N89-10853

F-15 SMTD Low Speed Jet Effects Wind Tunnel Test Results

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Summary

Key results from low speed wind tunnel testing of the F-15 SMTD with thrust reversers are presented. Longitudinally, the largest induced increments in the stability and control occur at landing gear height. These generally reflect an induced lift loss and a nose-up pitching moment, and vary with sideslip. Directional stability is reduced at landing gear height with full reverse thrust. Non-linearities in the horizontal tail effectiveness are found in free air and at landing gear height.

Introduction

One of the most promising means of achieving short landing capability on tactical aircraft is through the use of thrust reversal during ground rollout. Several studies have shown that thrust reversing can reduce landing rollout distances by as much as 75%. Numerous wind tunnel investigations (e.g. references 1-4) have studied the effects of thrust reversal on fighter aerodynamics at low speeds. Large changes in the stability and control characteristics of the aircraft can be induced by the reverse flow. These studies found the proximity of the reverser to the tail surfaces, the reverser efflux angle, and the reverser jet to free-stream dynamic pressure ratio to be key parameters affecting the reverser induced aerodynamics.

A full scale thrust reverser equipped aircraft, designated as the F-15 SMTD (STOL and Maneuver Technology Demonstrator), is currently being developed by McDonnell Douglas under USAF sponsorship. This aircraft is being designed for landings on a 50 x 1500 foot icy runway, in a crosswind gusting to 30 Knots. In addition its advanced STOL capability, the F-15 SMTD will be equipped with advanced rough/soft field landing gear and have a digital fly-by-wire integrated flight/propulsion control system. The objective of the program is to integrate all of these technologies with no degradation in the overall vehicle performance. As a part of the development program, wind tunnel tests were conducted to determine the jet induced effects on the aircraft during the approach and landing phases. The objective of these tests was to generate a data base for use in control law development and simulation. Key results from these tests will be presented, and where appropriate, a qualitative explanation of the phenomena in terms of the classical V/STOL flow effects will be postulated. Most of the stability and control results presented will be in terms of force and moment coefficient increments, defined as the jet-on minus the jet-off values.

<u>Nomenclature</u>

A_j	Aspect ratio of reverser port
b	Wing span ,ft
c	Wing mean aerodynamic chord, ft
C_L	Lift coefficient, $L/q_\infty S$
C_m	Pitching moment coefficient, $M/q_\infty Sc$
C_ℓ	Rolling moment coefficient, $\ell/q_\infty Sb$
C_n	Yawing moment coefficient, $n/q_\infty Sb$
d	Equivalent single jet diameter, ft
h	Height of center of gravity above ground, ft
K_y	Empirical lateral jet spacing factor, $1+1.2/(q_j/q_\infty)^{0.5}$ for the F-15 SMTD
NPR	Ratio of nozzle total pressure to free-stream static pressure
q_∞	Free-stream dynamic pressure, psf
q_j	Jet dynamic pressure, psf
q_j/q_∞	Dynamic pressure ratio (jet to free-stream)
S	Wing area, ft^2
X	Distance from jet exit to ground stagnation line
α	Angle of attack
β	Angle of sideslip
δ_h	Horizontal tail deflection angle
δ_r	Rudder deflection angle
δ_{uv}	Upper reverser vane angle
δ_{lv}	Lower reverser vane angle

Test Article

The Low Speed Jet Effects test was conducted in the McDonnell Aircraft 8 x 12 foot Low Speed Wind Tunnel at St. Louis. The test article was a 7.5% scale model of the three-surface F-15 SMTD (figure 1). It differs from a production F-15B through the addition of a canard mounted ahead of the wing at a 20 degree dihedral angle, as well as a set of 2-D nozzles which can be used for both thrust vectoring and reversing. The model was equipped with a six-component internal strain gauge balance for measuring the aerodynamic loads (figure 2). Each reverser port (figure 3) consists of a set of rotating vanes which can be used to provide axial as well as reverse thrust. The reversers are designed to allow a constant flow area at all deflection angles. Seven specific reverser vane angles were tested, ranging from 45 to 135 degrees The reverser ports were non-metric, so no direct jet forces and moment on the aircraft were measured by the balance. Cold high pressure air for the reverser plume simulation was routed through the twin sting which supported the model. The engine inlets were blocked, so there was no simulation of inlet mass flow. Ground simulation was achieved using a fixed ground board which had a trailing edge flap for controlling the leading edge stagnation point. This allowed for flow angularity control ahead of the ground board.

Test Approach

The test was conducted in two phases. During the first phase, testing was conducted in free air; at three intermediate ground heights (0.20, 0.35, and 0.5 h/b), at angles of attack from zero to twenty. Testing was also conducted at landing gear height (0.17 h/b), but only at zero angle of attack. The second phase of the test was conducted solely at landing gear height, at angles of attack up to six degrees. During this phase, a shortened ground board was used in order to minimize the ground board boundary layer effects. During both phases, testing was conducted at three nozzle pressure ratio settings; 1.0 (jet off), 2.2 (reduced power), and 2.7 (nominal approach power setting). The angle of sideslip and nozzle pressure ratio were held constant, while the angle of attack and tunnel speed were varied. Due to the crosswind requirement on the F-15 SMTD program, the sideslip angles tested varied from -30 to +30 degrees while on the ground. Parametric variations on all control surfaces (canard, tail, rudder, flaperon, and aileron) were tested to determine the impact of the reverser induced flow fields. The upper vanes were set at 135 degrees for all runs at landing gear height. The only exception to this was the series of differential (left/right) upper reverser runs. A matrix of lower reverser vane settings and forward velocities was tested to determine the impact of decreasing the lower vane angle during rollout on the stability and control characteristics. This reduction in lower vane angle with velocity is intended to preclude hot gas ingestion on the full scale aircraft.

Flow Field Mechanisms

Prior to the presentation of the test data, a brief summary of the basic flow field effects which are induced by thrust reverser jets will be presented. This summary is based on the results presented in references 4-7. The interpretation of the data will be in terms of these phenomena.

Free Air

In free air, the efflux from a thrust reverser can be interpreted as a growing solid body immersed in the free-stream. The jet grows as it moves along its trajectory, entraining air from around it. This entrainment action induces negative pressures, and is strongest in the wake immediately behind the jet. Upstream and around the jet, blockage is the dominant mechanism. The blockage decelerates the flow upstream, inducing positive pressures, and induces negative pressures as the flow accelerates around the jet. As the jet to free-stream dynamic pressure ratio increases, the entrainment mechanism increases, reducing the extent of the blockage induced positive pressures.

Many of the reverser vane angles tested in free air (45 to 90) represent forward thrust conditions. Here, the induced effects are analogous to those encountered with thrust vectoring. For these settings, the entrainment action of the jet can increase the local dynamic pressure at the tail surfaces, resulting in increases in the horizontal and vertical tail effectiveness. Flow will also be entrained over the upstream portion of the fuselage. This could result in a "jet flap" effect on the fuselage, if a pressure differential is established between the upper and lower body surfaces.

For reverse thrust settings (90 to 135) the jets primarily affect the flow around the tail surfaces and aft portion of the fuselage. At very high reverser angles, the jet can attach to the fuselage and move rapidly forward along the configuration through the boundary layer. The F-15 SMTD reverser was designed to avoid the possibility of jet flow attachment. For unattached jets, the induced flow fields are complex and not very well understood. It is known that the impact of the reversers on the aircraft stability and control depends largely on the relative orientation of the reverser efflux and the tail surfaces. This orientation is defined by the port location relative to the tails; the reverser vane angle; and the jet dynamic pressure ratio.

For twin vertical tail configurations, the reverser efflux can induce significant changes in directional stability. If the maximum efflux penetration is in between the tails, blockage is the predominant mechanism. The induced positive pressures will cause an outboard load on each tail. At sideslip, the free-stream shifts the efflux towards the leeward tail. The side load on the leeward tail will exceed the load on the windward tail, resulting in an increase in directional stability. If most of the vertical tail surface is aft of the efflux, the tail will experience the suction pressures associated with the entrainment action of the efflux wake. This causes inboard tail loads. At sideslip, the leeward tail will experience a greater inboard load, resulting in a decrease in directional stability.

Ground Effect

Additional flow mechanisms result from the interaction of the lower reverser and the ground. As the thrust reverser efflux impinges on the ground, a wall jet is formed which spreads radially outward from the impingement point (figure 4). This jet entrains flow around and underneath the aircraft, creating a negative pressure region which results in a suckdown (negative lift) force on the underside of the aircraft. The forward motion of the wall jet is opposed by the free stream. This eventually results in the separation of the wall jet from the ground, and a rearward deflection of the wall jet flow. A stagnation line forms at the point where the wall jet departs from the ground. The following empirical expression, adapted from reference 5, gives the distance between the jet exit and the forward extent of the ground stagnation line:

$$(X/d) = (h/d)\tan(\delta_{lv}/90) + 0.75\,K_y(\delta_{lv}/90)^2(q_j/q_\infty)^{0.5}$$
$$- 1.75\,K_y(h/d)^{2.5}(A_j)^{0.3}(1-\sin(\delta_{lv}-90))(\delta_{lv}/90)^2(q_j/q_\infty)^{-1.125} \quad (1)$$

A region of recirculating flow forms behind the stagnation line. Due to the rotational nature of this flow, this phenomenon is commonly referred to as a "ground vortex". It is not a vortex in the classical sense, rather, it is a point about which the free stream and wall jet flow rotate following the separation of the wall jet from the ground. Due to the deceleration of the free-stream flow as it moves up and over the ground vortex, positive pressures are induced upstream of the stagnation line. Downstream of the ground vortex, negative pressures are induced. The ground vortex defines the forward boundary of the suckdown region. As indicated by equation (1), the size of the suckdown region changes with the lower reverser angle and the jet dynamic pressure ratio. This can result in changes in the induced pitching moment, due to variations in the magnitude and center of pressure of the suckdown force.

When two or more jets are used for thrust reversal, their radial flow patterns on the ground converge, and can result in an upflow (or fountain) underneath the aircraft, which causes positive lift forces. As the distance between the jet exit and the ground impingement point increases, jets which are closely spaced tend to merge, and the fountain effect decreases. On a fighter aircraft with closely spaced reverser jets, as on the F-15 SMTD, the fountain effect is expected to be negligible for vane angles approaching 135 degrees. For nearly vertical (90 degree) lower vane angles, a fountain will form, but its impact is expected to be small compared the suckdown effect. Multiple jets can also affect the forward projection of the ground vortex. Empirical criteria for estimating the additive effect of multiple jets are given in reference 5. If the lateral spacing of the jets is sufficiently large, the jets are assumed to act independently. On the F-15 SMTD, the mutual interaction of the jets results in a more forward location of the stagnation line. This is reflected by the factor K_y in equation (1).

Longitudinal Results

Characteristics in Free Air

Effect of Reverser Vane Angle

Lift and pitching moment coefficient increments at zero angle of attack in free air are presented in figures 5 and 6 for combinations of upper and lower vane angles. When the upper and lower vane angles are equal, the lift and moment coefficient increments are both about zero. When the upper vane is deflected less than the lower vane, the induced lift is positive. Similarly, when the lower vane is deflected less than the upper vane, the induced lift is negative. One possible interpretation of this is a "jet flap" effect on the fuselage forward of the reverser ports. Differing amounts of entrainment on the upper and lower surfaces of the fuselage due to different upper/lower vane settings could cause a pressure and hence a lift differential across the upper and lower fuselage surfaces. The moment increments are very small compared to the lift increments, which indicates that the center of pressure of the induced forces is near the center of gravity. This rules out interpretations which assume the induced effects act on the horizontal tail. It is consistent, however, with the idea of flow entrainment ahead of the ports. The induced lift forces shown in figure 5 are in the same direction as the direct jet lift forces. While the induced moment produced is small, the direct jet moment is large.

Horizontal Tail Effectiveness

As seen in figure 7, horizontal tail effectiveness is affected by reverser angle. The increase in effectiveness results for the 45 degree vanes is felt to result from an increase in the tail dynamic pressure due to increased local velocities resulting from flow entrainment. The reverser ports are located 0.45 root chords aft of the horizontal tail leading edge, (0.14 chords forward of the hinge line). With the lower reverser vane at 135 degrees, there is a reduction in the horizontal tail effectivness for negative (trailing edge up) deflections, which is not evident at the positive deflection. With this vane setting, the reverser efflux opposes the free stream flow, and significant mixing will occur. This may result in a local dynamic pressure ratio decrease. With a negative tail setting, the leading edge of the tail is in this region, and this could account for the non-linearity. A similar non-linearity was not found with the upper reverers at high settings, presumably because of the presence of the vertical tails.

