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Lift-Cruise Fan V/STOL Configuration Characteristics near a Small Deck

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Two V/STOL model configurations utilizing lift-cruise fans for the propulsion system have been tested in the presence of a small landing platform with finite deck edge positions. Results and analysis of these tests are presented. The model was tested at both static (zero velocity) and forward speed conditions with several heights and deck edge positions. Configurations utilizing three and four fans were investigated. Incremental forces and moments induced by the various deck edge positions are analyzed as relating to the model height above the ground and the thrust velocity relationships. The test and analysis show the induced forces to be relatively unaffected by deck edge. The magnitude of forces over the partial deck are approximately the same as over the full deck.

Nomenclature

b	= wing span (8.209 ft)
$\bar{c}$	= mean aerodynamic chord (1.06 ft)
C_D	= total drag coefficient, D/qS
$C_{D_{aero}}$	= aerodynamic drag coefficient
C_{D_R}	= ram drag coefficient
C_l	= total rolling moment coefficient $\sim RM/qSb$
$C_{l_{aero}}$	= aerodynamic rolling moment coefficient
C_L	= total lift coefficient $\sim L/qS$
$C_{L_{aero}}$	= aerodynamic lift coefficient
C_M	= total pitching moment coefficient $\sim PM/qS\bar{c}$
$C_{M_{aero}}$	= aerodynamic pitching moment coefficient
C_T	= thrust coefficient, T/qS
D	= drag
h	= height measured to fuselage bottom
h/D	= height measured to fuselage bottom/diameter of one fan
L	= lift
q	= freestream dynamic pressure
PM	= pitching moment
RM	= rolling moment
S	= reference area (8.36 ft^2)
T	= total measured thrust
α	= angle of attack
δ_N	= nozzle angles
Δ	= power-induced effects
ϕ	= bank angle
θ	= thrust angle

Introduction

THE operation of V/STOL airplanes may require takeoff and landings from small elevated landing platforms. These small platforms will have edges which may influence the characteristics of the airplane. Many studies have been done which have investigated the induced effects of various thrust systems used for VTOL operation on the airplane. These studies have been done either in free air or over a full ground board. The purpose of this paper is to report on a study to determine the effect of the deck edges on the induced aerodynamic characteristics of a typical V/STOL configuration utilizing lift-cruise fans for the lift-propulsion system.

It was recognized that the induced characteristics are configuration dependent, and two different concepts were investigated to determine the results of the proximity to the deck edge. The effects of the deck edge were extrapolated to full scale, and the amount of control required to trim the forces are compared to the AGARD V/STOL requirements. The two concepts represented a three- and a four-fan concept. The four-fan concept was tested at conditions representing VTOL operation at wind over the deck speeds and at STOL conditions. The three fan was tested at VTOL conditions only.

Model

The basic model, Fig. 1, utilized for the experimental studies of this test, was a four-fan model scaled to approximately 1/8 scale of a multimission type airplane.

The model consisted of a supercritical, 15% thick airfoil mounted on the fuselage shoulder with two wing-mounted nacelles housing the engine simulators. The fuselage was square shaped with rounded corners, and the horizontal tail was mounted high on the single vertical tail. The wing was essentially unswept and had a taper ratio of 0.5 and an aspect ratio of 8. Two wing-mounted nacelles housed the engine simulators.

The model had four 5-1/2-in. tip driven fans mounted in two wing nacelles, two fans in each nacelle. Figure 2 shows the model nacelle configuration. One fan is mounted in the forward section of the nacelle in a conventional manner. The thrust from this fan is vectored from 0 to approximately 120 deg through two swivel nozzles, one on either side of the nacelle. The other fan is mounted in the aft section of the nacelle in a horizontal plane. The thrust of this fan can be vectored from 45 to 120 deg by a set of external turning vanes.

The model was modified to provide a three-fan concept by placing a fan in the fuselage nose and utilizing the two aft fans of the four-fan concept. A mounting similar to the aft nacelle fans was used. This configuration was investigated at deflections and forward speeds representing VTOL operations at reasonable wind over the deck speeds (see Fig. 3). The fan inlet was circular and located ahead of the windshield. The exit was simulated by louvers mounted to the fuselage bottom. Both the inlet and exit were closed during four-fan simulation. The forward nacelle-mounted nozzles were removed and faired over during three-fan testing, and the vertical inlet of the forward fan was plugged with a semicircular faired nose plug.

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Index categories: Aerodynamics; Performance; Testing, Flight and Ground.

