less than one-half of that which was available in the Doak airplane. It is also assumed that this reaction control has constant power, as represented by the dashed line in figure 8. The net moment available to balance the airplane at any given airspeed will be that available from the reaction control plus that available from the variable-incidence tail. (The elevator is considered to be reserved for maneuvering as specified in ref. 1.) For example, the net moments available for tail incidences of 0° and 12° are shown in figure 8. (The tail volume was assumed to be 0.7.) It is seen that the tail at 0° incidence not only does not contribute to the moment available but requires first a portion, and eventually all, of the reaction control to neutralize its adverse effect. This situation does not exist with a tail incidence of 12°. At this setting, there is no adverse effect of the tail, but it does not supply the full trim requirement until speeds of 35 knots with exit vanes and 50 knots without exit vanes have been reached (points 1 and 2 on fig. 8). Computations have shown that the elevator cannot supply the hover control requirement until a speed of 35 knots is reached. Therefore, a control deficiency exists up to this speed which is equal to that portion of the reaction control power absorbed in trimming the airplane less the power available from the elevator.

These deficiencies are illustrated in figure 9. It is seen that the trim deficiency at 0° tail incidence and without duct exit vanes is over three times the hover control requirement. The advantages of exit vanes and variable tail incidence are immediately apparent. The trim deficiency is reduced by nearly one-third in magnitude at 0° tail incidence when the exit vanes are added. However, a greater gain is made by increasing the tail incidence to 12°. Without the exit vanes, the trim deficiency is reduced to less than 25 percent of the initial value. By the addition of the exit vanes, the deficiency is reduced to less than 10 percent of the initial value.

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A control deficiency is seen to exist at very low speeds. This does not mean that it could not be alleviated. As mentioned previously, the study of the vanes was limited in scope. Proper programing of the vanes in this region could do much to relieve this deficiency and a more optimum tail incidence might well relieve the remaining trim deficiency shown on the lower right-hand graph of figure 9.

In the absence of such optimum programing, a considerable increase in reaction control would be required to meet these deficiencies. For example, to obtain adequate control power for the Doak airplane in transition the reaction control was more than twice the value prescribed by the specifications for control in hover given in reference 1.

Although requirements for variable trimming devices are apparent from these observations, they are not peculiar to this concept but are more or less characteristic of V/STOL machines. From the pilot's viewpoint, it would be a distinct advantage to have the stabilizer and exit-vane angles programed to the duct angle since the trimming of the aircraft would then require the pilot's attention to only one control. The shape of the curve for the programed moment (fig. 7) indicates that, over a sizable range of airspeeds, there could be little or no change in the longitudinal trim requirement of the airplane.

This study of the longitudinal handling-qualities characteristics has been made for a single location of airplane center of gravity corresponding to that of the Doak airplane. The range of movement of airplane center of gravity for an operational airplane would alter the shape and position of the moment-required curves and, hence, the deficient regions. A compromise of center-of-gravity location might be attempted to lower the peak value of the moment-required curve. This compromise would ultimately result in increasing the reaction control required at hover. While some benefit can be realized by adjustment of the duct position relative to the airplane center of gravity, it would appear that a means of reducing the duct pitching moment about its own axis is desirable.

A further consideration of the duct moment is its increase with gross weight as shown in figure 10. It is seen that, when the disk loading is held constant, the pitching moment does not vary linearly with weight but rather as the 3/2 power. These results assume that the chord-to-diameter ratio of the duct is maintained constant, which is a likely requirement. Since the remainder of the airplane probably would increase in size by the square-cube law, with the wing loading increasing as the cube root of the weight, problems could arise in designing and housing the duct turning mechanism in the adjacent wing structure. The space available would be less in proportion, the force required to turn the duct would increase, and the wing stresses, already increased by the higher wing loading, would be further increased by the higher duct moment, the stresses rising as the 3/2 power of the scaling factor. The moment can, of course, be reduced by increasing the disk loading as shown in figure 10. However, this would be at a cost in thrust-to-horsepower ratio. From these considerations, as well, it is desirable to reduce the duct moment about its own axis.