Characteristics in Height Transition

Effect of Lower Vane Angle

Lift and pitching moment coefficient increments as a function of height above the ground and lower vane angle are presented in figures 8 and 9. These are jet induced effects only, jet-off aerodynamic ground effects are subtracted. Both curves show increasing increments near the ground as the lower vane angle is increased. There is a large increase in the pitching moment increment, as the height decreases, while the lift increment changes from positive to negative. As the aircraft moves into ground effect, the ground vortex and associated suckdown region begin to form, and become larger as the height above the ground decreases. The magnitude of the induced pitching moment coefficients near the ground is larger than the free air effects noted above.

Effect of Angle of Attack

Increments at zero and twelve degrees angle of attack are presented in figures 10 and 11. Twelve degrees is the current approach angle of attack for the F-15 SMTD. Near the ground, larger increments are found at the higher angles of attack. This is not suprising in that as angle of attack increases, the horizontal tail and reverser ports move closer to the ground. In addition, positive angle of attack increases the effective lower reverser angle. As a result, the suckdown region becomes larger.

Characteristics at Landing Gear Height

Effect of Ground Board Boundary Layer

The presence of a ground board boundary layer will influence the flow field induced by the lower reversers. The upstream penetration of the ground vortex and the associated suckdown region should be primarily affected. Other test techniques can be used to modify or eliminate the ground boundary layer (e.g. moving ground board, moving model), but these have additional complexities. A fixed ground board is the simplest test technique, and has been used in numerous thrust reverser studies. During the second phase of this test, runs were made on a shortened ground board (figure 12), in order to analyze the effect of the ground board boundary layer on the reverser induced flow field. The distance from the leading edge of the ground board to the nose of the model was decreased from 92" to 50". Theoretically, with a thinner ground boundary layer, and thus more kinetic energy in the boundary layer to oppose the wall jet, the forward penetration of the ground vortex should be reduced. This should result in a smaller suckdown region, with a corresponding decrease in the lift loss. The results of repeat runs made following the ground board change showed an increase in both the lift loss and the pitching moment (figures 13 and 14). The reason for the added lift loss is not clear at this time. The nozzle pressure ratio varied slightly (2.67 vs 2.86) between the repeat runs, so the minor changes that were found may not be entirely attributable to the thinner boundary layer. With the exception of horizontal tail effectiveness data, all subsequent longitudinal data at landing gear height will be from the second phase of the test, with the short ground board.

Effect of Lower Reverser Vane Angle

The effect of lower reverser vane angle and forward speed on the reverser induced lift and pitching moment is shown in figures 15 and 16. A loss in lift coefficient of about 0.7 was induced at vane angles above 110 degrees, for all velocities. The smaller lift loss as the lower vane angle decreases is due to the smaller suckdown region caused by the resultant aft movement of the ground vortex. As the lower vane angle decreases (or the forward velocity increases), both the point of reverser impingement on the ground and the ground vortex move aft, so the center of pressure of the net suckdown force moves rearward, which results in an increase in pitching moment (figure 16). The pitching moment increments begin to decrease as the ground vortex moves back to the vicinity of the wing trailing edge. As the lower reverser angle decreases, the direct jet force will give positive lift and nose down pitching moment increments (assuming a constant 135 degree upper reverser setting), both of which act to offset the induced effects.

Effect of Angle of Attack

During the second phase of testing, each reverser configuration was tested over an alpha range of zero to six degrees. The results of these runs are presented in figures 17 and 18. These are jet-induced effects only, jet-off aerodynamic ground effects are subtracted. An additional lift loss was found at six degrees angle of attack for all lower vane angles tested. This was accompanied by a decreasing moment increment back to about a 100 degree vane setting, where the moment increment then started to increase. Two key changes happen at angle of attack: the effective reverser efflux angle increases from the vane angle to the vane angle plus the angle of attack, and the distance between the reverser ports and the ground decreases. The net effect is a forward movement of the ground vortex, so the suckdown region becomes larger. Using equation (1), each additional degree of angle of attack at 120 kts is estimated to produce a forward ground vortex movement of approximately 3% c. This forward movement results in a forward shift of the suckdown center of pressure, which gives the decreased moment increment. This is encouraging from an operational viewpoint, in that the reverser induced increments are stable.

Horizontal Tail Effectiveness

The impact of reversing on horizontal tail effectiveness as a function of the reverser jet to free-stream dynamic pressure ratio for a 110 degree vane setting is shown in figure 19. Two curves are presented, one based on the difference in pitching moment at zero and plus fifteen degrees elevator deflection, the other based on the difference at zero and minus fifteen degrees. A dynamic pressure ratio of 50 is representative of the touchdown condition. As the ground speed decreases, the dynamic pressure ratio increases (for a fixed nozzle pressure ratio). At high values of the dynamic pressure ratio, both curves show a decrease from the jet off value. At this condition, the ground vortex is far forward of the tail; the flow seen by the tail is the wake behind the ground vortex. For low dynamic pressure ratios, the tail effectiveness becomes highly nonlinear with tail deflection. At a dynamic pressure ratio of 50, the center of the ground vortex is estimated by equation (1) to be under the wing trailing edge. The complex interactions between the wing, tail, and ground vortex result in a significant loss in the tail effectiveness for the negative deflection.

Effect of Sideslip

One interesting result from this test was a large variation in the induced lift and pitching moment with sideslip angle (figures 20 and 21). As seen in figure 21 the pitching moment increments at high angles of sideslip are much higher than those found at zero sideslip for the 135 and 110 degree lower reverser settings. These increments were accompanied by a large reduction in the induced lift loss (figure 20), which indicates that the source of the additional moment is a positive lift force. In addition, a large negative increase in the rolling moment was found at positive sideslip, possibly indicating a greater lift on the windward side of the aircraft. These pieces of evidence point to the cause of the increased pitch-up being a shift of the ground vortex to the lee side of the aircraft. This moves the windward canard and forward portion of the windward wing out of the suckdown region and into the free-stream. An additional contributing factor may be induced upwash on the windward canard from the leading edge of the shifted ground vortex. The shift in the stagnation line was confirmed by flow visualization (figure 22). As the lower reverser vane angle decreases, the ground vortex and thus the induced center of pressure moves rearward, resulting in a decreased moment arm. Hence, the additional moment due to sideslip decreases with lower vane angle.

Lateral-Directional Results

Characteristics in Free Air

Effect of Upper Reverser Vane Angle

The reverser induced increment in directional stability as a function of upper vane angle is presented in figure 23. All data represent a nozzle pressure ratio of 2.7 and a lower vane angle of 110 degrees. Also included is a full reverse case (135 degree setting) taken from testing at landing gear height. For all vane angles less than 90 degrees, an increase in the directional stability is found. This may be due to an increase in the local dynamic pressure due to entrainment. Negligible changes were found in lateral stability with thrust reversers in free air.

The reverser induced rudder effectiveness increment as a function of upper vane angle is presented in figure 24. Included with the free air data is a full reverse (135 degree upper vane) case taken from testing at landing gear height. The trends are similar to the directional stability trend, the largest increase in rudder effectiveness is found with the reverser angles near vertical. It is interesting to note that the 110 degree vane results in no change compared to the jet off value, while it did result in a moderate loss in directional stability at the same flight condition.

Characteristics at Landing Gear Height

Directional Stability

For the upper reverser setting of 135 degrees, a reduction in the directional stability was found for all flight conditions representative of ground rollout. As shown in figure 25, the induced directional stability increment is negative and roughly constant over the dynamic pressure ratio range from 50 to 115. This loss is due to the reverser efflux penetrating forward (approximately two root chords) of the vertical tail leading edge. This results in negative pressures between the tails, due to entrainment. The resultant inboard tail loads act to reduce the directional stability. The dynamic pressure ratio of 50 corresponds to a nozzle pressure ratio of 2.7 at touchdown speed. Data taken at very low dynamic pressure ratios during high speed tests of the F-15 SMTD conducted at the Arnold Engineering Development Center are also presented. At these conditions, directional stability is regained, and increases slightly over the jet off value. Here, the efflux penetration does not project forward of the vertical tail, so the tails experience blockage induced positive pressures. Outboard tail loads result which act to increase the directional stability. The induced directional stability was found to be independent of the lower vane angle. This supports the belief that at landing gear height, the upper reverser interaction with the vertical tail is the dominant effect directionally.

An investigation of the effect of axial location of upper reverser ports on a YF-17 configuration is reported in reference 3. The aft-most locations (0.9 and 0.4 root chords aft of the vertical tail leading edge) yielded an increase in the directional stability for all upper vane angles and dynamic pressure ratios tested. For these locations, the efflux is in between the tails, where the blockage induced pressures increase the stability. The forward location (0.12 chords forward of the trailing edge) showed a decrease in directional stability for high (>75) values of the dynamic pressure ratio. This is consistent with the F-15 SMTD data, since the efflux penetration increases with dynamic pressure ratio. For comparison, the F-15 SMTD ports are located 0.33 root chords forward of the vertical tail trailing edge.

Lateral Stability

The effect of jet dynamic pressure ratio on lateral stability is shown in figure 26. A large increase in lateral stability is found as the dynamic pressure ratio increases. Increasing the lower vane angle at a constant dynamic pressure ratio also increased the induced lateral stability. These increases are due to the shift in the ground vortex induced flow field towards the leeward side of the aircraft (see figure 22). This shift causes the center of pressure of the induced lift losses to move to the leeward side of the aircraft. It also causes portions of the windward wing and canard to move from the suckdown region into the free-stream. Both of these effects act to cause positive rolling moments at a negative sideslip angle, so the lateral stability is increased. It would be expected that the upper reverser/vertical tail interaction would also contribute to lateral stability changes. Due to the decreased tail effectiveness, this interaction should result in a decrease in the lateral stability. It is impossible to assess this contribution, because no vertical tail-off runs were conducted.

Differential Upper Reversing

Differential upper reversing (differing upper left/right vane settings) was tested in order to investigate the induced aerodynamic effects to determine the potential for using differential upper vanes for yaw control. Incremental yawing moment coefficient data versus sideslip angle are presented in figure 27 for a fixed left upper vane setting. For the asymmetric settings, a zero beta yawing moment increment of about -0.025 is present for all cases. This is in the same direction as the induced forces, and is equivalent to about a fifteen degree rudder deflection. Even though the trends are non-linear, all of the differential settings tested induce roughly neutral directional stability.

An asymmetric yawing moment is apparent in the symmetric 135/135 upper vane setting. It is believed that this asymmetry may arise from small differences in the left/right reverser nozzle pressure ratio settings.

The induced effect of differential upper reversing on rudder effectiveness is given in figure 28. The trend is identical to that found with symmetric upper vanes (figure 24). The magnitude of the increases with differential reversing is smaller than with symmetrical reversing. With differential reversing, the left upper reverser remains at the 135 degree setting, so only the right hand vertical tail benefits from the vane angle reduction. It should be noted that while differential upper reversing favorably impacts the stability and control characteristics, it also causes significant (possibly unacceptable) losses in reverse thrust.

Conclusions

A low speed wind tunnel test with a 0.075 scale model of the F-15 SMTD with thrust reversers has been conducted. The test was conducted in the McDonnell Aircraft 8 x 12 Low Speed Wind Tunnel, using a fixed ground board whose length was reduced in order to minimize the effect of the ground boundary layer. The thrust reversers were found to induce:

(a) Small lift and negligible pitching moment increments in free air.

(b) Increasing lift and pitching moment increments during transition into ground effect.

(c) Large lift losses and nose-up pitching moment increments at landing gear height. These increments varied with the lower vane angle, velocity, nozzle pressure ratio, and sideslip angle.

(d) Non-linear horizontal tail effectiveness characteristics in all flight regimes.

(e) Negligible changes in lateral stability in free air.

(f) Large increases in lateral stability at landing gear height.

(g) Changes in directional stability and rudder effectiveness, which were strongly affected by the upper vane angle. These changes were independent of the height above the ground.

(h) Large favorable yawing moment increments with differential upper reversing.

