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7. AERODYNAMIC CHARACTERISTICS OF A V/STOL TRANSPORT MODEL WITH LIFT AND LIFT-CRUISE FAN POWER PLANTS

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SUMMARY

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The aerodynamic characteristics of lift fans mounted ahead of the wing, rotating cruise fans, and tandem mounted lift fans faired into the wing have been studied. The tests results indicated that the complete configurations, that is, the lift-cruise fan and tandem lift fan configurations, had generally acceptable aerodynamic characteristics. The positive induced lift due to fan flow interference with the airplane flow field was a small percentage of the installed thrust but was adequate to provide significant increases in payload with STOL operation.

Author

INTRODUCTION

Ames Research Center is conducting a study of the low speed aerodynamic characteristics of V/STOL transport configurations powered by lift fans, cruise fans, or combinations of lift and cruise fans. This paper will present the most recent results from this program, and show the aerodynamic characteristics of configurations having lift fans mounted ahead of the wing, rotating cruise fans, and tandem mounted lift fans faired into the wing. The effect of interference between the fan flow and the airframe flow field on lift and moment will be discussed. Individual lift contributions of the various airplane components will be presented, and the overall characteristics when the components are assembled into a complete configuration will be shown. Limited lateral and directional data from the two complete configurations will also be presented.

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NOMENCLATURE

c local wing chord, ft

C_D drag coefficient

C_L lift coefficient

C_{l_β} variation of rolling-moment coefficient with angle of sideslip

C_m moment coefficient

C_n yawing-moment coefficient

CP	center-of-pressure location, x/R
C_{Y_β}	variation of side force with angle of sideslip
D_e	equivalent diameter, $[(n/2)D_f^2]^{1/2}$, ft
D_f	fan diameter, ft
i_D	duct incidence angle, deg
i_t	angle of incidence of the horizontal tail
l	rolling moment, ft-lb
L	lift, lb
L/T_s	ratio of lift-to-fan static thrust
L_w/T_s	ratio of wing-lift-to-fan static thrust
M	pitching moment, ft-lb
n	number of fans
N	yawing moment, ft-lb
P_T/P_o	exhaust pressure ratio of fan
R	fan radius, ft
V	airspeed, knots
V/V_j	ratio of airspeed in free stream to jet exhaust
x	distance from fan axis, positive forward, ft
Y	side force, lb
α	model angle of attack, deg
α_t	angle of attack of the horizontal tail, deg
$\Delta\alpha$	angle-of-attack increment
β	angle of sideslip
β_v	lift fan vector angle from the fan axis, deg
δ_f	flap deflection angle, deg

TEST EQUIPMENT

Model

Figures 1 and 2 are photographs of the model installed in the Ames 40- by 80-foot wind tunnel. The basic wing planform has an aspect ratio of 5.8, sweepback angle of 35°, area of 230 square feet, taper ratio of 0.3, and a 65-412 airfoil section. Two basic configurations were studied; one (shown in fig. 1) was a combination rotating cruise fan and folding lift-fan arrangement with the cruise fan aft and lift fan forward. The other configuration (fig. 2) had tandem lift fans mounted on the fuselage adjacent to the wing leading and trailing edges; fairings covered the gap between the fan and the wing.

For these studies, the four 3-foot-diameter GE X-376 tip turbine driven lift fans were driven by one J-85 engine. The engine exhausted through a diverter valve into a plenum chamber located inside the fuselage. From the plenum chamber, the J-85 exhaust was ducted to the tip turbines of the individual fans. The fan locations and associated ducting arrangements could be varied in order to determine advantageous fan locations. All lift fans were equipped with exit louvers to deflect the flow aft for thrust in fan-powered flight.

Both model configurations were equipped with single-slotted trailing-edge flaps and a horizontal tail mounted high on the vertical fin.

Reduction of Data

Results from tests of V/STOL models in the Ames 40- by 80-foot wind tunnel are usually presented without wind-tunnel wall corrections. Reference 1 presents a correlation of full-scale wind-tunnel data with flight test results for several V/STOL concepts; these results are used to define a preliminary set of model-to-wind-tunnel sizing constraints that have given small wind-tunnel wall effects (as proven by the correlation of flight test and wind-tunnel test data) and therefore acceptable accuracy of the test results. The size of the subject model, referenced to the wind tunnel, and the constraints from reference 1 are presented in figure 3. Lifting-element area ratio is well within the suggested limit, but the momentum area and wing span ratios are slightly larger than the guidelines. The boundaries of reference 1 represent constraints based on limited experience rather than maximum acceptable size boundaries; thus rather than apply wind-tunnel wall corrections of questionable accuracy, the results presented herein are presented without corrections.

