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Aerodynamic Effects of an Attitude Control Vane on a Tilt-Nacelle V/STOL Propulsion System

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Tests were performed in the Ames 40×80-ft wind tunnel on a large-scale, tilt-nacelle V/STOL propulsion system, with and without an attitude control vane assembly mounted in the propulsion system exhaust. The objective was to determine the aerodynamic effects of the control vane. Aerodynamic characteristics are analyzed in terms of nacelle aerodynamics, vane aerodynamics, and vane-induced effects on the nacelle aerodynamics. Each of these components is a significant part of the total forces produced by the propulsion system and must be included in the estimation of aircraft performance. Large pitching-moment changes, accompanied by substantial changes in lift and drag of the entire propulsion system, can be obtained by deflecting the vane.

Nomenclature

A_F	= fan area, 1.206 m^2 (12.98 ft^2)
C_D	= wind-axis drag coefficient, D/qA_F
$C_{D_{aero}}$	= aerodynamic drag coefficient, $C_D - C_{DR} + C_J\cos\alpha$
C_{Di}	= vane-induced drag coefficient, $\Delta C_D - C_{DV}$
C_{DR}	= ram-drag coefficient, D_R/qA_F
C_{D_v}	= vane wind-axis drag coefficient, $(D_v\cos\alpha + L_v\sin\alpha)/qA_F$
C_J	= thrust coefficient, T/qA_F
C_L	= wind-axis lift coefficient, L/qA_F
$C_{L_{aero}}$	= aerodynamic lift coefficient, $C_L - C_J\sin\alpha$
C_{Li}	= vane-induced lift coefficient, $\Delta C_L - C_{L_v}$
C_{L_v}	= vane wind-axis lift coefficient, $(L_v\cos\alpha - D_v\sin\alpha)/qA_F$
C_m	= pitching-moment coefficient about the nacelle pivot axis, M/qA_Fd
C_{mi}	= vane-induced pitching-moment coefficient about nacelle pivot axis, $\Delta C_m - C_{m_v}$
C_{m_v}	= vane pitching-moment coefficient about nacelle pivot axis, $(M_v - 2.405\ L_v + 0.34\ D_v)/qA_Fd$
d	= fan diameter, 1.397 m (4.583 ft)
D	= total measured wind axis drag, N
D_R	= ram drag, N
D_v	= measured vane drag in nacelle body axis, N
L	= total measured wind-axis lift, N
L_v	= measured vane lift in nacelle body axis, N
M	= total measured pitching moment about the nacelle pivot axis, m-N
M_v	= measured vane pitching moment about the vane pivot axis, m-N
q	= freestream dynamic pressure, N/m^2
T	= total gross thrust, N
V_∞	= freestream velocity, m/s
α	= nacelle angle of attack, deg
δ_v	= vane deflection angle, deg
ΔC_D	= total vane effect on drag coefficient, C_D (vane on) $- C_D$ (vane off)
ΔC_L	= total vane effect on lift coefficient, C_L (vane on) $- C_L$ (vane off)
ΔC_m	= total vane effect on pitching-moment coefficient, C_m (vane on) $- C_m$ (vane off)

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Introduction

ONE possible technique for obtaining longitudinal control on a tilt-nacelle V/STOL airplane is the use of a variable attitude vane assembly mounted in the propulsion system exhaust. Deflecting the vane produces large forces and moments without depending on forward speed of the aircraft. Tests were performed in the Ames 40×80 ft wind tunnel on a large-scale, tilt-nacelle V/STOL propulsion system, with and without a variable attitude control vane assembly. The purpose of this research was to determine the aerodynamic effects of the control vane, to assist in the design and performance estimates of tilt-nacelle V/STOL aircraft. Aerodynamic characteristics were analyzed in terms of nacelle aerodynamics, vane aerodynamics, and vane-induced effects on the nacelle aerodynamics.

