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EFFECTS OF THRUST REVERSING IN GROUND PROXIMITY

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Abstract

This paper describes the changes in stability and control characteristics encountered by a thrust-reversing aircraft during its final approach, landing, and ground roll. These changes include a strong pitch-up accompanied by the loss of horizontal tail and aileron control effectivenesses. The magnitudes of reverser-induced changes in ground effect are much larger than corresponding changes in free air. The paper also describes some unexpected unsteady motions exhibited in wind tunnel by an aircraft model with reversers operating in ground proximity. The cause of this oscillatory behavior was determined to be an unsteady interaction between the wall jets formed by impingement of reverser jets on the ground and the on-coming free stream. Time histories of rolling moments measured by the wind tunnel balance were analyzed. The effects of dynamics of the model balance/support system were removed and frequencies were scaled by Strouhal number to full scale. Corrected time series were used to simulate the motion of a fighter aircraft with thrust reversers in ground effect. The simulation predicted large roll angles and nose-down attitude at touch-down. Finally, the paper discusses some phenomena of jet attachment to solid surfaces and recommends areas for future research.

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I. Introduction

The next generation of fighter aircraft will be required to have better STOL capabilities than the current generation. The emphasis on STOL results from the requirement that future fighters be able to operate from bomb-damaged runways. The emerging technology of in-flight thrust reversing enhances STOL capability by significantly reducing landing distances. Thrust reversing also has potential advantages under up-and-away conditions due to increased maneuverability of the aircraft.

Northrop Corporation, Aircraft Division, has recently completed an Air Force Program "Generic Thrust Reverser Technology for Near-term Application". The objective of this program was to develop design guidelines for integration of thrust reversers into an aircraft such that resulting stability and control impacts are minimal, both in and out of ground effect. As a part of this contract and concurrent Independent Research and Development Programs, a thrust-reversing aircraft model was tested in the Northrop 7 x 10 ft. low-speed wind tunnel. Testing was conducted both in and out of ground effect.

In this workshop, some results from the ground effect part of the test program will be presented. Additionally, limited data which are applicable to both free air and ground effect will be presented. Basic flow mechanisms will be identified. Main consideration will be an unexpected unsteady flow phenomenon encountered during tests. Finally, some recommendations for future studies are given.

II. Test Model and Facility Description

Tests were conducted in the Northrop Aerosciences Laboratory 7 x 10 ft. low-speed wind tunnel. This is a single return, closed throat wind tunnel operating at atmospheric static pressure. The thrust-reversing aircraft model (Figure 1) was derived from a 0.08-scale model of the YF-17 aircraft by retaining the wing, forward and center fuselage sections. The afterbody/empennage assembly attached at an existing fuselage break near the wing trailing edge. This assembly represented a twin engine, twin vertical tail configuration based on 0.068-scale F/A-18A aircraft with reversing 2D-CD nozzles. A circular board in the test section simulated the ground plane.

The reverser jets emerged out of a non-metric plenum chamber mounted on the sting. The plenum was made non-metric to eliminate any contributions to true jet-induced loads from unbalanced reaction forces due to multiple reverser port arrangements. The plenum consisted of a rectangular steel box and an air pressure reduction and distribution system. Cold, high pressure air was supplied to the plenum by two lines connected to compressed air supply. Interchangeable, honeycomb inserts of rectangular shape, mounted flush with the plenum surface, were used to obtain reverser jets at various efflux angles, port areas, and port aspect ratios. The axial position of the jets relative to the horizontal and vertical tails was varied by adding or removing spacers to and from the fuselage.

Aerodynamic loads induced on the metric part of the model by the reverser jets were measured on a 6-component balance. In addition, the vertical tails and the left and right panels of the horizontal tail were instrumented with individual 3-component balances for a direct measurement of induced loads in the near-field of the reverser jets. These balances yielded the normal forces, bending moments and torsional moments on the tails. To evaluate the contribution of the non-metric plenum box to the aircraft, a large number of static pressure measurements were obtained on both upper and lower surfaces of the plenum.

The model was tested at three different ground heights; free air, intermediate, and landing gear height. In "free air", the model was set midway between the circular groundboard and the tunnel ceiling. This corresponds to a ratio of height above ground to the wing span of approximately 1.2. The intermediate ground height represented 0.36 wing span above the ground plane. At landing gear height the main gear was located 0.75 inches off the ground board (height/span = 0.18). This safety clearance was necessary to avoid grounding the metric airframe. Electrical contact "feelers" mounted below the main gear wheels alerted the tunnel operators of any contact between the ground board and the model.

The test approach was to vary each test parameter (reverser axial location, trailing edge flap deflection, for example) from its baseline and to obtain force, moment, and pressure measurements for a range of values of jet/free stream dynamic pressure ratio. The latter was varied by changing the tunnel speed at a fixed nozzle pressure ratio to simulate changing aircraft speed at constant power setting. Reverser parameters investigated were axial port location, jet efflux angle, cant or splay angle of lower reverser jets, port aspect ratio, and asymmetric thrust reversing. Several aircraft parameters were also varied. These included angle-of-attack, sideslip, horizontal tail deflection, wing trailing edge flap angle, and roll angle. Figure 2 shows schematically the various test parameters. Reference or baseline values of the parameters are shown in Table I.

III. Results and Discussion

Results on reverser-induced effects in ground proximity are grouped under the following three headings:

(i) Stability and Control Effects

(ii) Unsteady effects

(iii) Jet/Airframe Attachment Effects

Of these three effects, main emphasis will be on unsteady effects. Furthermore, the discussion on stability and control effects will be limited to the effects due to variation of aircraft height above the ground plane. A complete discussion of influence of aircraft/reverser parameters on induced effects

TABLE I

Definition of Versatile Model Baseline Configuration

Wing Flaps:	25 degree (leading)/20 degree (trailing)
Horizontal Tail Definition:	0 degree
Rudder Deflection:	0 degree
Landing Gear:	ON
Nozzle Pressure Ratio:	3.3 (Intermediate Power)
Nozzle Aspect Ratio:	2.0
Nozzle Port Area:	100 percent (No Aft Nozzle Flow)
Axial Port Location:	0.284 Wing Chords Aft of Vertical Tails
Nozzle Efflux/Cant Angles:	60 degree/0 degree

in ground proximity may be found in Reference 1.

(i) Stability and Control Effects

Figures 3 and 4 show the effects of varying ground height on jet-induced changes (i.e. jet-on minus jet-off values) in longitudinal stability and control for the baseline aircraft/ reverser configuration. Corresponding changes in lateral-directional stability and control are shown in Figure 5. All data are presented with trailing edge flaps down (flap setting 25/20) and over a wide range of jet/free stream dynamic pressure ratios. The value of this ratio for typical approach speed of the F/A-18A aircraft is approximately 60.

Figures 3a and 3c contain increments in lift and pitching moment coefficients at the approach angle-of-attack of 8.5 degrees. It is seen that the configuration lift increases slightly at first (relative to its free air value) and then decreases rapidly as the aircraft comes in close ground proximity. This loss of lift increases significantly with increase in reverser jet/free stream dynamic pressure ratio. The incremental pitching moment curves in Figure 3c reveal that in free air and at intermediate ground height (h/b = 0.36), the reversers induce a relatively small pitch-up moment. However, in close ground proximity (h/b = 0.1 , the aircraft experiences a strong jet-induced pitch-up at approach dynamic pressure ratio of 60.

The changes in lift and pitching moment at zero degree angle-of-attack in ground effect, a condition which is representative of the aircraft attitude after touch down and rotation, are shown in Figures 3b and 3d. In contrast to the 8.5 degree angle-of-attack case, at landing gear height, the lift increases up to a dynamic pressure ratio of 70 and decreases thereafter. This increment in lift is accompanied by a strong pitch-up. Comparing the results for the two angles-of-attack, it is seen that at 8.5 degrees, the reverser-induced lift loss occurs aft of the moment reference center, in the vicinity of the trailing edge flap. On the other hand, at zero angle-of-attack, the initial reverser-induced lift gain occurs in the LEX/forebody region.

The reverser-induced pitch-up in ground proximity discussed above should be considered in conjunction with the induced changes in the horizontal tail control, which is used to trim out the incremental pitching moments. Figures 4c and 4d show the changes in horizontal tail effectiveness as a function of jet/free stream dynamic pressure ratio, with the ground height as a parameter. It is seen that in free air, there is a moderate increase in effectiveness at both zero and 8.5 degree angle-of-attack. In close ground proximity, however, there is a significant loss in effectiveness at 8.5 degree angle-of-attack. The situation is worse at zero degree angle-of-attack, where there is actually a reversal of the horizontal tail control. Thus, the loss of control effectiveness in ground effect can be a potentially serious problem.

Figures 4a and 4b show the reverser-induced changes in longitudinal stability, dC_m/dC_L, as a function of dynamic pressure ratio with the ground height as a parameter. Two horizontal tail settings, -10 and 0 degrees are shown. The values of dC_m/dC_L have been obtained from data at only two angles-of-attack, 0 and 8.5 degrees. Therefore, they should be interpreted only in qualitative terms. In free air, there is a small stabilizing change in dC_m/dC_L for both tail settings. As the aircraft approaches ground, the stability changes not only depend upon the ground height, but also upon the tail deflection. At the intermediate ground height (h/b = 0.36) and around approach dynamic pressure ratios, stability decreases significantly due to the reversers, for both tail settings. With the aircraft at landing gear height, the stability increases for $\delta H = 0$ degrees, Figure 4b, for all dynamic pressure ratios. However, a large decrease in stability occurs for $\delta H = -10$ degrees. The physical mechanisms behind this dependence of longitudinal stability on horizontal tail deflection are not fully understood. The mechanisms are complicated due to highly nonlinear wing and tail aerodynamics in ground effect. This is because a complex flowfield results when the reverser jets impinge on the ground and interact with the free stream. A substantial change in stability, accompanied by a large decrease in tail effectiveness, can be a cause of concern because the aircraft may not respond sufficiently quickly to tail deflection.

The effects of thrust reversing in ground effect on lateral-directional stability and control parameters are shown in Figure 5 for an angle-of-attack of 8.5 degrees. As seen in Figure 5a, over a wide range of jet/freestream dynamic pressure ratios, the directional stability increases significantly in free air as well as in ground effect. At the approach dynamic pressure ratio of 60, the increment in directional stability at landing gear height is larger than that in free air or intermediate height. The lateral stability also exhibits similar behavior (Figure 5b) in that it increases as the aircraft approaches ground at a given dynamic pressure ratio. The increase is the greatest in close ground proximity, small at intermediate height, and negligible in free air.

The effects of approaching ground with reversers deployed on rudder effectiveness and aileron effectiveness are shown in Figures 5c and 5d respectively. In free air the rudder effectiveness increases due to thrust reversing. As the ground height is reduced the rudder initially becomes less effective (relative to the jet-off value), and then becomes as effective as in free air. Figure 5d shows that reversers have negligible influence on aileron effectiveness in free air as well as at intermediate ground height. Aileron effectiveness data at landing gear height with the trailing edge flaps down are not available. However, data with trailing edge flaps up indicate a substantial loss in aileron effectiveness in close gruond proximity.

The flow mechanisms which result in the reverser-induced stability and control changes discussed above are extremely complex. However, some gross features of the jet-induced flowfield about the aircraft can in identified. The flowfield can be broadly divided into two portions, shown schematically in Figure 6. The top portion contains the two upper reverser jets in a cross flow determined by upstream aircraft components. The bottom portion consists of the two lower jets, their impingement on the ground plane and the resulting wall jets, a "fountain" region resulting from an interaction between the laterally-spreading wall jets, and an interface region resulting from streamwise separating wall jets as they meet the on-coming stream. It will be shown later that this interface exhibits markedly unsteady behavior which can lead to large unsteady forces and moments on the aircraft.

The upper reverser jets pass inbetween and close to the vertical tails and thus affect mainly the directional characteristics of the aircraft. Before discussing these effects, however it is helpful to understand the basic mechanisms associated with a jet in cross flow.