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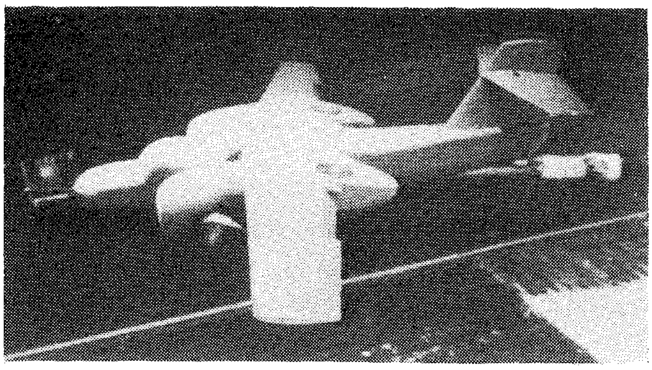


Fig. 1 Wind-tunnel model.

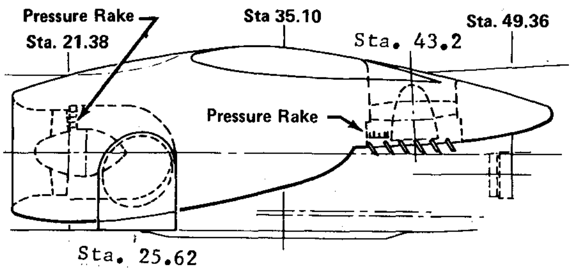


Fig. 2 Nacelle fan installation.

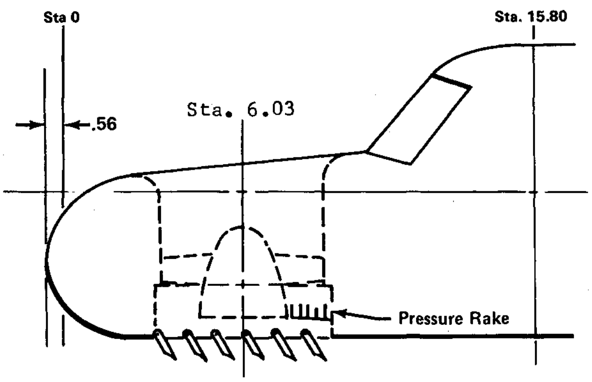


Fig. 3 Nose fan installation.

The ground board fabricated for the investigation was made in sections to provide the required edge positions. The five deck positions are shown in Fig. 4.

The full and lateral partial board configurations were identical for both static and wind-on testing, while the longitudinal board configurations differed slightly during the static or wind-on testing. During the static testing, the board was segmented, and either the front or aft portion was removed. The forward or aft edge was located at the model center of gravity (0.25 $\bar{c}$), and the board extended either aft or forward to overhang the model length by approximately 6 in. During the wind-on tests, the board length was maintained at 8 ft and was moved forward or aft to provide the desired deck edge position under the center of gravity. The overhang was therefore increased from 4 to 5 ft. It is not felt that this change would materially affect the deck edge effects.

Test Procedure and Data Reduction

The induced loads were determined at static ($V=0$) and at forward speed ($V>0$) conditions. The forward speed tests were conducted in the 14.5 × 21.75-ft V/STOL wind tunnel of the Langley Research Center. Static tests were conducted at the contractor's test facility. Figure 5 shows the model mounted in the LaRC tunnel, and Fig. 6 shows the model in the static test stand.

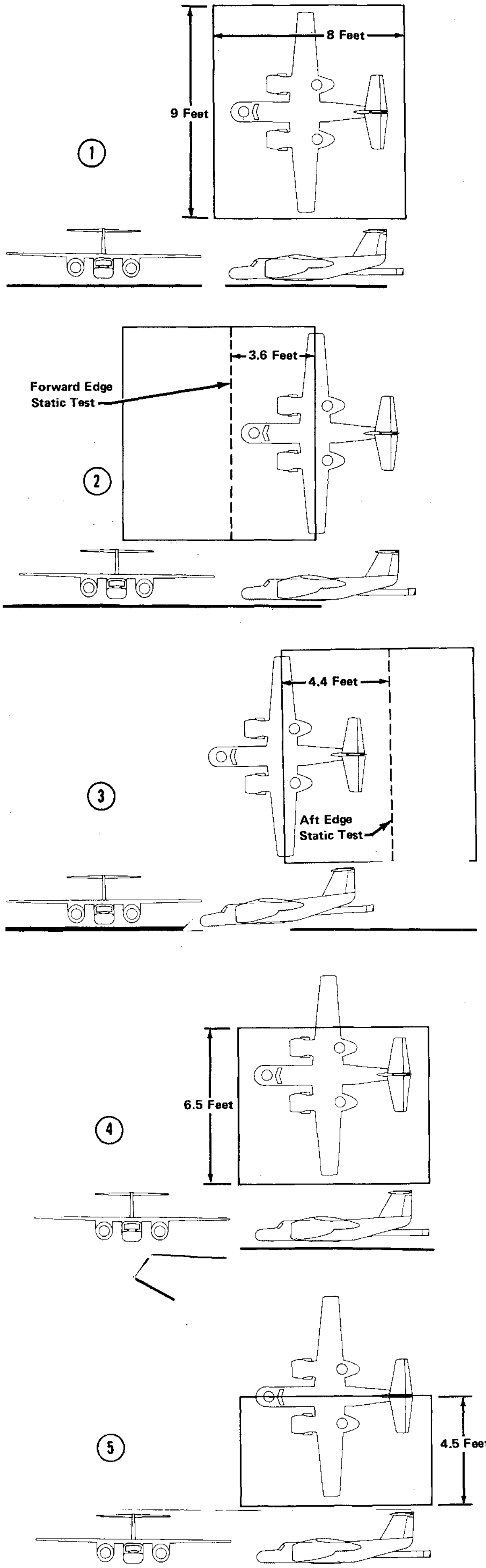


Fig. 4 Ground board configurations.