Propulsion System Description

The propulsion system consisted of the Hamilton Standard Q-Fan, which is a 1.4-m (55-in.), 13-bladed, variable-pitch fan driven by a Lycoming T55-L-11A, 2800-kW (3750 hp) gas turbine core engine with a bypass ratio of 17:1. The fan was driven through a 4.75:1 gear reduction to a maximum speed of 3365 rpm. Additional information on the fan and core engine is available in Ref. 1. The inlet was an asymmetric inlet designed by the Boeing Company for a tilt-nacelle lift/cruise fan propulsion system. It had a higher contraction ratio on the windward side than on the leeward side, which allowed testing at angles of attack up to 105 deg without separating the inlet flow or stalling the fan. The cowling was designed to provide a nacelle suitable for wind-tunnel testing. The components of the propulsion system and its major dimensions are shown in Fig. 1. A more detailed description of the propulsion system and inlet is available in Ref. 2.

The attitude control vane assembly, designed by the Grumman Aerospace Corporation, consisted of a symmetric airfoil with a rectangular planform, 0.772-m (30.4-in.) chord, 1.619-m (63.75-in.) span, and a 10% thickness-to-chord ratio. The vane was supported by a boom on each end which was attached to the nacelle. The vane pivoted about the 45% chord station and incorporated a trailing edge flap pivoted about the 70% chord station. The flap was controlled by two links attached to the boom to provide a flap-to-vane deflection ratio of 1.0.

The nacelle was mounted approximately 4 m (13 ft) above the wind-tunnel floor on a single strut which was shielded from the wind by a fairing. The nacelle rotated in a horizontal plane about the strut centerline for angle-of-attack variation. Figure 2 shows the propulsion system with control vane in the Ames 40 × 80-ft wind tunnel.

Test Procedure

Most of the data for the nacelle without the vane were acquired by varying thrust at constant nacelle angles of attack up to 105 deg and constant velocities. The vane support hardware was removed from the nacelle when vane-off data were acquired. The data for the nacelle with the vane were acquired by varying vane deflection angle at constant thrust, angle of attack, and velocity. Angle of attack varied from 0 to 95 deg, and velocity varied up to 93 m/s (180 knots). Vane deflection angle varied from −30 to +30 deg. Changing engine speed and fan blade angle varied the gross thrust up to a maximum of 31,600 N (7100 lb). The operating limits of the propulsion system were determined and are discussed in Ref. 3. All of the data presented here were obtained with unseparated flow in the inlet.

Data Reduction

Force and moment data, obtained from the wind-tunnel balance system, were used to compute coefficients for the total nacelle forces and moments in the wind-axis system. The fan annulus area (1.206 m^2) and fan diameter (1.397 m) were used for the reference area and length, respectively. The moment center was located on the engine centerline at the axis of rotation, 1.928 m aft of the inlet leading edge. Thrust coefficients were computed from gross thrust, which was determined from total and static pressure and total temperature measurements in the inlet, fan duct, and core engine inlet. Vane forces and moments were measured with two balances mounted at the attachment points of the vane to the boom. The vane flap links were strain gaged to provide corrections to the vane balance data. Vane coefficients were computed in the wind-axis system, normalized by the fan area and diameter, and transferred to the nacelle moment center. The axis system and sign convention are shown in Fig. 3.

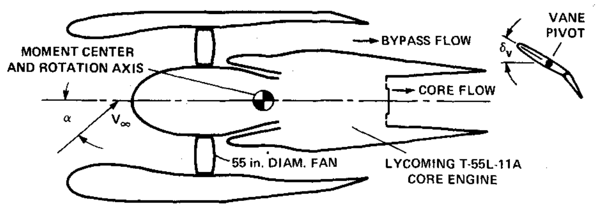
Results and Discussion

Aerodynamic Characteristics of Nacelle with Vane

Figure 4 shows the aerodynamic characteristics of the propulsion system with and without the vane for thrust coefficients of 10 and 20. The dashed lines represent the lift component of the thrust. Comparison of the vane-off results with the thrust force $C_J \sin\alpha$ shows a substantial aerodynamic lift on the nacelle.[4] In addition, there is a large vane contribution to the total nacelle forces and moments when the nacelle is at an angle of attack, even though the vane deflection angle is 0 deg. This, along with the nacelle aerodynamics, must be accounted for in the estimation of aircraft performance.