Figure 7 shows the schematic of a circular jet in a cross flow. There are two key mechanisms: blockage and entrainment. The blockage mechanism of jet/free stream interaction is related to the deflected jet acting as an equivalent solid body in the free stream. The presence of this body decelerates the flow upstream of it and accelerates the flow around it. Also, the flow separates behind the "bluff" body of the jet. These flow changes cause regions of positive pressures immediately ahead of the jets and negative pressures around and behind the jets. The entrainment mechanism of jet/free stream interaction is related to the shearing of the jet fluid by the free stream and the resulting jet growth. The jet entrains or "sucks" free stream fluid from all around as it grows. Strongest entrainment, however, occurs in the region immediately behind the jet in the "wake" (Reference 1).

The mechanisms of blockage and entrainment operate simultaneously for a jet in cross flow. Each is dominant in different regions of the flow field around the jet. Furthermore, the extent of these regions varies with the dynamic pressure ratio.

Blockage is the dominant mechanism in the immediate vicinity upstream of and around the jet. The result is to induce positive pressures due to flow deceleration ahead of the port through which the jet issues. Negative pressures exist around the port due to flow acceleration. Entrainment causes the flow to accelerate into the jet. It therefore tends to counter the flow deceleration upstream of the jet and augments acceleration of the flow toward the wake region. Note that at distances sufficiently away from the jet (i.e., in the far-field), weak jet-induced entrainment persists all around the jet.

As the dynamic pressure ratio is increased, there is a general increase in relative strength of the entrainment mechanism. The result is to reduce the extent of the blockage-dominated positive pressures upstream of the jets and to increase the extent of entrainment-dominated negative pressures around the jets. Increase in dynamic pressure ratio also dramatically increases the entrainment behind the jets.

In addition to blockage and entrainment, another effect called impingement or atttachment can occur if a jet directly impacts a solid surface or exhausts at a very shallow angle relative to a surface. Asymmetric attachment/impingement of reverser jets to an aircraft surface can lead to strong asymmetric forces and moments on the airframe. The mechanism of jet attachment is described briefly in a later section.

The reverser-induced increase in the directional stability of an aircraft with twin vertical tails (Figure 5c) can be interpreted in terms of the blockage and entrainment mechanisms. In positive sideslip, or with the nose of the aircraft to the left of the relative wind, the left-hand jet moves closer to the left vertical while the right-hand jet moves away from the right vertical (see inset in Figure 6). This increases blockage or positive pressure on the inner surface of the left vertical with simultaneous increase in entrainment (or reduction of blockage) on the right vertical. Then, the jet-induced incremental forces on the two verticals produce a yawing moment tending to point the aircraft into the wind. The result is increased directional stability in presence of the reverser jets. The reader may consult Reference 2 for a detailed description of flow mechanisms and stability and control effects.

The reverser-induced lift loss (Figures 3a and 3b) is partly understood in terms of the well-known suck-down effect observed for VTOL jets. This loss occurs primarily over the wing because the reverser jets propagate upstream after impingement on the ground. Smoke and water tunnel flow visualizations at Northrop have indicated that the jets eventually separate from the ground plane in a region under the wing. Upon separation, which was observed to be an intermittant process, the complete aircraft was immersed in a highly non-uniform, unsteady, vortical flow field. This flow field, in which the wings are likely to be immerged, can also contribute to the reverser-induced lift loss. The large degradation of horizontal tail effectiveness in ground effect can be attributed to this "spoiled" flow. The latter may also be responsible for the dependence of longitudinal stability on horizontal tail deflection.

The preceding paragraphs discussed the effects of ground height on jet-induced aerodynamic changes experienced by the airframe. It was seen that the induced changes in ground proximity differ characteristically from the induced changes in free air. For example, in free air, thrust reversers do not affect the lateral stability and control parameters, unlike in ground proximity. Also, for a given reverser configuration, the jet-induced pitch-up near ground is signifi-cantly greater than that in free air. The reasons for such differences can be understood by comparing the relative magnitudes of the contributions of various components of the air frame (horizontal tail, vertical tail, etc.) to the total induced change.

The contributions of horizontal and vertical tails can be readily obtained from the direct measurements of tail forces and afterbody pressures. The afterbody is the plenum box through which the jets emerge (Figure 2). The instrumentation for measuring the pressures and forces has been described under Test Model and Facility Description. The contribution of the wing-fuselage combination was determined by subtracting the contributions of the tails and afterbody from the main balance measurements. The latter represent reverser-induced effects on the complete aircraft.

Figure 8 contains the contributions of various aircraft components to the pitching moment, in free air and in ground effect. In free air, both the horizontal and the canted vertical tails contribute nose-up moments, Figures 8a and 8b. The afterbody and wing-forebody contribute nose-down moments, Figure 8c and 8d. Near the approach dynamic pressure ratio of 60, the moments due to the horizontal and vertical tails and the afterbody are comparable in magnitude. The wing-forebody moment is also of a similar magnitude, although slightly smaller. It is noted that the individual moment contribution due to each component is small. Moreover, their algebraic sum is even smaller. The largest contribution, due to the vertical tail, is equivalent to approximately 5 degrees of equivalent horizontal tail deflection. One further observation in free air is that there is negligible change in the configuration lift (Figure 3a). This suggests that most of the wing-fuselage effect occur on the portion of the body just forward of the plenum (Figure 2).

During transition from free air to landing gear height, around the approach dynamic pressure ratio, the horizontal tail contribution decreases from a nose-up moment to a nose-down moment (Figure 8a). The afterbody moment becomes more negative, i.e., there is a greater pitch-down than in free air (Figure 8c). The wing-fuselage contribution increases dramatically from a small pitch-down to a large pitch-up, equivalent to 30 degrees of horizontal tail deflection, jets-off. Furthermore, the magnitude of this contribution is several times greater than the contributions due to horizontal tail, vertical tail and afterbody. It may be recalled that the pitch-up at landing gear height is accompanied by large lift changes on the aircraft (Figures 3a and 3b). This suggests that in ground proximity the reverser jets primarily affect the aerodynamics of the wing, with only a small contribution from the fuselage.

At landing gear height, as the aircraft decelerates, or equivalently, as the dynamic pressure ratio increases, the reverser-induced pitching moment on the wing-fuselage decreases. However, this contribution is still much greater than that due to the horizontal and vertical tails and the afterbody.

In summary, in free air, the effects of reverser jets on the aerodynamics of the aircraft are generally small. These small effects are mostly felt on the tail-afterbody region of the aircraft. By contrast, in ground proximity, the reverser-induced effects are large and occur primarily on the wing, and are sensitive to the cant angle of the lower jets. The magnitude of these effects reduces as the jets are canted outboard.

(ii) Reverser-induced Unsteady Effects

During the ground plane test to evaluate reverser-induced stability and control effects, it was observed that the model experienced large (and totally unexpected) oscillations for certain reverser port arrangements. To the naked eye, the oscillations appeared to be primarily in roll. Upon recording the time-histories of outputs from the 6-component balance, it was found that oscillations occurred in yaw and pitch as well. The latter were much smaller in magnitude than roll oscillations, however. The oscillations were largest for uncanted lower reverser jets and diminished as the lower jets were canted outboard.

To better understand the flow field associated with reverser jets in ground proximity, smoke streaks were injected upstream of the model. It was observed that an unsteady boundary or interface existed between the reverser jets propagating upstream after impinging on the ground and the free stream. For uncanted lower reverser jets, the interface was located mainly underneath the wing, but it periodically engulfed the leading edge region of the wing. Large clumps of fluid were observed to break away from the oscillating boundary, sometimes passing over the wing and sometimes under.

The key question to be answered after the ground plane test was whether it was the model motion that was causing the unsteady jet/free stream interaction or whether there existed an unsteady jet/free stream interaction that was causing the model to respond. The possibility that the jet itself may be unsteady, either due to a flapping motion or time-dependent mass flow, was ruled out by monitoring the weight flow through the reverser nozzles and by observing that a string attached at the nozzle exit remained steady. These diagnostic experiments were conducted during the ground plane testing. It was also made certain that the model did not exhibit any unsteadiness in close ground proximity when the free stream was off with only the reverser jets blowing and also when the jets were off with only the tunnel running.

To answer the question of the origin of the force, it was necessary to hold the model rigid during testing. A test was conducted in the Northrop water tunnel on rigid model/support system. Dye was injected in the reverser jets. It was observed that there existed a vortical interface between the separated reverser wall jets and the free stream. Moreover, this interface displayed oscillations in streamwise direction as well as periodic variations in its size. Figure 9 shows a still photograph from the water tunnel test and a schematic of the reverser jet/free stream interaction.

Upon determining that the existence of unsteady reverser jet/free stream interaction leads to the model motion observed in the wind tunnel, the next question to be answered is what are the consequences, if any, for a full scale aircraft. The nature of oscillating motions recorded in the wind tunnel depends on the dynamic characteristics of the model support system. To obtain the true "forcing function" resulting from the unsteady jet/free stream interaction, the wind tunel time histories must be first corrected to filter out the support characteristics, and then their frequency content must be scaled properly. Such an analysis was performed in the frequency domain on the rolling moment output from the 6-component balance. As mentioned earlier, the model response in roll was the most significant. Furthermore, the high quality wind tunnel balance eliminated any significant interactions between motions in roll, pitch or yaw.

Figure 10a shows a typical time history of rolling moment response at approach dynamic pressure ratio for uncanted lower reverser jets. Also shown is the equivalent aileron deflection (assuming linear aileron effectiveness) to give the reader an appreciation for the large amplitudes of the oscillating rolling moments. A power spectrum of rolling moment showed a strong peak around 16.5 Hz which corresponded to the natural frequency of the balance/support system of the model in torsion. A simple single-degree-of-freedom analysis shown in Figure 10b was performed to filter out the balance/support characteristics. This led to Power Spectral Densities (PSDs) of the rolling moment forcing function due to jet/free stream interactions. Analysis was performed for a number of reverser geometries (jet efflux angles and lower jet cant angles) and jet/free stream dynamic pressure ratios. Results are shown in Figures 11 through 16.

Figure 11 shows the PSD of the rolling moment forcing function for an aircraft at zero angle of attack, landing gear height (h/b = 0.18) and jet/free stream dynamic pressure ratio of 120. The latter corresponds to the aircraft in ground roll after touch down. Effects of jet/free stream dynamic pressure ratio on the forcing function are discussed later. The frequencies in Figure 11 have been converted to full scale aircraft using the Strouhal number. It is noted that the forcing function contains frequencies to which typical fighter aircraft are sensitive. The PSD is expressed in terms of (rolling moment coefficient)^2 per Hz. It is seen that the rolling moment forcing function due to 40-degree canted jets is at least an order of magnitude smaller than that for uncanted or slightly canted jets. This is expected since canted jets have a smaller dynamic pressure component which is directed upstream. For 40-degree canted jets, the effect of increasing the jet efflux angle (Figure 2) is to further reduce the forcing function magnitude.

Figure 12 shows the rolling moment forcing function expressed in terms of an equivalent aileron deflection (peak-to-peak) against the lower reverser cant angle, for various efflux angles. This plot was obtained from integrations of the curves similar to Figure 11 for 8-degrees angle of attack. To convert the rolling moment coefficients to aileron deflections, a representative aileron effectiveness for the F/A-18A aircraft was used. It is clear from Figure 12 that the aircraft is subjected to large rolling moment inputs for uncanted and insufficiently canted lower jets, in a frequency range to which the aircraft is sensitive. Even for practical values of lower jet cant angles, the rolling moment forcing is not reduced to insignificant levels. Another practical aspect is that the magnitudes and frequencies (say 1-2 Hz, typically) of the input disturbance may require aileron deflections and actuation rates which are beyond the state-of-the-art.

Figure 13 shows the effect of jet/free stream dynamic pressure ratio on the rolling moment forcing function. These results are presented for reverser jets with lower cant angle of 40 degrees. This case is chosen because in practice the jets will be most likely canted outboard to avoid hot gas reingestion. Another reason for selecting canted jets is that the forcing function levels reduce with increase in outboard cant angle (Figure 11) and it is of interest to know if the reduced levels are still significant at dynamic pressure ratios typical of approach and touch down. Figure 13 shows that the forcing function has a maximum around dynamic pressure ratio of 90, which corresponds to a condition just after touch down and rotation for the F/A-18A aircraft. Near the approach dynamic pressure ratio of 60, the forcing function drops to approximately 30 degrees peak-to-peak equivalent aileron input. This level is not insignificant, and given the frequencies of 1-2 Hz, the aileron actuation rates required may be high.

