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Aerodynamic Characteristics of a Large-Scale, Twin Tilt-Nacelle V/STOL Model

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The twin tilt-nacelle design is one of several subsonic V/STOL concepts which has evolved out of the search to develop an aircraft capable of operating from small ship platforms. This concept, developed by Grumman Aerospace Corporation, is powered by two turbofan engines mounted on a single carry-through structure designed to maintain the thrust axis close to the aircraft's center of gravity at nacelle incidences between 5 and 95 deg. Aircraft control during V/STOL operation is provided by a vane assembly submerged in turbofan exhaust. To investigate the transition capability of the concept, a large-scale model with a 11.2-m wing span and powered by two TF-34 turbofan engines was fabricated and tested under a cooperative program between NASA, Navy, and Grumman. The wind-tunnel results indicate that the concept can operate over a broad transition corridor with ample maneuver capability about the trim points. The control vane concept exhibited a strong linear response characteristic over a wide deflection range which was generally unaffected by power, angle of attack, or ground proximity in hover. While operating in the hover mode the model experienced a positive ground effect that increased as wheel height was approached and strake angle increased.

Nomenclature

A = engine exit area, m^2 (ft^2)
b = wing span, m (ft)
c = mean aerodynamic wing chord, m (ft)
C_D = drag coefficient = drag/qS_W
$C_{D_{TR}}$ = drag coefficient with direct thrust component and ram drag removed
C_L = lift coefficient = lift/qS_W
$C_{L_{TR}}$ = lift coefficient with direct thrust component removed
C_l = rolling moment coefficient = roll moment/qS_Wb
$C_{m_{CG}}$ = pitching moment coefficient = pitching moment/qS_Wc, referenced to aircraft center of gravity
$C_{m_{CGTR}}$ = pitching moment coefficient with direct thrust removed
C_n = yawing moment coefficient = yawing moment/qS_Wb
C_y = side force coefficient = side force/qS_W
C_μ = momentum coefficient = $2F_g/qS_W$
d = fan diameter, m (ft)
F_g = engine gross thrust, N (lb)
h = height from ground to fuselage lower surface, m (ft)
i_s = horizontal tail incidence, deg
L = lift force, N (lb)
PMT = hover pitching moment ratio = pitching moment/$2F_gc$
S_W = wing reference area, m^2 (ft^2)
V_∞ = freestream velocity, knots
W_C = corrected engine mass flow, kg/s (lb/s)
YMT = hover yawing moment ratio = yawing moment/$2F_gb$
α = model angle of attack, deg
δ_n = nacelle deflection, deg
δ_{HV} = horizontal vane deflection, positive trailing edge down, deg
δ_{VV} = vertical vane deflection, positive trailing edge left, deg
$\Delta\delta_{HV}$ = differential horizontal vane deflection, left vane negative and right positive, deg
γ = climb angle, deg
θ = hover attitude angle, deg

Introduction

FOR several years, NASA, the Department of Defense, and several aircraft companies have been investigating V/STOL aircraft concepts with an eye toward improving the operational and basing versatility of military aircraft. Much of this effort has been to develop a subsonic aircraft capable of performing antielectronic warfare (AEW), antisubmarine warfare (ASW), and air-sea rescue roles while operating from small carriers.

One concept that has evolved out of this research is a twin tilt-nacelle design developed by Grumman Aerospace Corporation (GAC). This concept is powered by two turbofan engines mounted on a single carry-through structure designed to maintain the thrust axis close to the center of gravity at nacelle incidences between 5 and 95 deg. Aircraft control during V/STOL operation is provided by vertical and horizontal vanes suspended in the turbofan exhaust and differential engine thrust. This design greatly reduces the longitudinal trim power required for transition.

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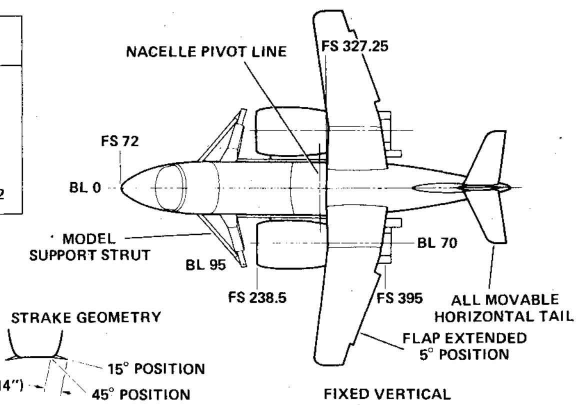
	WING	HORIZONTAL TAIL	VERTICAL TAIL
SPAN, m (ft)	11.18 (36.67)	3.56 (11.67)	–
AREA, m^2 (ft^2)	16.44 (177)	3.07 (33)	3.53 (38)
ASPECT RATIO	7.6	4.1	.95
LEADING EDGE SWEEP, DEG	2.5 / –7.5	25	40
TAPER RATIO	0.466	0.489	.53
DIHEDRAL DEG	0 / 13 / –7	0	
AIRFOIL	–	NACA 64A012	NACA 64A012