Since the reduction of the pitching moment is of such consequence to satisfactory operation of this type of machine, it would be desirable to know more of its origin. A limited approach to this subject may be had by examining the breakdown of the duct and fan moments as shown in figure 11. These results were obtained from tests of a 5/16-scale model in the Langley 7- by 10-foot tunnel. It may be seen that the moment is caused primarily by the duct; the contribution from the fan being primarily that due to the fan normal force times its moment arm from the duct rotation axis, assumed to be the location of the airplane center of gravity. The duct moment arises from the duct normal force times its arm from this same axis and from the differential thrust on the duct lips. The location of the duct normal-force vector relative to the airplane center of gravity thus is seen to be an important factor in limiting the magnitude of these moments. Thus far, little has been known of the location of the center of pressure on the duct. It is hoped that recent measurements of pressure distributions on the duct will provide information concerning this problem.

A concern for the ducted-fan concept has been that, at high rates of descent and low power conditions, the duct inlet lip may stall, thus creating a large, and perhaps uncontrollable, change in trim. Even at powers corresponding to one-half those required and for duct angles somewhat larger than those indicated for steady level flight, no lip stall was encountered on the full-scale test model. In subsequent tests, the duct has been forced to stall under extreme operating conditions and stall is not beyond the realm of reasonable expectancy on other configurations with sharper inlets. However, for this duct configuration at normal operating conditions, the problem would not appear to be as great as was expected.

The effects of lip stall can be graphically illustrated by results of tests of the 5/16-scale model which are shown in figure 12. In these tests, because of the lower Reynolds number, stall occurred even at the steady level flight condition and it was necessary to double the upstream inlet-lip radius to prevent its occurrence. The large reduction in pitching moment verifies the expected change in trim. However, perhaps of even greater significance is the large increase in power required to a value which exceeded the value at hover by about 30 percent for the small-scale tests. From these results, it is apparent that operation in the region of lip stall should be avoided.

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An additional stalling phenomenon encountered during the full-scale tests, which was attributed to an interference between the wing and the duct at conditions of high power and high wing lift, caused a fan blade stalling to occur. This interference also caused some separation to occur on the wing near the wing-duct juncture. The onset of this phenomenon was delayed by several degrees of wing angle of attack in the full-scale tests as a result of the addition of a leading-edge droop to the outboard third of the wing.

Lateral Characteristics

A comparison of the results of tests of two methods for obtaining lateral control by differentially varying duct thrust is shown in figure 13. It will be noted that the inlet vanes were effective only to a deflection of 16° after which they stalled. This value of incremental thrust corresponds to a fan-blade-angle change of 2°.

The significance of these results in terms of roll-control handling qualities will be examined in the next paragraph. However, first a comment about inlet guide vanes for thrust control at higher forward speeds is in order. As was noted, the largest effective-blade-angle change which could be obtained with inlet vanes was about 2°. While the increase in forward speed would change these relations slightly, it would not alter the vane effectiveness significantly and the large blade-angle changes which are required to maintain efficient fan operation at higher forward speeds could not be obtained. Thus, it would appear that, in the absence of variable duct geometry, a variable-pitch fan would be preferable to a configuration using inlet vanes for an operational airplane.

The ability of the inlet-guide-vane configuration to meet the roll-control handling-qualities requirements as set forth in reference 2 is shown in figure 14. These results are based on a moment of inertia representative of aircraft more sophisticated in design than the test-bed aircraft. It is apparent that, although the inlet vanes have limited capabilities for thrust control in forward flight, they would be sufficient to provide acceptable lateral control power at hover and low-speed forward flight. There is a loss in control power shown with increasing forward speed because of the reduction in thrust required. However, no account of the aileron contribution has been taken in this study. The value of control power would be nearly constant when the aileron is considered. For the larger moment of inertia of the Doak airplane, the control power and damping would be about one-half the values shown in figure 14.

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CONCLUDING REMARKS

The ducted-fan concept of V/STOL aircraft has longitudinal-control problems similar to those of some other concepts; however, it appears that solution of these problems is possible. One distinct advantage of this concept is the ability to avoid operation at high wing lift conditions, especially in descent, where stalling of primary lifting surfaces may occur. This flexibility results from the ability to vary the thrust vector independent of the wing angle of attack and is characteristic of any concept which has this feature.

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2. Tapscott, Robert J.: Criteria for Control and Response Characteristics of Helicopters and VTOL Aircraft in Hovering and Low-Speed Flight. Paper No. 60-51, Inst. Aero. Sci., Jan. 1960.