The results presented above described the spectral characteristics of the disturbances due to unsteady interactions between the reverser jets impinging on (and then separating from) the ground plane and the free stream. How the full-scale aircraft responds to the disturbances is a matter of practical importance. Two types of analyses were performed to predict the motion of an F/A-18A aircraft with thrust reversers operating in ground effect. First was a simplified analysis shown in the lower half of Figure 10b which led to the estimation of probabilities that the aircraft may exceed a given roll angle. This analysis assumes the aircraft response to be a narrow-band process. The second analysis was a simplified six-degree-of-freedom simulation of aircraft motion using the rolling moment time history obtained in the wind tunnel. The time history was corrected to full-scale by inverse of frequency determined from Strouhal number scaling. The details of both approaches are discussed in Reference 3 and only the final results are mentioned here.

Figure 14 shows a plot of the probability that the aircraft exceeds a given peak roll angle. The data are presented for reversers with 45 degrees efflux angle and 40 degrees outboard cant angle of the lower jets. Three different dynamic pressure ratios are shown. It is seen that even at the smallest dynamic pressure ratio of 60, which is typical of approach, the aircraft may exceed 20 degrees roll angle. For an aircraft such as the F/A-18A the wing tips will be very close to the ground for roll angles of this magnitude.

Figure 15 shows the results of a simulation of F/A-18A aircraft coming in to land with thrust reversers on. The efflux angle is 45 degrees and lower reverser jets are uncanted. The forcing function is in the form of a rolling moment time series. The aircraft response is plotted in terms of altitude, roll or bank angle, and pitch angle as a function of time. During the simulation the control augmentation system was off, so that the response is purely a result of the aircraft's natural stability and control characteristics. It is seen that the aircraft lands in 'about 4 seconds with a 10 degree nose down altitude and 20 degree bank angle. The latter is significant and thus a cause of concern. The foregoing simulation results are somewhat simplified (for reasons to be discussed in next paragraph) and may exaggerate the response of an aircraft during a true landing transient. A novel study to obtain more accurate data for simulations has been planned and will be discussed later in this paper.

The analyses for predicting full-scale aircraft behavior using time series data obtained from the wind tunnel imply some obvious limitations/assumptions. The most important limitation is that the time histories were obtained for aircraft at fixed height above the ground, thus ignoring the build-up of ground effect as the aircraft descends to the ground. Another is that in the six-degree-of-freedom digital simulation, steady state, free air aerodynamic coefficient and control effectiveness data were used. An accurate simulation would require changing aerodynamic data due to the presence of the reverser jet/free stream/ground plane interaction as the aircraft approaches ground. It is necessary to simulate the aircraft's actual descent in an experiment. This is explained in Figure 16. As noted earlier (Figure 11), the characteristic frequency of the unsteady interactions between reverser jets and the free stream is of the order of 1Hz, full scale. Equivalently, the characteristic period is of the order of 1 second. A STOL fighter will typically spend 1 to 2 seconds in ground effect prior to touch down, which is of the same order as the period of unsteadiness. It follows that an aircraft landing with thrust reversers will experience a continually changing flow field in ground effect. Moreover, the characteristics of this "transient" unsteadiness will probably be different from the "fully-developed" unsteadiness measured at a fixed ground height. Therefore, it is necessary to simulate the aircraft's descent during thrust reverser testing in ground effect.

The question naturally arises, "What is the rate of descent that must be simulated?" The answer is provided by the following similarity analysis. The dimensionless parameter to be matched between the model and full scale for unsteady flow problems is the Strouhal number, i.e.

$$S_{ms} = S_{fs} \quad (1a)$$

where

$$S = \frac{fL}{U} \quad (1b)$$

with f = frequency, L = characteristic length, and U = free stream velocity

'ms' denotes model scale and 'fs' denotes full scale

In addition, for dynamic similarity, the model must experience the same number of cycles of unsteadiness as the full scale, i.e.

$$N_{ms} = N_{fs} \quad (2a)$$

where

$$N = fT \quad (2b)$$

with T denoting the time spent in the unsteady transient.

Defining a vertical rate of descent,

$$V = \frac{L}{T} \qquad (3)$$

and combining the relations (1a), (1b), (2a), (2b), and (3), it may be verified that

$$\frac{V_{ms}}{U_{ms}} = \frac{V_{fs}}{U_{fs}} \qquad (4)$$

which shows that the rate of descent of the model in the wind tunnel must equal that for the full scale if the free stream velocity is maintained the same.

The rates of descent of modern fighter aircraft, which are of the order of 10 ft/sec, cannot be duplicated by conventional vertical traverse mechanisms of model support systems in wind tunnels. These mechanisms have vertical descent rates of a few inches per second. Then, the free stream speed will have to be reduced substantially to obtain the similarity in Equation (4). The reverser jet velocities will also have to be reduced to obtain a desired jet/free stream dynamic pressure ratio. At these very low jet and free stream speeds, the aerodynamic forces on the model are not of sufficient magnitiude for accurate measurement.

Northrop and NASA Langley Research Center with the support of the Air Force Flight Dynamics Laboratory have developed a novel test concept to simulate the required rates of descent (Figure 17). The proposed test facility is the Vortex Flow Research Facility at Langley. This facility was formerly a towing basin for measuring hydrodynamic forces on submerged and semi-submerged bodies. Currently, the facility is not being used for hydrodynamic testing. The water has been drained completely, but the trolley from which the model support strut hangs is operational. It runs on rails, powered by an Oldsmobile engine, capable of speeds up to 70 mph. The model can be supported on a sting attached to a support strut. Forces and moments can be measured on a balance inside the model. Data are telemetered to a control room for processing in real time.

The test concept is to simulate the approach, touch down, and ground roll of a thrust reversing aircraft by traversing the model horizontally over a ramp followed by a straight section. Given a typical ramp angle of 5 degrees, rates of descent of up to 9 ft/sec can be simulated by traversing the trolley at different speeds. Transient time series data from six component balance outputs will be recorded on analog tapes for post-test analysis. In addition, strip chart recordings will also be obtained for visual examination. The duration of transient data samples is expected to be 4 to 5 seconds. A number of repeat runs are planned to obtain representative ensemble averages. Some flow visualizations using tufts on the model and on the ground plane are also planned. An important feature of the proposed test approach is that the boundary layer problems normally associated with ground plane testing are obviated.

Testing will be conducted on a NASA 0.07-scale YF-17 model with thrust reversing provided by the same plenum chamber/nozzle assemblies (Figure 2) as that used in Northrop's earlier tests. Test parameters will include different reverser geometries and aircraft control surface deflections. The objectives of the test will be (i) to obtain transient aerodynamic data which can be used in a realistic simulation of motion of thrust-reversing aircraft in ground effect, (ii) to determine transient forcing function characteristics, and (iii) to identify critical aircraft/reverser parameters which affect jet/free stream interactions. The data analysis scheme for the proposed test is shown schematically in Figure 18.

The NASA/Northrop/USAF test will be conducted in the December 1985/January 1986 time frame.

(iii) Jet/Airframe Attachment Effects

During the calibration of reverser nozzles on a static rig prior to the wind tunnel test, an interesting jet flow attachment phenomenon was encountered. The rectangular reverser nozzles, shown schematically in Figure 19, were flush-mounted in pairs on a flat plate. Nozzle geometry variations included efflux angle (θ) and cant angle (Ψ). The actual efflux angles of the jet centerline were recorded as a function of nozzle pressure ratio under quiescent ambient conditions. A 4-inch length of thread was anchored at the centroid of the nozzle exit, and its position recorded by a video camera.

It was found that for certain combination of nozzle efflux and cant angles, the jets were "bent" down toward the flat plate, giving an error of 20 - 25 degrees between the actual and intended efflux angles. Surface flow visualization (Figure 20a) on the plate showed that under these conditions, jet flow was contacting the plate. A strong cross flow existed in the scrubbed areas beneath the jet, suggesting perhaps an energetic vortex either surrounding the jet or between the jet and the plate. Under some conditions, the jets were observed to switch rapidly between the attached and detached conditions (Figure 19b).

For purposes of the Northrop wind tunnel test, the immediate objective was to "fix" the problem and restore the intended jet angles, and consequently, further investigation of the jet/surface reattachment phenomena was not undertaken. The fix was a low fence or spoiler (Figure 20a) mounted close to the exit on the side where attachment was observed, such that the upper edge of the spoiler just cleared the expected jet boundary. This was entirely successful in providing the required jet angles.

The jet reattachment phenomenon has been encountered on full-scale aircraft (Reference 4) and has serious implications in terms of asymmetric loads and thermal effects on the airframe. It is suggested that the presence of the ground might exacerbate the tendency of the lower jets to reattach during approach and landing. For example, the negative pressures underneath the airframe resulting from jet impingement and wall jet formation on the ground may be conducive to reattachment. Much work remains to be done in the area of jet attachment, and some recommendations are made in the following sections.

IV. Summary and Conclusions

In this paper three types of effects due to thrust reversing in ground proximity have been described: (i) Stability and Control Effects, (ii) Unsteady Effects Due to Jet/Free Stream Interaction, and (iii) Jet/ Airframe Attachment Effects.

The stability and control effects in ground proximity are characteristically different than those in free air. The effects are generally much larger in magnitude in ground proximity more so longitudinally than lateral-directionally. In ground proximity, the jet-induced flow field affects the entire aircraft, expecially the wing. This is in contrast to jet-induced effects in free air, which are confined to a region close to the jets in the vicinity of the empennage. The reverser-induced flow field in ground effect is significantly more complex than in free air. Some gross characteristics of this flow field were identified and used to explain the observed reverser-induced changes in stability and control parameters.

Large and totally unexpected rolling motions were observed on a thrust-reversing aircraft model in ground proximity. Time histories of rolling moment were analyzed to determine the spectral content of the forcing functions which drove the oscillations. The analysis revealed that the forcing function contained significant energies at frequencies to which typical fighter aircraft are sensitive (1 - 2 hz). The magnitude of the forcing function was found to be a strong function of the cant or splay angle of the lower reverser jets. It was postulated that the unsteady behavior in ground effect was a result of an unsteady interaction between the reverser jets and the free stream. Water tunnel tests provided visual verification of this hypothesis and confirmed that the interface between the jet flow separating from the ground plane and the on-coming stream exhibits streamwise oscillations. The time histories from the wind tunnel test were used for a simplified digital simulation of aircraft motion in ground effect, after correcting for model support characteristics and proper frequency scaling. It was found that the aircraft experienced both large roll angles and a nose-down attitude at touch-down. A co-operative NASA/Northrop/USAF test is planned to measure transient unsteady loads on a thrust-reversing aircraft during approach and landing.

A jet flow reattachment phenomenon was encountered during testing of rectangular reverser nozzles. Surface flow visualizations showed that for certain combinations of jet efflux and cant angles, the jets were attaching to the flat surface of the plenum through which they were exhausting. There were indications of strong vortical cross flow underneath the jets. Tendencies for intermittent separation and reattachment were also seen. The reattachment phenomena, which may be exacerbated in the presence of ground, have serious implications in terms of asymmetric and unsteady induced loads and thermal effects on the airframe.

V. Recommendations for Future Research

The following areas for further work in thrust reverser-induced effects have been identified from Northrop's experience in this field. Some areas apply to both free air and ground effect regimes.

(i) Ground effect test techniques:

A study is needed to establish accurate techniques for ground effect testing. The effects of moving ground plane boundary layer thickness need to be determined.

(ii) Effects of the main propulsive jet during partial reverser deployment:

The influence of the propulsive jet on the reverser-induced aerodynamics of the airframe needs to be determined through an afterbody test on a pressure-instrumented model.

(iii) Effects of jet temperature on entrainment:

Testing with hot jets to determine flow characteristics along adjacent control surfaces and changes in stability and control parameters is recommended.

(iv) Accurate measurements of transient, unsteady effects during approach and landing with thrust reversers:

The NASA/Northrop/USAF test should yield valuable data.

(v) Definition of reattachment effects:

Improved definition of angles at which jet attachment occurs, including effects of various nozzle shapes and moldline contours. Also, determination of the influence of ground proximity on reattachment of lower jets is essential.

(vi) Determination of the importance of inlet flow interactions on jet-induced forces and moments:
Aeroforce testing with inlet and exhaust flow simulation will be necessary.

