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AERODYNAMICS OF A FAN-IN-FUSELAGE MODEL

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INTRODUCTION

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Recent full-scale wind-tunnel tests of various VTOL designs at Ames Research Center include studies of the submerged-fan concept. One of these studies utilized a general research model with a high-disk-loading fan mounted in a deep duct in the model fuselage. These are the first large-scale complete-model results known to be available on either wing- or fuselage-mounted fan configurations. As indicated in a previous paper by Mark W. Kelly, the problems associated with submerged-fan vehicles will be similar for both wing and fuselage installations. Analysis of these data for the subject fan-in-fuselage model will, therefore, have some general applicability to the submerged-fan concept.

MODEL AND TESTS

Figure 1 is a photograph giving an overall view of the model installed in the Ames 40- by 80-foot wind tunnel. An unswept wing having an aspect ratio of 5, a taper ratio of 0.5, and 10-percent-thick sections was used. Wing incidence was 0°. Full-span plain trailing-edge flaps were installed. The high horizontal tail used had a volume coefficient of 0.6. The wing was sized to provide a fan-to-wing area ratio of 8 percent.

The lift fan is driven by a tip turbine which is powered by the exhaust gases from a General Electric prototype J85 engine. The fan is comprised of 36 blades with fixed pitch and a design disk loading of about 350 lb/sq ft. A single fixed vane in the duct inlet, visible in figure 1, aided in turning the inflow air at forward speed.

Details of the propulsion system can be seen in figure 2. The engine jet exhaust was ducted to the fan tip turbine by a flexible elbow to a scroll encircling half the tip-turbine arc. The lift-vectoring exit vanes at the base of the duct were remotely controlled and tested from 0° to approximately 40° rearward of the full-open position.

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Some of the tests were made with the model balanced in lift, drag, and pitching moment for selected wing loadings up to 20 lb/sq ft. A vertical jet-reaction nozzle at the rear end of the fuselage was used to balance the model at trim conditions. A separate source of high-pressure air was used which was capable of producing more than adequate pitch control for the test purposes.

Combinations of low fan speed and relatively high forward speed were avoided when serious distortion of the fan inlet flow occurred.

RESULTS

The wind-tunnel study was directed at obtaining information pertinent to performance, stability, and control during transition from hovering in fan-supported flight to wing-supported flight.

The propulsion system developed a maximum static fan lift (or thrust) of about 7,000 pounds at a weight rate of engine airflow of about 515 lb/sec and 3,900 gas horsepower. This fan lift includes the induced effects on the shroud. The variation of fan thrust and overall model lift with forward speed is illustrated in figure 3. These data are for a constant fan speed with the model at 0° angle of attack; the exit vanes are fully open, and the horizontal tail is off. There are large increases in both fan thrust and overall lift with increasing forward speed. The data show no evidence of a "suck down" effect at low forward speeds. (In this connection, it is to be noted that the model was essentially out of ground effect with the duct exit about 3 fan diameters above the tunnel floor. Furthermore, there was no measurable evidence of tunnel-wall influence or recirculation effects in the closed test section.) Overall lift exceeds thrust indicating induced lift due to fan operation. At 100 knots forward speed total lift has increased to 90 percent more than its static value, and induced lift accounts for 35 percent of this total. With the wing at 0° incidence and 0° angle of attack, this lift gain is directly attributable to wing loading due to fan operation. Small-scale tests of a similar model with lower-disk-loading fans (about 60 lb/sq ft) had not shown the existence of this lift. The power required to maintain constant fan speed did not vary materially through the speed range.

Lift, drag, and pitching-moment coefficients are plotted as functions of tip-speed ratio in figure 4. Tip-speed ratio is defined as the ratio of forward speed to fan-blade tip speed. Increases in tip-speed ratio thus correspond to increases in forward speed or decreases in fan speed. These data were obtained with the model at 0° angle of attack; the exit vanes were fully open, and the horizontal tail was off.