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F-15 S/MTD AIRCRAFT

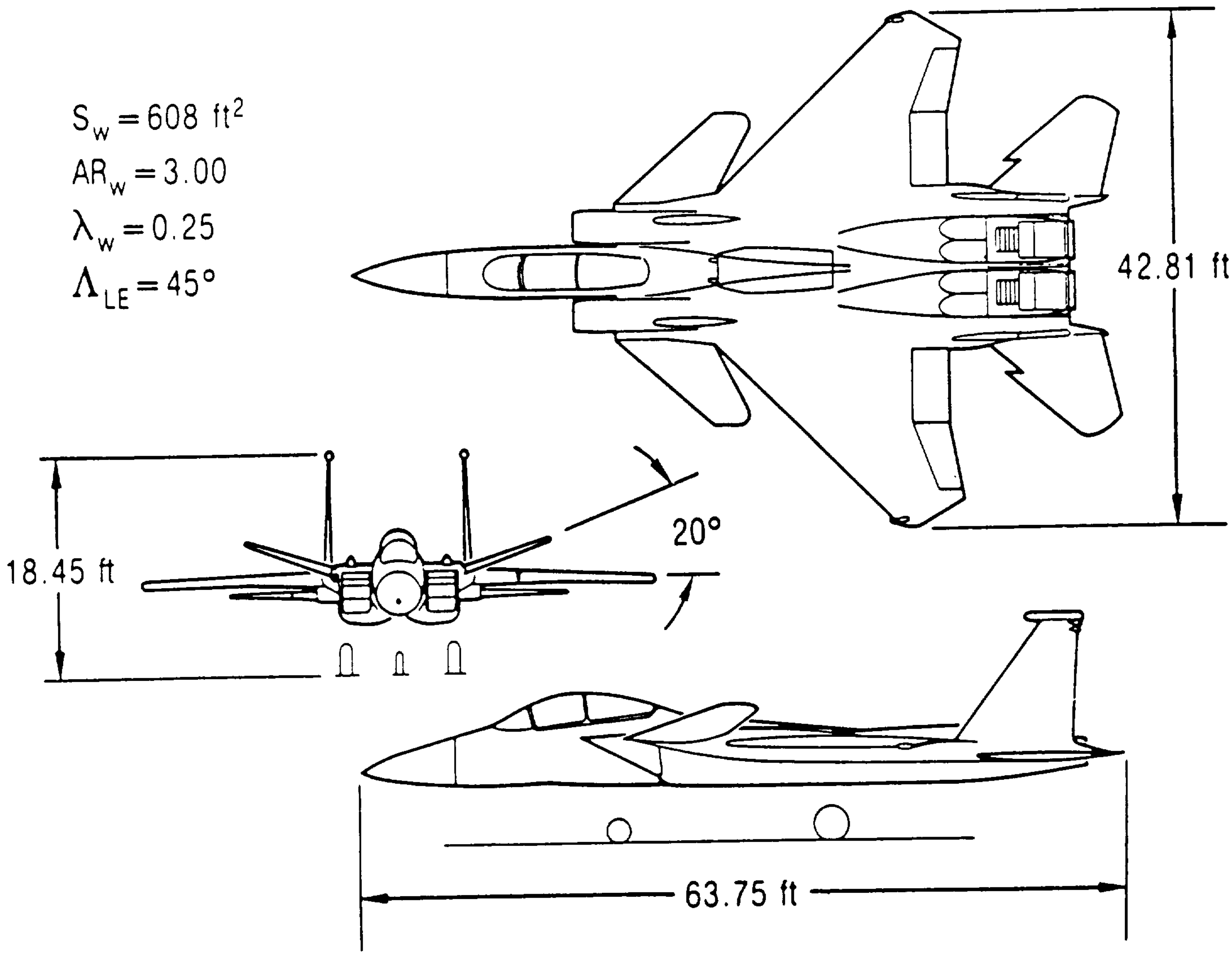

Figure 1. F-15 SMTD Three View.

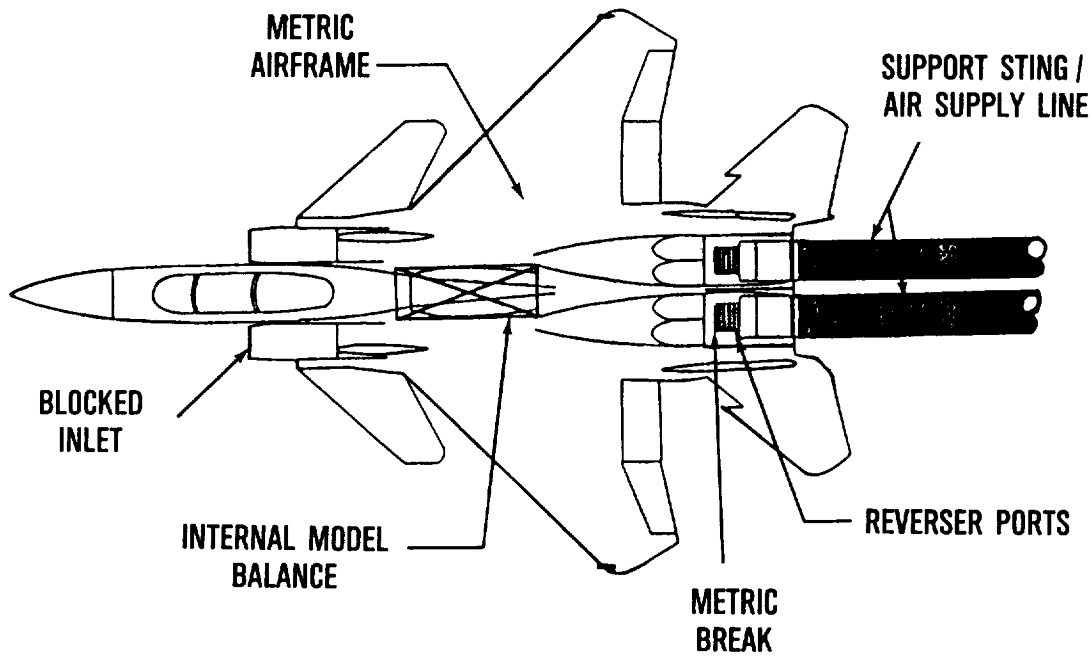

Figure 2. Jet Effects Model Schematic.

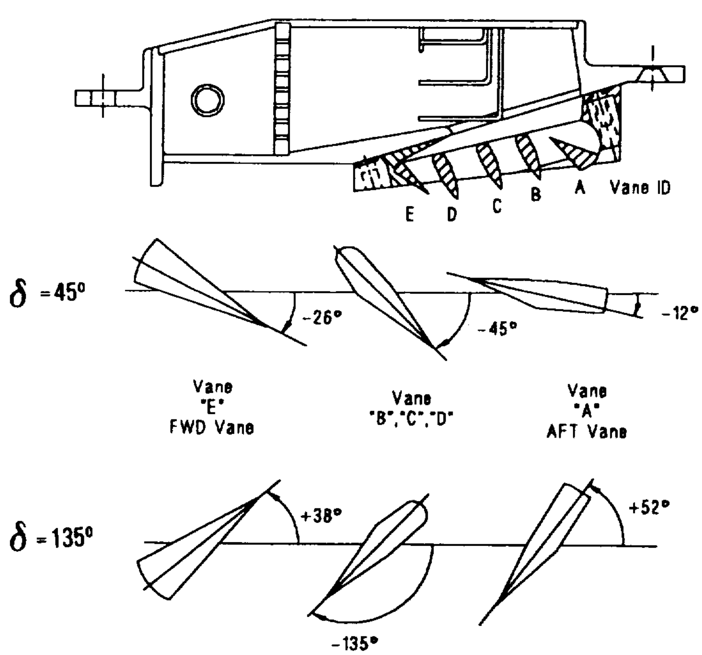

Figure 3. Reverser Vane Pack Assembly.

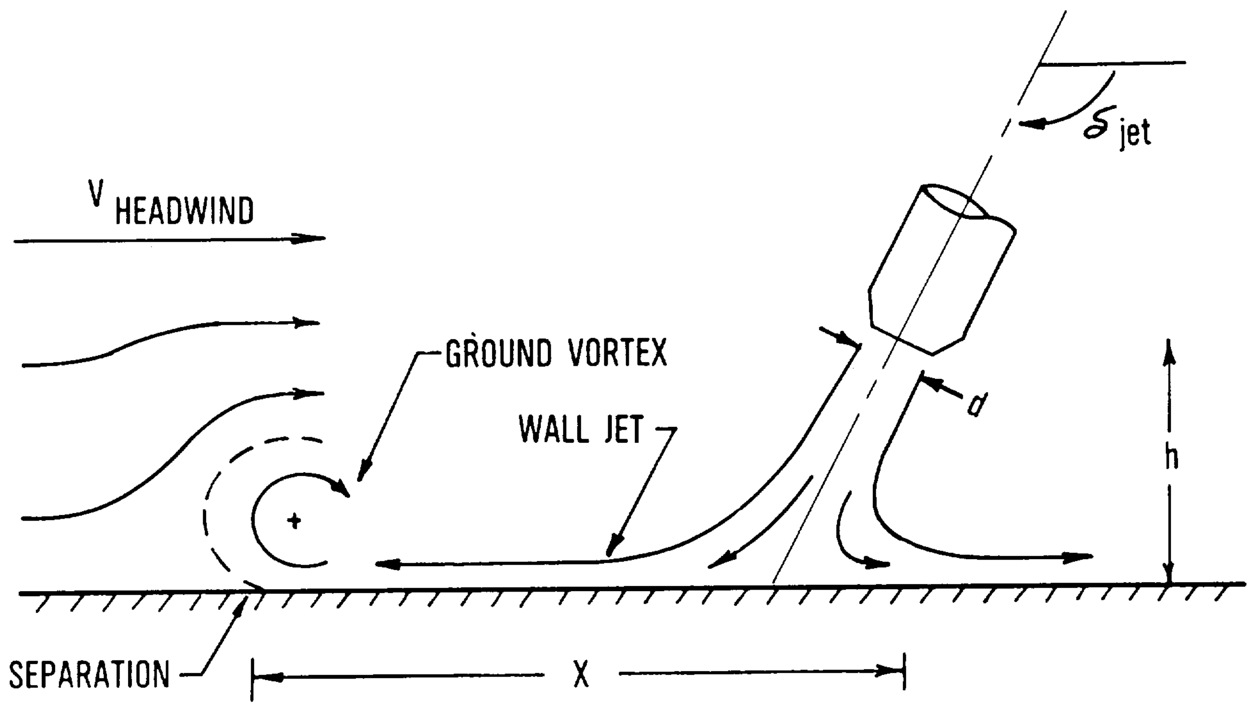

Figure 4. Formation of the Ground Vortex.

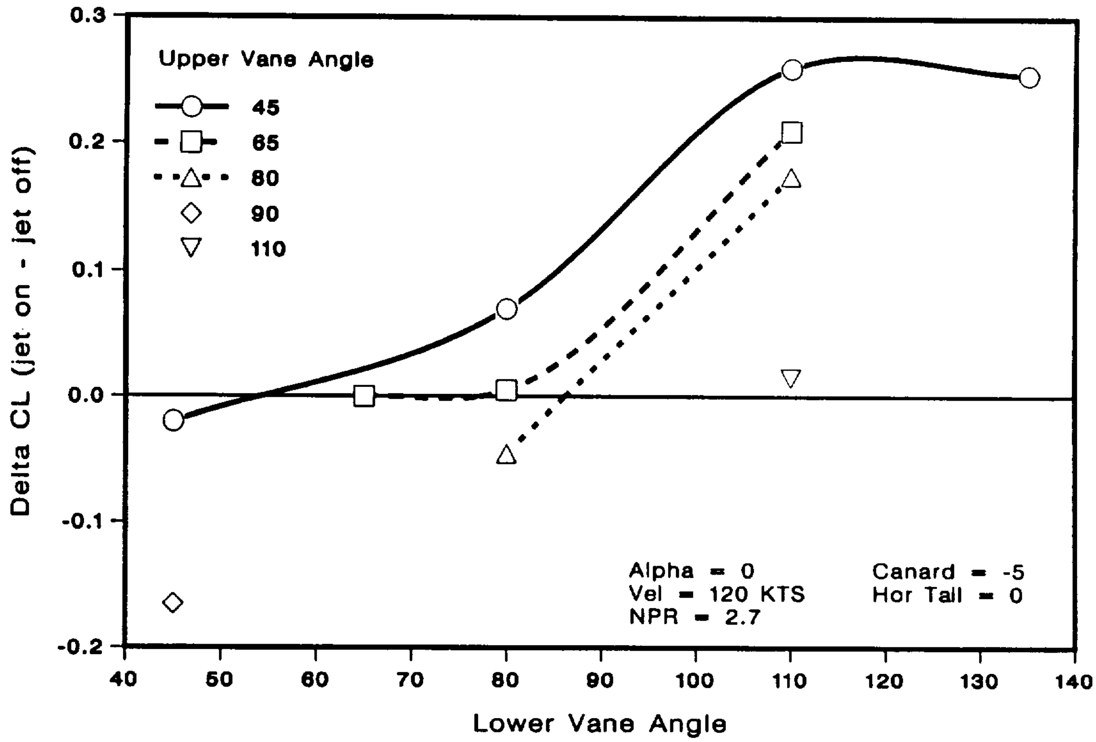

Figure 5. Lift Coefficient Increment as a Function of Upper and Lower Vane Angle. Free Air.