(vii) Criteria for the importance of induced forces in ground effect:
Reverser-induced changes in stability and control parameters in ground effect may appear large in terms of dimensionless coefficients. However, these changes occur at relatively low free stream dynamic pressures which are typical during approach and landing. It is necessary to interpret the reverser-induced changes in terms of aircraft weight-on-wheels and runway friction at touch-down and during ground roll, for example.

(viii) Better understanding of jet/free stream flow fields:
Effects of jet exit velocity profile, nozzle geometry and mutual interference for multiple jets should be studied experimentally. Detailed flow field measurements of jets-in-cross flow and jet/free stream interactions after impingement on ground plane are recommended.

VI. References

1. Joshi, P.B., et. al, "Generic Thrust Reverser Technology for Near-term Application", Volumes I - IV, AFWAL TR-84-3094, Air Force Wright Aeronauticcal Laboratories, Wright-Patterson AFB, Ohio 45433, February 1985.

2. Glezer, A., et. al, "Thrust Reverser Effects on Tail Surface Aerodynamics of an F-18-type Configuration," AIAA-83-1860.

3. Joshi, P.B. and Compton, M., "Unsteady Thrust Reverser Effects in Ground Proximity," AIAA Paper No. 85-4035, to be presented at AIAA/AHS/ASEE Aircraft Design, Systems and Operations Meeting, Colorado Springs, Colorado, October 1985.

4. Hellstrom, G., "Effects of Thrust Reversal on Aircraft Stability at Ground Roll for A/C 37," Paper No. FKMB-37-70.74, USAF/RSAF Propulsion Conference, Wright-Patterson AFB, Ohio, December 1970.

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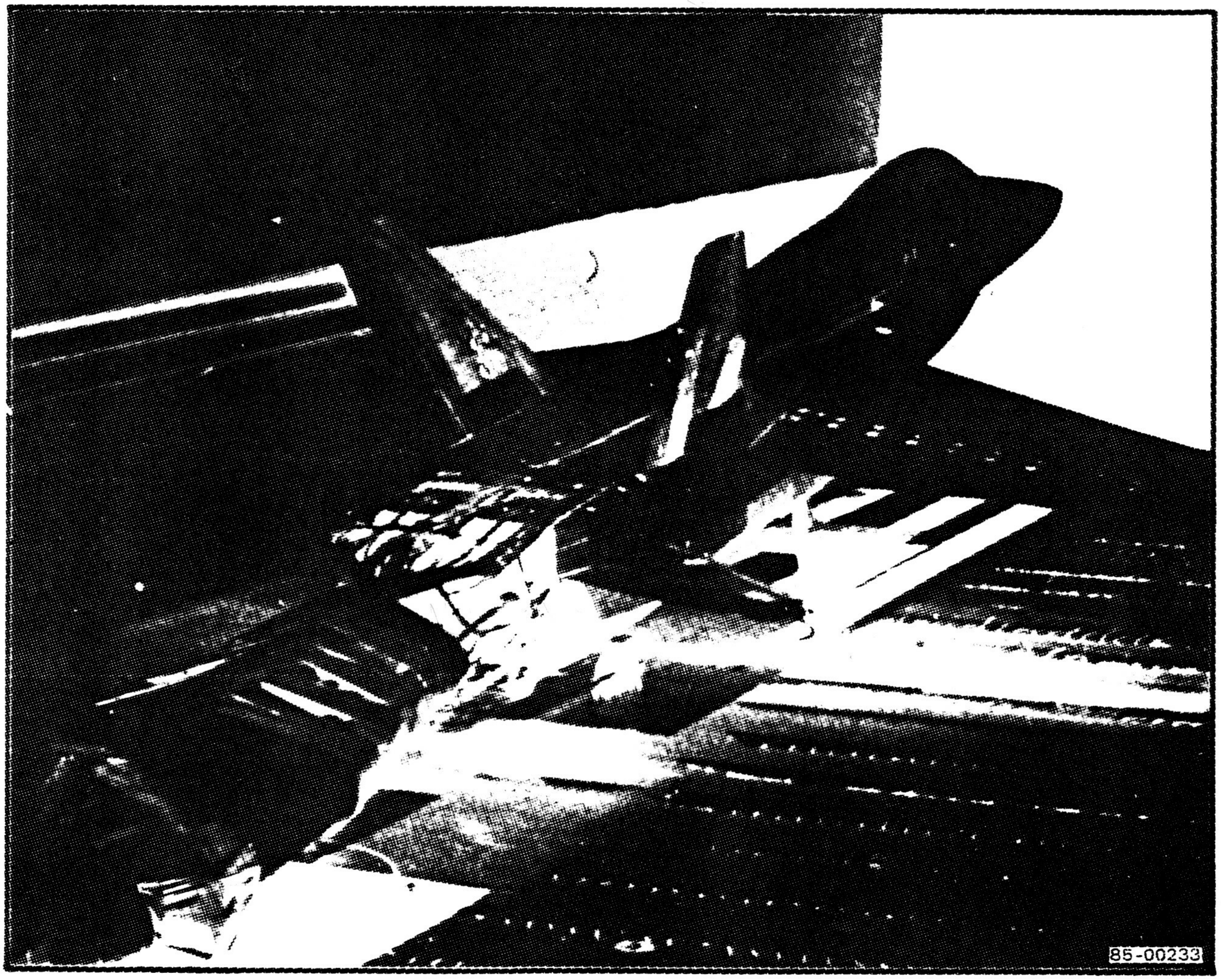

FIGURE 1. THRUST-REVERSING AIRCRAFT MODEL IN GROUND EFFECT TEST

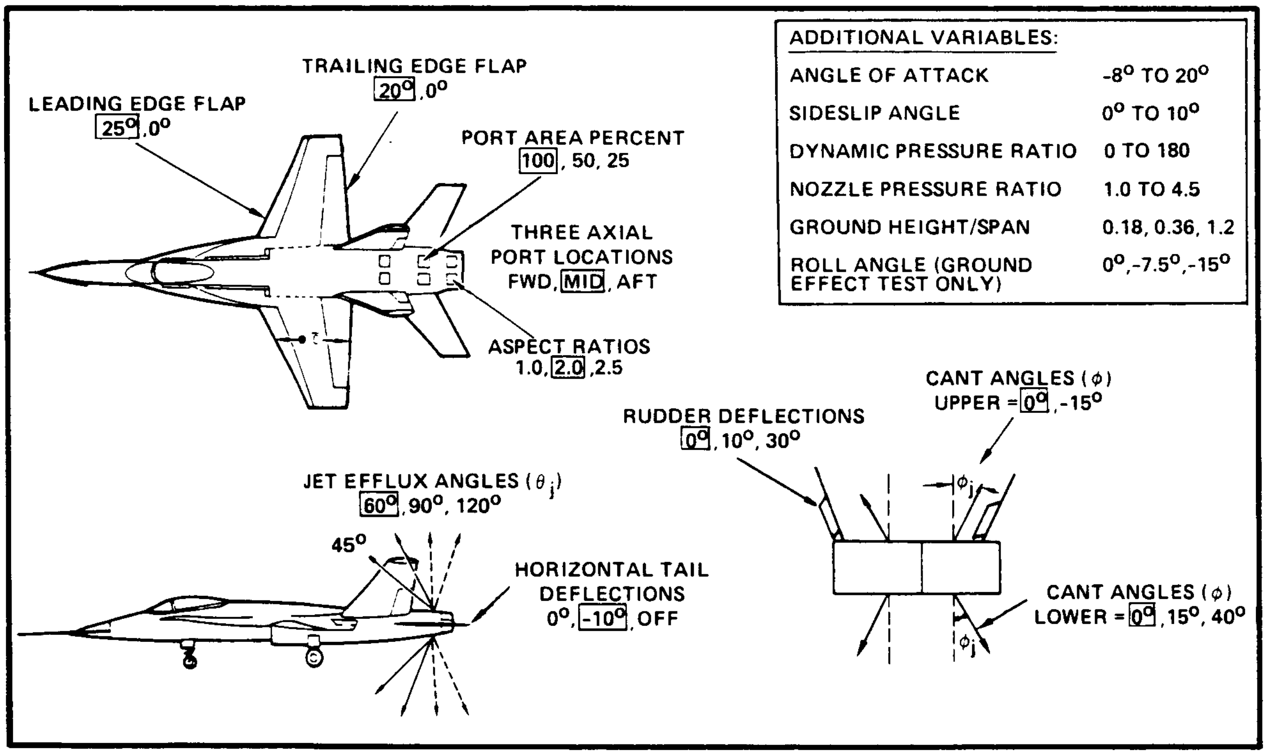

FIGURE 2. AIRCRAFT AND REVERSER TEST VARIABLES

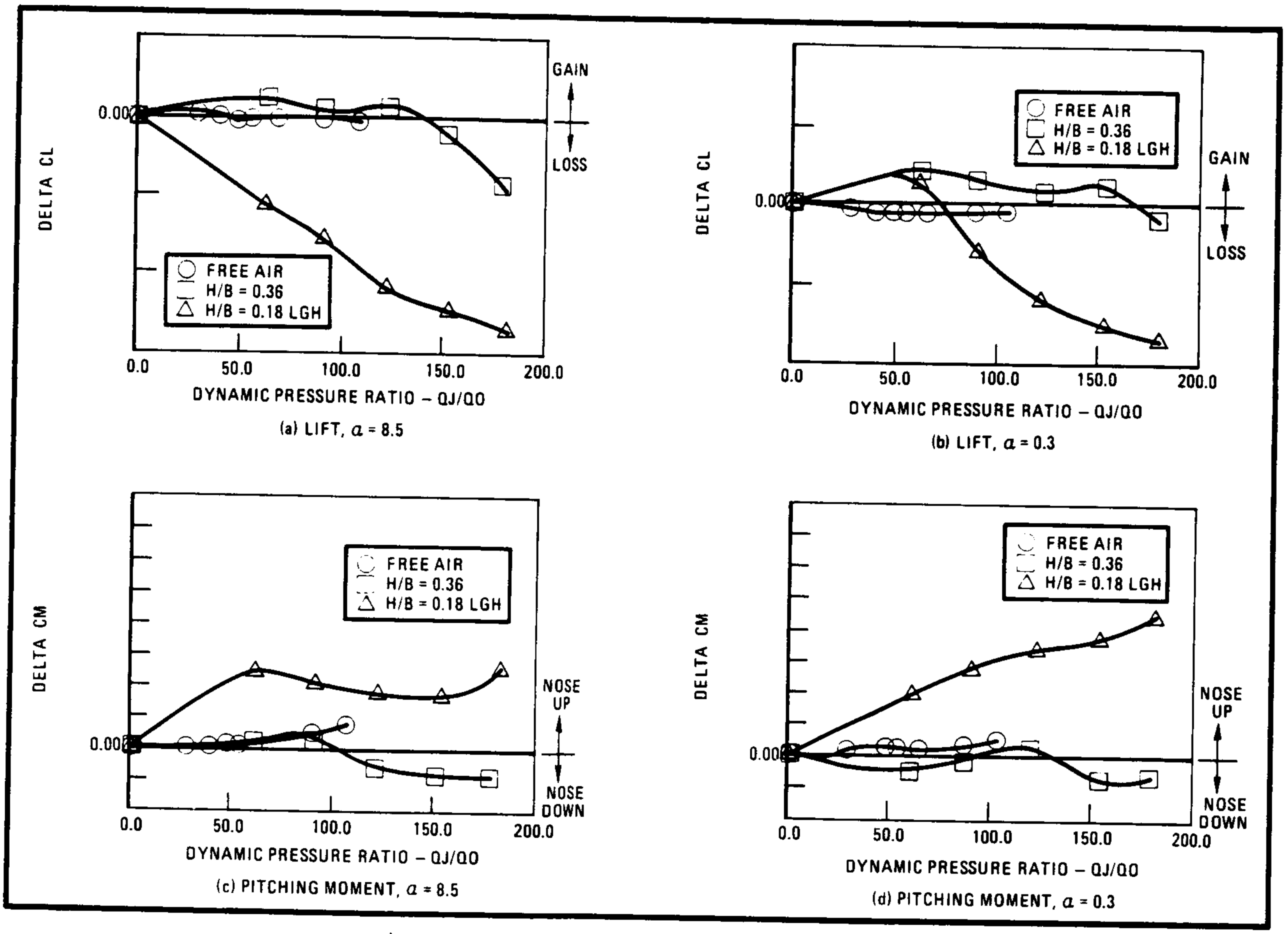

FIGURE 3. EFFECT OF GROUND HEIGHT VARIATION ON REVERSER-INDUCED LIFT AND PITCHING MOMENT, $\delta n/\delta f = 25/20$, $\delta H = -10$