The component contributions to lift and drag account for 80 to approximately 100 percent of the measured values. Wing lift accounts for an increasing percent of total lift with increasing tip-speed ratio - almost 30 percent of the total lift at a tip-speed ratio of 0.3.

The power-off drag is a measured value. Ram drag is that force necessary to arrest a mass of free-stream air equal to the mass of air flowing through the duct. The gas-generator ram drag is also included but is small in magnitude.

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Pitching moments were measured about a point on the fan thrust axis longitudinally and near the fuselage center line vertically. Of the total measured pitching moments only a small portion is attributable to the wing lift and drag on the engine package. The major portion of the measured moments is due to the effects of turning the inflow air into the duct. Calculations showed that almost half of this moment increment arises as a consequence of the vertical displacement of the chosen moment center below the duct inlet. A shallow duct configuration, such as would be used in fan-in-wing vehicles, might avoid this part of the duct moments.

The effects of deflecting the duct exit vanes on the lift, drag, and moment characteristics are shown in figure 5. Tip-speed ratio is again used as the independent parameter. Vane deflection is measured rearward from the full-open position as indicated in the inset sketch. The loss in lift with vane deflection at finite forward speed is expected; however, part of the loss is due to a reduction of the induced wing lift. Sizable thrust forces are available through the speed range. Adequate thrust for trimmed flight to a forward speed of about 100 knots was attained with vanes deflected approximately 40°. Exit-vane deflection caused large moment increases at low forward speeds, as would be expected with the vanes positioned well below the center of gravity. These moments could be alleviated by duct redesign or duct inclination, as will be shown subsequently.

Longitudinal characteristics of the model at several power settings (or tip-speed ratios) and with the horizontal tail on are presented in figure 6. The effect of power on the lift-curve slope is negligible. Operation of the fan induced more negative pressures on the wing leading edge, with small effects still evident at the wing tips. Fan operation did not materially affect longitudinal stability. Data with the horizontal tail off showed sizable downwash at the tail throughout the speed range tested.

DISCUSSION

The data presented are a brief digest of the test program. These test results have been used to study the longitudinal control characteristics in steady-flight transitions at 1 g from hovering to flight on the wing at forward speed. These studies serve to illustrate the various problems that can be encountered with fan-in-wing and fan-in-fuselage VTOL airplanes.

A variety of transition programs are possible and many were, in fact, studied. The purpose here is not to seek an optimum method of accomplishing transition but rather to illustrate the general problem areas. Three transition programs were selected for this purpose and are depicted in figure 7. The selected airplane weight, 5,000 pounds, corresponds to a wing loading of 20 lb/sq ft on the model. The transition programs are shown in terms of the variation of angle of attack with speed.

A type of transition which has been proposed is to utilize a low-drag configuration at a low constant angle of attack to provide high acceleration to a speed at which flight on the wing is possible. The first transition plan of figure 7 illustrates this method with the model at 0° angle of attack. (The model is limited to about 100 knots in this configuration due to thrust-vectoring limitations of the duct exit vanes.) Note that the angle-of-attack program is discontinuous at the end of the transition. A large abrupt increase in angle of attack is required to support 1 g flight on the wing. Not only is this angular rotation undesirable but, as is shown in figure 8, serious pitching-moment problems make this type of transition unacceptable. Shown in figure 8 is the variation of untrimmed pitching moment with speed. The low-drag method of transition (plan ①) develops high moments and has a large trim discontinuity at the end of transition.

As was pointed out in the discussion of figure 4, the duct moments with the model at 0° angle of attack are quite large. Rotating the model to negative angle of attack should relieve the duct moments. Transition plan ② (fig. 7) was programed at -7.5° angle of attack to study this effect. Wing flaps were deflected 30° to retain positive lift at this attitude; flap deflection also aids in reducing the positive moments. It is seen in figure 8 that the moments are reduced considerably, but large trim and angle-of-attack discontinuities still occur at the end of transition. (The speed selected for transfer of lift from fan to wing is 30 percent above stall speed, the same as for transition plan ①.) It is therefore necessary to vary angle of attack gradually through transition, as in transition plan ③ of figure 7, to eliminate both the discontinuous angle-of-attack change and the trim discontinuity (fig. 8).