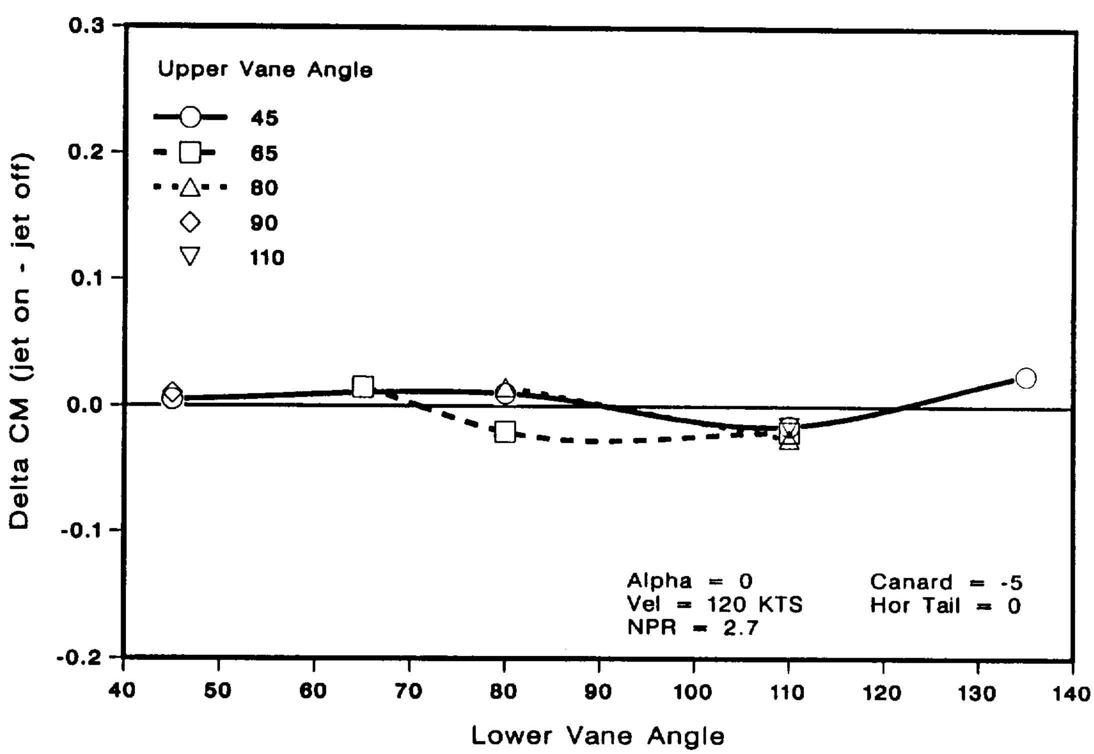

Figure 6. Pitching Moment Coefficient Increment as a Function of Upper and Lower Vane Angle. Free Air.

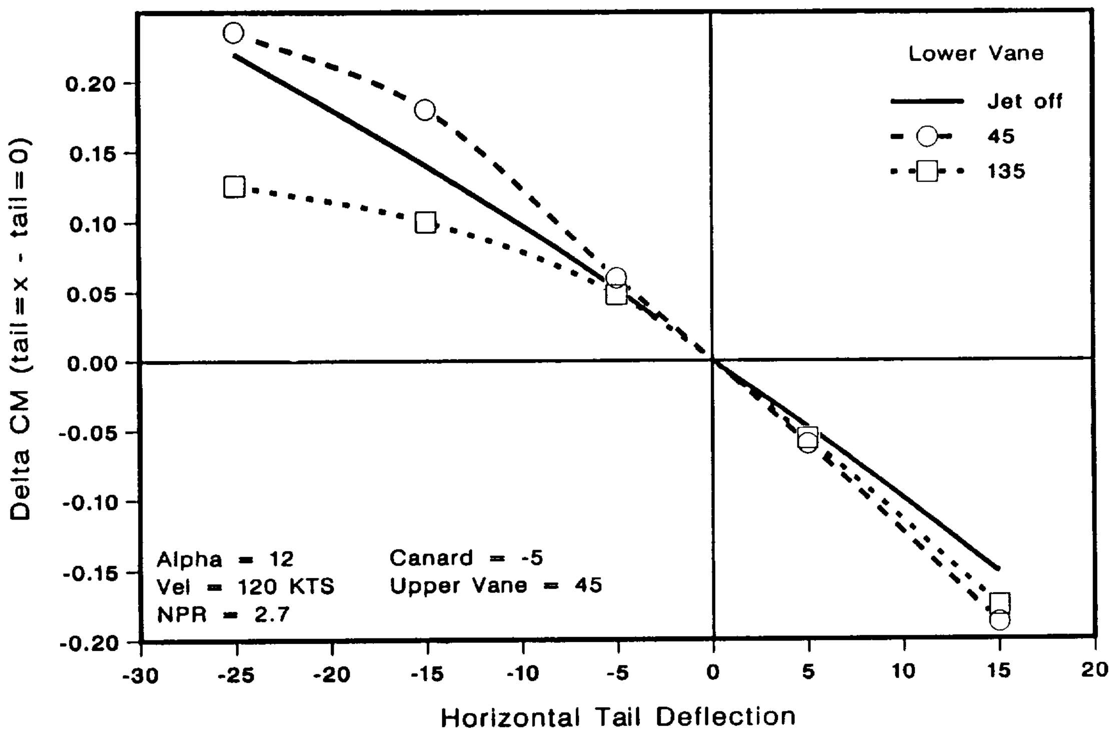

Figure 7. Increment in Pitching Moment Coefficient due to Horizontal Tail Deflection. Free Air.

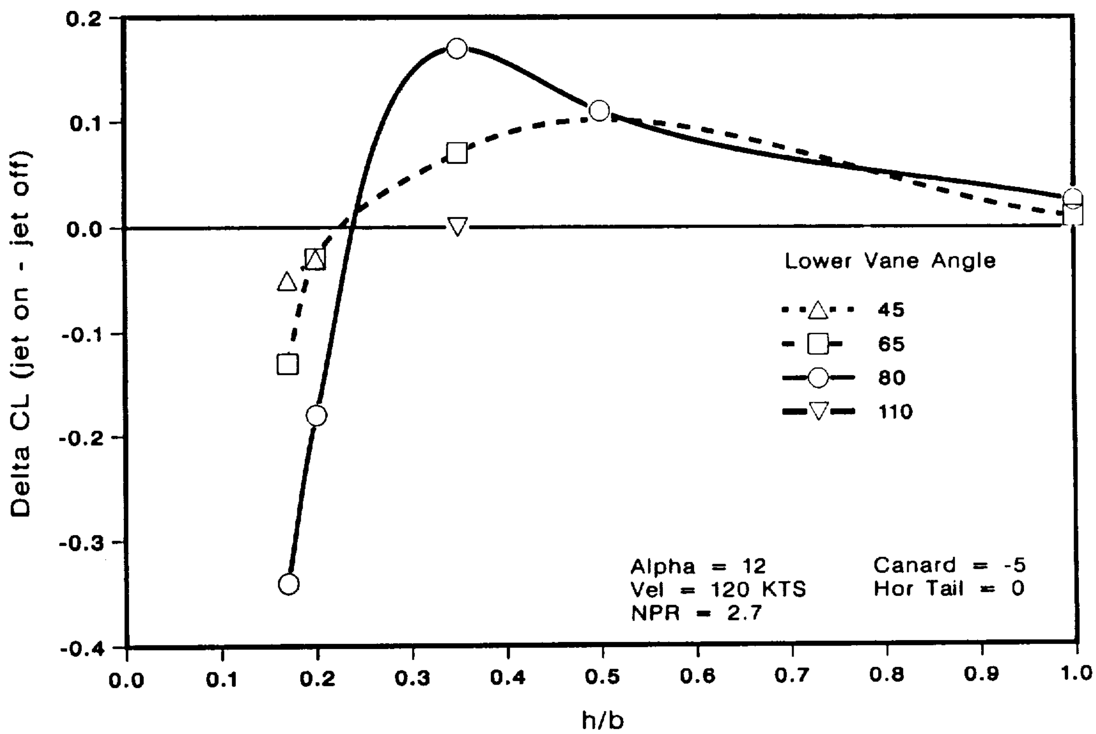

Figure 8. Lift Coefficient Increment as a Function of Lower Vane Angle. Height Transition.

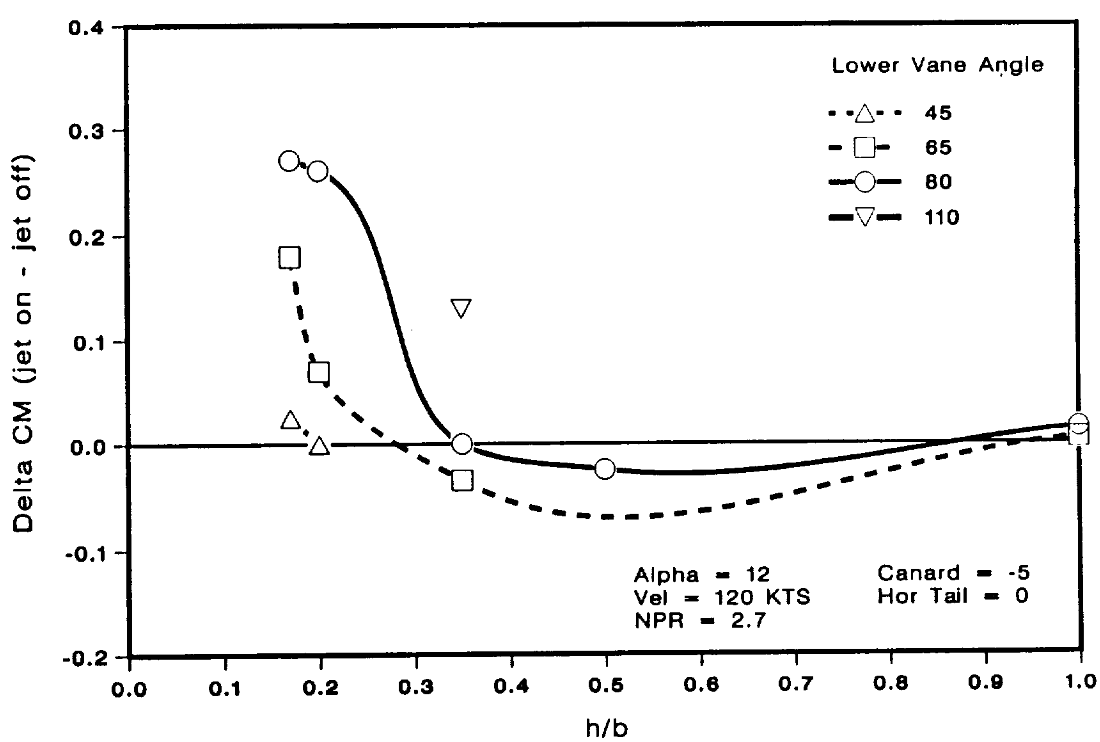

Figure 9. Pitching Moment Coefficient Increment as a Function of Lower Vane Angle. Height Transition.

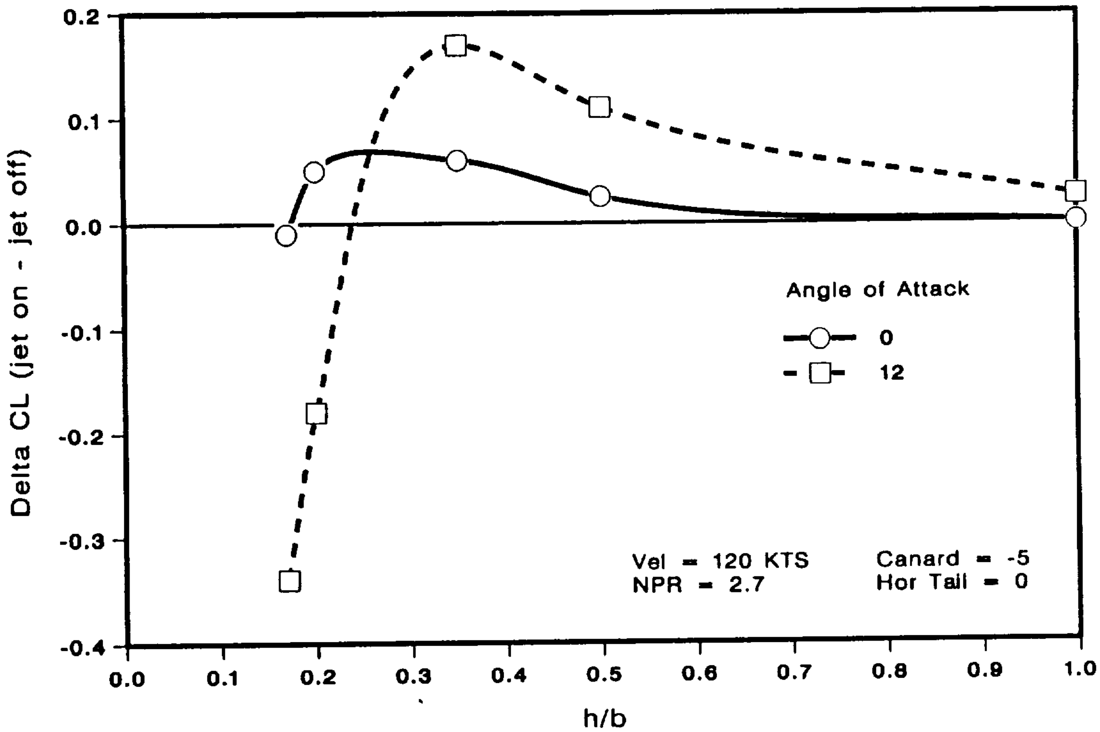

Figure 10. Lift Coefficient as a Function of Angle of Attack. Height Transition.