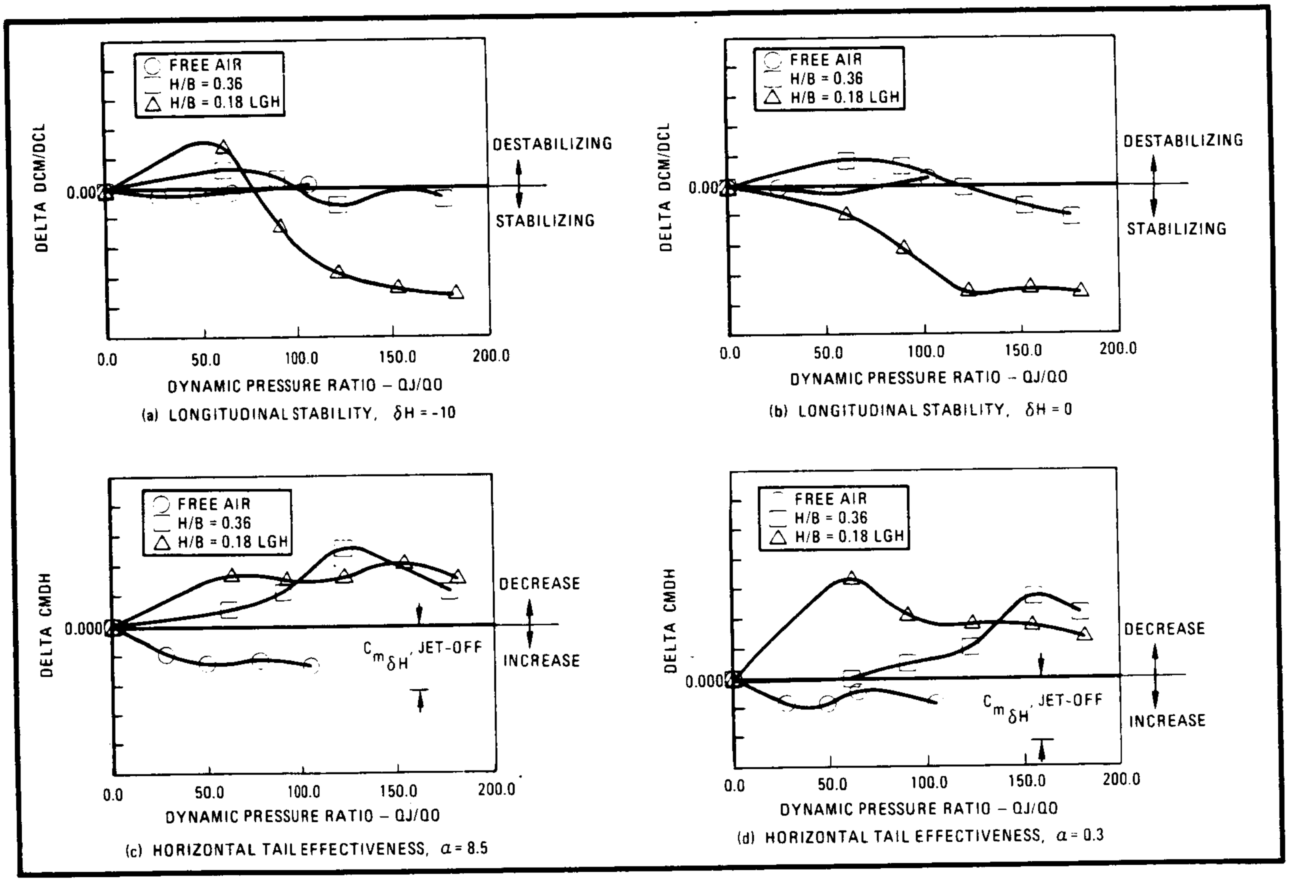

FIGURE 4. EFFECT OF GROUND HEIGHT VARIATION ON REVERSER-INDUCED CHANGES IN HORIZONTAL TAIL EFFECTIVENESS AND LONGITUDINAL STABILITY, δn/ δf = 25/20

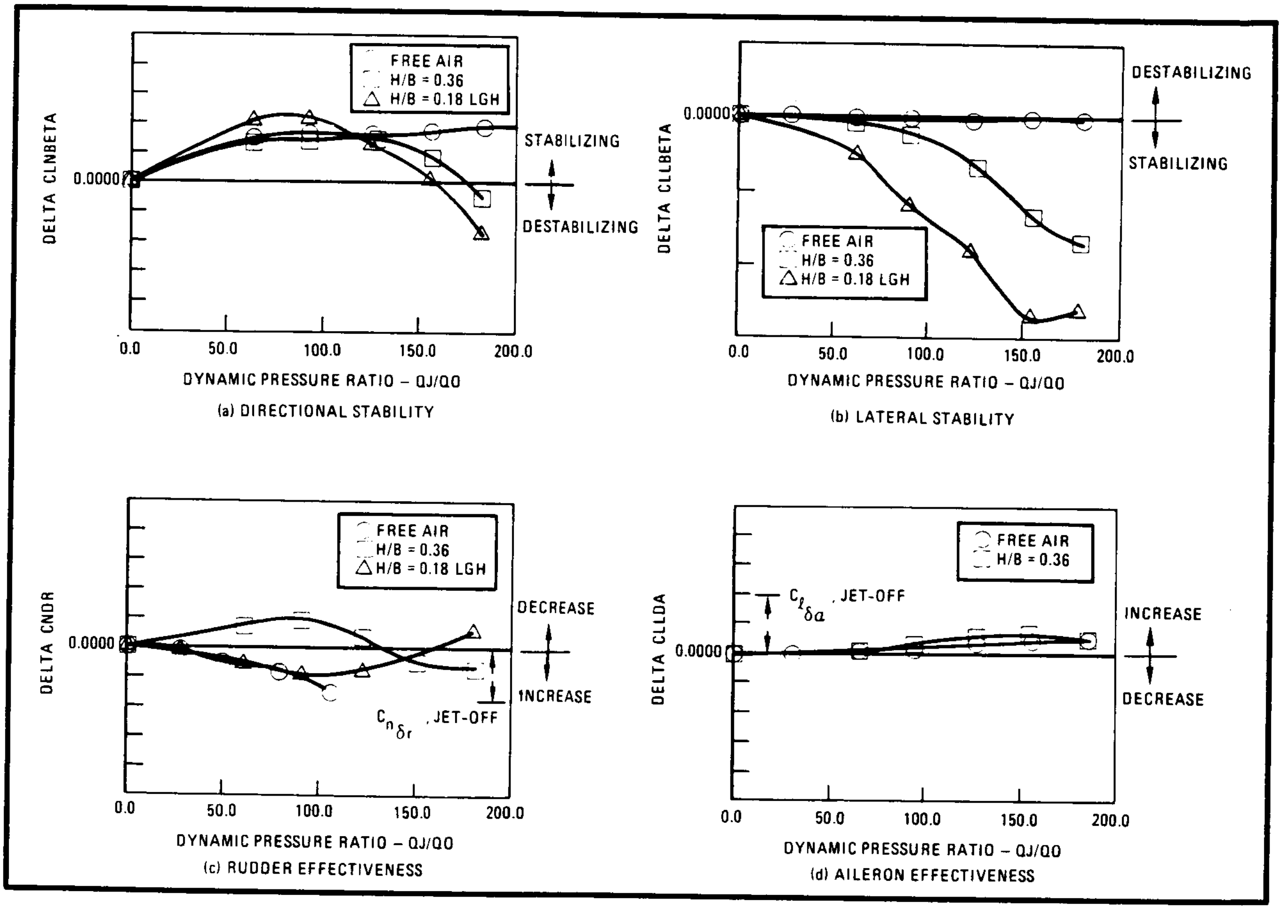

FIGURE 5. EFFECT OF GROUND HEIGHT VARIATION ON REVERSER-INDUCED CHANGES IN LATERAL-DIRECTIONAL STABILITY AND CONTROL, $\alpha = 8.5$, $\delta n/\delta f = 25/20$, $\delta M = 0$