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The necessity of varying angle of attack in this manner to reduce the untrimmed moments and to allow a smooth continuous transition introduces a new problem which is shown in figure 9. For the low-drag method of transition, fan power is abruptly stopped at the end of transition, and direct engine thrust applied for normal airplane flight. This is desirable since it requires only a two-position jet-exhaust diverter valve. For the variable angle-of-attack plan, on the other hand, the power required by the lift fan reduces gradually to zero. (These transition results were extrapolated through the region where fan speed is low.) Therefore, some direct jet thrust must also be provided to supplement the limited thrust available from duct exit vane vectoring of the fan lift in this intermediate speed range. In order to obtain this division of the gas-generator exhaust, the jet engine must be operable with the flow diverter valve in positions intermediate to either full fan drive or full jet thrust.

One additional point should be noted in connection with figure 9. As the fan speed must decrease gradually to zero in the variable angle-of-attack transition, fan-inlet-flow distortion will occur. Since the fan rotating stresses will be low, it had been expected that the oscillating stresses would cause no difficulty. (More recent tests of the model have been conducted under such conditions with no serious effects.)

In figure 10 the untrimmed pitching-moment variations with speed are repeated (from fig. 8) for transition plans ① and ③. The purpose here is to compare the trim requirements with the stabilizer capability. It can be seen that stabilizer power is insufficient for trim throughout transition for the constant 0° angle-of-attack case and insufficient up to 55 knots for the variable angle-of-attack case. Addition of elevator control would provide some additional trimming power but would also be relatively ineffective at the lower speeds. A pitch control device effective at hover and low forward speeds is necessary to handle these trim deficiencies. Vertical jet-reaction control in the region of the horizontal tail was used for the wind-tunnel tests and is used in this analysis. The elevator is reserved for control rather than trim, as demanded by handling-qualities criteria.

The moments required from the reaction control to handle the trim deficiencies for the low-drag and the variable-angle-of-attack transition programs are plotted against speed in figure 11. The requirements are plotted in terms of the control parameter M/I_Y. The incremental control power required for maneuvering and damping as specified by VTOL handling-qualities criteria is shown by a shaded area above each of the trim-deficiency curves. (Where the shaded areas reduce and/or disappear, estimated elevator control is being phased in as it becomes effective at the higher dynamic pressures.) For the constant-angle-of-attack transition (plan ①), the maximum control moment required represents a reaction force of 9 percent of the airplane gross weight. When angle of attack was varied through transition (plan ③), the maximum requirement is only one-third as large, and no reaction control is needed above 60 knots forward speed. It is to be noted that in either case the magnitude of the reaction control force is specified by the requirements in transition, not those in hovering; this force could be as much as 6 times the hover requirement for the constant-angle-of-attack transition.

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These control requirements are, of course, applicable to the specific fan-in-fuselage model tested and could be altered materially by changes in design such as those suggested in figure 12. The sketch at the left side of the figure is a simplified diagram of the duct geometry as tested. It has been calculated that with a design as shown on the right side of the figure, in which there is about 15° of tilt in the duct and less duct depth, the pitch control problems would be alleviated. Moment diagrams applicable to each design are shown below the sketches. It is estimated that this revised design would almost eliminate any added control-power requirement over that for maneuvering and damping at hover with the center of gravity positioned as shown. The moments arising from operation of submerged fans are, however, quite sensitive to center-of-gravity changes so that even with careful duct design normal center-of-gravity travel will introduce moment problems of the nature discussed in this paper.