RESULTS AND DISCUSSION

Lift-Cruise Fan Configuration

Induced effects of the configuration components.- Unloading of the wing by downwash induced by fan operation has long been of concern for fore and aft mounted lift-cruise fan configurations. Therefore, before the complete configuration was tested, the lift fans in front of the wing were tested in three locations to assure a location which would produce a near minimum wing download for the tests with the complete configuration. Figure 4 presents the ratio of total lift-to-fan static thrust as a function of flight velocity ratio for these three front lift fan locations (only the two front fans were operating). Power-off wing lift is also shown. The low fan position just forward of the wing leading edge has the largest lift-to-thrust ratio over the whole velocity ratio range. Furthermore, even if power-off wing lift is subtracted from the total, an increase of lift with forward speed is indicated rather than the expected reduction of lift due to fan induced wing download. In order to analyze this result, wing lift was obtained from static pressure distributions and is shown in figure 5(a). The results indicate that in all locations fan operation did cause negative wing lift over part of the velocity ratio range and in the worst fan location caused negative wing lift at all airspeeds. (Wing lift was positive at 0° angle of attack with fan power off because of lift due to camber.) The equivalent average reduction in wing angle of attack is shown in figure 5(b).

Total front fan lift can be calculated from the results in figures 4 and 5 by subtracting the wing lift in figure 5 from the total lift in figure 4; the upper shaded band in figure 6 shows this result as a function of airspeed. The lower band of data represents the fan thrust measured by a pressure survey of the fan wake. The shaded areas indicate the uncertainty of the data. Lift on the fan fairings, induced by fan operation, is indicated by the difference between the two sets of data. This lift was calculated by the method suggested in reference 2, and is shown by the lower line in figure 6. The lift is about the same as indicated by the large-scale experimental results. These results indicate that the lift induced on the front fan fairings by fan operation is large enough to overcome the download on the wing caused by downwash from the fan so that lift increased with airspeed.

The lift of the various individual lift-cruise fan model components is shown in figure 7. The variation of lift with airspeed with only the front fans operating and the exit louvers deflected to make thrust equal to drag is shown in figure 7(a). Balancing drag has a small effect on lift at low speed but at high speed causes a marked reduction in lift. The lift of the model with just the cruise fans operating is shown as a function of airspeed in figure 7(b) for two duct angles. The locus of the thrust equal drag curve is also shown. For values where airplane drag is trimmed the total lift of the duct (wing lift subtracted from the data in figure 7(b)) is greater than static thrust in spite of the trigonometric relationship between lift and thrust. This lift is a significant feature of ducted fan aerodynamics.

The variation of lift-to-thrust ratio with velocity ratio or airspeed (assuming a fan pressure ratio of 1.3) for a complete lift-cruise fan configuration for which the thrust has been vectored to balance the drag is shown in figure 8. The lines in the shaded area represent constant duct angle; the drag was balanced by deflection of the lift fan exit louvers. The shaded area indicates the sensitivity of lift-to-thrust ratio to the combinations of duct and vector angles required to balance drag. These results show a marked increase in the lift ratio with flight velocity ratio which is due to the trailing-edge flap. At high velocity ratios, the lift-to-static thrust ratio without the wing lift is less than 1.0, indicating that the propulsion system lift has become less than the static value. This, of course, is to be expected at higher transition speeds where the fans or exit louvers are oriented to provide thrust. The airspeed scale for an aircraft with 1.3 pressure ratio fans shows that at 50 knots (the approximate flight airspeed required for about a 1000-foot landing and take-off distance) an overload of 10 to 20 percent of the installed thrust can be carried. Thus payload can be increased sizably with STOL operation of a VTOL machine of this design when suitable runways are available.

Transition characteristics.- The variation of thrust required, cruise-fan duct incidence angle, exit louver deflection angle, and horizontal tail incidence angle, and angle of attack for trim are shown as a function of airspeed in figure 9 for a transition at 0° angle of attack. The thrust required data indicate there was no lift reduction with airspeed for this design. The paper by Kenneth W. Mort discusses the cruise-fan duct stall boundaries using the duct incidence angle required for trim in this figure as an example. Mr. Mort shows that duct inlet stall does not appear to be a problem for this configuration. The tail angle of attack for trim varied from 12° at 60 knots airspeed to 7° at 175 knots airspeed; this variation is not extreme, and the magnitudes are small enough so that tail stall would not be a problem. About one-half of the tail moment capability is available for maneuvering or providing stability. Even less trim would be required of the tail with a hover control contribution to trim.

Figure 10 shows longitudinal characteristics near trim drag and moment at several airspeeds. The model, with its high horizontal tail, has a basic pitch-up problem. Lift-cruise fan operation did not significantly affect this problem.

Figure 11 shows the directional characteristics of the lift-cruise fan configuration at three different duct angles. The variation of side force and rolling moment with sideslip (tabulated on the figure) was linear and stable. The variation of yawing moment with sideslip appears to be neither linear nor stable, and therefore constitutes a possible area of concern for this type of configuration. The available data are not adequate for isolating the cause of the problem.

Tandem Lift-Fan Configuration

The variation of the ratio of lift-to-static thrust with flight velocity ratio for the tandem lift-fan configuration is shown in figure 12. The lift ratio with front fans, rear fans, or all four fans operating is shown on the figure. The rear fans induced a large amount of positive lift, while the front fans induced a negative lift. When all four fans were operating, lift fell approximately midway between that for the other two cases. In figure 13, fan thrust and wing lift have been removed from the basic data so that only induced lift is shown for the three operating conditions. The shaded bands indicate the range of certainty of the data. The positive induced lift noted with the rear fans operating is similar to that described in reference 2; the flow from the fan induces lift in a fashion similar to a jet flap. An attempt was made to use the method described in reference 2 to estimate lift for both the rear fan and the front fan configurations. However, the estimated lift did not agree well with the experimental value. A more sophisticated three-dimensional approach to this unusual wing planform evidently is required. Since many VTOL designs will consist of multiple lift fans or lift engines, a theory for the induced effects of multiple lifting elements should be developed.