ALL DIMENSIONS IN m (ft)



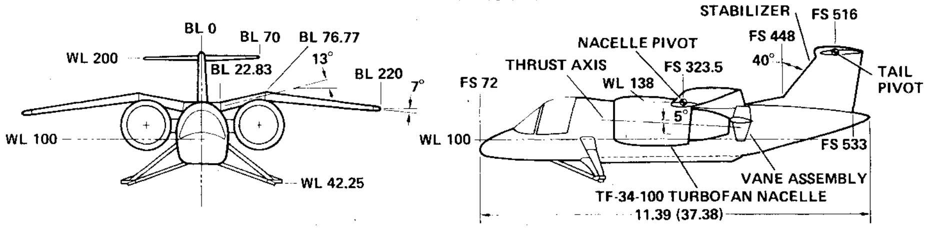


Fig. 1 Twin tilt-nacelle model geometry.

Many hours of research with wind-tunnel and radio control models[1-5] have culminated in the fabrication of an 11.2-m-span twin tilt-nacelle model powered by TF-34-100 turbofans. This program was a cooperative effort between NASA, Navy, and GAC to investigate the V/STOL transition capability of the concept.

This paper presents the preliminary results of the model transition characteristics measured during a recent investigation in the Ames 40×80-ft Wind Tunnel and initial results from the investigation of its hover characteristic in and out of ground effect at the Ames Static Test Facility.

Model Description

The model geometric details are presented in Fig. 1. The basic airframe structure, fabricated by NASA, includes the fuselage, wing, empennage, and support struts. The empennage consisted of a fixed vertical stabilizer and remotely controlled all-movable horizontal tail. The 11.2-m gull wing had a 7.5-deg forward-swept leading edge and a trailing-edge flap fixed at 5 deg. The fuselage was equipped with longitudinal strakes designed to house conformal radar on a military aircraft. For the wind-tunnel test, the strakes were fixed at 15 deg; for the hover test, both 15- and 45-deg deflections were investigated.

The propulsion assembly was designed and fabricated by GAC. It consists of two TF-34-100 turbofan engine nacelles joined by a cross-box structure passing over the top of the fuselage ahead of the wing. The TF-34 lubrication system was modified by General Electric to provide adequate gearbox and bearing lubrication throughout the nacelle incidence range. Aft of each nacelle, immersed in the fan efflux, is a vane assembly consisting of a horizontal vane equipped with a 30% chord trailing-edge flap and twin vertical vanes (see Fig. 2). The vertical vanes are mounted on the horizontal vane and move with it. The entire vane assembly is supported from the cross-box structure by an inboard boom. During vertical flight, pitch and yaw are controlled by symmetric and differential deflection of the horizontal vanes. Vertical vane deflection and differential thrust provide roll control. Prior to the design of the large-scale model, the vane assembly concept was tested on a T55/Q-fan nacelle in the Ames 40×80-ft Wind Tunnel and GAC Static Test Facility.[3,4] These tests demonstrated the feasibility of using the high dynamic pressure of the turbofan exhaust for V/STOL control.

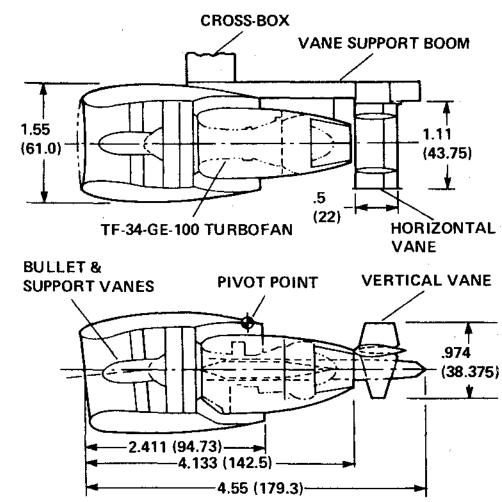


Fig. 2 Nacelle-vane geometry.

The TF-34's were equipped with specially designed inlets to prevent flow separation and high inflow distortion over the range of inflow angles and mass flows necessary for V/STOL operation while maintaining good up-and-away conventional flight performance. The inlet geometry was developed during a series of tests using a 50.8-cm (20-in.) fan nacelle[2] and then adapted to the TF-34 requirements. The basic design philosophy was similar to that of the inlet on the T55/Q-fan nacelle reported in Ref. 3 in that it was an asymmetric design with a higher contraction ratio on the windward lip than on the leeward lip.