The effect of the freestream velocity on the engine exhaust is to turn the flow so that the vane is at an angle of attack even though the vane deflection angle is 0 deg with respect to the nacelle axis. Since the engine exhaust is turned more as angle of attack is increased, there is a substantial change in slope of the C_L vs C_m curve when the vane is added to the nacelle (Fig. 4). The increase in pitching moment as angle of attack increases is much smaller with the vane at 0 deg than without the vane. The addition of the vane at 0 deg deflection increases the maximum lift of the nacelle and it occurs at a lower angle of attack.

Figure 5 shows the nacelle aerodynamic characteristics at a constant thrust coefficient of 10 for several vane angles. The primary purpose of the vane is to provide longitudinal trim



BYPASS RATIO: 17:1
MAX. FAN SPEED: 3365 rpm
FAN AREA: 1.206m^2
FAN DIAMETER: 1.397m
FAN EXIT AREA: 1.064m^2
CORE EXIT AREA: 0.25m^2

Fig. 1 Nacelle schematic.

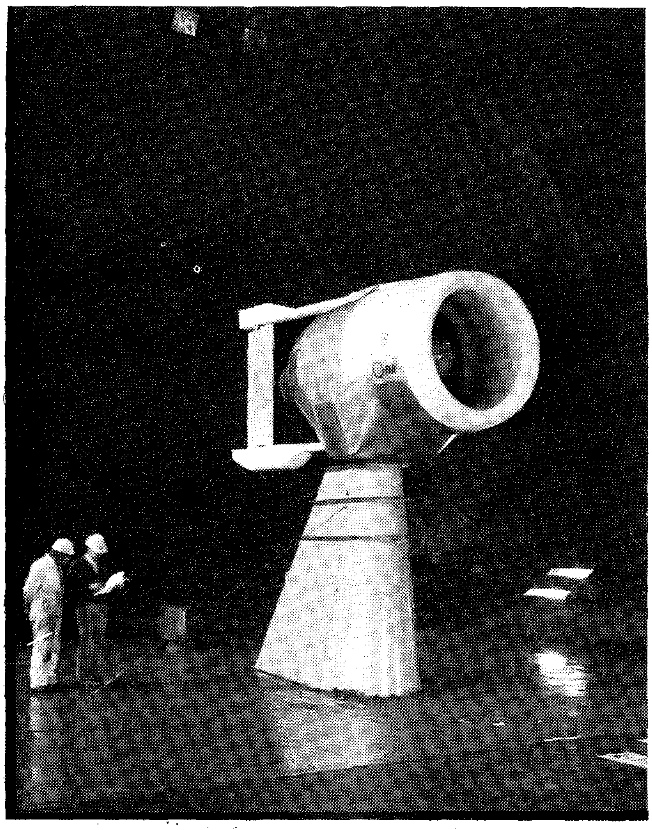
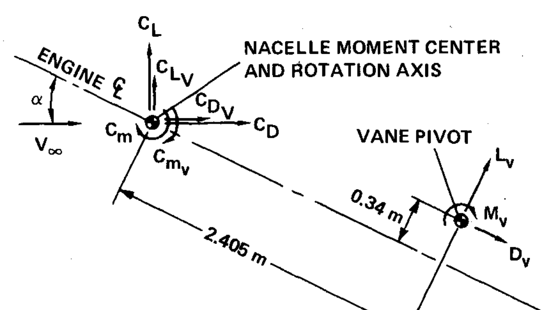