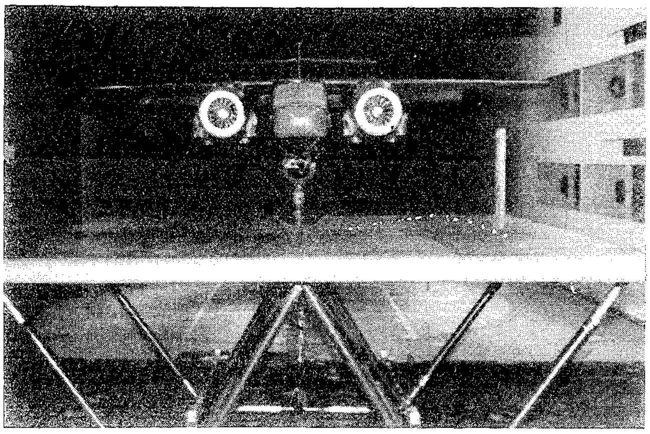


Fig. 5 Model front view with ground board in LaRC tunnel.

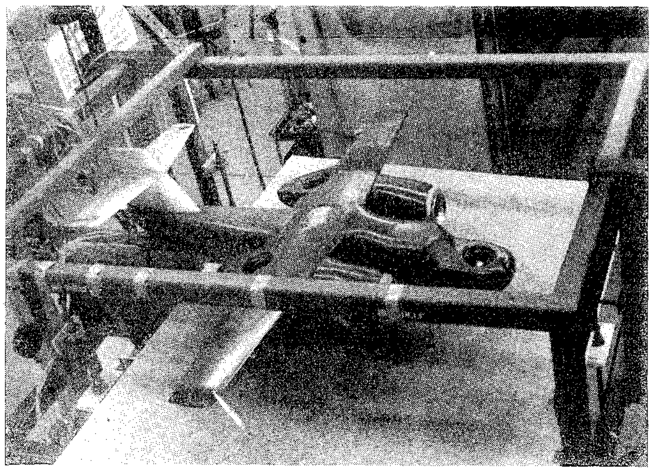
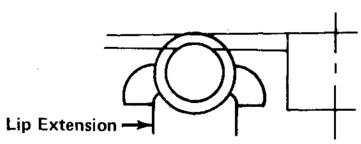


Fig. 6 Model in static test rig.



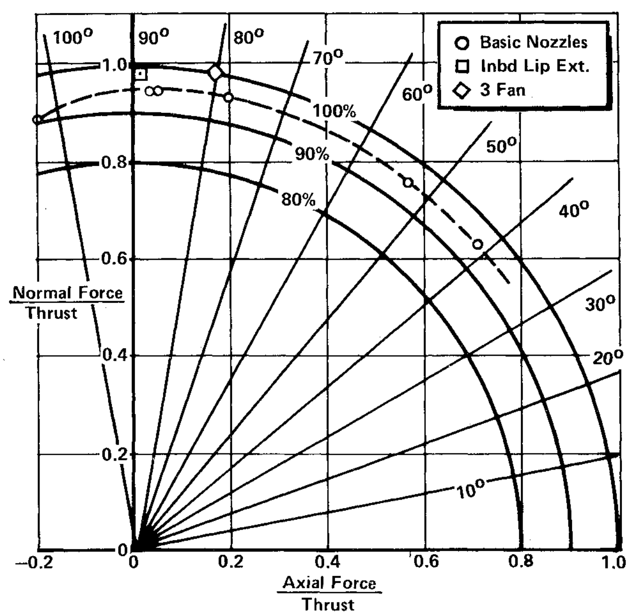


Fig. 7 Normal force vs axial force in free air; $V/V_j = 0$, $\alpha = 0$ deg, and $\phi = 0$ deg.

Tunnel solid blockage corrections were applied to all forward speed data; wall corrections (Heyson corrections) were applied to the free air data. The angle of attack corrections were less than 3 deg for the maximum thrust coefficients tested. Wall corrections were not applied to the ground plane in data. A check was made with the "ground in" correction and found to be small. No wall corrections were applied to the static data. The static data were obtained in a large room to prevent recirculation effects.