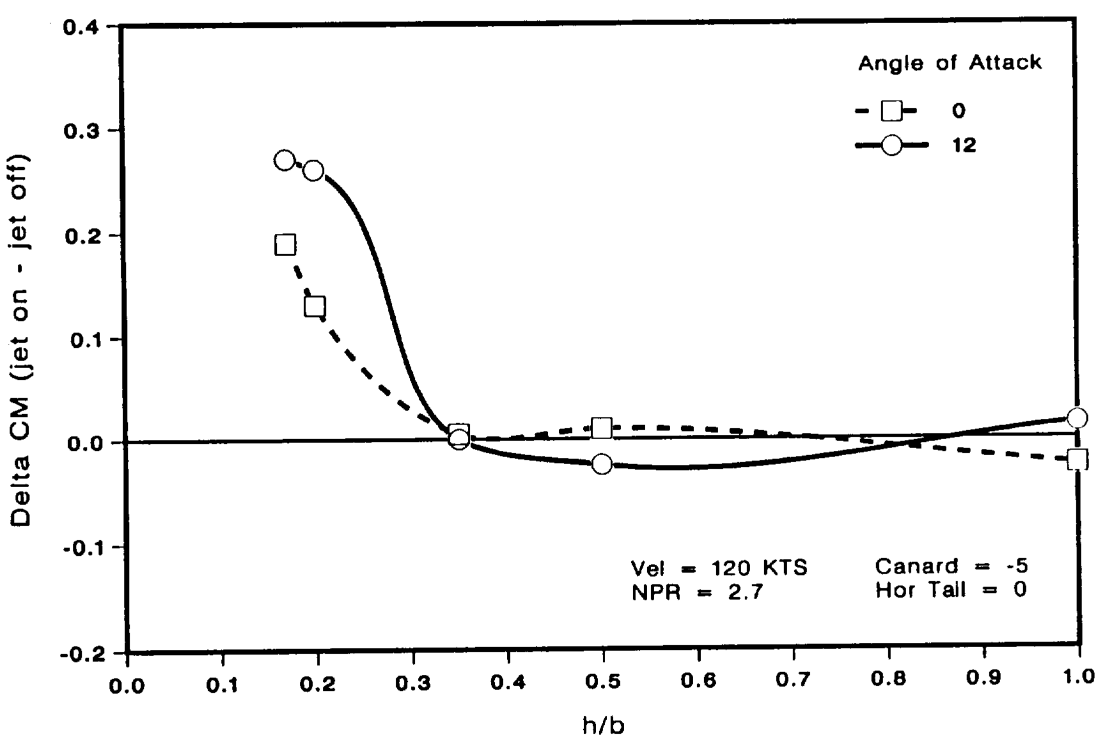

Figure 11. Pitching Moment Coefficient Increment as a Function of Angle of Attack. Height Transition.

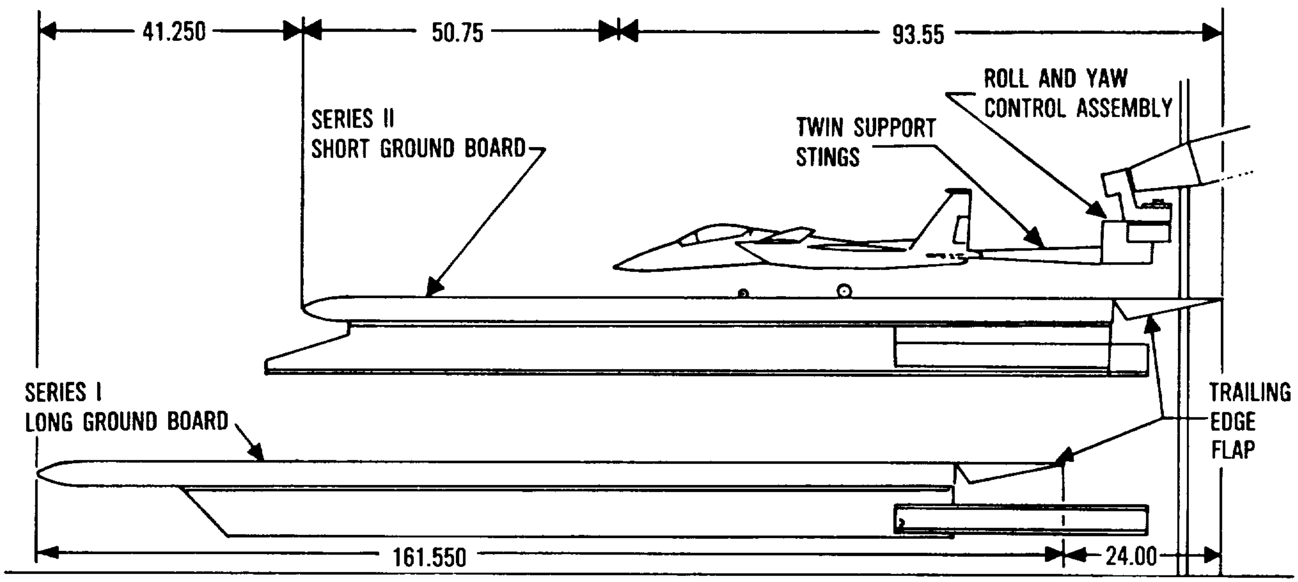

Figure 12. Comparison of Ground Board Installations.

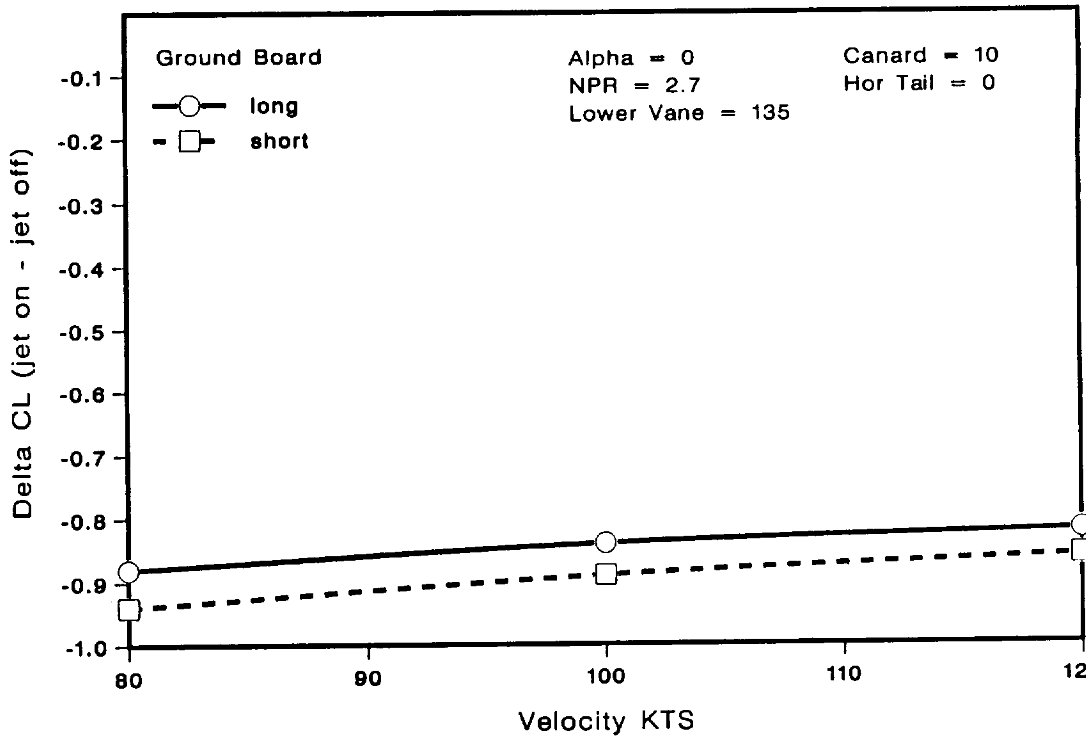

Figure 13. Effect of Ground Board Length on the Reverser Induced Lift Coefficient Increment. Landing Gear Height.

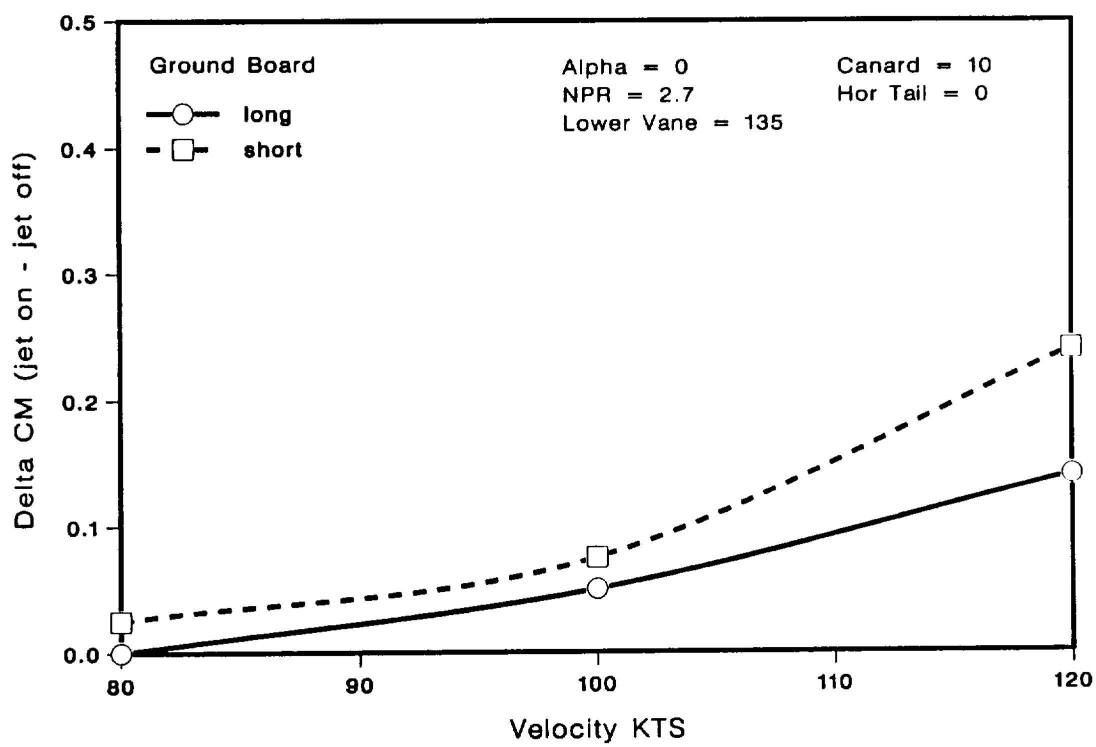

Figure 14. Effect of Ground Board Length on the Reverser Induced Pitching Moment Coefficient Increment. Landing Gear Height.