Fig. 2 Tilt-nacelle V/STOL propulsion system with control vane in the Ames 40 × 80 ft wind tunnel.



$$C_{L_V} = \frac{L_V \cos\alpha - D_V \sin\alpha}{qA_F}$$

$$C_{D_V} = \frac{D_V \cos\alpha + L_V \sin\alpha}{qA_F}$$

$$C_{m_V} = \frac{M_V - 2.405\, L_V + 0.34\, D_V}{qA_F d}$$

NOTE:
ALL PARAMETERS SHOWN IN POSITIVE DIRECTION

Fig. 3 Axis system and sign convention.

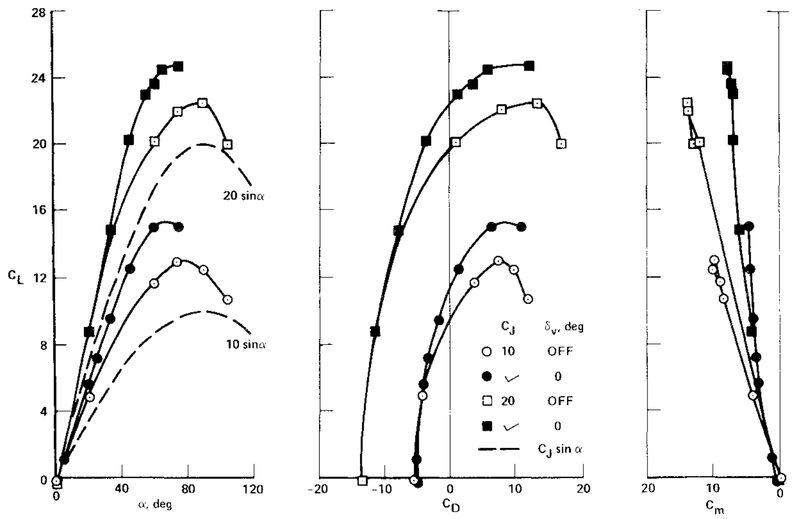


Fig. 4 Aerodynamic characteristics with and without control vane.

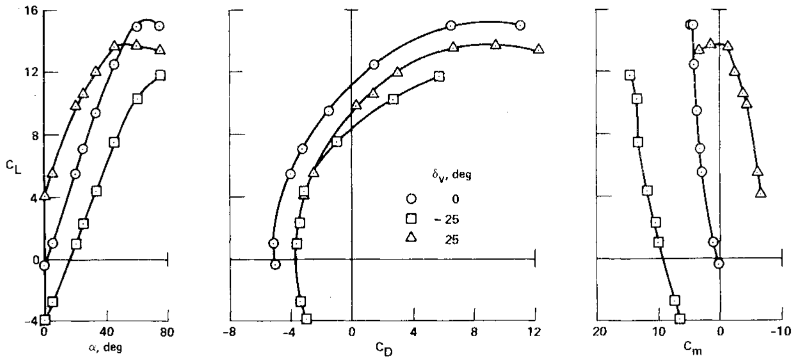


Fig. 5 Aerodynamic characteristics for various vane deflections, $C_J = 10$.