Thrust and mass flow were determined by calibration of the fans. The fans were calibrated individually on a thrust stand. The model was shielded to eliminate any induced loads on the model structure. Mass flows were determined with the model nozzles installed and a calibrated bellmouth inlet. The effect of ground proximity on the thrust of isolated fans was investigated, and the results show the thrust to be a function of the fan exhaust pressure ratio regardless of the ground proximity.

The direct thrust contributions to aerodynamic forces and moments were computed using geometric arms and angles. Thrust angles were obtained from the fan calibration tests as well as the fan thrust and mass flow. The aerodynamic components were then determined from

$$C_{L_{\text{aero}}} = C_L - C_T \sin\theta$$

$$C_{D_{\text{aero}}} = C_D + C_T \cos\theta - C_{D_R}$$

$$C_{M_{\text{aero}}} = C_M \Sigma C_T \times \frac{\text{arm}}{\bar{c}} - \Sigma C_{D_R} \times \frac{\text{arm}}{\bar{c}}$$

$$C_{l_{\text{aero}}} = C_l - \Sigma C_T \times \frac{\text{arm}}{\bar{c}}$$

The induced forces were then determined by

$$\Delta C_L = C_{L_{\text{aero}}} - C_{L_{\text{power off}}}$$

$$\Delta C_D = C_{D_{\text{aero}}} - C_{D_{\text{power off}}}$$

$$\Delta C_M = C_{M_{\text{aero}}} - C_{M_{\text{power off}}}$$

$$\Delta C_l = C_{l_{\text{aero}}} - C_{l_{\text{power off}}}$$

Power-off coefficients were obtained at a windmilling condition.

Results

Installation Losses

The static tests of the model showed a loss of approximately 5% thrust at all nozzle angles tested on the four-fan model. No loss was experienced on the three-fan model. The thrust loss of the four-fan model appears to be primarily associated with the front fans. The nozzle exits are adjacent to the nacelle bottom, and substantial negative pressures are induced on the bottom of the nacelle. The nozzle lips were extended as shown, and the loss was reduced from 5 to approximately 1%. Figure 7 shows the combined fan losses in a free air test condition. The four-fan configuration was tested statically through a range of nozzle angles from 105 to 45 deg for the basic nozzle. The modified nozzle (lip extension) was tested at 90 deg only. The three-fan configuration was tested with an 80 deg nose fan and 90 deg aft fans.

STOL

The four-fan model has a positive effect to lift at forward speed conditions due to the strong-induced jet flap effect of the aft fans. The forward fans are forward and below the wing leading edge and have a negative-induced lift which is more than compensated for by the aft fans. Figure 8 shows the lift of the four-fan configuration in a typical STOL configuration. The zero C_T condition is a windmilling condition. The increment in lift is essentially constant with angle of attack at angles less than basic wing stall. As the thrust coefficient is increased, an increase in stall angle of attack is shown.

The lift and pitching moment coefficients for the free air STOL condition were presented in Fig. 9 as function of the velocity ratio. For a typical configuration with these low-pressure ratio fans ($P_R = 1.25$), the takeoff would occur at a V/V_j of approximately 0.2. The data show a positive lift increment of 0.27 thrust and a pitch up at this speed. The data are presented for a nozzle angle deflection of 30 deg forward and 60 deg aft. A slightly different gearing is needed to trim the configuration at the takeoff speed. Reducing the forward angle and increasing the aft angle will provide pitch down to compensate for the induced moments and would likely increase the induced lift slightly, since most of the induced lift is the result of the circulation caused by the aft fans.

The various ground board configurations had only small effects on the STOL configuration. Figure 10 presents the lift and pitching moment coefficients at an $h/D = 1.0$. A somewhat reduced induced lift is shown with the forward located ground board. An h/D of 1.0 is equivalent to wheel height for this configuration. Figure 11 presents the same data at a h/D of 4.0, and no effect of data is shown due to any of the ground board configurations. Ground board configuration 4 represents a narrow deck with 50% of the right-hand wing overhanging.

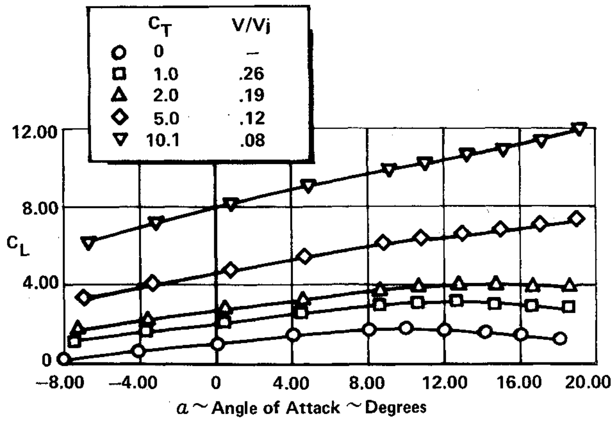


Fig. 8 Effect of thrust on the basic aerodynamic characteristics in free air; $\delta_{N_{fwd}} = 30$ deg, $\delta_{N_{aft}} = 60$ deg.