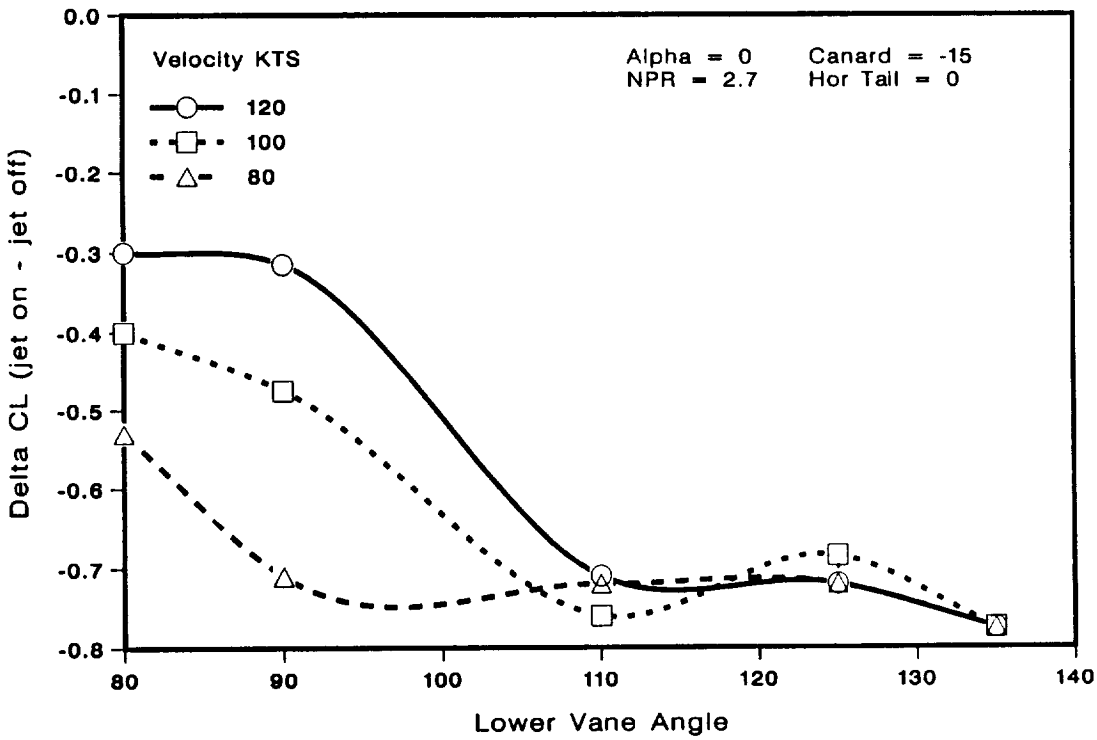

Figure 15. Effect of Free Stream Velocity and Lower Vane Angle on the Reverser Induced Lift Coefficient Increment. Landing Gear Height.

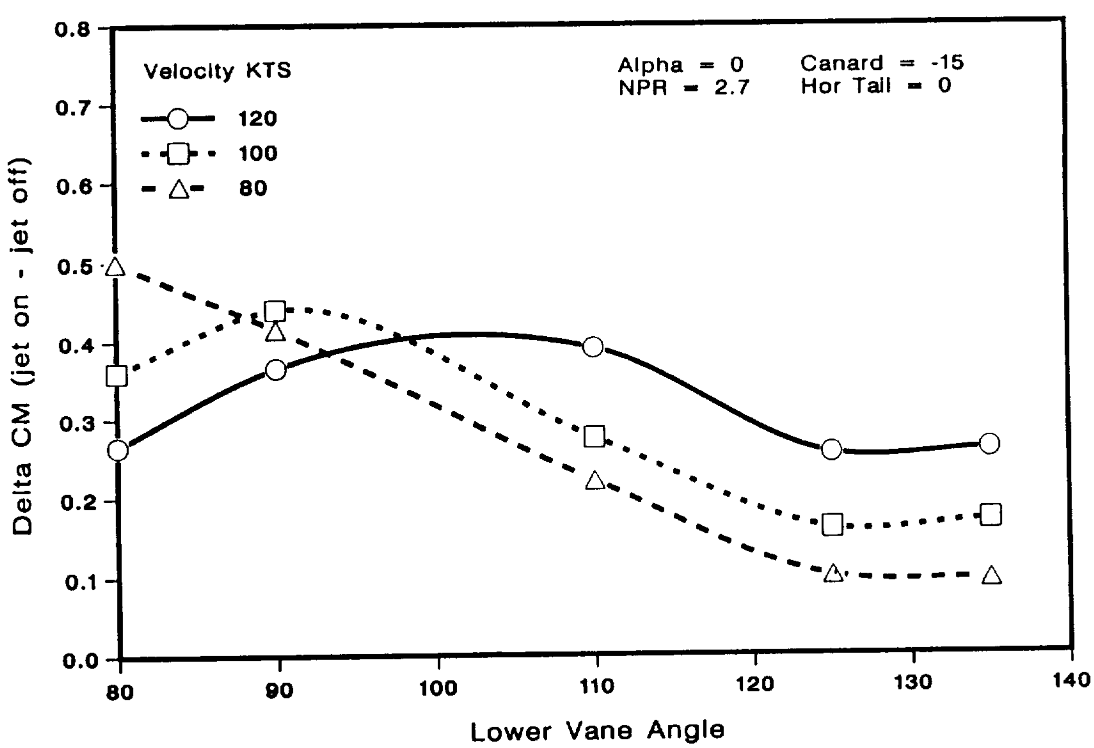

Figure 16. Effect of Free Stream Velocity and Lower Vane Angle on the Reverser Induced Pitching Moment Coefficient Increment. Landing Gear Height.

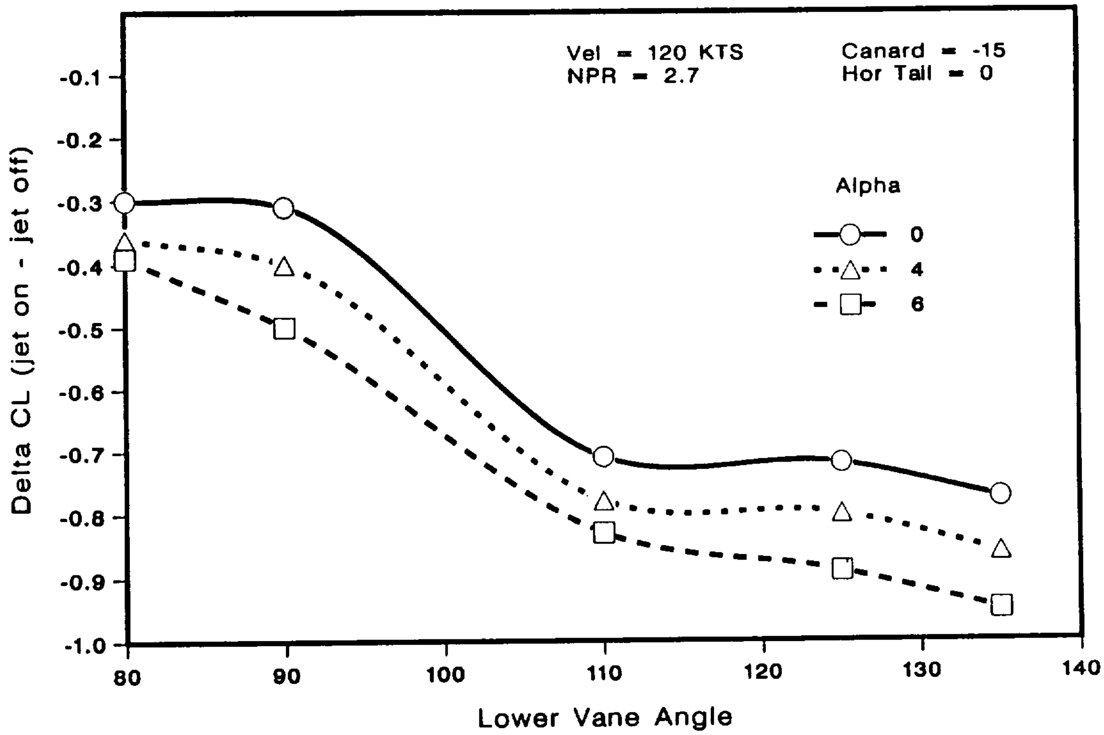

Figure 17. Effect of Angle of Attack and Lower Vane Angle on the Reverser Induced Lift Coefficient Increment. Landing Gear Height.

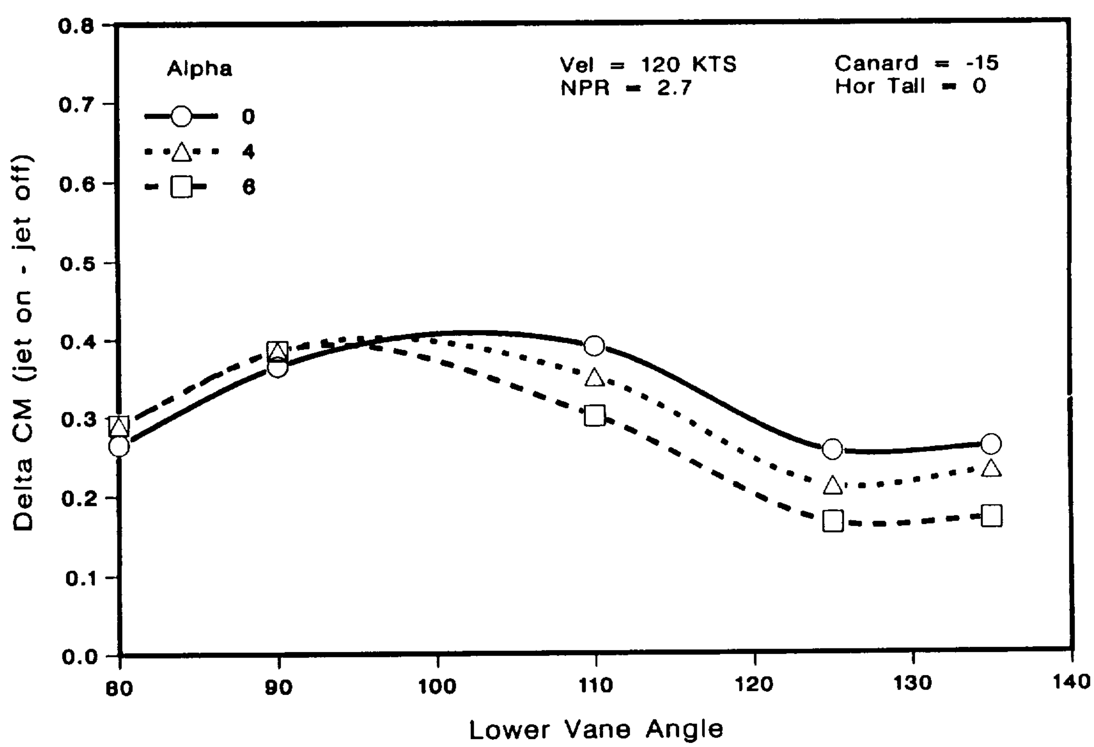

Figure 18. Effect of Angle of Attack and Lower Vane Angle on the Reverser Induced Pitching Moment Coefficient Increment. Landing Gear Height.

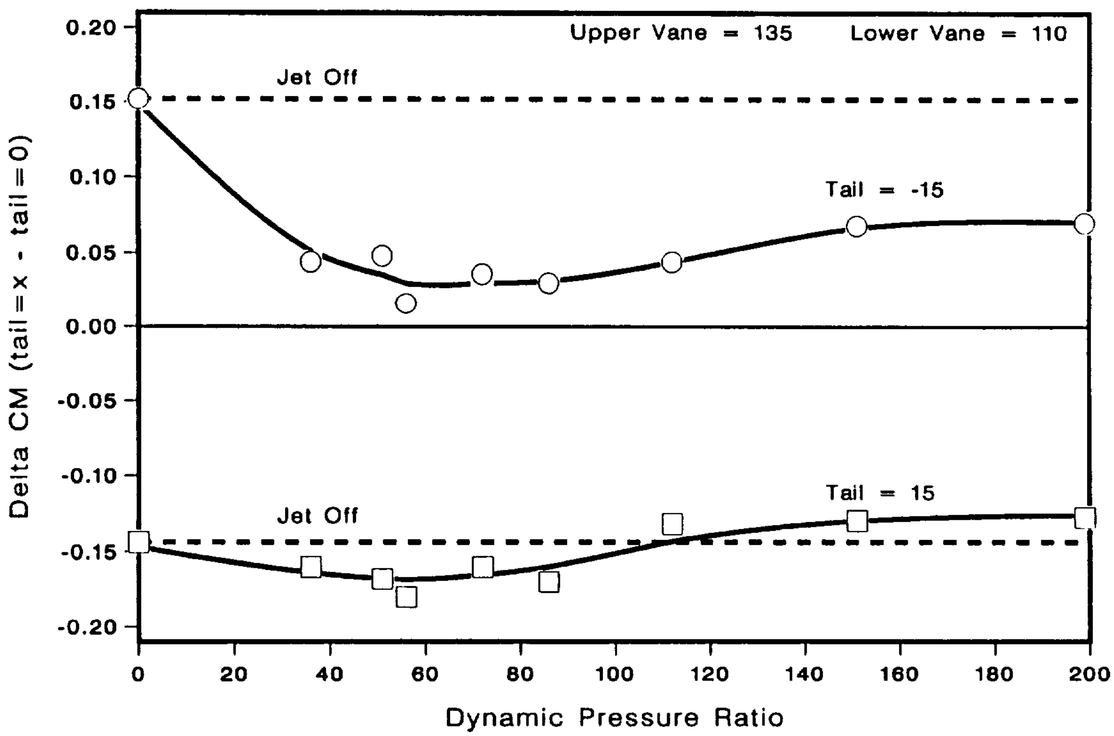

Fig 19. Pitching Moment Coefficient Increment due to Tail Deflection as a Function of the Reverser to Free Stream Dynamic Pressure Ratio. Landing Gear Height.