DOAK DUCTED FAN AND SEMISPAN WING
IN AMES 40'× 80' WIND TUNNEL

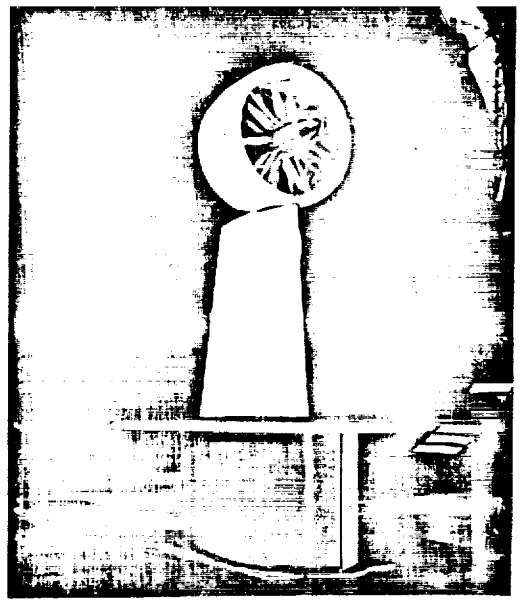

Figure 1

DUCT ANGLE AND SHAFT HORSEPOWER FOR
STEADY LEVEL FLIGHT

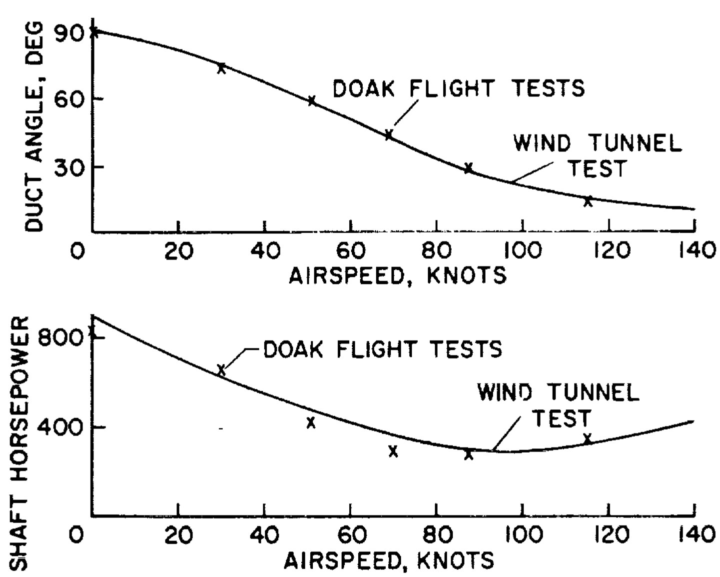