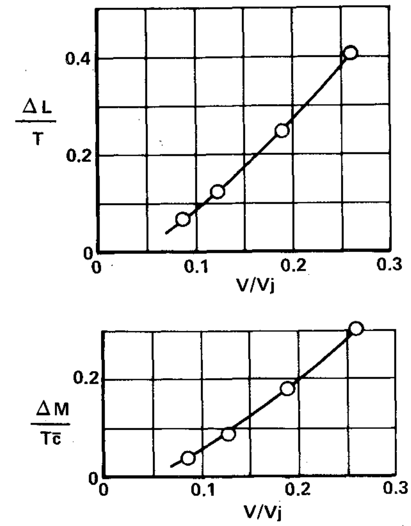


Fig. 9 Effect of velocity ratio on the thrust-induced lift and pitching moment in free air; $\delta_{N_{fwd}} = 30$ deg, $\delta_{N_{aft}} = 60$ deg, $\alpha = 0$ deg, and $\phi = 0$ deg.

VTOL

The tests representative of VTOL operation show greater overall deck effects than those experienced in STOL operation. Nozzle deflections representative of VTOL operation were investigated on both the four- and three-fan configurations. Additional lift losses of 5-10% were encountered on both configurations at lower heights. Sizable negative pitching moments were encountered. Induced rolling moment coefficients were shown as the ground board was removed from under the right-hand wing. Figure 12 shows the induced rolling moments of the four-fan configuration due to bank angle with variation of lateral deck edge. The suckdown and fountain are altered by deck edge position and bank angle. As can be seen from the data, moments due to bank over the full board are as large as those with the partial decks. The rolling moments with full deck are influenced by both a fountain shift and wing lower surface pressure change. As the model banks, the fountain shifts toward the upgoing wing, causing a rolling moment in the direction of the downgoing wing. In addition, the downgoing wing approaches the deck and experiences an increased negative pressure. The removal of the ground board segments under one wing alters the fountain and pressure inputs to roll; however, these are, in general, equal to or less than the roll encountered over the full deck with a ±10 deg roll angle. Some rolling moment is shown with the symmetrical ground board at $\phi = 0$. These are due to some model asymmetries.

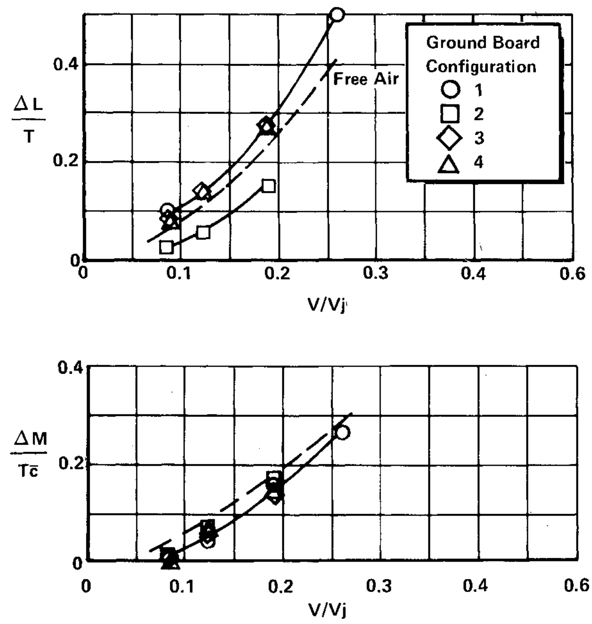


Fig. 10 Effect of velocity ratio on the thrust-induced lift and pitching moment; $\delta_{N_{fwd}} = 30$ deg, $\delta_{N_{aft}} = 60$ deg, $h/D = 1$, $\alpha = 0$ deg, and $\phi = 0$ deg.

Impact on Airplane at VTOL Conditions

The magnitude of forces and moments encountered due to proximity of the ground and deck edges are better understood compared to control requirements. The data are presented as the incremental force or moment divided by the control required to satisfy Ref. 1; therefore, a negative sign indicates a lift loss, a pitch down, or a left roll. The complete data and analysis are presented in Refs. 2 and 3. In order to demonstrate the effect of induced forces on control requirements, a typical configuration has been established with weights and