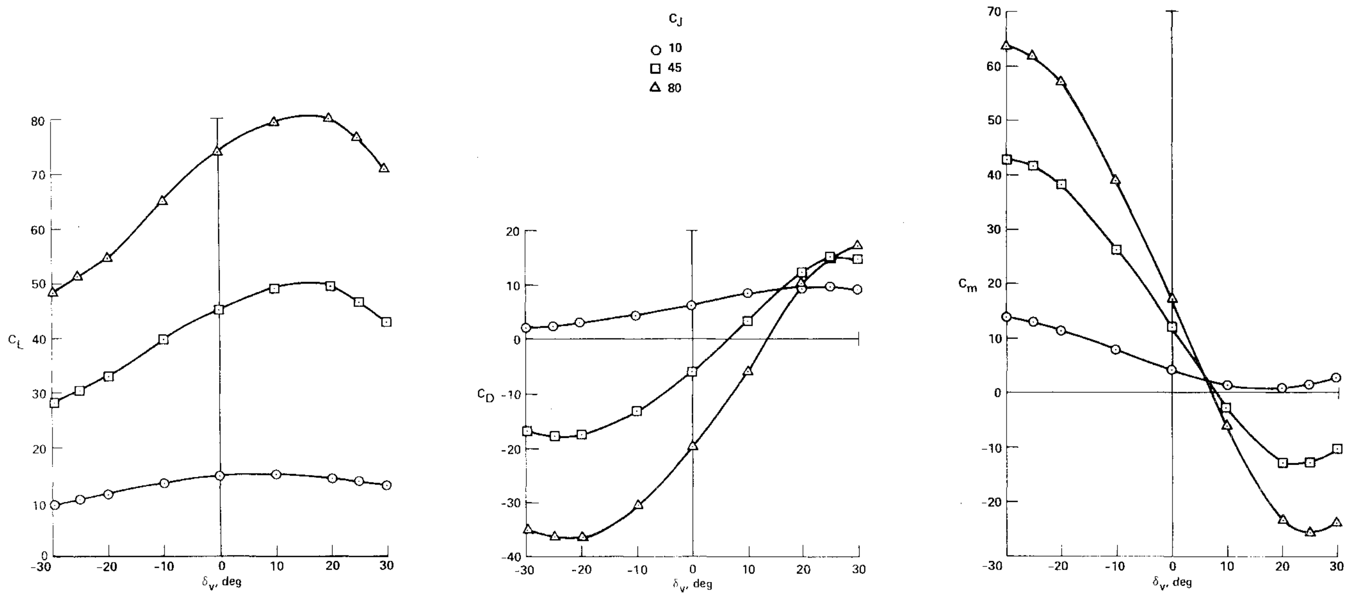


Fig. 6 Effect of vane deflection, $\alpha = 60$ deg.

and control. However, along with the large changes in pitching moment obtained by deflecting the vane, substantial changes in lift and drag are also produced. When the vane is deflected in a positive direction with the nacelle at a positive angle of attack, the freestream velocity increases the vane angle of attack, which causes the vane to stall at a lower nacelle angle of attack. This results in a lower maximum lift coefficient for a vane deflection of +25 deg than for 0 deg, as shown in Fig. 5. This also causes asymmetry of the pitching moment about $\delta_v = 0$ deg at high angles of attack. This asymmetry is also apparent in Fig. 6, which shows nacelle lift, drag, and pitching moment plotted vs vane deflection angle, at a 60 deg nacelle angle of attack for several thrust coefficients. The pitching-moment plot shows that this asymmetrical effect diminishes as thrust coefficient is increased. At a thrust coefficient of 80, the pitching-moment curve is almost symmetric because the freestream velocity has a very small effect compared to that of the jet velocity. When the nacelle angle of attack is 60 deg, maximum lift occurs at a lower vane deflection than the maximum pitching moment because the pitching moment contribution from the vane is a result of both vane lift and vane drag as well as vane pitching moment.

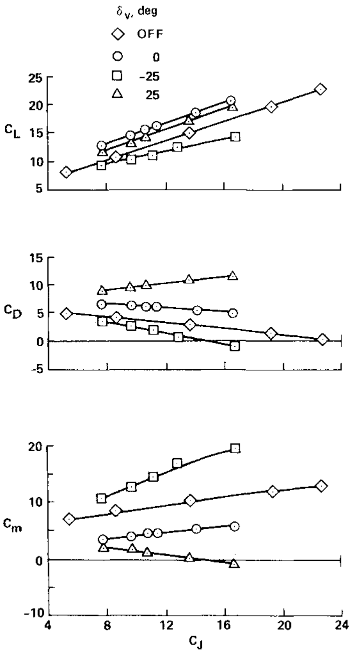


Fig. 7 Effect of thrust coefficient, $\alpha = 60$ deg.