Figure 2

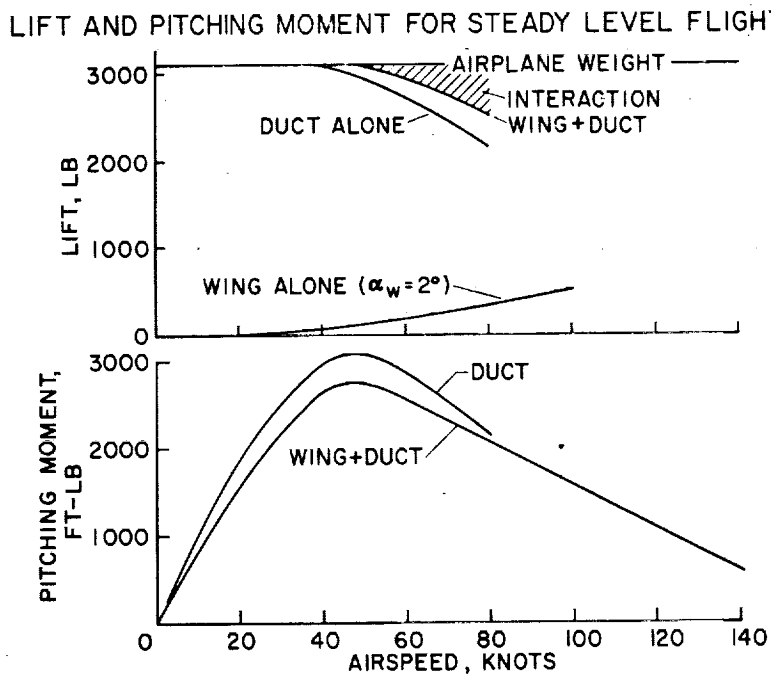

Figure 3

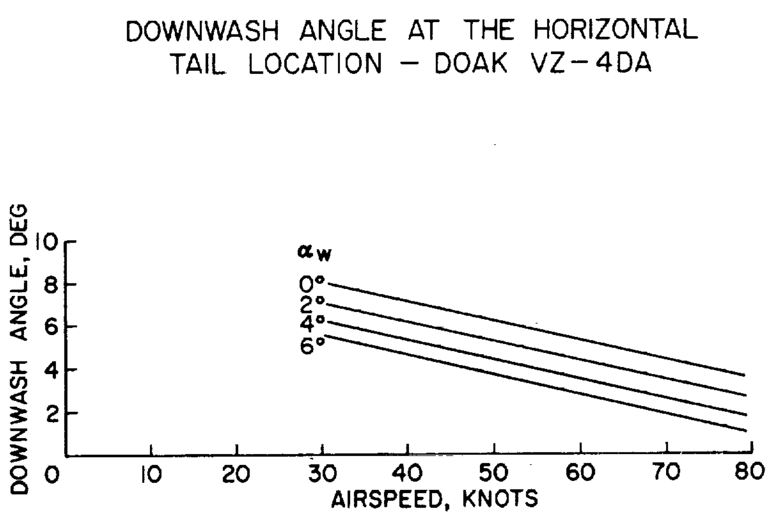

Figure 4

MODEL WITH DUCT EXIT VANE

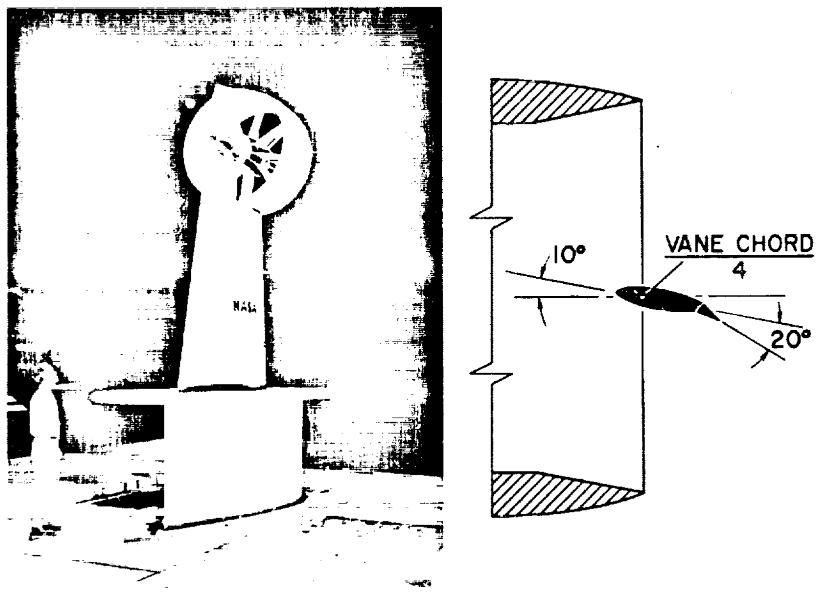

Figure 5