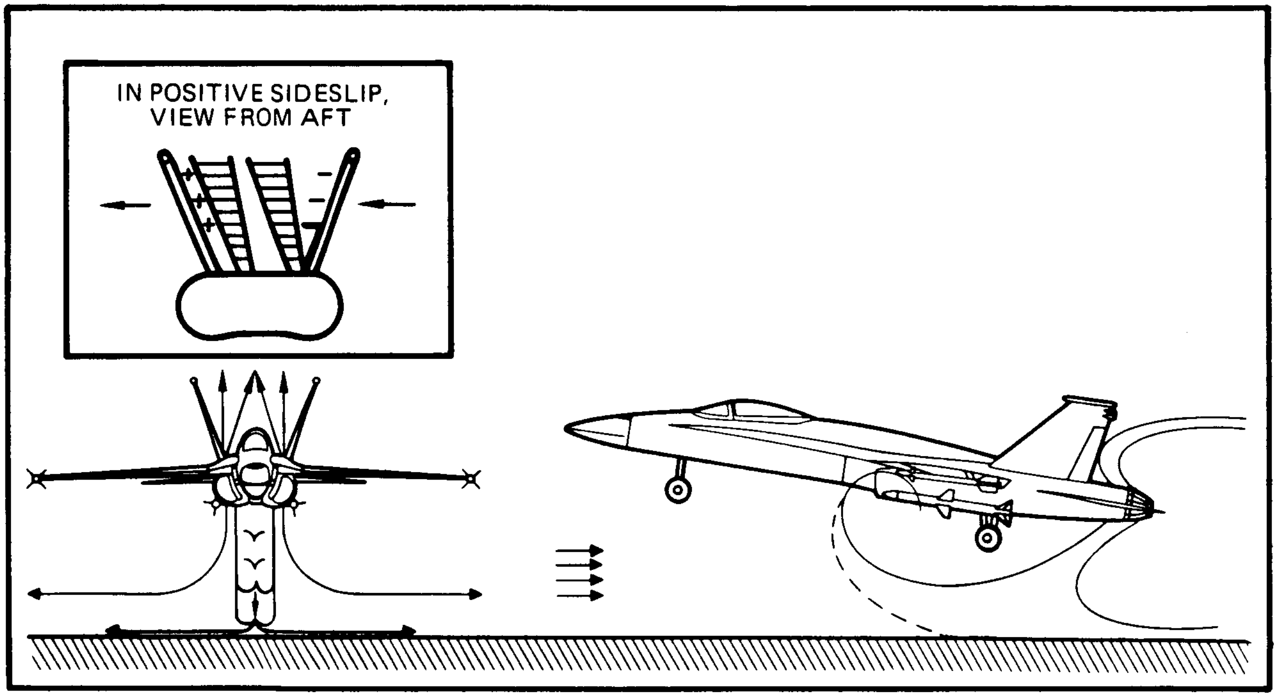

FIGURE 6. SCHEMATIC OF FLOW MECHANISMS IN GROUND EFFECT

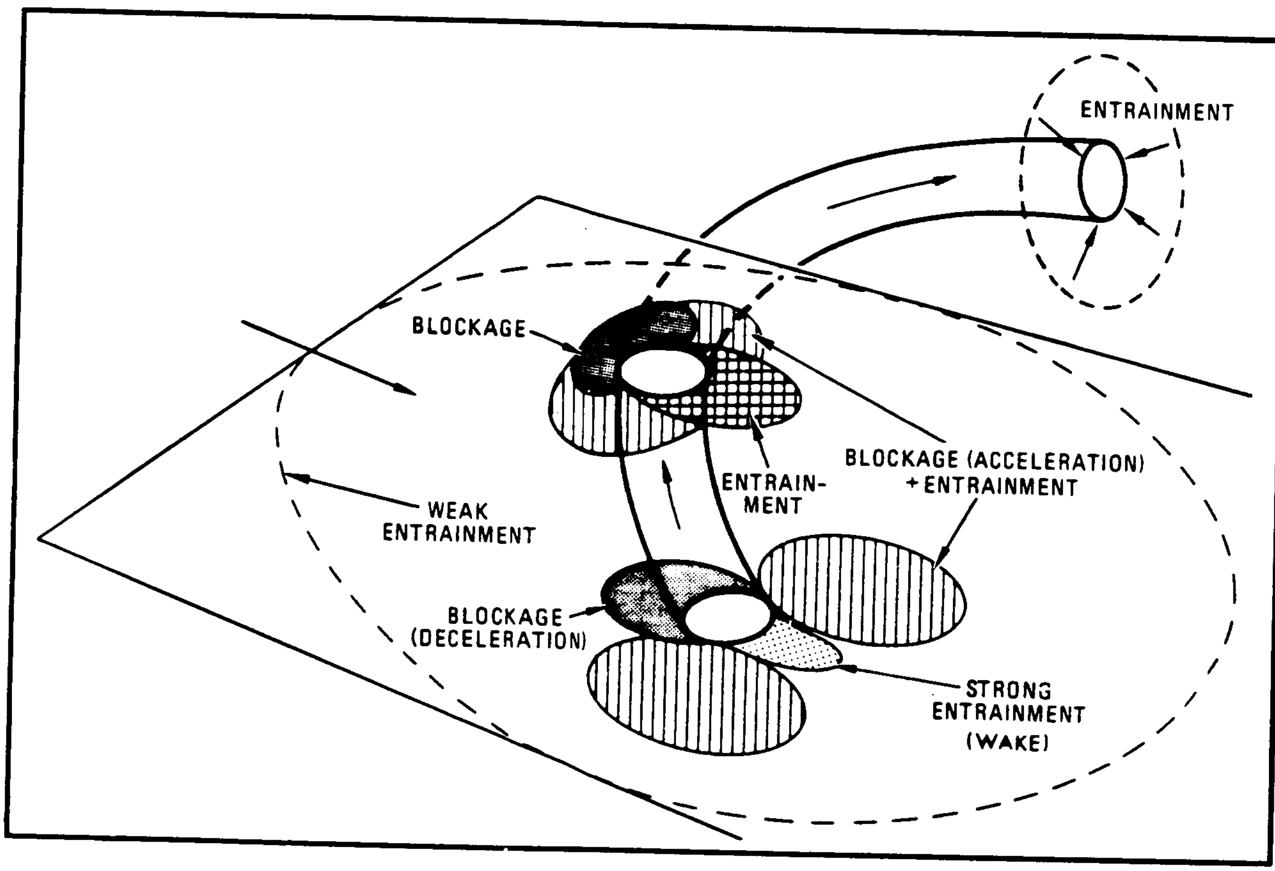

FIGURE 7. BLOCKAGE AND ENTRAINMENT DOMINATED REGIONS FOR A CIRCULAR JET IN CROSS FLOW

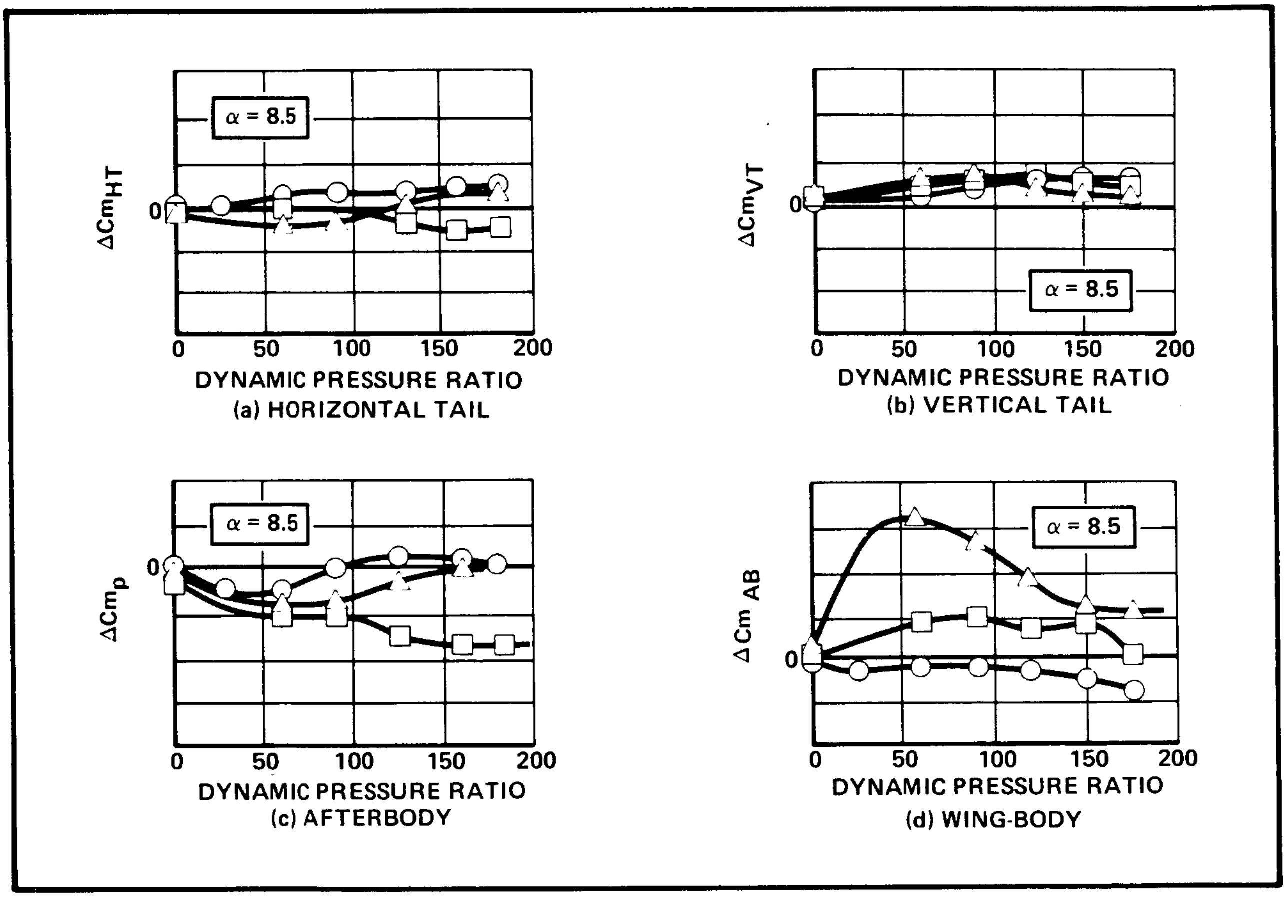

FIGURE 8. CONTRIBUTIONS OF AIRCRAFT COMPONENTS TO REVERSER-INDUCED PITCHING MOMENT AS A FUNCTION OF GROUND HEIGHT, α= 8.5, δH = -10, δn/ δf = 25/20

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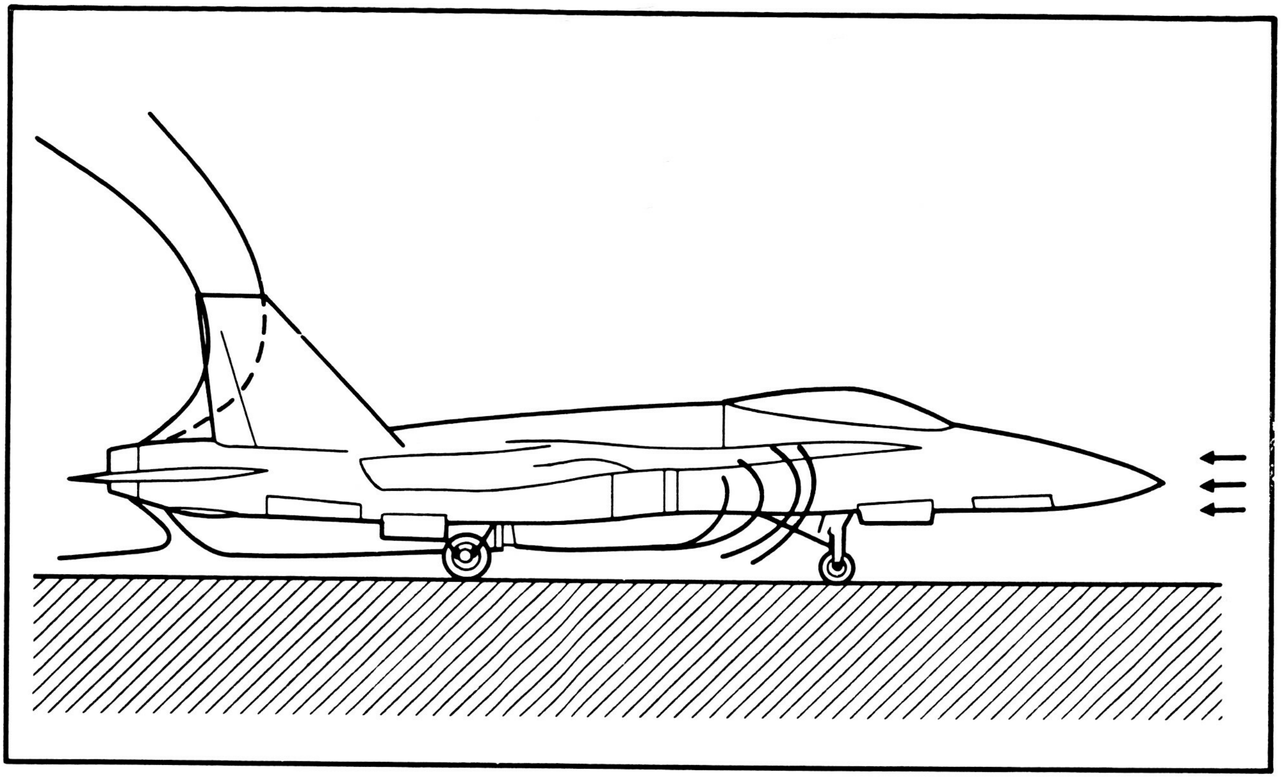
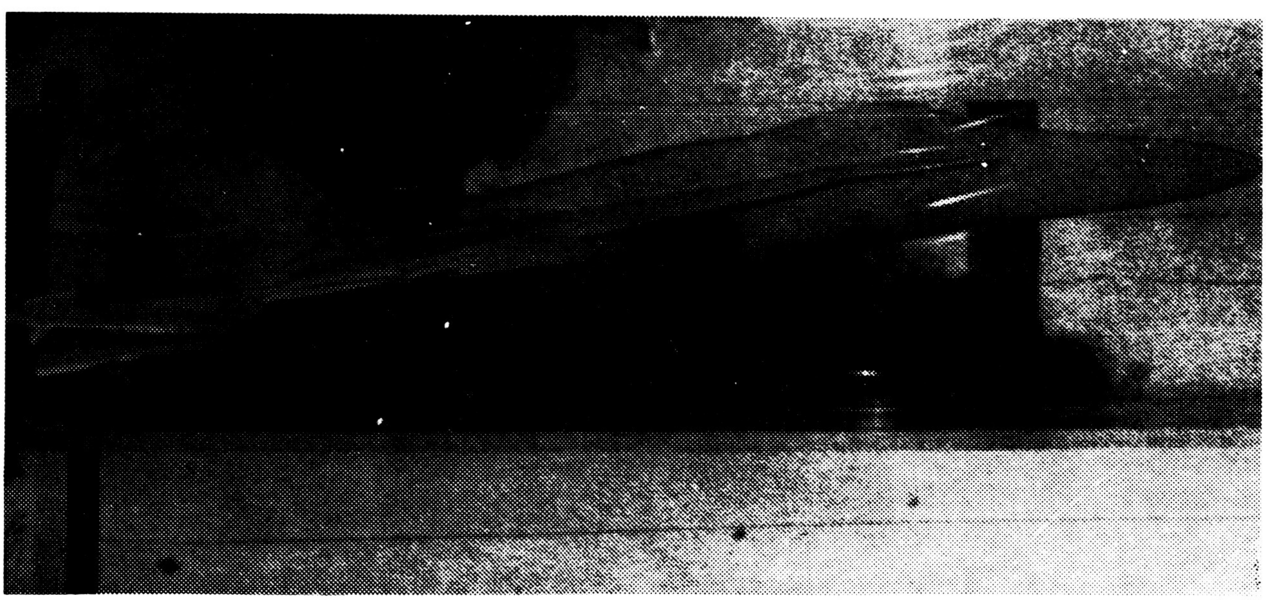