The propulsion unit was highly instrumented to measure the overall forces and moments, vane loads, gross thrust, vane installation losses, and external aerodynamics. The TF-34's were also instrumented to monitor engine health, especially the lubrication system.

Test Description

The model underwent a series of two investigations: a test in the 40×80-ft wind tunnel and a hover test. After a successful functional check of the propulsion system, the model was installed in the test section of the wind tunnel. The primary objective of the wind-tunnel investigation was to determine the V/STOL transition envelope including static stability and control derivatives. These tests also produce inlet performance boundaries, nacelle external aerodynamics, and induced aerodynamics. The test covered the following range of variables:

$$V_\infty = 40\text{-}160 \text{ knots}$$
$$\alpha = -4\text{-}18 \text{ deg}$$
$$\beta = -25\text{-}10 \text{ deg}$$
$$\delta_n = 5\text{-}68 \text{ deg}$$
$$\delta_{HV} = \pm 25 \text{ deg}$$
$$\delta_{VV} = \pm 20 \text{ deg}$$
$$i_s = \pm 25 \text{ deg}$$
$$F_g = \text{idle-}28{,}500 \text{ N (6400 lb)}$$

The wind-tunnel data have not been corrected for wall effects. Previous comparisons of results[6] from models and aircraft in the wind tunnel and flight have shown wall effects to be small during accelerating and trimmed flight. Corrections for V/STOL untrimmed, decelerating flight conditions are a strong function of the model propulsion configuration, making it difficult to accurately predict them with existing theoretical techniques.

The hover test was performed at the Ames Static Test Facility to evaluate hover performance and control in and out of ground effect (Fig. 3). To achieve this objective, the engine operational envelope was extended to $\delta_n = 93$ deg, requiring several additional modifications to the lubrication system. Following calibration of the engine thrust, tests were performed at three ground heights ($h/d = 5.07$, 1.5, and 1.15) and two strake deflections (15 and 45 deg). The ground height ratios are based on a fan diameter of 111.8 cm (44 in.). At the lowest ground height ($h/d = 1.15$), the horizontal vane trailing edge was 0.91 m (3.0 ft) above the ground plane. At each of these test configurations, the effect of model attitude, control deflection, power setting, and nacelle incidence was investigated.

Results and Discussion

The primary objective of the twin tilt-nacelle V/STOL program was to investigate the capability of this concept to perform various military and civilian V/STOL roles. Toward this end, the large-scale model program was initiated to:

1) investigate its V/STOL transition capability from hover to up-and-away conventional flight;

2) demonstrate the capability of a typical, commercially available turbofan engine equipped with a special inlet to operate in the unique environment encountered with V/STOL operation;

3) develop a data base for programming flight simulators;

4) develop scaling parameters.

The data presented are preliminary in that the final reduction process did not occur in time to incorporate here. The final computation may alter these data slightly but will not alter the conclusions.

Basic Longitudinal Characteristics

To completely document the transition corridor, the model was investigated over a wide range of nacelle incidences, power settings, angle of attack, and forward speeds. The basic longitudinal characteristics derived from the tests are summarized in Figs. 4 and 5. Figure 4 shows that, over the range of C_μ investigated, lift was directly proportional to C_μ for a constant α as was C_D for a constant C_L. Power, C_μ, had only small effects on lift curve slope or polar shape. The pitching moment characteristics indicate only small power effects on stability or control required for trim, indicating that all forces associated with the propulsion system were acting close to the aircraft's center of gravity. This includes ram drag and in-

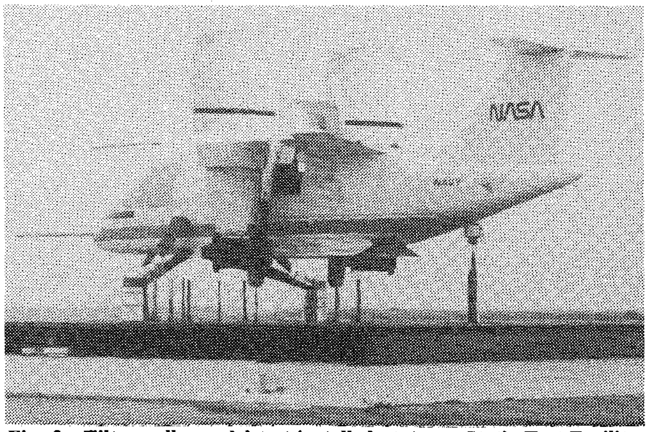


Fig. 3 Tilt-nacelle model test installed at Ames Static Test Facility; $h/d = 1.15$.

duced forces as well as the direct engine thrust. As expected, varying δ_n produces large change in lift and drag (see Fig. 5). The lift curve slope decreases with increasing δ_n and at low α lift is directly proportional to δ_n to the first order. The longitudinal static stability was neutral at $\delta_n = 5$ deg and became increasingly positive with δ_n. Nacelle incidence also creates a positive shift in the C_m trim point, which was well within the control capability of the horizontal vanes.