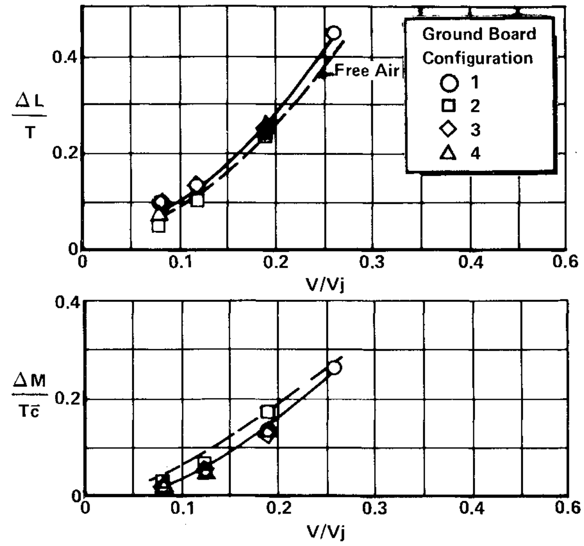


Fig. 11 Effect of velocity on the thrust-induced lift and pitching moment; $\delta_{N_{fwd}} = 30$ deg, $\delta_{N_{aft}} = 60$ deg, $h/D = 4$, $\alpha = 0$ deg, and $\phi = 0$ deg.

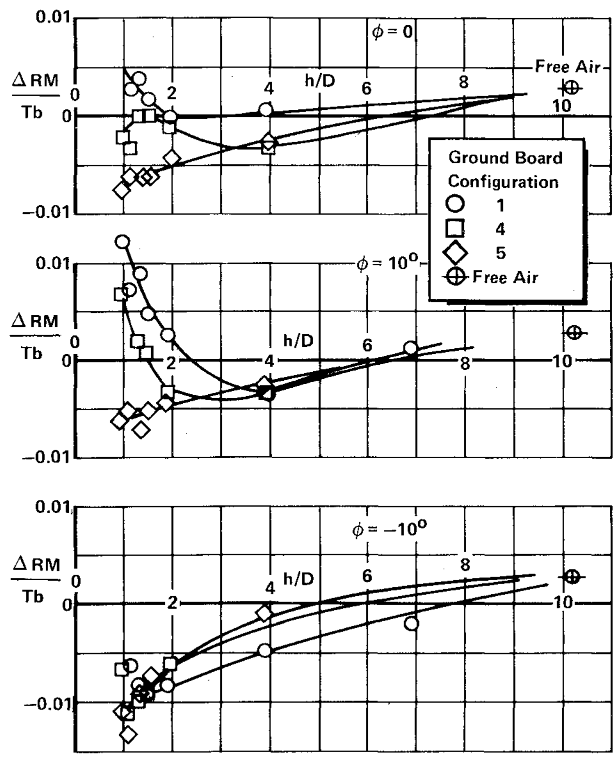


Fig. 12 Effect of height on the thrust-induced rolling moment; $\delta_N = 90$ deg, $V/V_j = 0$, and $\alpha = 0$ deg.

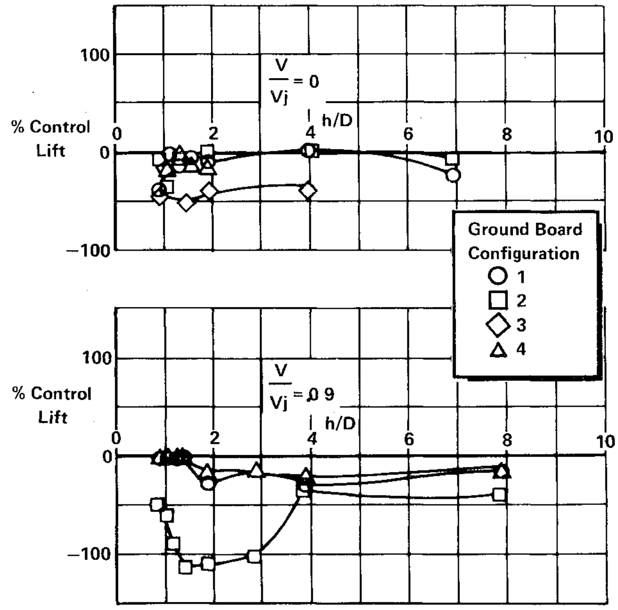


Fig. 13 Percent of available lift control required to trim airplane initially trimmed in free air; $\delta_N = 90$ deg, $\alpha = 0$ deg, and $\phi = 0$ deg.

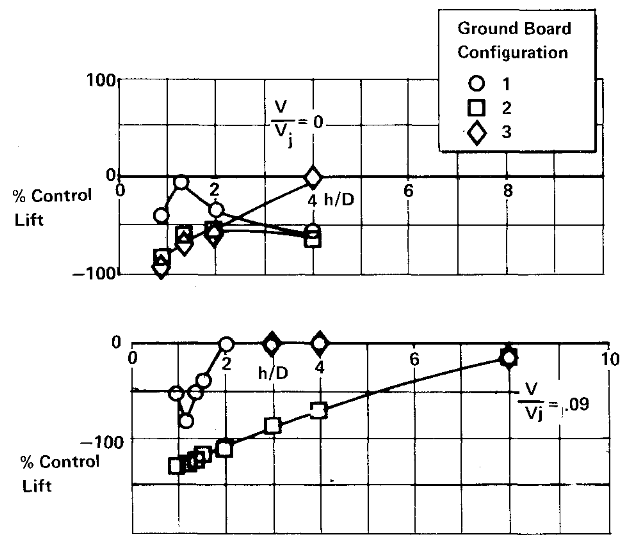


Fig. 14 Percent of available lift control required to trim airplane initially trimmed in free air, 3-fan; $\delta_{N_{nose}} = 80$ deg, $\delta_{N_{aft}} = 90$ deg, $\alpha = 0$ deg, and $\phi = 0$ deg.

inertias. The significant parameters are

Weight	35,000 lb
Pitch inertia	95,000 slugs/ft^2
Roll inertia	100,000 slugs/ft^2

Control requirements are established based on Ref. 1.