To see whether the fairings between the lift fans and the wing would significantly change induced lift when the four fans were operating, the fairings were removed during the tests of the tandem fan-in-wing configuration. The results (fig. 14) show the effect to be small. When only the front fans were operating, the fairings had a large detrimental effect, as can be seen by a comparison of figures 4 and 12. These results should be viewed with caution, however, because the rear fan was not installed when the data in figure 4 were obtained.

The variation of lift-to-static thrust ratio with airspeed with the drag trimmed and the trailing-edge flaps down is shown in figure 15 for the tandem lift-fan configuration. At 50 knots airspeed (based on a 1.3 P_T/P_O fan) the overload capability is about 12 percent of the installed static thrust. This would provide a significant payload advantage for STOL operation from a 1000-foot field.

Pitching moment of the tandem fan-in-wing configuration.- The large variation of pitching moment with airspeed has been a concern for lift-fan powered aircraft. Reference 2 correlated the results available at that time by presenting the partial derivative of the center-of-pressure location with respect to flight speed ratio evaluated at zero speed as a function of the ratio of diameter-to-local chord. The results from reference 2, along with similar data from the tandem fan-in-wing model, are presented in figure 16. The results with either the front fans or rear fans operating agree well with the data from reference 2. In spite of the large difference in induced lift between fore and aft fans, the variation of pitching moment with airspeed was nearly the same. With four tandem fans running, the variation of moment with airspeed was smaller, and was comparable to single fan-in-wing configurations having twice the ratio of diameter to chord. Figure 17 presents the variation of moment with lift for the tandem lift-fan configuration and for the fan-in-wing configuration (the point on fig. 16 of $D_e/c = 0.425$) from reference 2. The configurations have nearly the same value of $\partial CP/(\partial V_\infty/V_j)$ at $V_\infty/V_j = 0$ but very different effective diameter-to-chord ratios. The variation of moment near zero airspeed is nearly the same. However, the maximum nose-up moment of the tandem lift-fan configuration is about half that of the fan-in-wing configuration because the point of maximum moment occurred at one-half of the velocity ratio of the single fan-in-wing configuration. This peaking of the pitching moment at low flight speeds occurred only with the tandem lift-fan configuration and appears to be a desirable characteristic of this type of configuration.

Lateral-directional stability.- Lateral and directional stability of the tandem fan-in-wing configuration is shown in figure 18 as a function of flight velocity ratio. The variation of side-force gradient and lateral stability with airspeed is large but stable. The directional stability parameter is stable over most of the range, but at low speed becomes unstable. This could prove to be a problem area for this type of aircraft.

CONCLUDING REMARKS

Lift fans and lift-cruise fans have been tested in several different locations and in two different arrangements on a V/STOL transport configuration. The results indicated that these configurations had generally acceptable aerodynamic characteristics. Induced lift due to fan flow interference with the airplane flow field was a small percentage of the installed thrust and was positive. Isolated fan operation could cause either large positive or negative induced lift on the wing. However, the overall induced lift with all fans operating was positive. This positive induced lift was large enough to provide significant STOL capability.

Longitudinal trim requirements of both complete configurations were moderate and easy to provide. However, both configurations were directionally unstable over a portion of the transition speed range, and this may present a problem.

REFERENCES

1. Cook, Woodrow L.; and Hickey, David H.: Comparison of Wind-Tunnel and Flight-Test Aerodynamic Data in the Transition Speed Range for Five V/STOL Aircraft. Presented at NASA V/STOL Conference, Ames Research Center, April 4 and 5, 1966. Paper no. 26.

2. Goldsmith, Robert H.; and Hickey, David H.: Characteristics of Lifting-Fan V/STOL Aircraft. Astronaut. Aerospace Eng., Oct. 1963.