(a) SCHEMATIC OF INTERACTION



(b) WATER TUNNEL FLOW VISUALIZATION

FIGURE 9. UNSTEADY INTERACTION OF REVERSER JETS WITH FREE STREAM IN GROUND EFFECT

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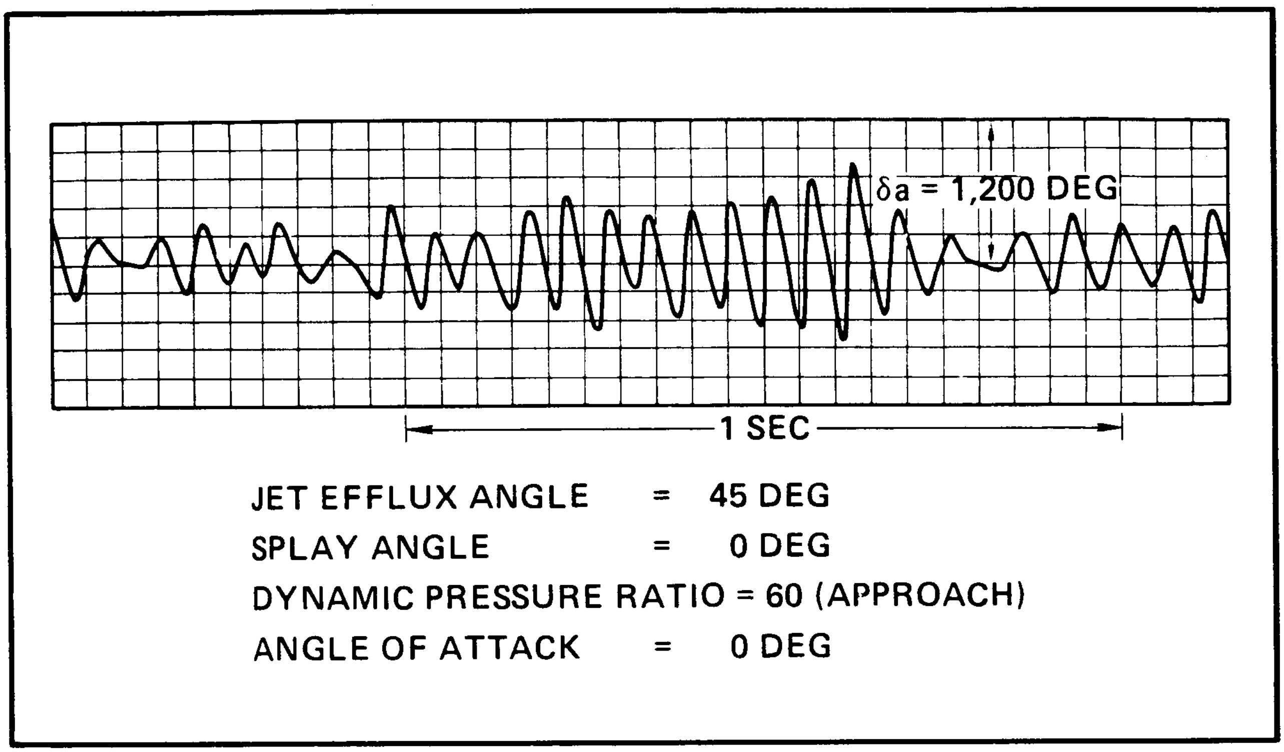