Nacelle deflection and power obviously strongly influence the longitudinal characteristics as a result of the direct thrust force, ram drag, and induced forces acting on the airframe. To evaluate the magnitude of the induced forces, the components of the gross thrust in the lift and drag direction were removed from the overall forces. The ram drag was also subtracted from the drag data. Figure 6 summarizes the thrust removed characteristics for several nacelle incidences. The presence of the propulsion system induces a positive lift force which is small compared to the direct thrust component and increases with δ_n up to 60 deg. The propulsion system has a strong induced drag effect, especially at high δ_n, due in part to the shape of the cross-box structure between the nacelles. The propulsion system induced a positive pitching moment on the airframe but had little effect on the static stability. The moment shift is due partly to ram drag which was not removed from $C_{m_{CGTR}}$ because the point of action of this force is not known accurately.

Vane Control Effectiveness

The hover and low transition speeds encountered during V/STOL operation require the use of propulsion forces for control power rather than the aerodynamic forces used in conventional aircraft, with the magnitude of the control power usually being sized by the hover requirements. This and the need for sizable trim forces in transition generally penalizes the V/STOL aircraft cruise performance. To minimize these penalties, the twin tilt-nacelle concept minimizes pitch trim requirements through V/STOL transition by maintaining the line of action of the forces associated with the propulsion system near the center of gravity at all nacelle incidences. This includes the direct engine thrust, ram drag, and induced forces. The required trim and maneuver control power was provided by the vane assembly submerged in the turbofan exhaust.

The longitudinal control is provided by symmetric deflection of the horizontal vanes. The high dynamic pressures of the exhaust produce a very powerful control device with linear response characteristics over a wide deflection range, both in hover and through transition (see Figs. 7 and 8). In hover, the response is linear until the vane reaches a negative attitude where it begins to come out of the fan efflux. At forward speed, the response becomes nonlinear at $\delta_n > 15$ deg as the freestream velocity inhibits the vane flow

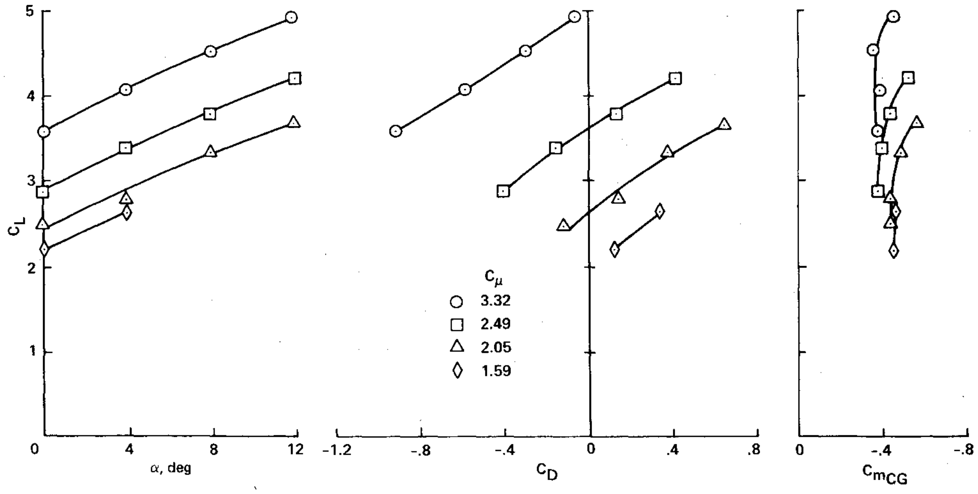


Fig. 4 Effect of power on longitudinal characteristics; $\delta_n = 50$ deg.