THE LIFT-CRUISE FAN MODEL

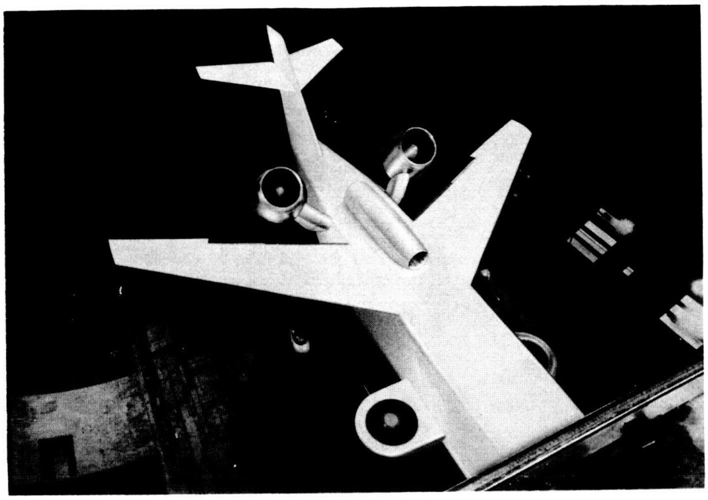

Figure 1 A-35554.1

THE TANDEM LIFT FAN MODEL

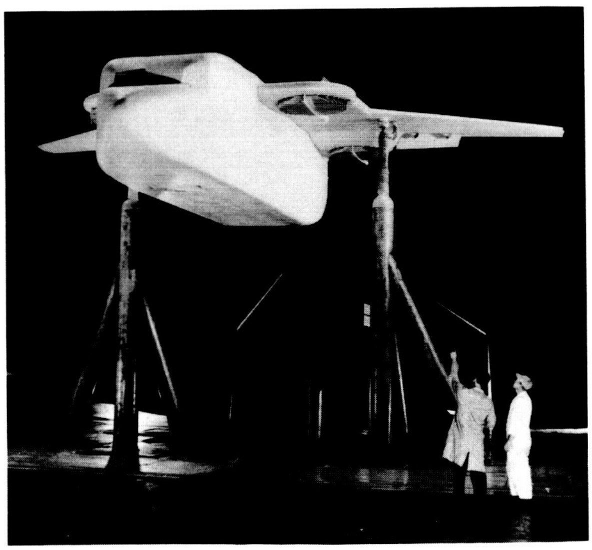

Figure 2 A-35376.1

RATIO OF MODEL TO WIND TUNNEL SIZE

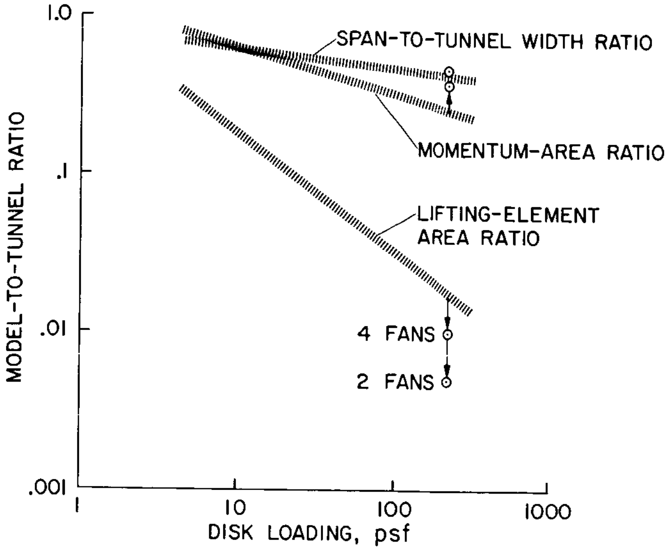

Figure 3

VARIATION OF LIFT WITH AIRSPEED, FRONT FANS OPERATING