Lift control	3,500 lb (+10% weight)
Pitch control	±47,500 ft/lb (0.5 rad/s^2)
Roll control	±90,000 ft/lb (0.9 rad/s^2)

Lift control requirements due to the induced forces are presented in Fig. 13 for the four-fan configuration and in Fig. 14 for the three-fan configuration. The four-fan configuration shows only one ground board configuration where large control requirements are required. Ground board position #2, aft edge under c.g., data indicated 110% of lift control required at a wind over deck of approximately 35 knots ($V/V_j = 0.09$). This board consistently showed larger lift losses, and one suspects a test interference problem although none could be isolated. The three fans required approximately 90% control allowance at zero speed and also showed an increase in control requirement at forward speed with the #2 board configuration, where approximately 125% of the total allowance would be required at an $h/D = 1.0$.

No attempt was made to reduce the induced lift of this board configuration by alterations to the model or by nozzle angles. If later investigations show this loss to be a result of a fountain or an interference which cannot be eliminated, the region can be avoided by approaching at greater heights (greater than $h/D = 4$) and completing the landing vertically.

The pitching moment control requirements are presented in Figs. 15 and 16 for the four- and three-fan configurations,

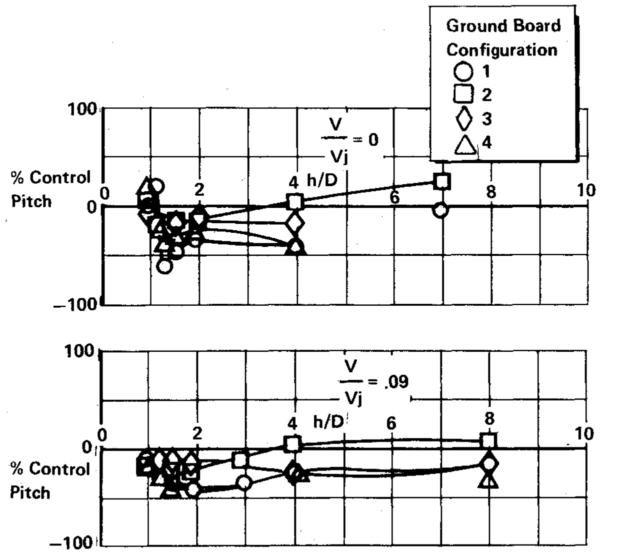


Fig. 15 Percent of available pitch control required to trim airplane initially trimmed in free air; $\delta_N = 90$ deg, $\alpha = 0$ deg, and $\phi = 0$ deg.

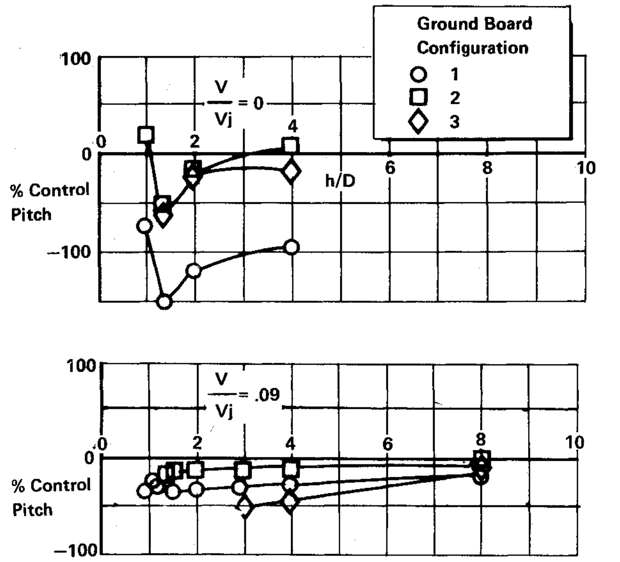


Fig. 16 Percent of available pitch control required to trim airplane initially trimmed in free air; $\delta_{N_{nose}} = 80$ deg, $\delta_{N_{aft}} = 90$ deg, $\alpha = 0$ deg, and $\phi = 0$ deg.

respectively. The data show approximately 50% of the control allowance will be used for both configurations and all ground board configurations with the exception of the three fan and the full deck. A large pitch down (150%) was shown for this configuration at static ($V=0$) conditions. If wind over deck is present, the data do not show the large induced pitching moments. The maximum pitching moment requirement is 50% at wind over the deck speeds for the three fan and 40% for the four-fan configuration.