REDUCTION IN PITCHING MOMENT DUE TO DUCT EXIT VANE DEFLECTION

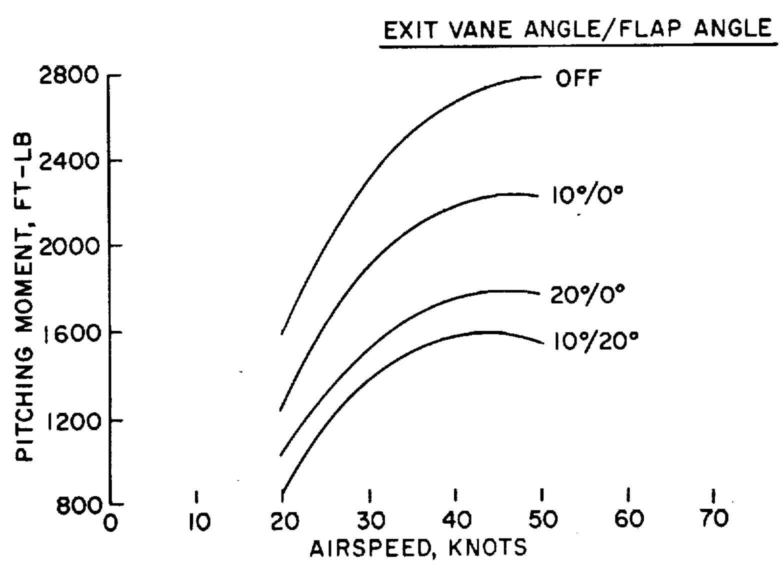

Figure 6

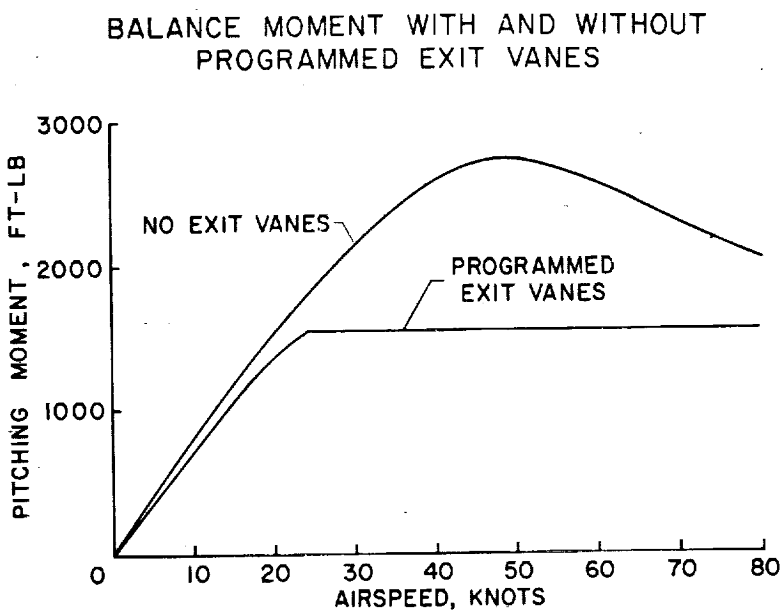

Figure 7

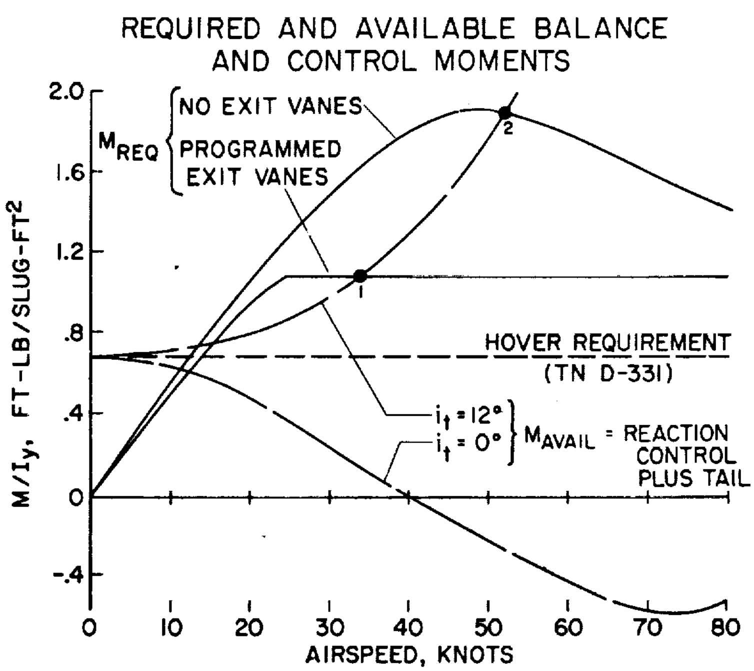