$\alpha = 0°, \delta_f = 0°, \beta_v = 0°$

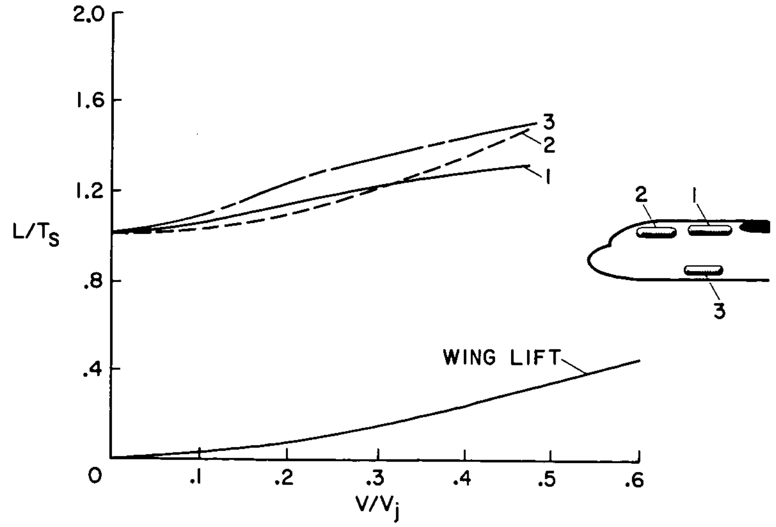

Figure 4

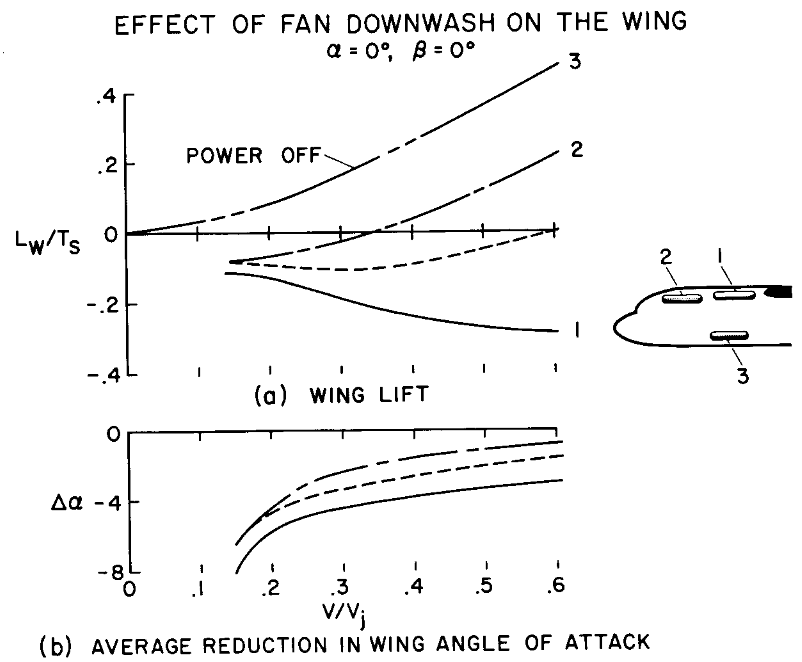

Figure 5

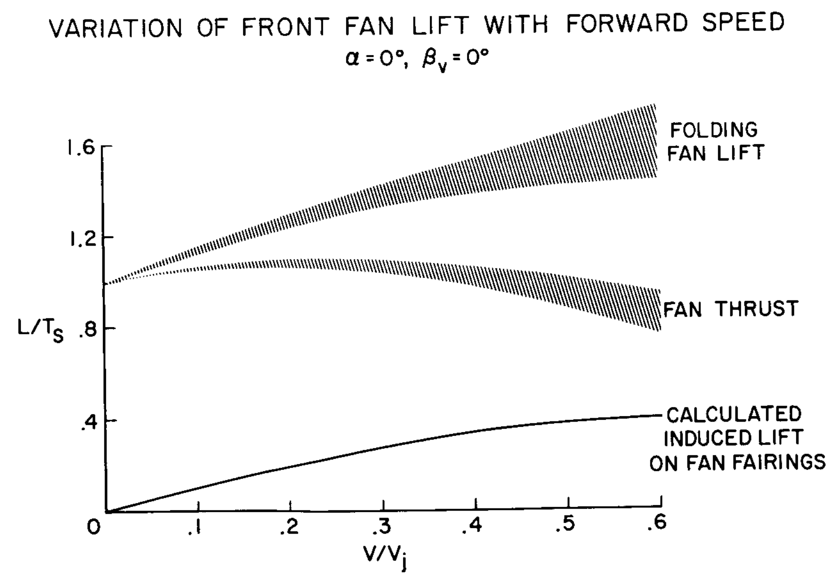

Figure 6

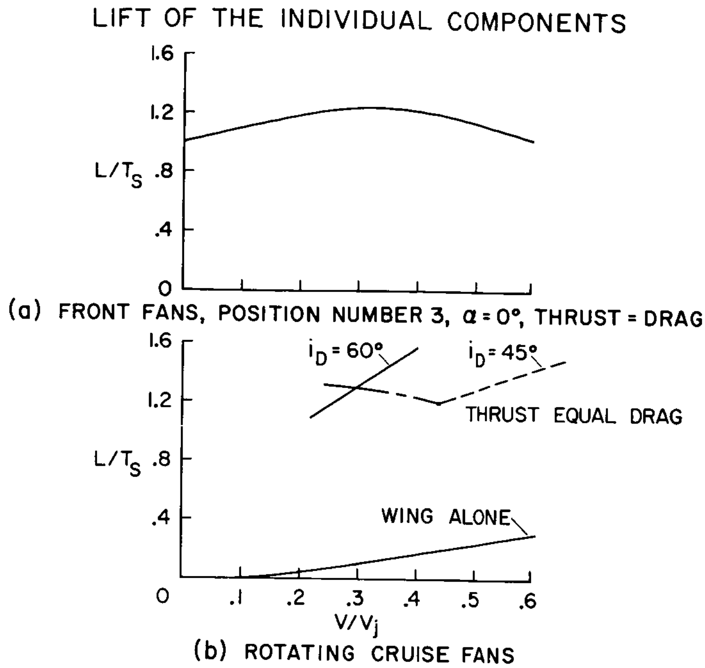

Figure 7

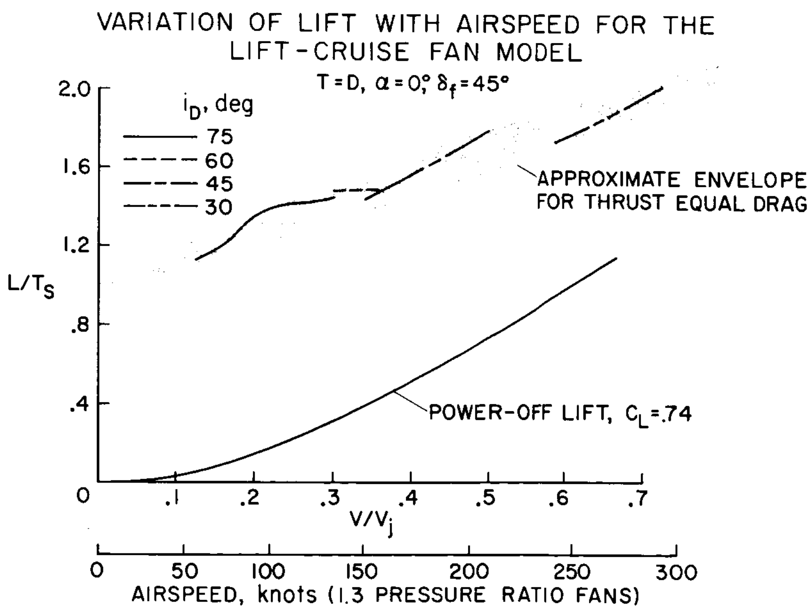

Figure 8