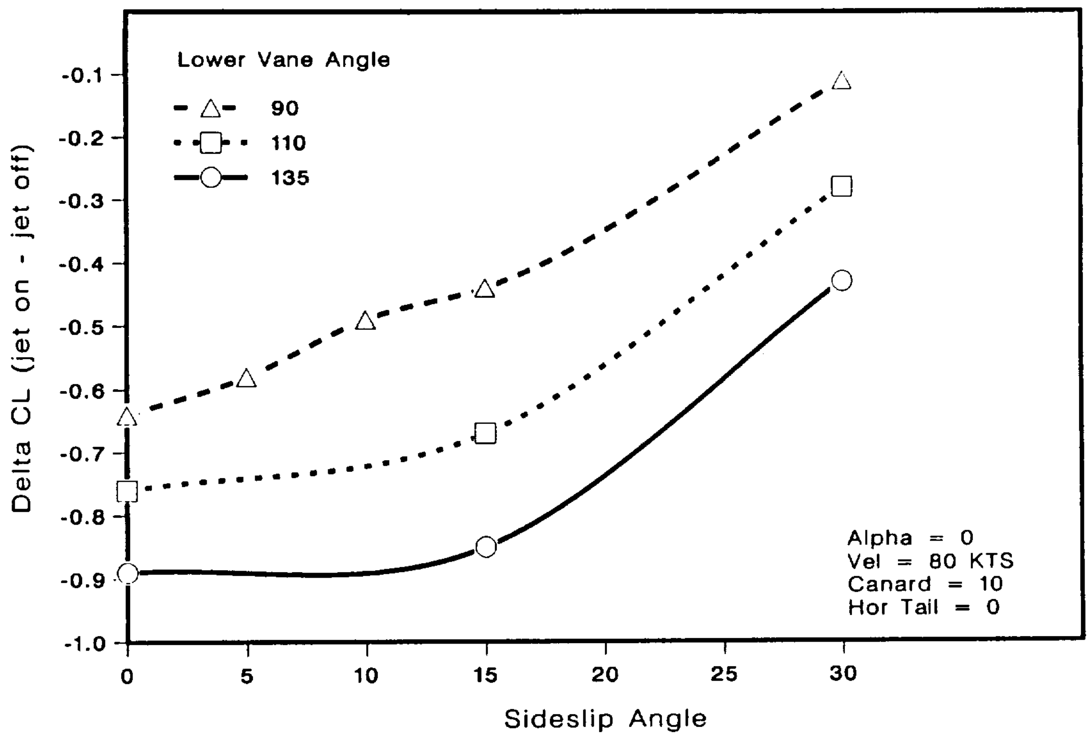

Figure 20. Effect of Sideslip Angle on the Reverser Induced Lift Coefficient Increment. Landing Gear Height.

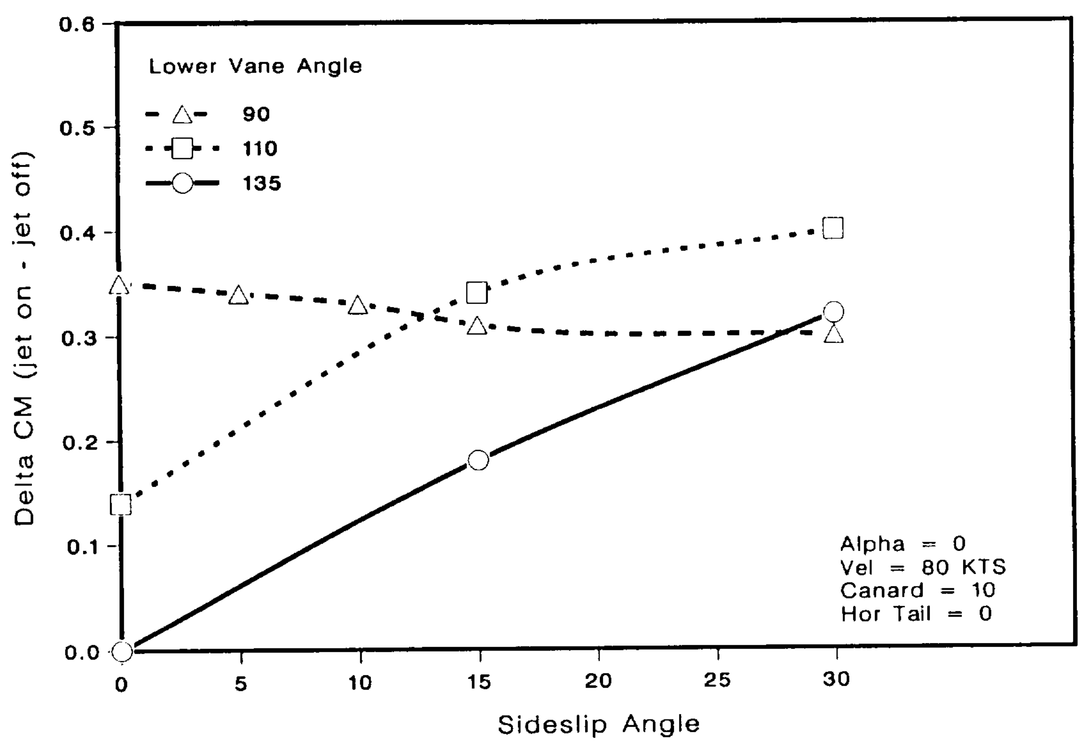

Figure 21. Effect of Sideslip Angle on the Induced Pitching Moment Coefficient Increment. Landing Gear Height.

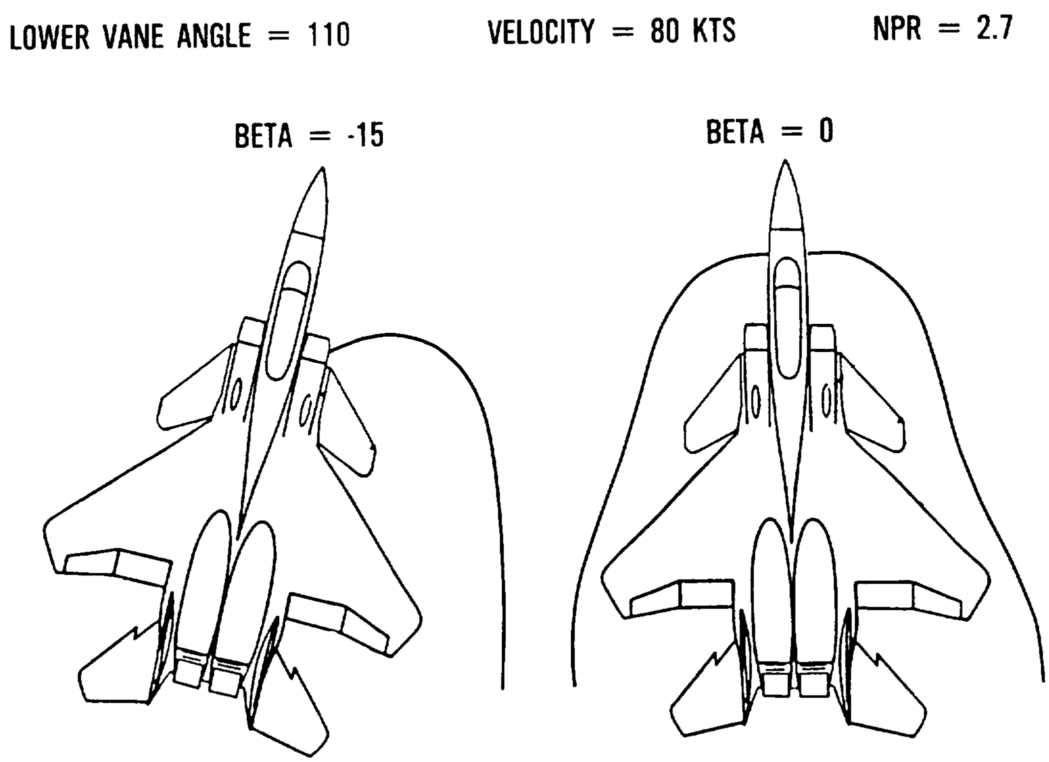

Figure 22. Ground Stagnation Line at Zero and Negative Sideslip.

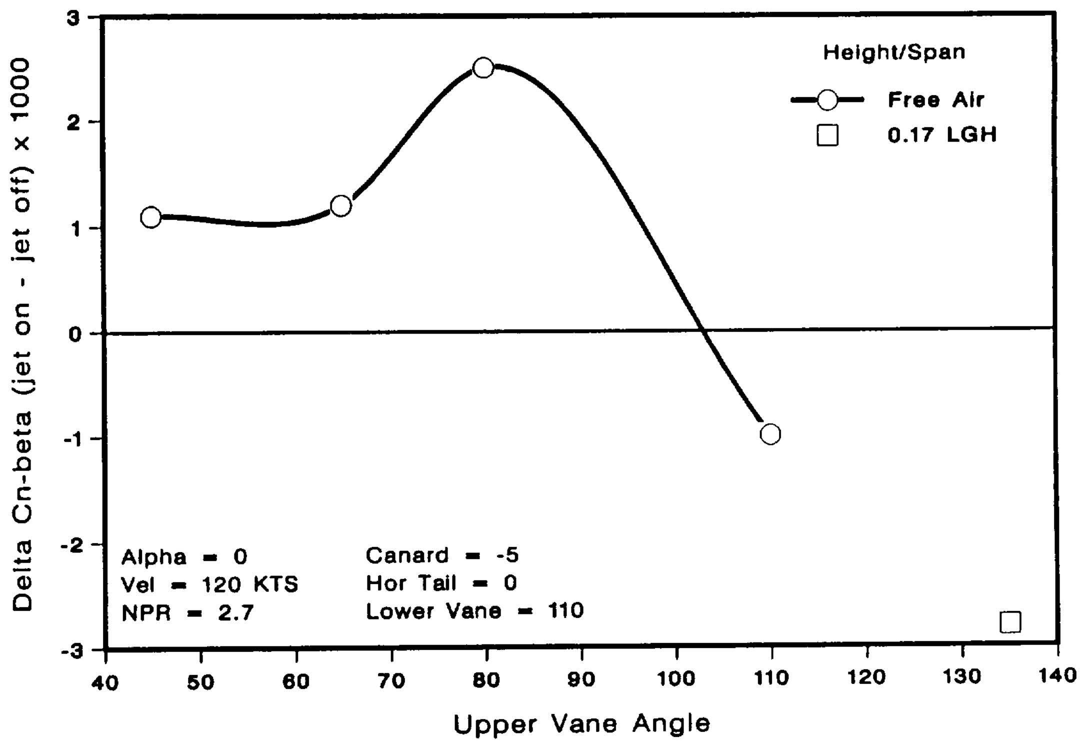

Figure 23. Increment in Directional Stability as a Function of Upper Vane Angle. Free Air.