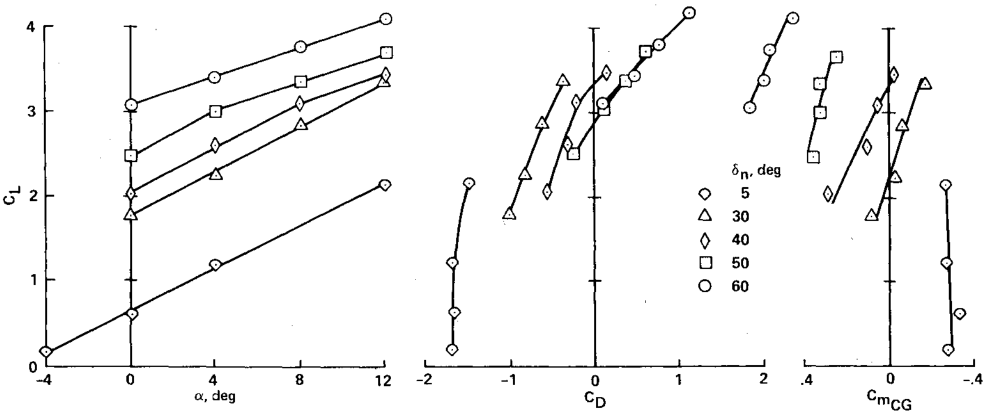


Fig. 5 Effect of nacelle deflection on longitudinal characteristics; $C_\mu = 1.9\text{-}2.5$.

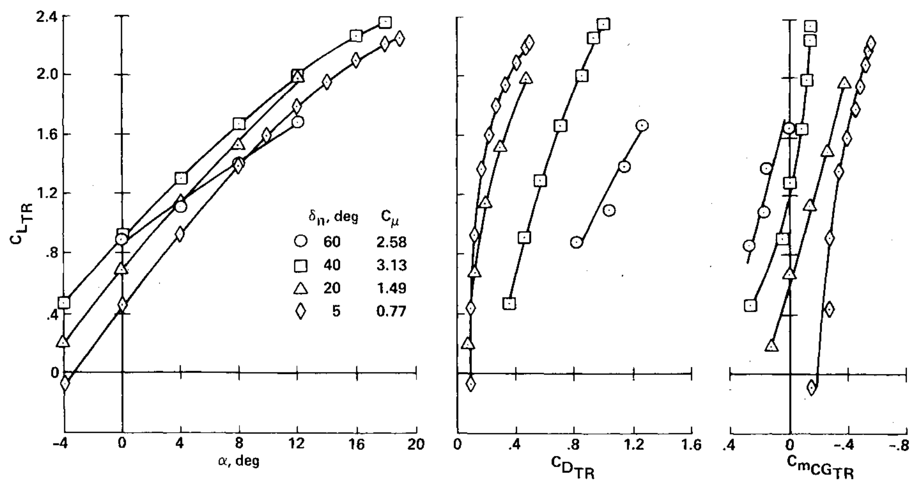


Fig. 6 Aerodynamic characteristics with direct thrust removed.

turning capability. At all transition points investigated, a horizontal vane deflection of less than 10 deg was necessary to trim the pitching moment, leaving large control capability for maneuvering. This control effectiveness is generally not affected by variations in power or angle of attack. In hover, the aircraft must rely entirely on the propulsion system for control. As the vehicle approaches the ground, the controls must remain effective as the exhaust impinges on the ground and airframe. The twin tilt-nacelle longitudinal control effectiveness and trim point were not affected by the ground even at heights approaching touchdown (Fig. 8).

Lateral and directional control in hover is provided by the vertical vanes and differential horizontal vanes, respectively, with differential thrust providing additional lateral control. As the aircraft proceeds through transition to conventional flight, these control modes reverse with decreasing δ_n. As with longitudinal control, the vane system generates strong control forces capable of providing roll and yaw accelerations in excess of 1.0 rad/s^2 for an aircraft with a gross landing weight of 6191 kg (13,654 lb). The horizontal and vertical vanes are capable of creating either pure roll or yaw moment with a side force when combined (see Fig. 9). For instance, the combination of positive vertical vanes and differential horizontal vanes will generate a pure negative roll moment because the differential horizontal vanes can be adjusted to cancel the yawing moment created by the vertical vanes while producing additional negative roll moment. As for symmetric deflection of the horizontal vanes, differential horizontal vane control