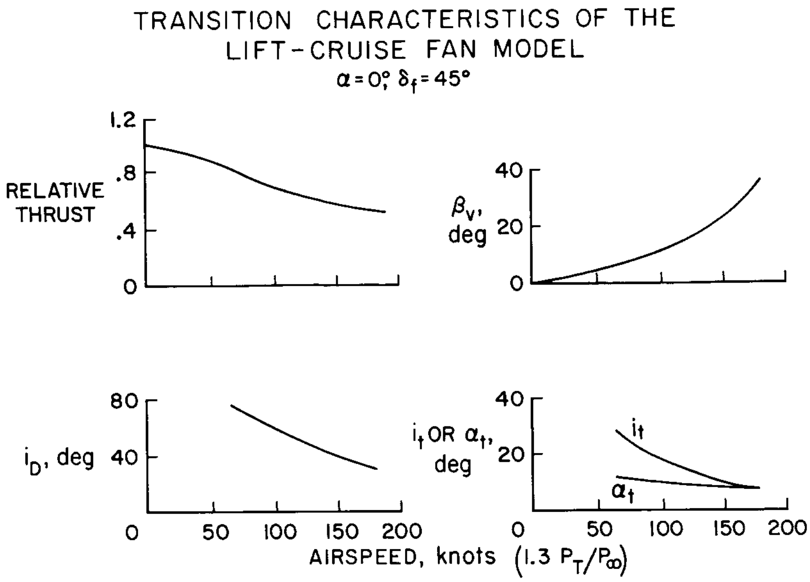

Figure 9

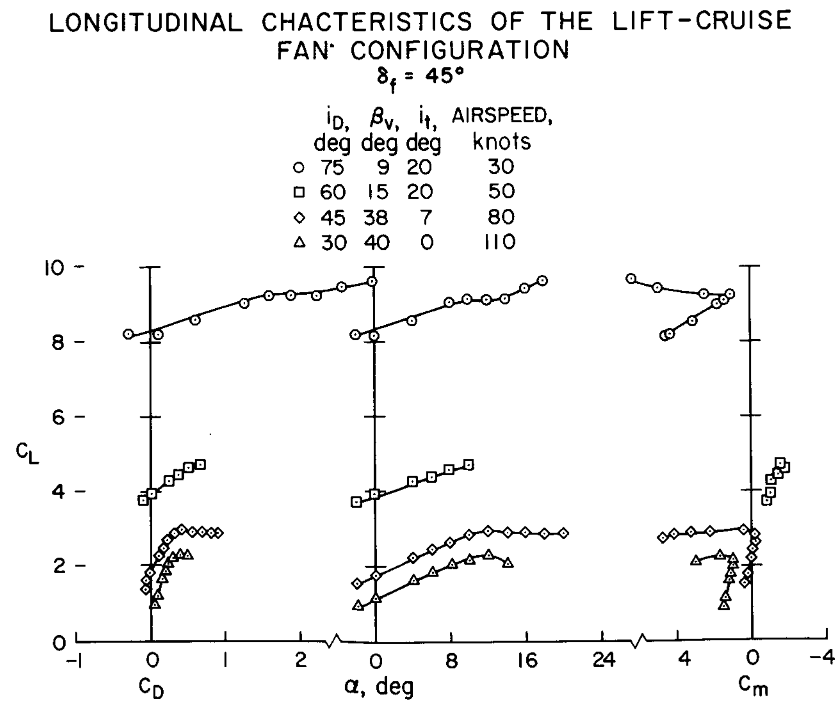

Figure 10

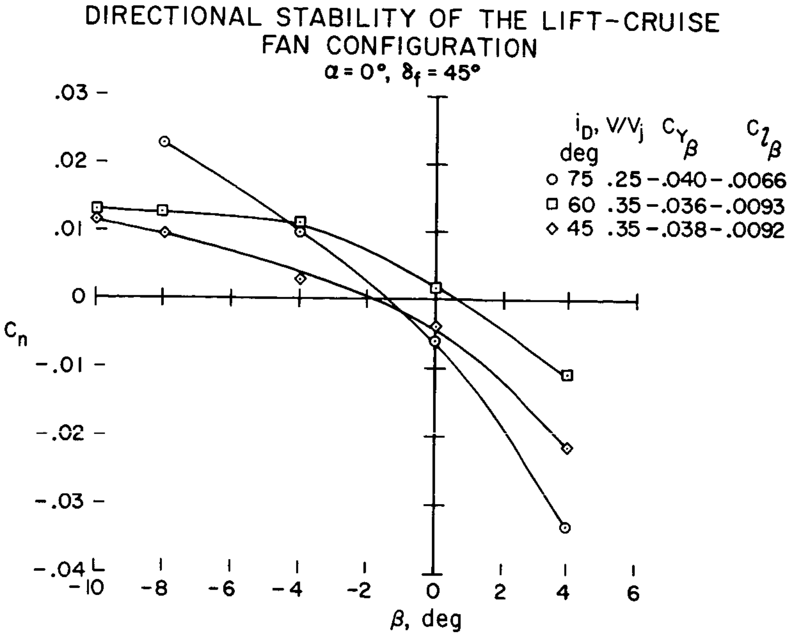

Figure 11

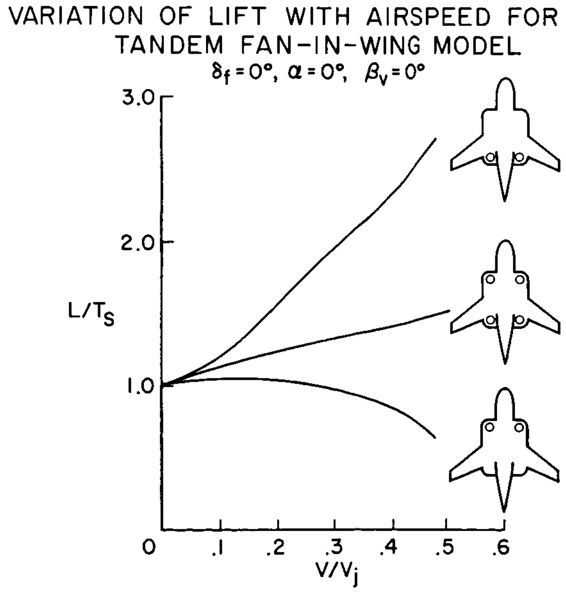

Figure 12

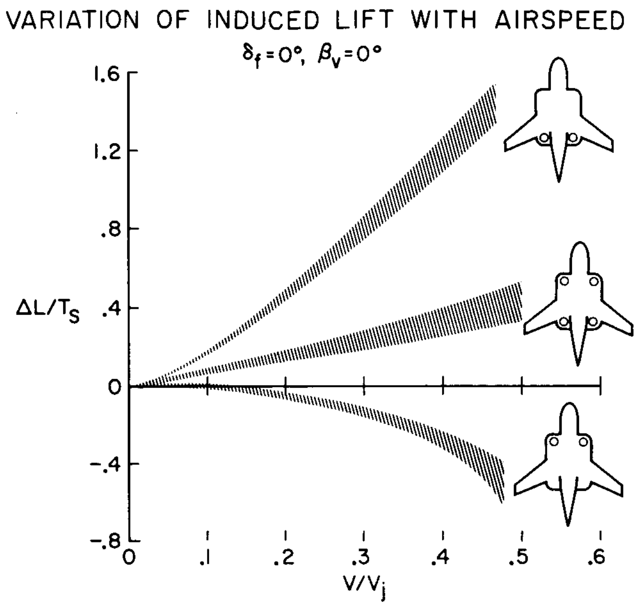

Figure 13

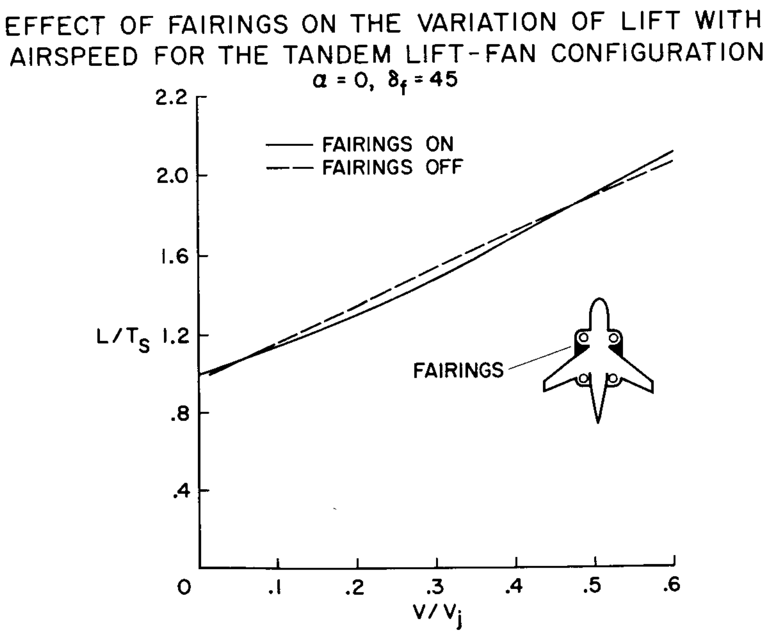

Figure 14