Figure 8

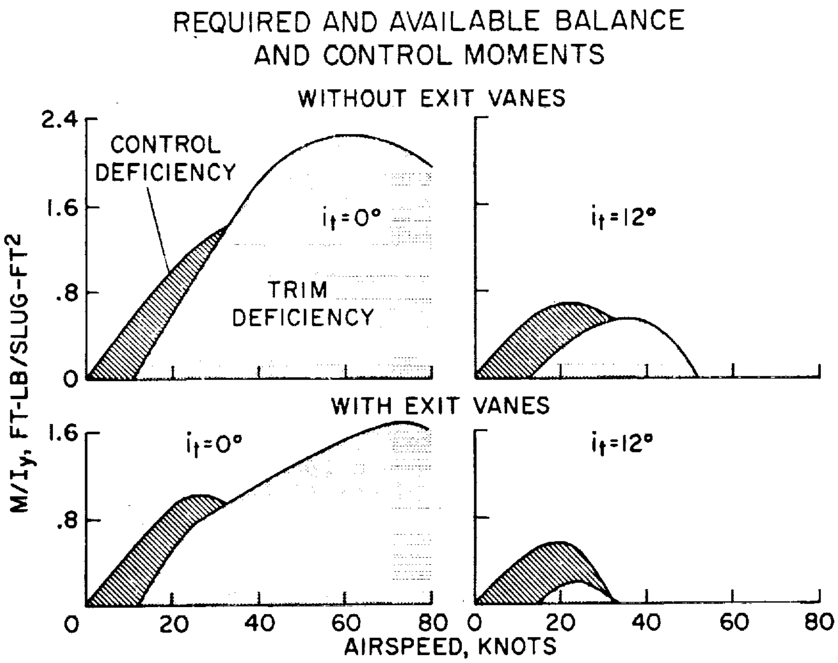

Figure 9

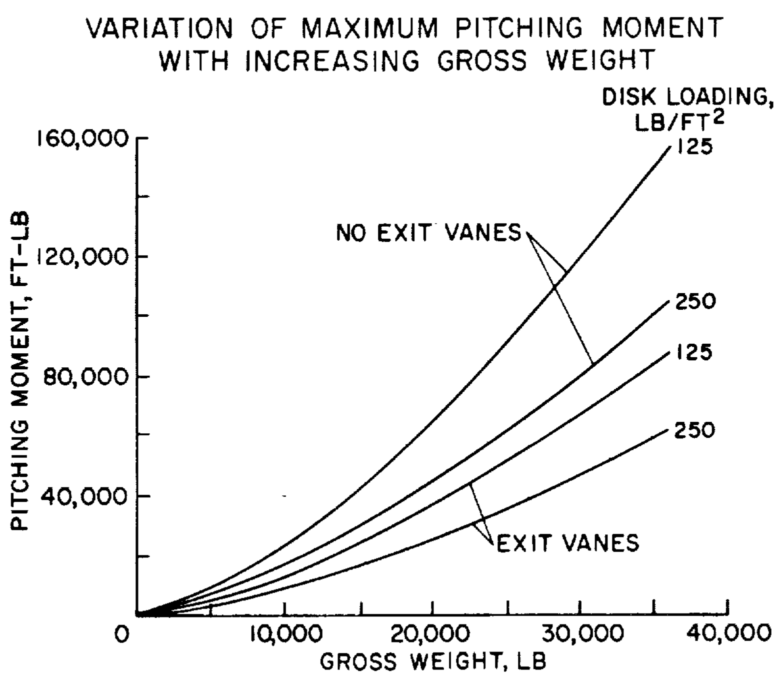

Figure 10

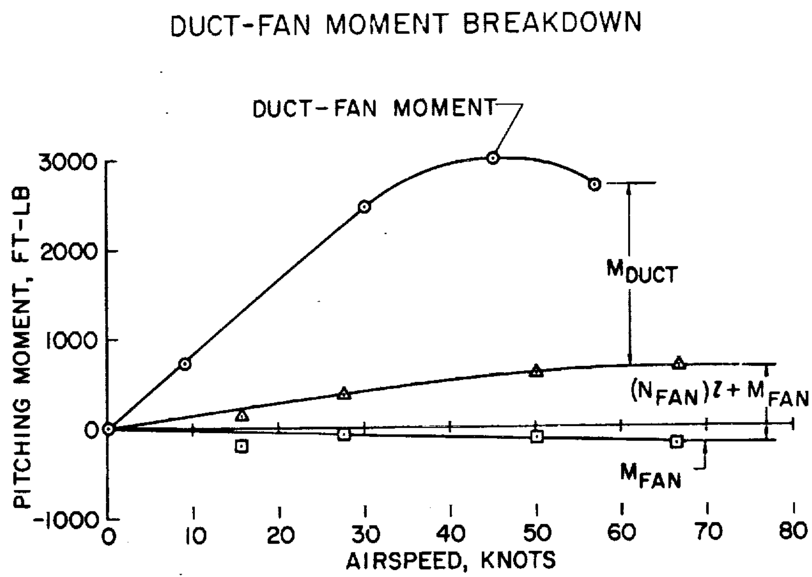

Figure 11

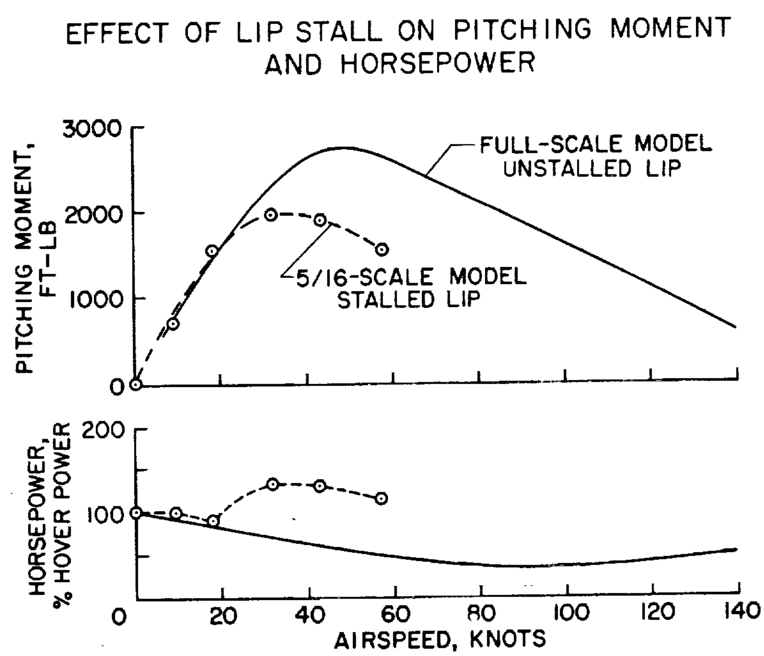