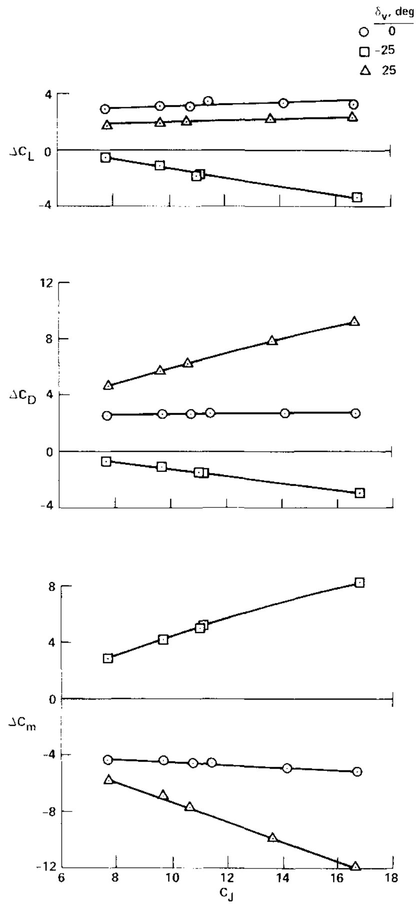


Fig. 8 Variation of vane effect with thrust coefficient, $\alpha = 60$ deg.

Effect of Vane

Figure 7 shows the variation of longitudinal components with thrust coefficient for a nacelle angle of attack of 60 deg and several vane angles. Figure 8 shows the incremental effects on the longitudinal components of placing the vane in the fan exhaust at several attitudes, as a function of thrust coefficient. The coefficients ΔC_L, ΔC_D, and ΔC_m were computed by subtracting vane-off data from vane-on data. Therefore, they represent the total vane effects, including induced effects and the effect of the vane support structure. The variation of the longitudinal components with thrust coefficient is essentially linear. Placing the vane in the exhaust at 0 deg deflection produces a substantial effect on all three components that is nearly independent of thrust coefficient over the range shown.

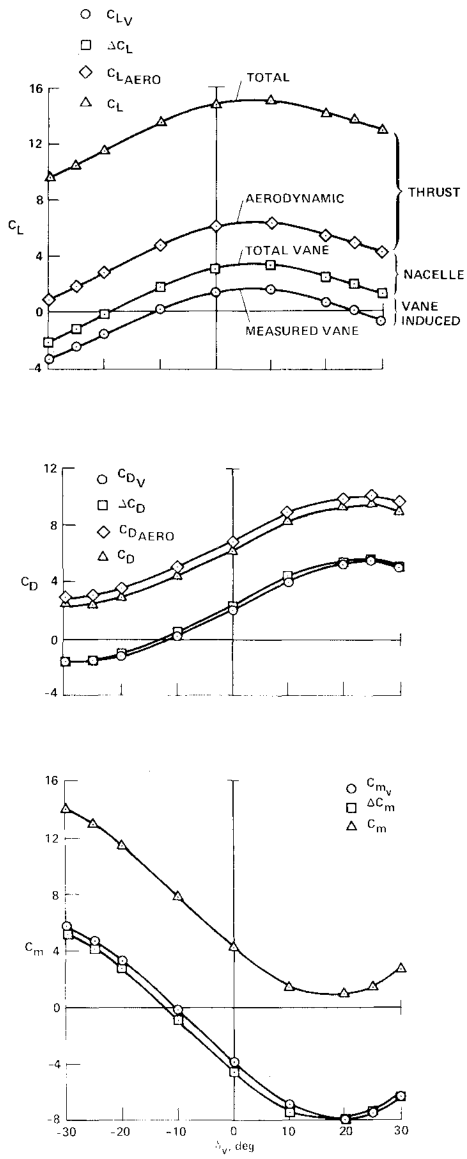


Fig. 9 Total force and moment components vs vane deflection angle, $\alpha = 60$ deg, $C_J = 10$.