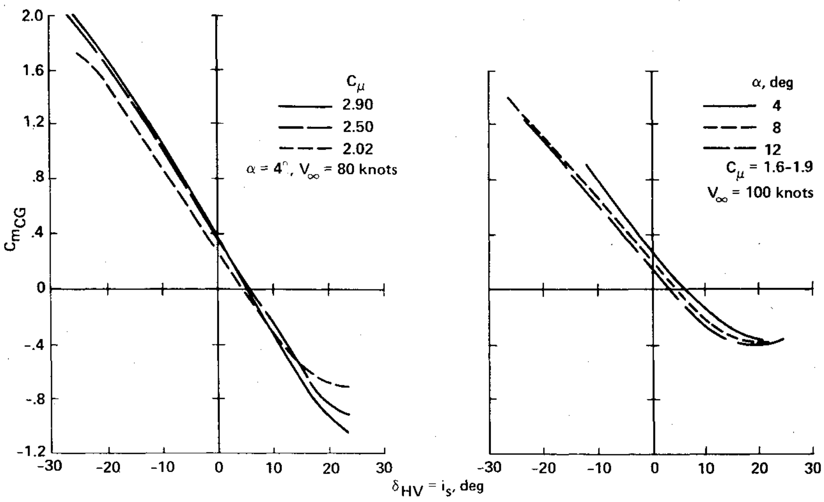


Fig. 7 Longitudinal control effectiveness; $\delta_n = 50$ deg.

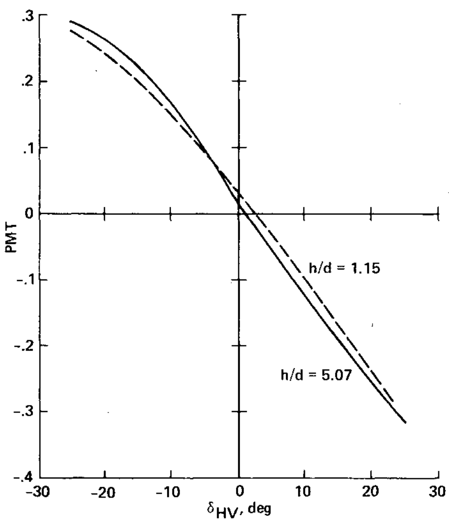


Fig. 8 Effect of ground proximity on longitudinal control effectiveness; $\delta_n = 90$ deg, $\theta = 0$ deg.

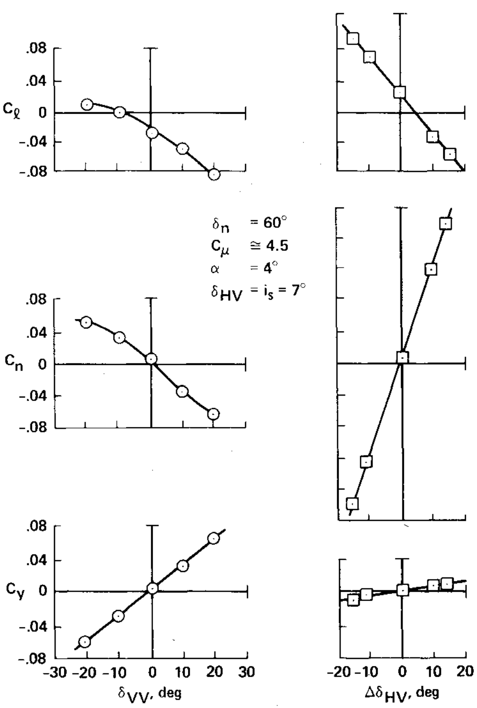


Fig. 9 Lateral/directional control.

effectiveness during hover was not affected by ground proximity (see Fig. 10). Because the load cells used to measure the model forces during the hover test were not gaged to measure side force, it was not possible to investigate the vertical vane effectiveness in hover.

Inlet Performance

The propulsion system was equipped with inlets designed to provide the engine with uniform flow while minimizing losses over the extreme ranges of velocity, nacelle incidence, and mass flow encountered during V/STOL operation. The inlet geometry was developed through a series of tests with small-scale models[2] and then adapted to the TF-34. The principal modification for the engine installation was to replace the large spinner (coaxial with the fan centerline) used on the small model with a fixed bullet (coaxial with the drooped inlet centerline) supported by four struts. This modification produced a higher inlet diffuser angle in the TF-34 inlet than was tested on the small model.

To ensure safe engine operation, the initial wind-tunnel test runs established the inlet separation and distortion boundaries. The inlet diffuser separation was measured with a boundary-layer probe mounted near the fan face on the lower diffuser wall. Fan inflow distortion limits were deduced from strain measurements on 12 fan outlet guide vanes. The strain limits were based on strain/distortion correlations provided by GE from previously performed TF-34 experiments. To establish these boundaries, freestream velocity and engine power were held constant while nacelle incidence was increased until either diffuser separation or outlet guide vane (OGV) strain limits were encountered. This was repeated for each velocity and power setting to be investigated.