Figure 12

TWO METHODS OF THRUST CONTROL

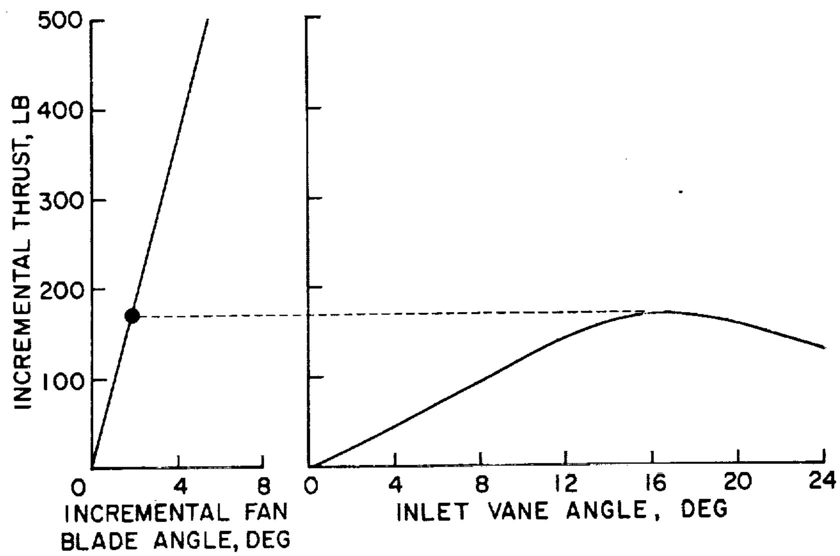

Figure 13

LATERAL CONTROL AVAILABLE WITH INLET VANES

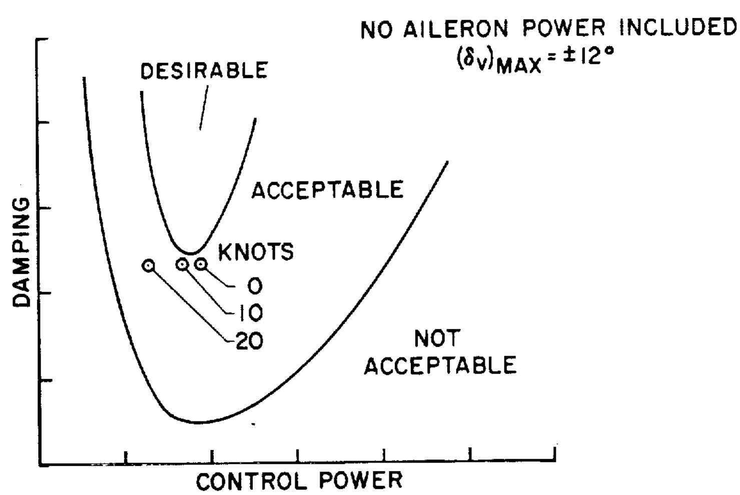

Figure 14