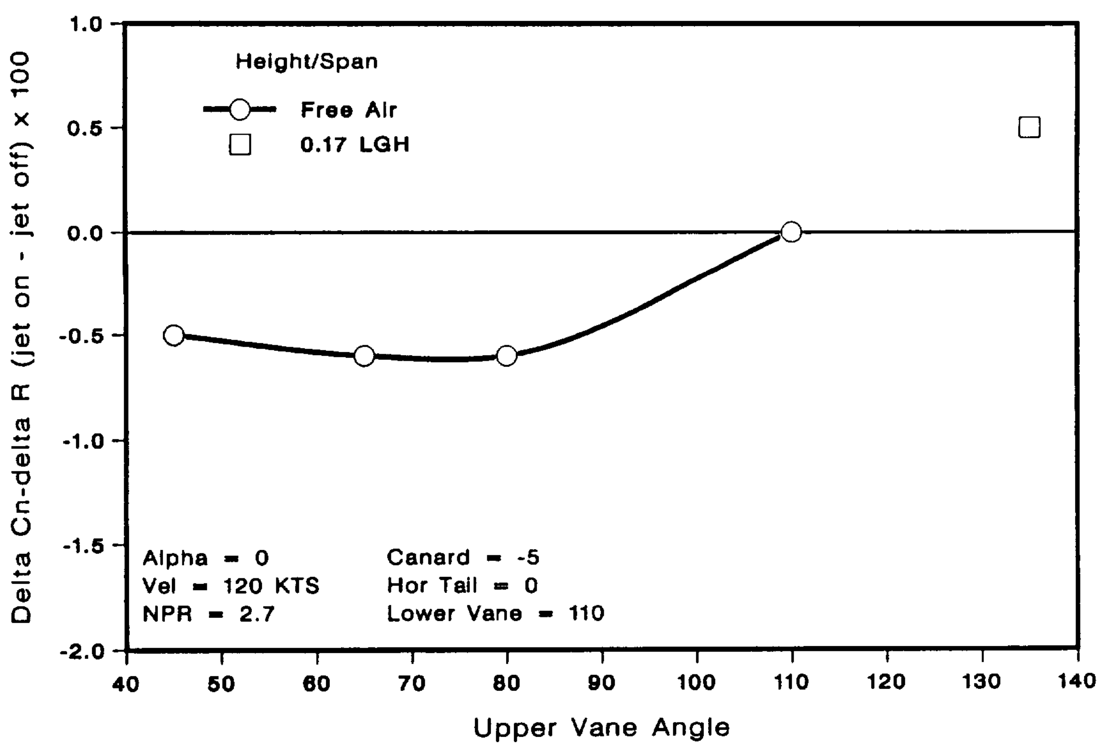

Figure 24. Increment in Rudder Effectiveness as a Function of Upper Vane Angle. Free Air.

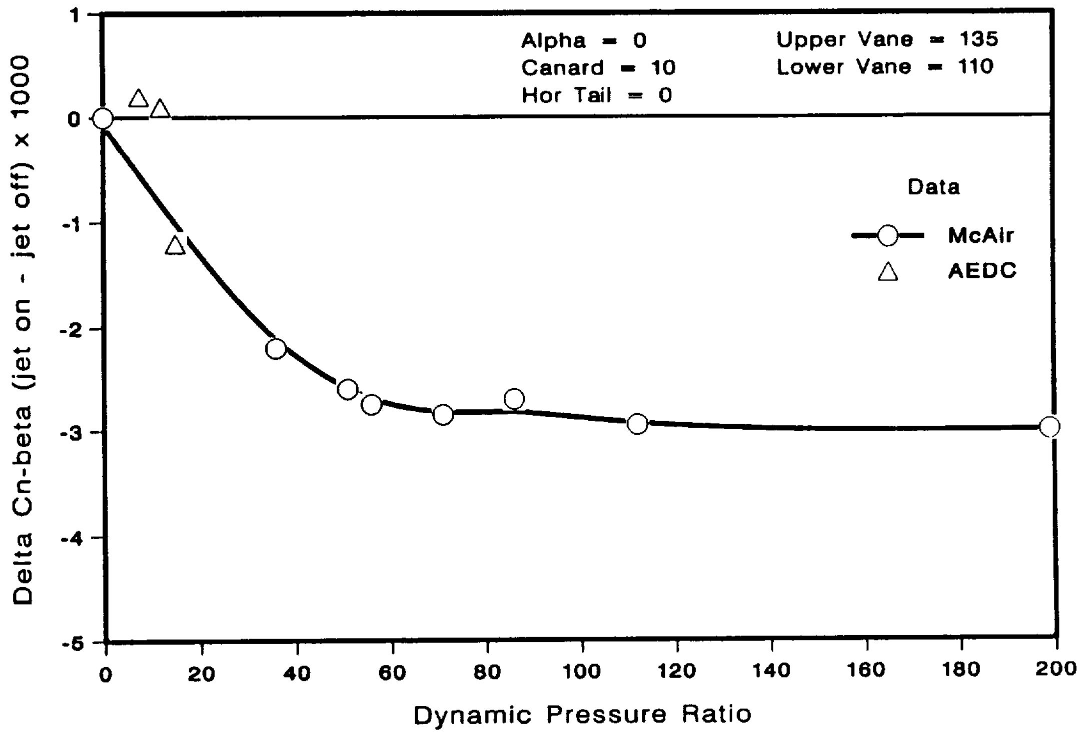

Figure 25. Increment in Directional Stability as a Function of the Reverser to Free Stream Dynamic Pressure Ratio. Landing Gear Height.

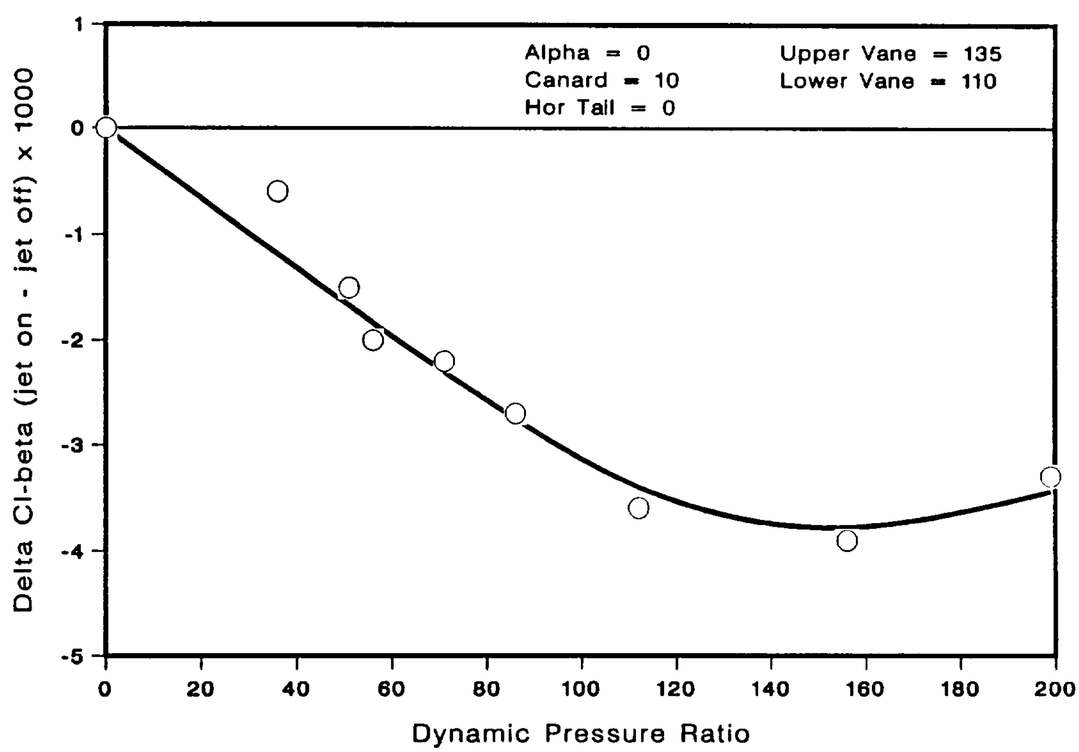

Figure 26. Increment in Lateral Stability as a Function of the Reverser to Free Stream Dynamic Pressure Ratio. Landing Gear Height.

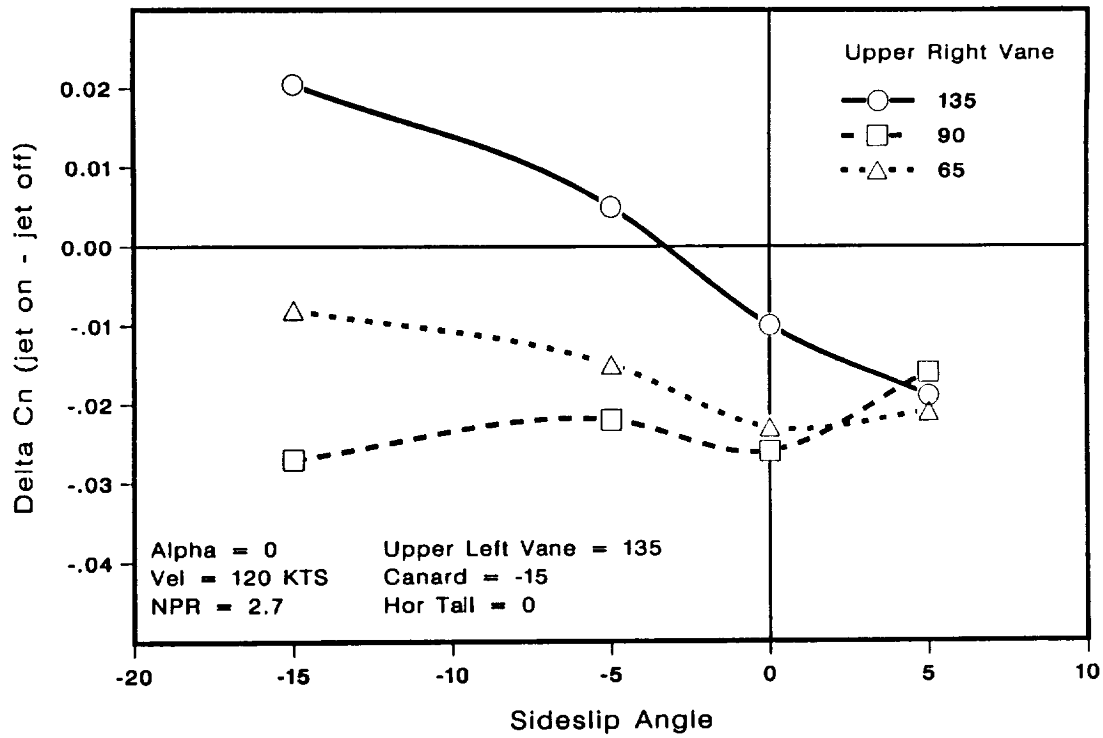

Figure 27. Yawing Moment Coefficient Increment as a Function of Upper Right Vane Angle. Landing Gear Height.

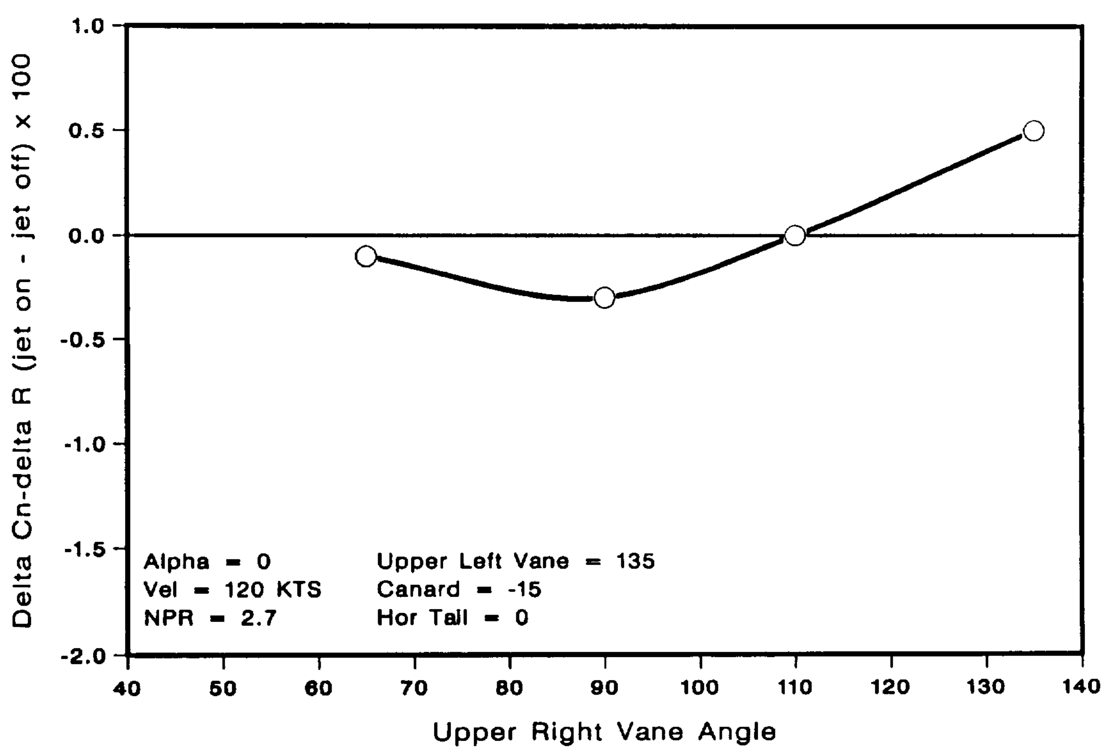

Figure 28. Increment in Rudder Effectiveness as a Function of Upper Right Vane Angle. Landing Gear Height.