Figure 9 shows total vane effects ΔC_L, ΔC_D, and ΔC_m as functions of vane deflection angle for a thrust coefficient of 10 and an angle of attack of 60 deg. Also shown are the vane forces and moments C_{L_v}, C_{D_v}, and C_{m_v} measured on the vane balances. The differences between the total vane effects and the measured vane loads are defined as the vane-induced effects. No attempt was made to separate the effect of the vane support structure which is included in the vane-induced effects. Aerodynamic lift and drag coefficients $C_{L_{aero}}$ and $C_{D_{aero}}$ were computed by subtracting the thrust and ram drag components from the total lift and drag and are shown in Fig. 9. The differences between the aerodynamic coefficients and the total vane effect coefficients represent the nacelle aerodynamic contributions. The aerodynamic pitching moment is not shown since the thrust and ram drag contributions to pitching moment could not be separated.[4] The

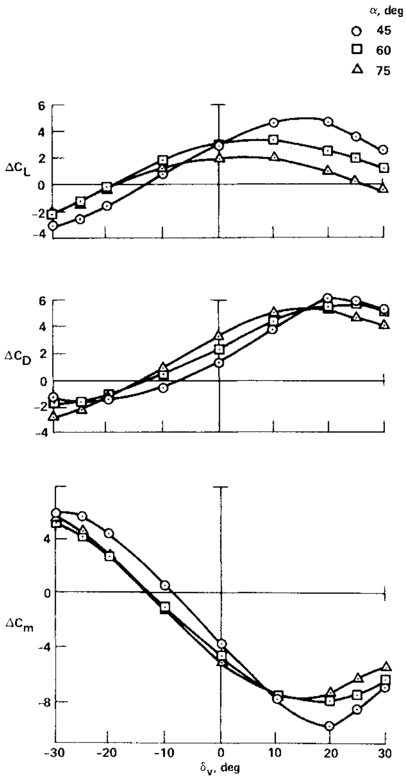


Fig. 10 Variation of vane effect with vane deflection angle, $C_J = 10$.

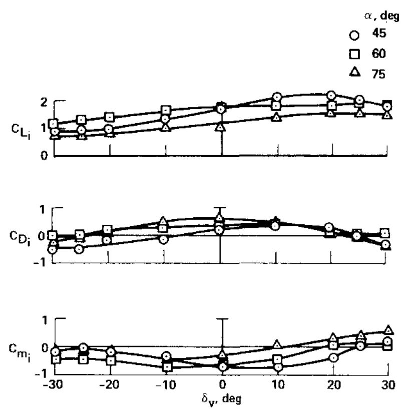


Fig. 11 Variation of vane-induced effects with vane deflection angle, $C_J = 10$.

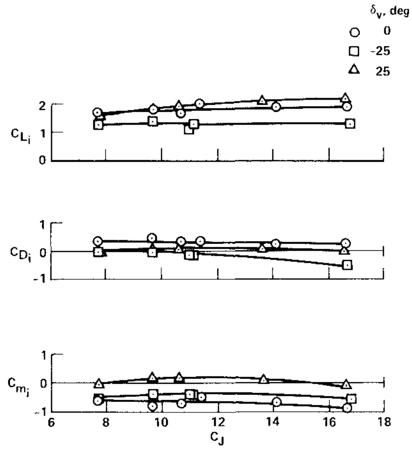


Fig. 12 Variation of vane-induced effects with thrust coefficient, $\alpha = 60$ deg.

total force and moment coefficients are also shown in Fig. 9. The differences between the total coefficients and the aerodynamic coefficients represent the thrust and ram drag contributions.