The 80-knot boundary for the TF-34 inlet is compared with the small-scale inlet boundary and the boundary for a similar large-scale inlet on a T55/Q-fan nacelle[5] in Fig. 11. For a given specific mass flow, the TF-34 inlet flow separated at lower angles than either of the other inlets. Its boundary is 8-10 deg below the small-scale model consistently over the full freestream velocity range investigated. In most cases, all other factors being equal, Reynolds number effects delay the onset of separation in a larger inlet. This loss in performance most likely results from a combination of the design modifications and airframe-induced, flowfield differences. Tests are now being planned to duplicate the bullet installation on the 50.8-cm (20-in.) fan nacelle to evaluate the geometry effects. When the large-scale model is tested in the 80 × 120-ft wind tunnel, an effort will be made to determine the flow upwash in the region of the inlet.

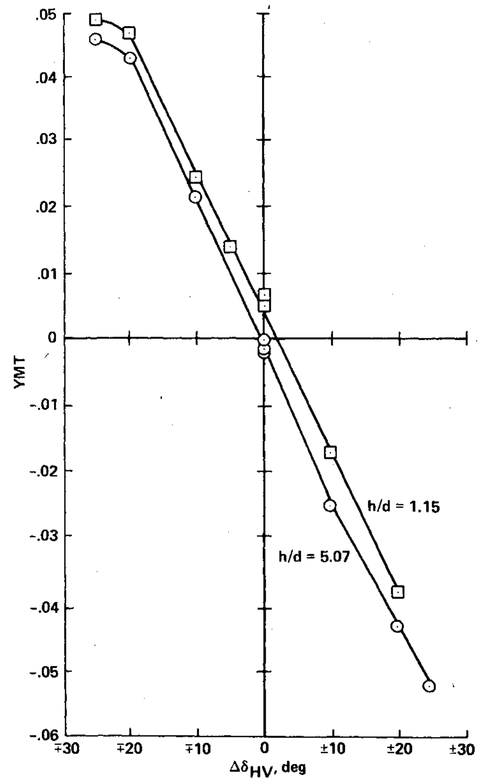


Fig. 10 Effect of ground height on directional control in hover; $\delta_n = 90$ deg, $\theta = 0$ deg, strake = 15 deg.

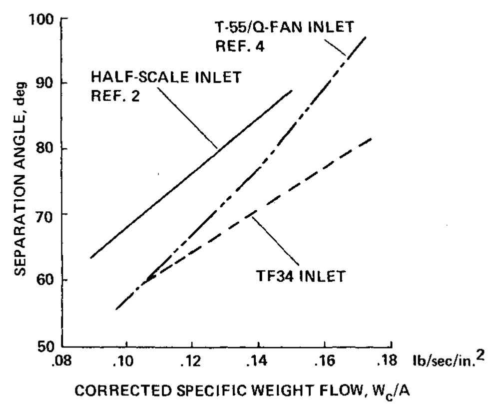


Fig. 11 Inlet separation characteristics; $V_\infty = 80$ knots.

Transition Performance

To enable a V/STOL aircraft to operate from different platforms under a variety of weather conditions and operational roles, it must be capable of operating over a wide transition corridor. The trimmed transition conditions investigated with the large-scale model are summarized in Fig. 12. Even with the inlet operating below its potential, the twin tilt-nacelle concept can fly at climb and descent angles of 25 deg over a wide velocity range. This operational flexibility is again demonstrated in Fig. 13 where trimmed transition at constant γ is present. The thrust required ratio for these transition paths are presented in Fig. 14. The wind-tunnel results indicate that the twin tilt-nacelle concept can operate over a broad transition corridor with ample maneuver capability about the trim points.

Hover Characteristics

The objectives of hover investigation were: 1) to measure the variation in lift with ground height and strake con-

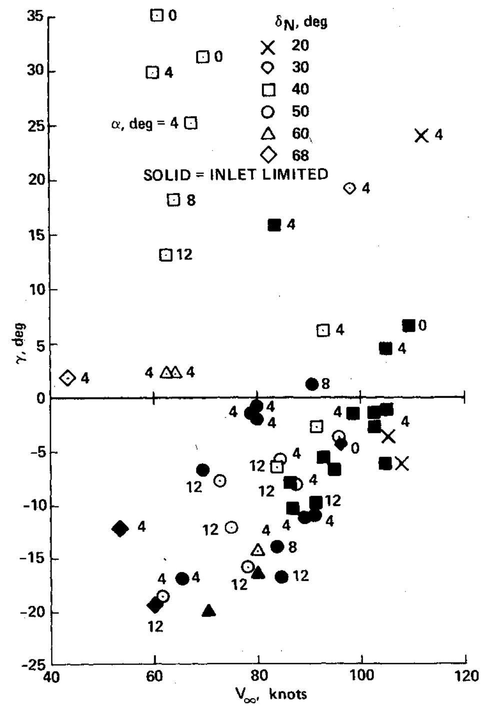


Fig. 12 Twin tilt-nacelle climb capability; $C_{m_{CG}} = 0$, landing weight = 6191 kg (13,650 lb).