EFFECT OF FLAP DEFLECTION ON THE VARIATION OF LIFT WITH AIRSPEED FOR THE TANDEM LIFT-FAN CONFIGURATION

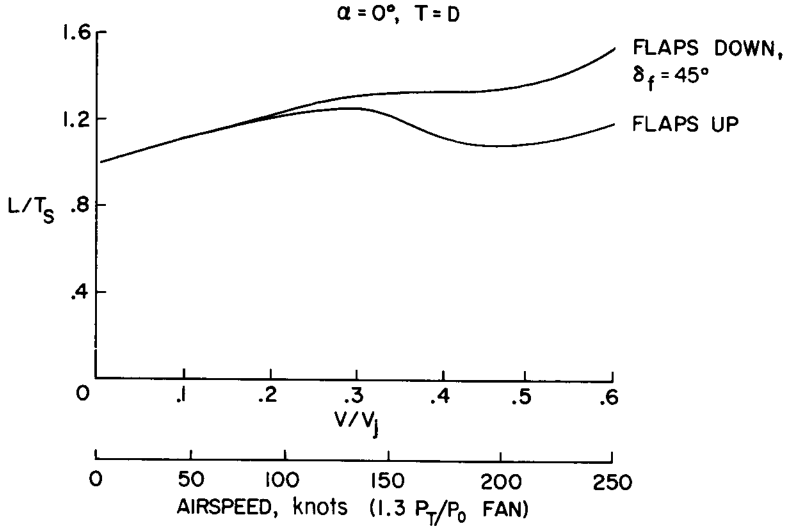

Figure 15

VARIATION OF THE CENTER OF PRESSURE LOCATION WITH AIRSPEED FOR FAN-IN-WING DESIGN

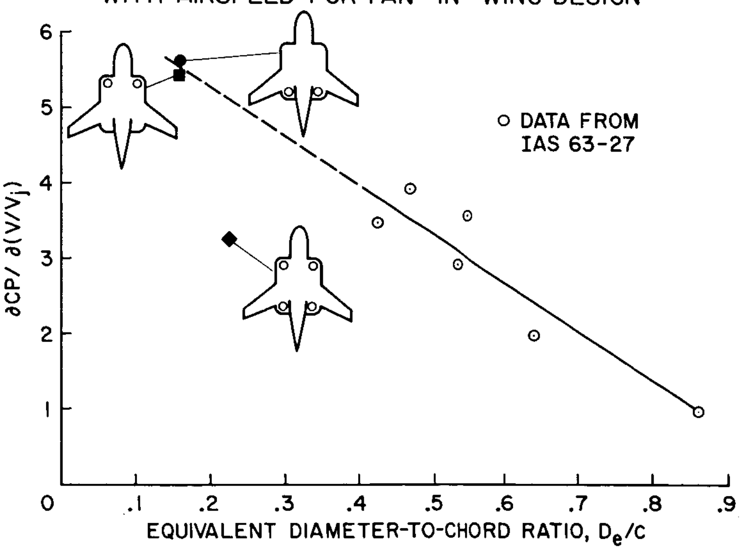

Figure 16