As shown in Fig. 9, each component of the total lift is significant. The vane-induced lift is 12-15% of the total lift and is relatively constant over the entire range of vane deflections. The vane-induced drag is relatively small and goes to zero at large vane deflection angles. As defined previously, the vane-induced drag is not drag due to lift but is the difference between the total vane effect on drag and the measured vane drag. The vane-induced pitching moment is a small negative increment except at high positive vane deflections where it goes to zero. Substantial changes in total lift and drag occur as a result of vane deflection. The total drag coefficient changes from a minimum of 2.3 to a maximum of 9.5 as the vane is deflected when the nacelle angle of attack is 60 deg and the thrust coefficient is 10. The vane is very effective in producing large changes in pitching moment and can be used to almost completely compensate for the large positive pitching moment resulting from the nacelle. Without the vane, the total pitching-moment coefficient for this condition is about 8.7, which can be reduced to 0.9 with the vane at a deflection of +20 deg.

To determine how the total vane effect changed as the nacelle angle of attack varied, the vane effects were plotted vs vane deflection angle for several angles of attack at a thrust coefficient of 10 (Fig. 10). The trends are the same for all three angles of attack with some variations in the magnitudes. For positive vane deflections, the increase in lift due to the vane is reduced as the nacelle angle of attack is increased. This is primarily because the resultant force on the vane has a smaller component in the wind-axis lift direction as angle of attack increases. A larger variation in vane lift is obtained due to vane deflection when the nacelle angle of attack is 45 deg, which results in a larger variation in pitching moment also. The drag contribution from the vane increases slightly for low vane deflections (±10 deg), as angle of attack increases. The maximum negative pitching-moment contribution from the vane occurs at a vane deflection between +15 and +20 deg for all three angles of attack. The maximum drag contribution also occurs in this range, but the maximum lift contribution occurs at a slightly lower deflection angle (+5 to +15 deg).

Figure 11 shows the vane-induced coefficients as functions of vane deflection angle for a thrust coefficient of 10 and several nacelle angles of attack. The vane-induced coefficients were determined by subtracting the measured vane coefficients from the total vane effect coefficients. Nacelle angle of attack has a very small effect on the induced aerodynamics. The vane-induced lift shows a slight increase as vane deflection goes from negative to positive. The vane-induced drag and pitching moment remain very small for angles of attack of 45, 60, and 75 deg. As discussed earlier, the induced lift is the most significant induced effect. At an angle of attack of 75 deg, the induced lift is slightly less than at 60 deg; at an angle of attack of 45 deg, there is a larger variation in induced lift as vane deflection changes than there is at higher angles of attack.

Figure 12 shows the induced effects plotted as functions of thrust coefficient for several vane deflections and a nacelle angle of attack of 60 deg. The induced effects show very little variation for thrust coefficients between 8 and 17. The induced lift for a −25 deg vane deflection remains lower than for the 0 and +25 deg vane angles throughout the range of thrust coefficients shown.

Conclusions

1) The aerodynamic forces due to the nacelle without the vane can be a significant part of the total forces produced by the propulsion system.

2) The control vane effectively produces large changes in pitching moment which are accompanied by significant changes in total lift and drag.

3) The vane has a substantial effect on the aerodynamics of the propulsion system, even when $\delta_v = 0$ deg.

4) The vane effects on C_L, C_D, and C_m for $\delta_v = 0$ deg are almost independent of thrust coefficient.

5) The maximum negative pitching-moment coefficient contribution from the vane occurs at a vane deflection between +15 and +20 deg for angles of attack between 45 and 75 deg and thrust coefficients about 10. For greater thrust coefficients the maximum negative pitching moment occurs at vane angles up to +25 deg.

6) The vane-induced lift is a significant component of the total lift, whereas, the vane-induced drag and pitching moment are relatively insignificant.

7) The vane-induced lift is always positive throughout the range of test conditions investigated.

8) The vane-induced effects are almost independent of thrust coefficients between 8 and 17.

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