CONCLUDING REMARKS

From consideration of 1 g steady-flight conditions derived from wind-tunnel data, it has been shown that a variety of transition flight plans are possible with the fan-in-fuselage model tested. In order to satisfy the longitudinal handling-qualities criteria, angle of attack must be varied to provide smooth transition from fan-supported flight to wing-supported flight. Inherent in both fan-in-wing and fan-in-fuselage designs is a large untrimmed pitching-moment variation with forward speed. The transition flight plan must be selected with care; otherwise, excessive trim and control power will be required. It was shown that lift-force vectoring must be supplemented by some direct thrust during transition flight to eliminate discontinuous attitude and trim changes. Such a provision for division of the gas-generator flow between fan drive and direct thrust implies the development of engines operable with the exhaust diverter valve in intermediate positions. Such a valve would allow more flexible programing of duct exit vanes to obtain further reductions in trim pitching moment. The need for variation of several controls to provide trim through transition suggests a programed linkage of all trim controls to a single pilot cockpit control. Detailed design considerations can do much to reduce the control-power demands for successful transition flight.

FAN-IN-FUSELAGE MODEL

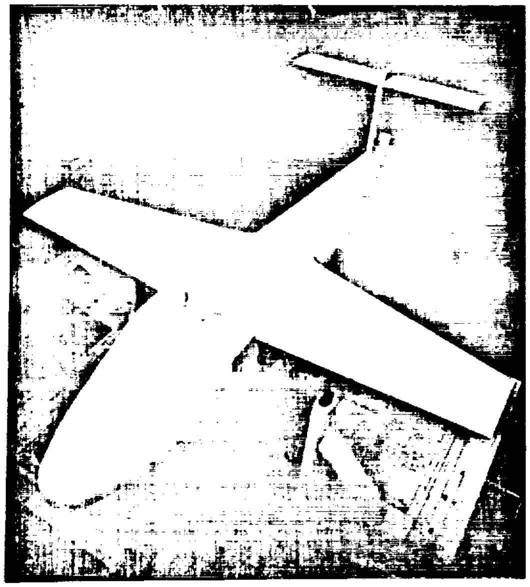


Figure 1

PROPULSION SYSTEM DETAILS

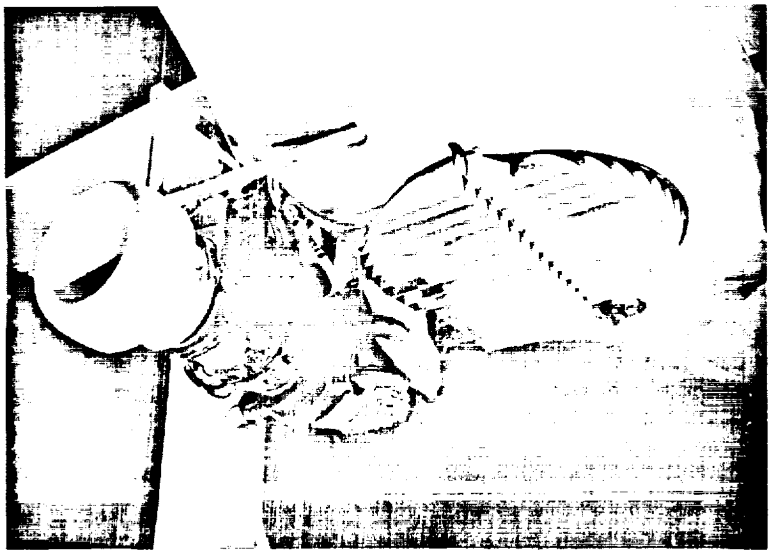


Figure 2

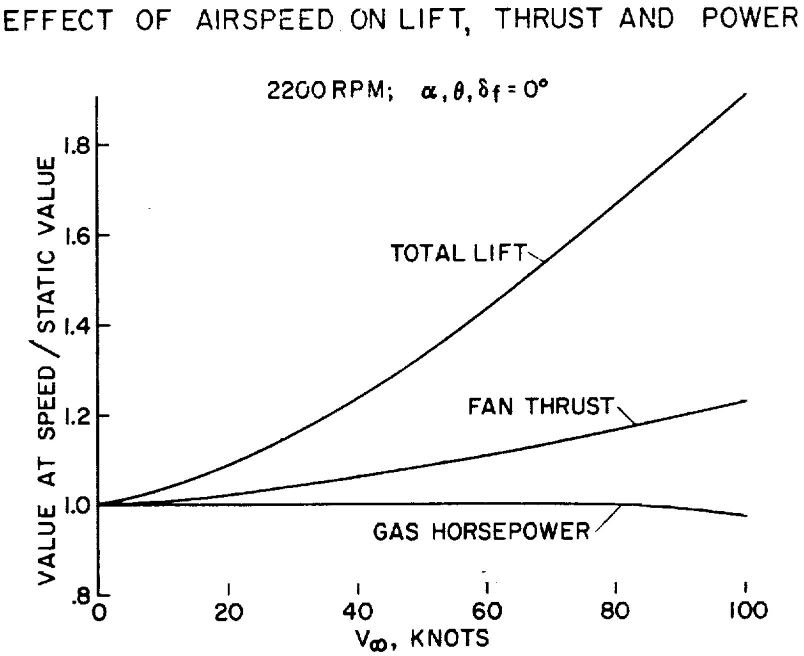


Figure 3

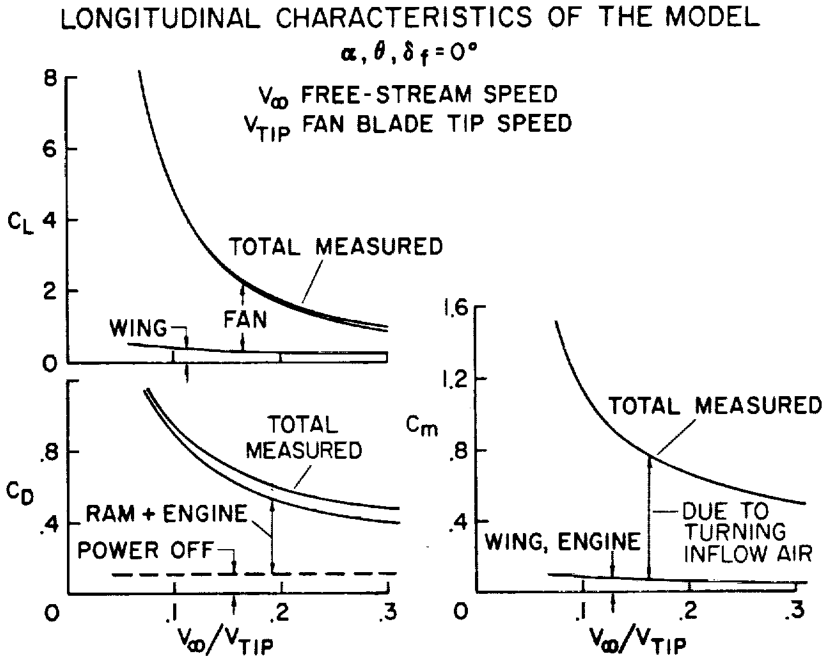


Figure 4

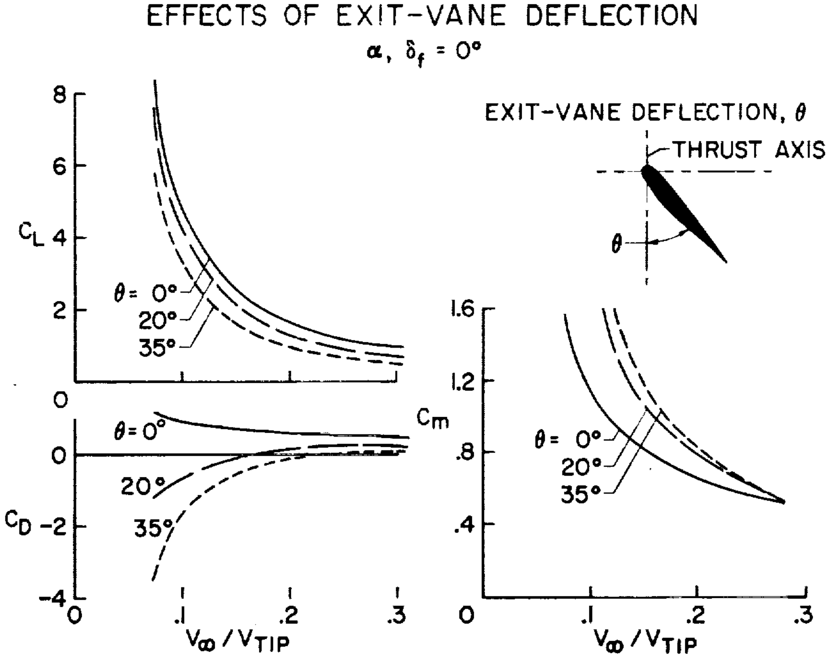


Figure 5

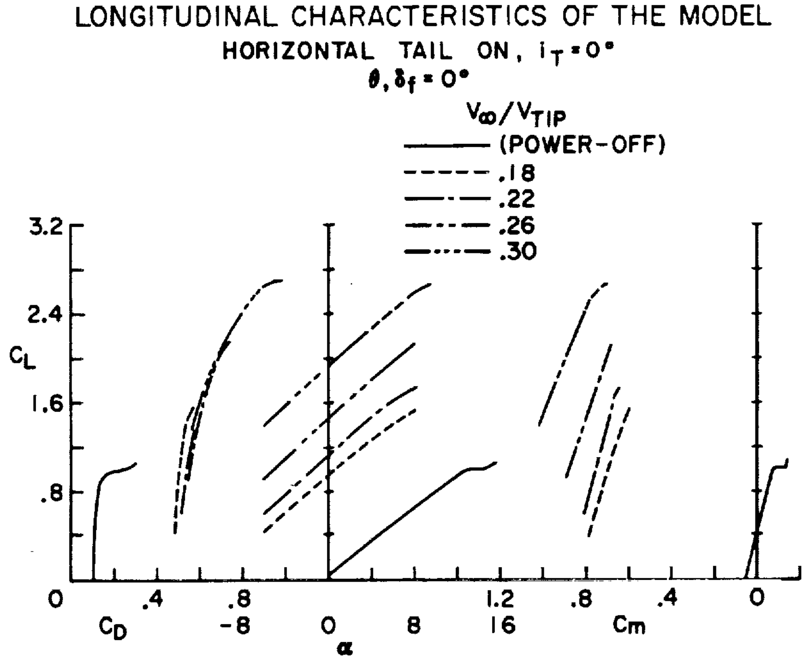
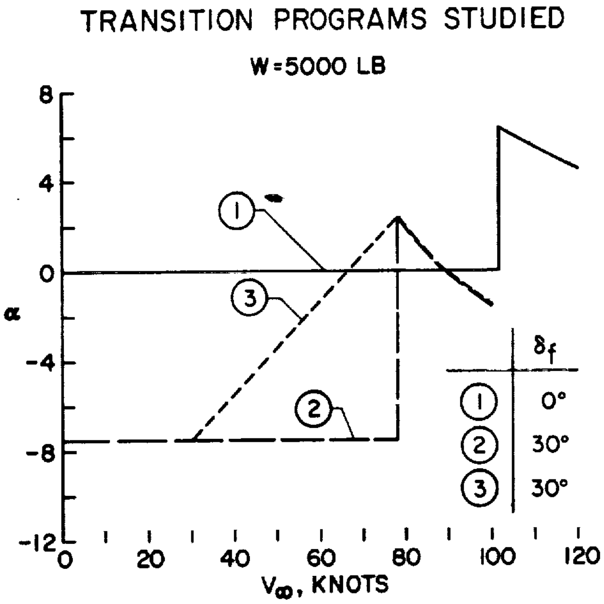