Figures 17 and 18 present the rolling moment control requirements for the largest moments encountered. The largest moments for the four fan occurred at zero speed, and at $V/V_j = 0.068$ (corresponding to approximately 27 knots) for the three fan. The requirement for both configurations amounts to approximately 40% of that required to provide 0.9 rad/s^2 acceleration.

Conclusions

The deck edge location does not show a significant effect on the operation of a lift-cruise fan V/STOL configuration. In

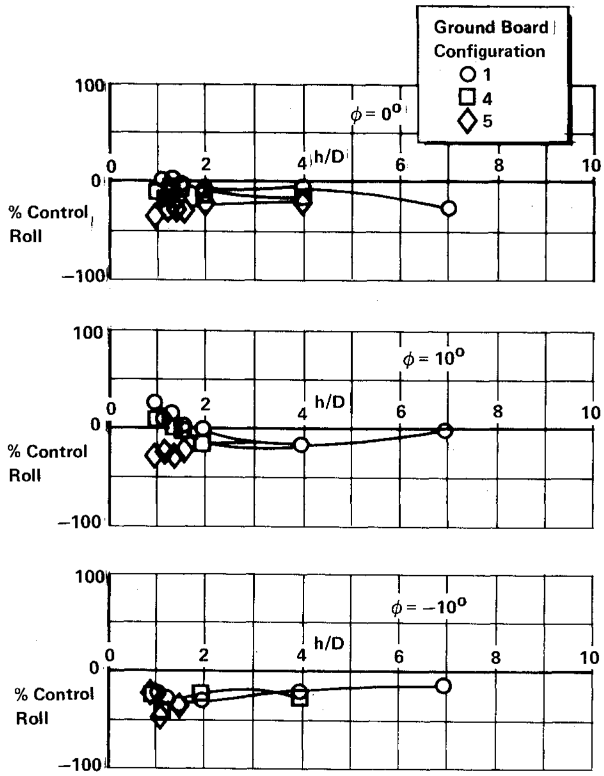


Fig. 17 Percent of available roll control required to trim airplane initially trimmed in free air; $\delta_N = 90$ deg, $V/V_j = 0$, and $\alpha = 0$ deg.

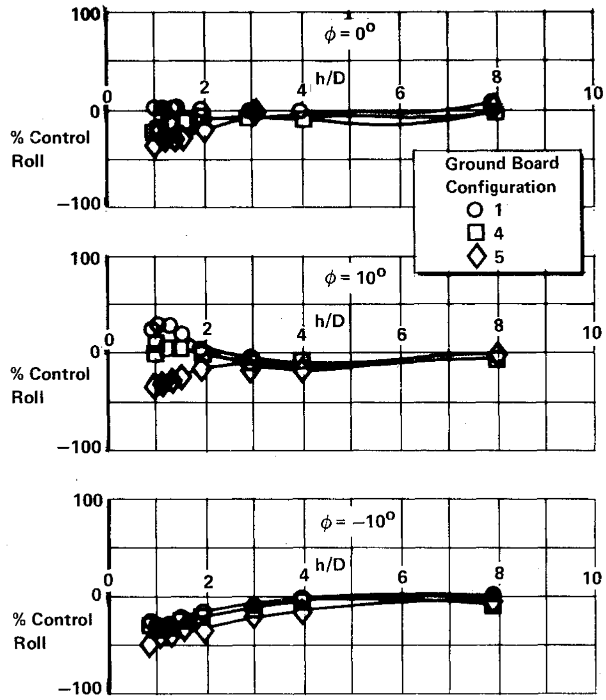


Fig. 18 Percent of available roll control required to trim airplane initially trimmed in free air, 3-fan; $\delta_{N_{nose}} = 80$ deg, $\delta_{N_{aft}} = 90$ deg, $V/V_j = 0.068$, and $\alpha = 0$ deg.

most cases, the transients with a full deck are equal to those with the partial deck.

STOL operation with a wing overhanging will be identical to full deck operation.

Some conditions did show larger effects. The deck #2 (aft edge under c.g.) indicated a sizable lift loss at wind over deck speeds. This may have been the effect of tunnel interference rather than an edge effect. A sizable pitch down with a full deck (three fan) was shown.

The test and analysis of the ground board and deck edge effects were made with no attempt to improve the characteristics or induced effects with the single exception of the free air interference test. All deck edge studies were done with the basic model. It is felt that lift loss occurring with ground board #2 could materially be affected by nozzle modifications if it is established that the cause is real and not an external cause developed by the installation. The same is true of the pitch down with the three fan and full ground board. Several other configurations of this nature have been investigated with full ground board without demonstrating the pitch down.

Acknowledgment

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References

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