VARIATION OF PITCHING MOMENT WITH AIRSPEED FOR DIFFERENT FAN-IN-WING DESIGNS

$\alpha = 0°, \delta_f = 0°, \beta_v = 0°$

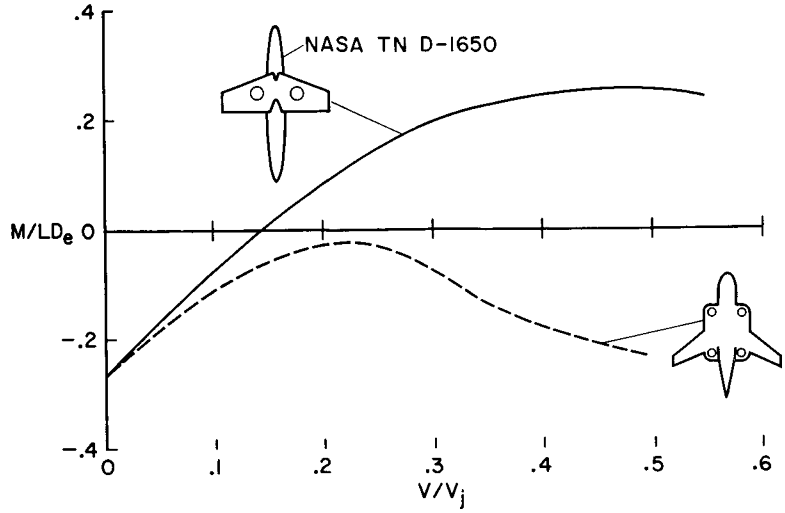

Figure 17

LATERAL-DIRECTIONAL CHARACTERISTICS OF THE TANDEM LIFT-FAN CONFIGURATION

$\alpha = 0°, T = D, \delta_f = 45°$

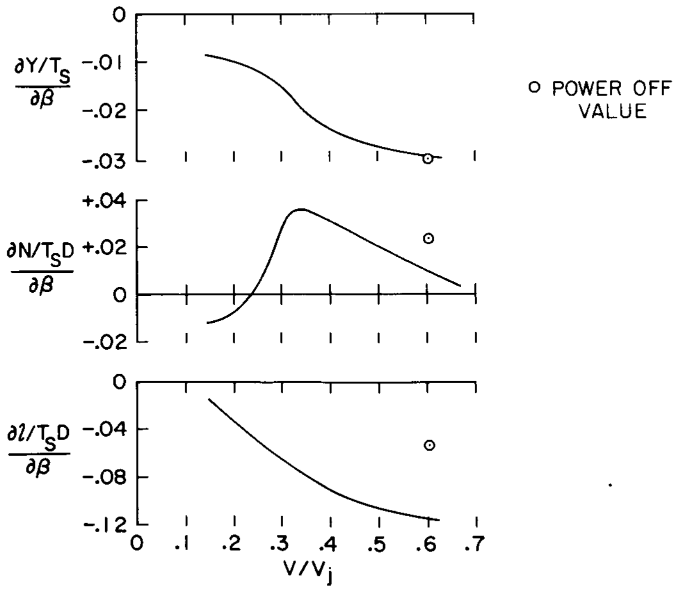

Figure 18