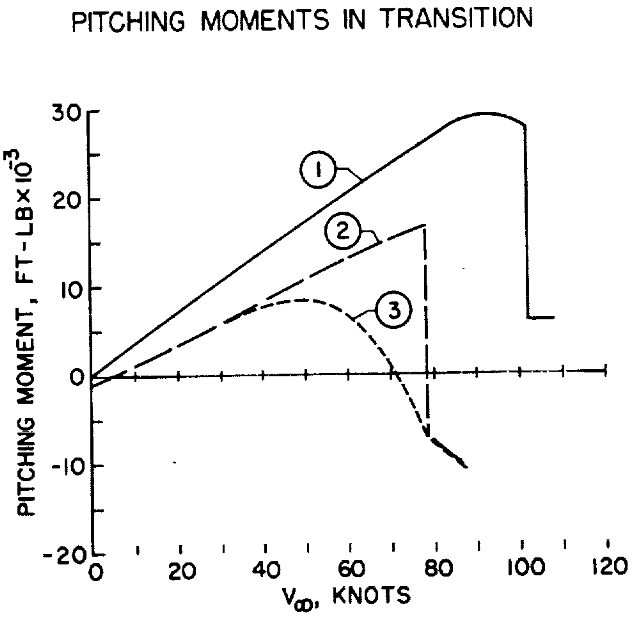
Figure 6



TRANSITION PROGRAMS STUDIED

W=5000 LB

Figure 7



PITCHING MOMENTS IN TRANSITION

Figure 8

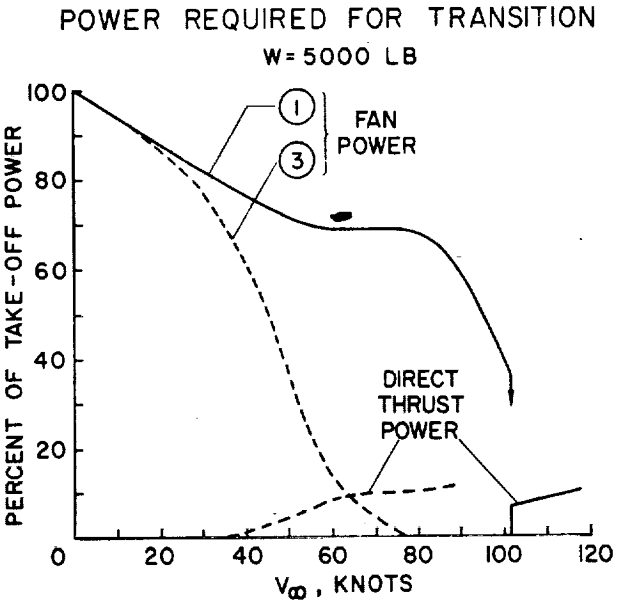


Figure 9

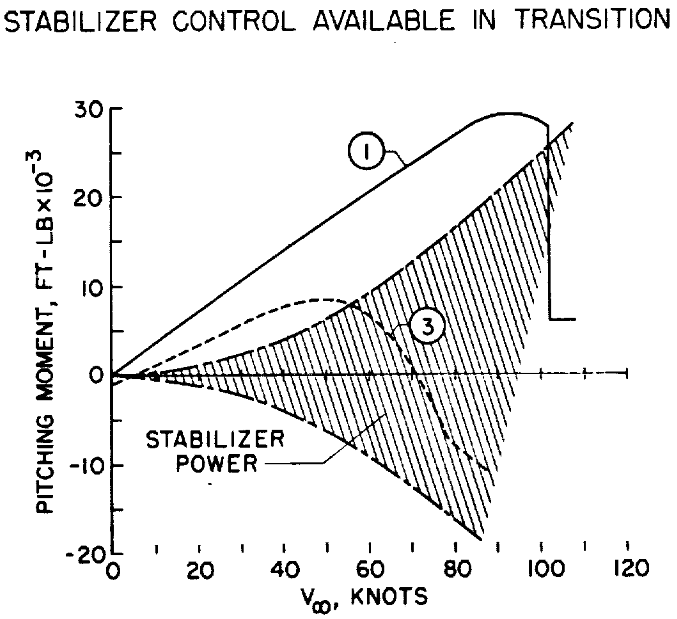