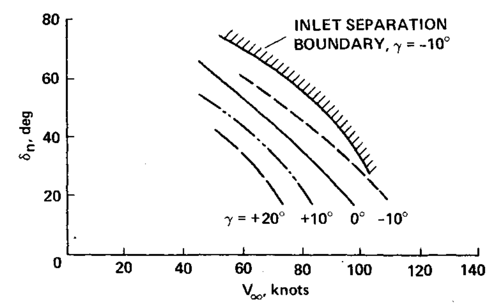


Fig. 13 Transition flight characteristics for twin tilt-nacelle concept; $\alpha = 12$ deg.

figuration, 2) to measure control effectiveness in and out of ground effect, and 3) to determine operational limits created by inlet exhaust gas ingestion. As previously discussed, ground proximity had little effect on the control effectiveness of the horizontal vanes. Of equal importance, no significant exhaust gas ingestion was experienced at any of the conditions investigated, including runs made with crosswinds up to 10 knots.

Numerous V/STOL research programs have shown that a V/STOL aircraft can experience either positive or negative lift changes as they approach the ground, depending on their engine number and spacing, planform shape, and fuselage contour. The twin tilt-nacelle concept experienced a positive lift change as the ground was approached (see Fig. 15). This lift was created by the fountain which was formed when the two exhaust streams merged under the fuselage. The large variations in this lift show this fountain to be an unstable phenomenon. Increasing the strake deflection captured and stabilized more of the fountain flow indicated by the higher, more repeatable lift force. The magnitude of the lift and its fluctuation decreases rapidly with increasing ground height as the fountain formation weakens. This unstable fountain also manifested itself in random variations in rolling moments as the fountain stagnation point shifted laterally on the fuselage. This stagnation point motion was observed on the fuselage lower surface static pressures.

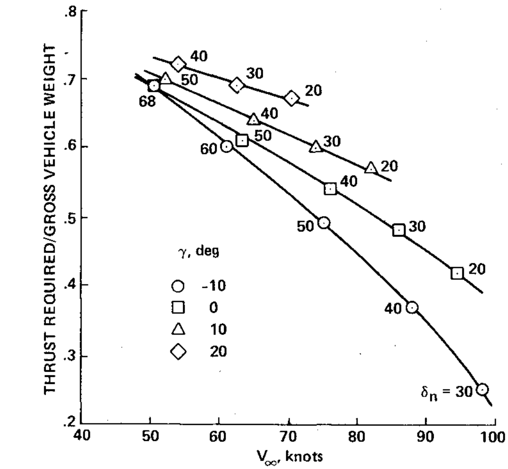


Fig. 14 Thrust/weight ratio for trimmed transition; vehicle weight = 7290 kg (16,082 lb).

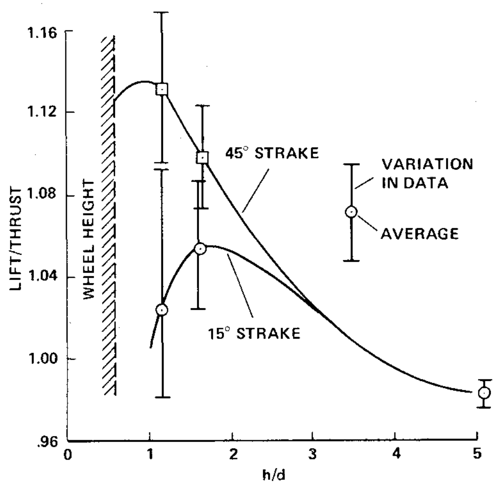


Fig. 15 Variation or lift with ground height in hover; $\delta_n = 90$, $\theta = 0$ deg.

Conclusions

The large-scale, twin tilt-nacelle model program has been highly successful, completing the wind-tunnel and hover tests and fulfilling all the principal research objectives. The following specific conclusions can be drawn from an analysis of the preliminary data presented here:

1) The twin tilt-nacelle concept proved capable of operation over a wide transition envelope with ample control for maneuvering about the trim points.

2) The model experienced a positive but variable ground effect in hover.

3) The vane control effectiveness was not affected by ground proximity in hover.

4) The concept can be operated in ground effect with no significant inlet exhaust gas ingestion.

5) The TF-34 inlets experienced separation earlier than predicted by small-scale, isolated nacelle tests, most likely due to design differences and airframe installation effects.

6) With relatively simple modifications to the lubrication system, the TF-34 turbofans operated continuously at high power at nacelle incidents up to 90 deg.

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