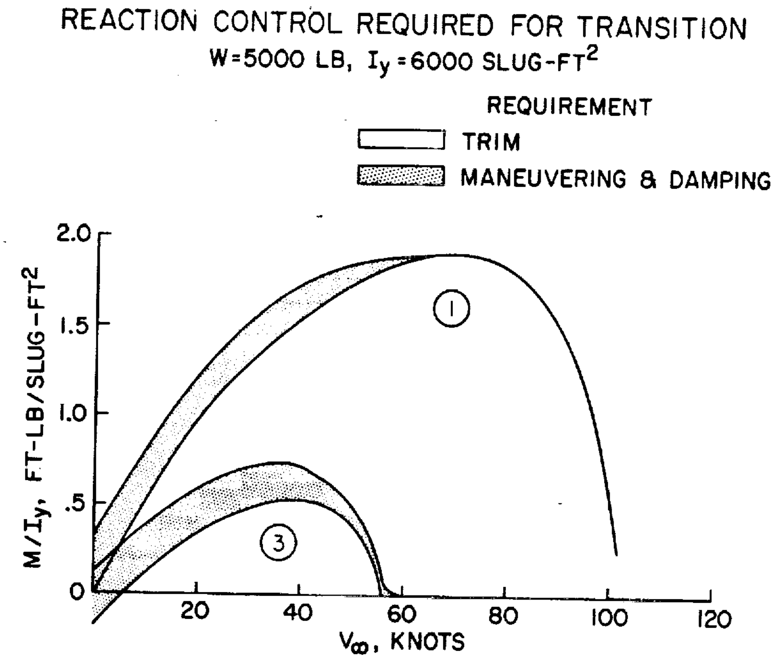


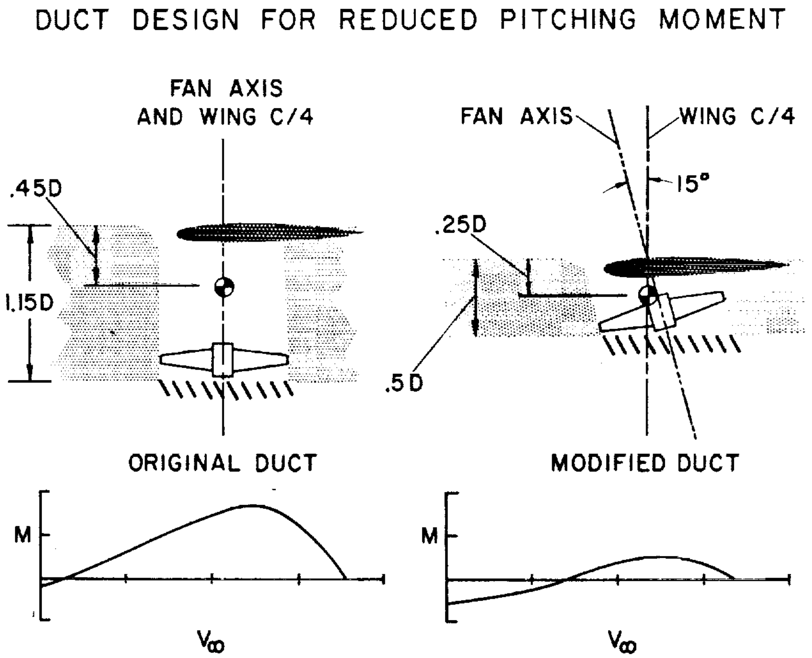
Figure 10



REACTION CONTROL REQUIRED FOR TRANSITION

W=5000 LB, I_y=6000 SLUG-FT^2

Figure 11



DUCT DESIGN FOR REDUCED PITCHING MOMENT

Figure 12