FIGURE 10a. TYPICAL ROLLING MOMENT TIME HISTORY

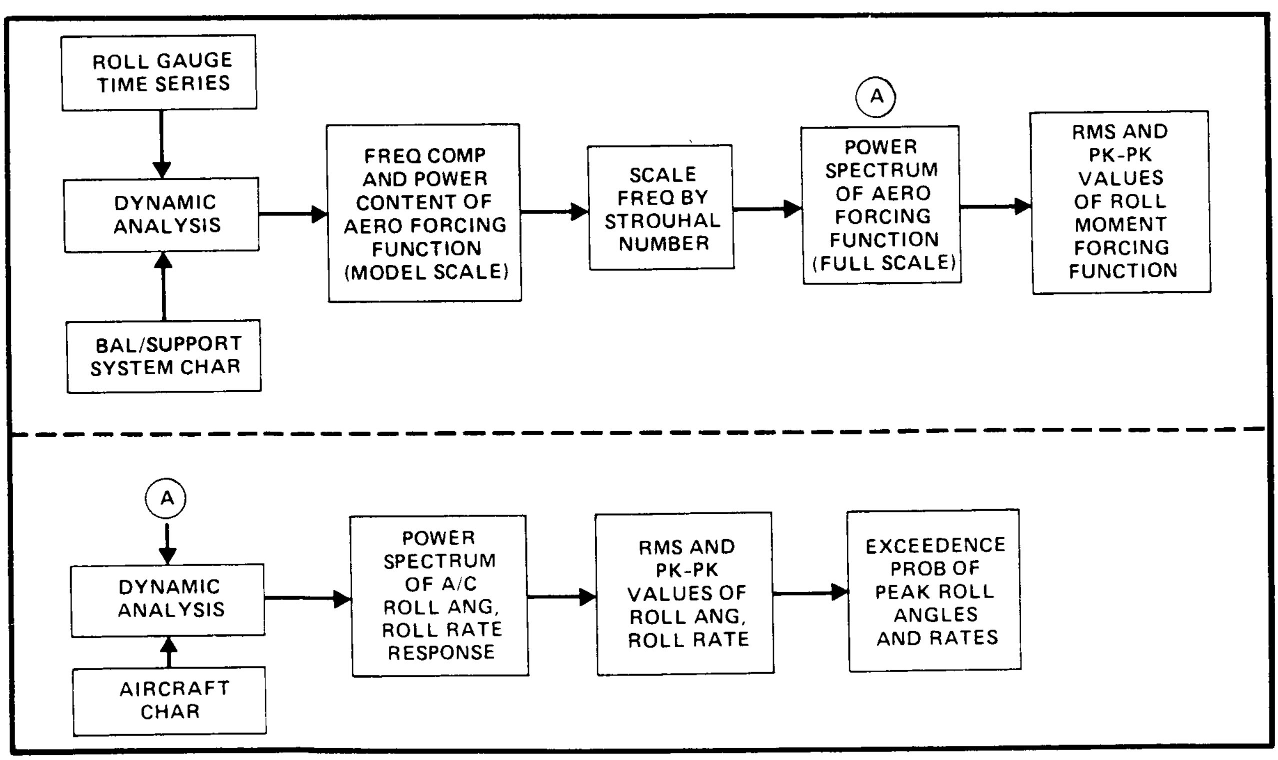

FIGURE 10b. SIMPLIFIED ANALYSIS OF ROLLING MOMENT TIME HISTORY

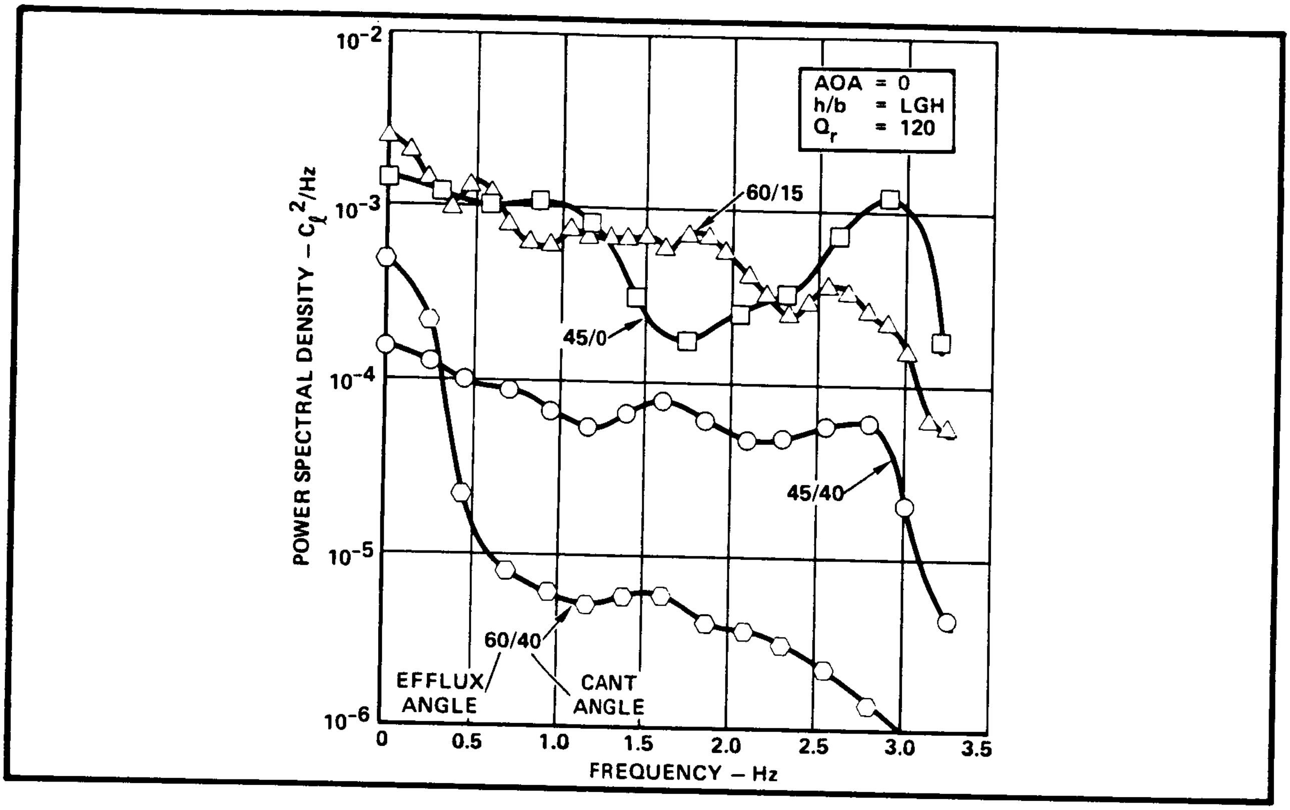

FIGURE 11. ROLLING MOMENT FORCING FUNCTION DUE TO REVERSER JET/FREE STREAM INTERACTION

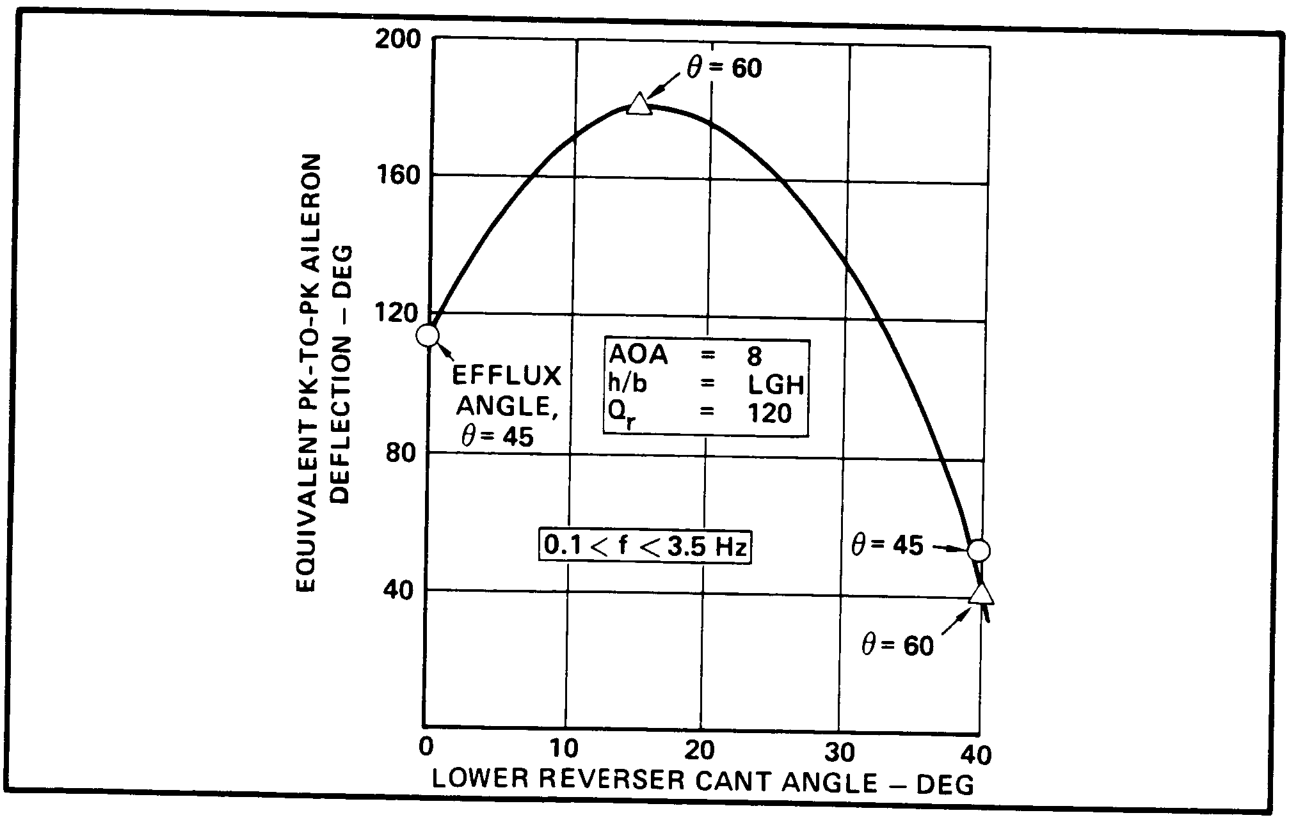

FIGURE 12. FORCING FUNCTION EXPRESSED AS EQUIVALENT AILERON INPUT

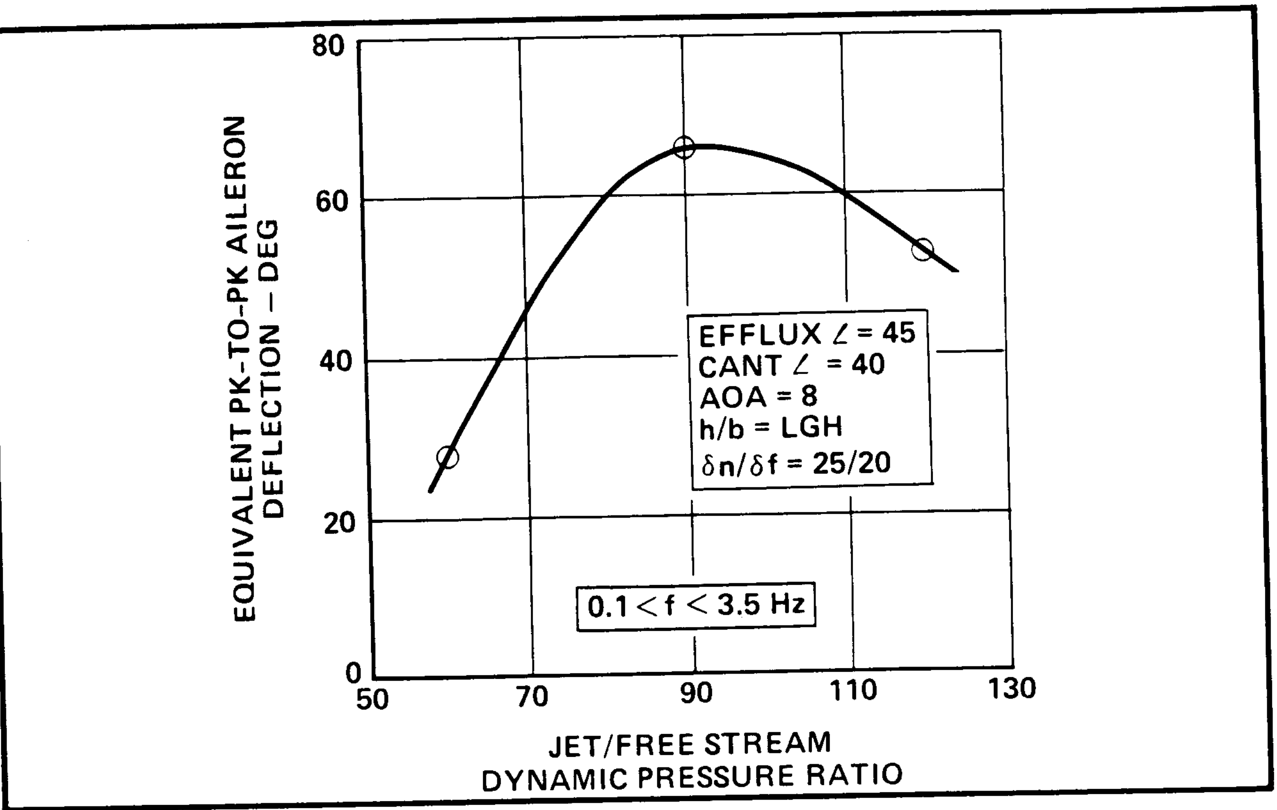

FIGURE 13. EFFECT OF JET/FREE STREAM DYNAMIC PRESSURE RATIO ON ROLLING MOMENT FORCING FUNCTION

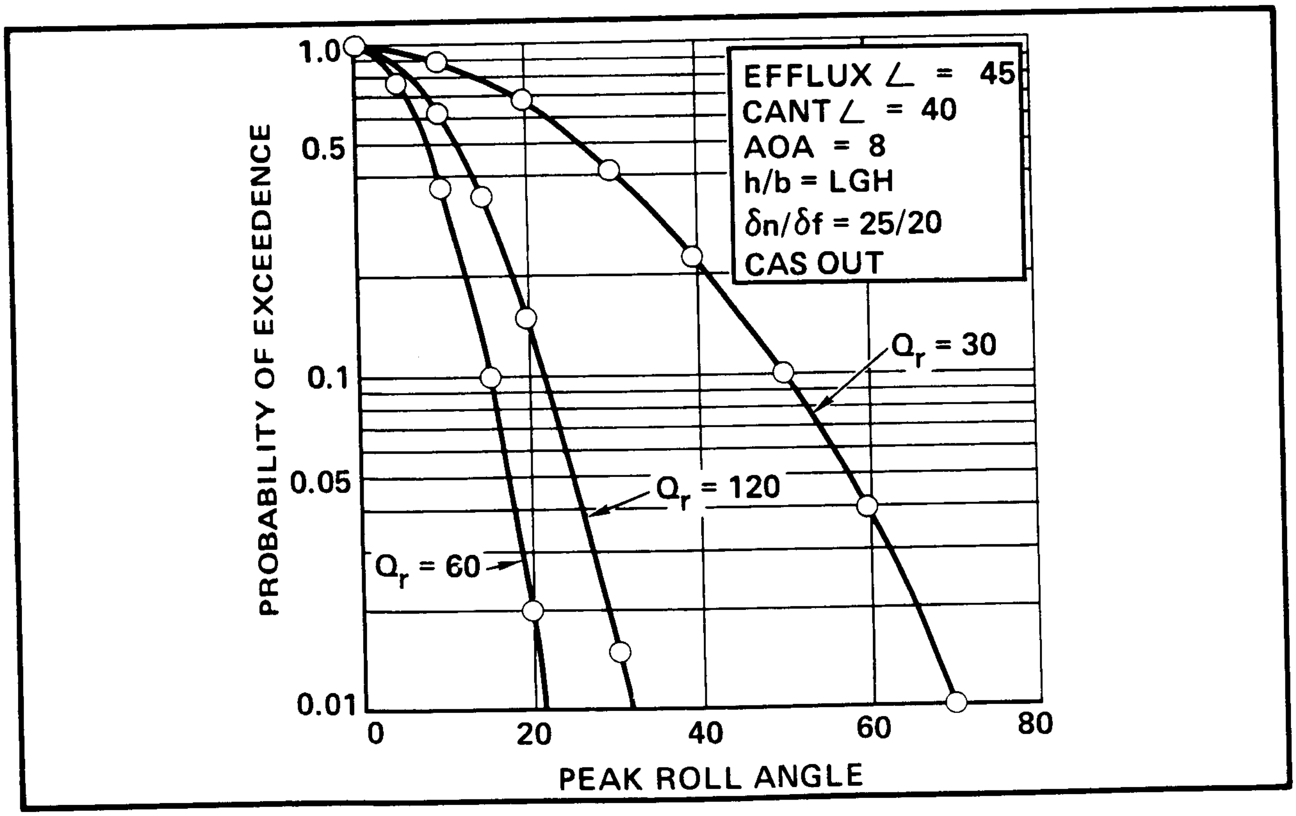

FIGURE 14. ROLL ANGLE EXCEEDENCE PROBABILITY

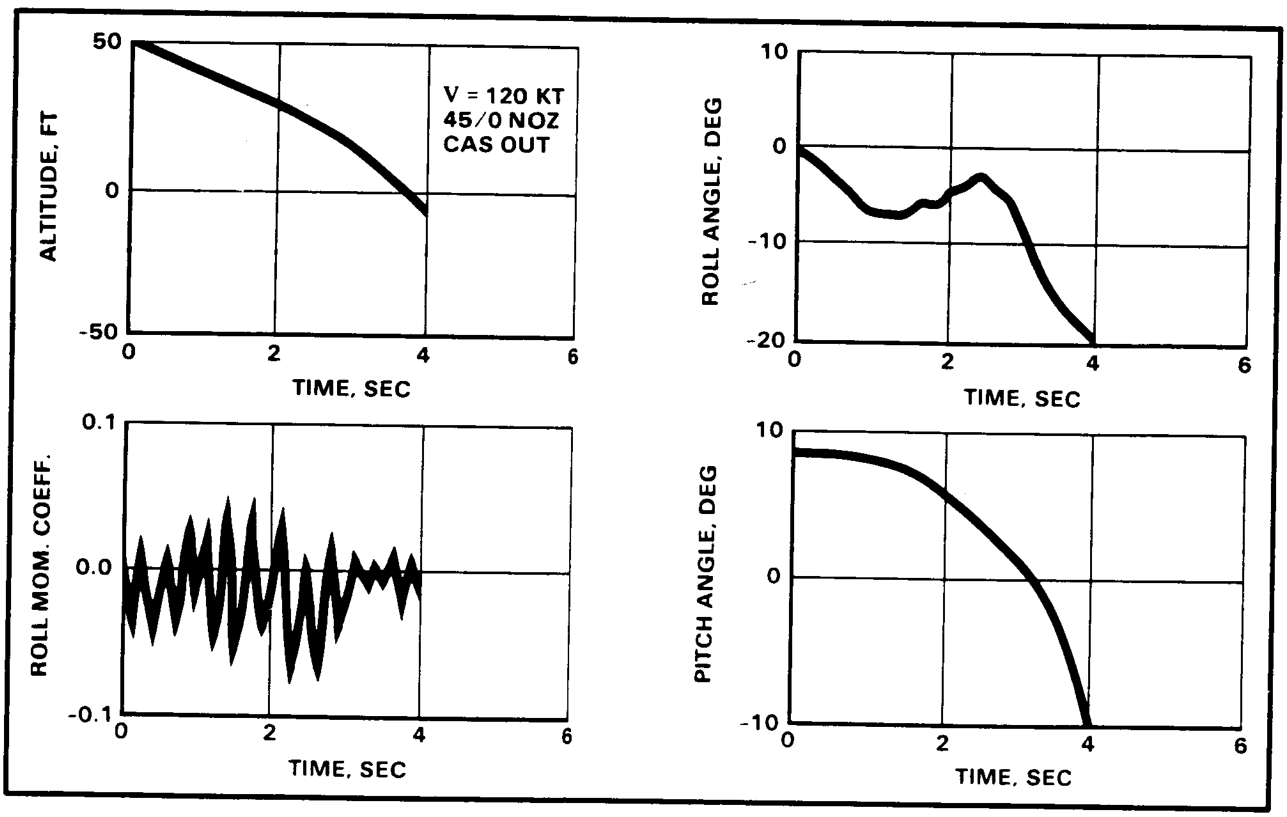

FIGURE 15. SIMULATION OF MOTION OF A THRUST-REVERSING AIRCRAFT IN GROUND EFFECT

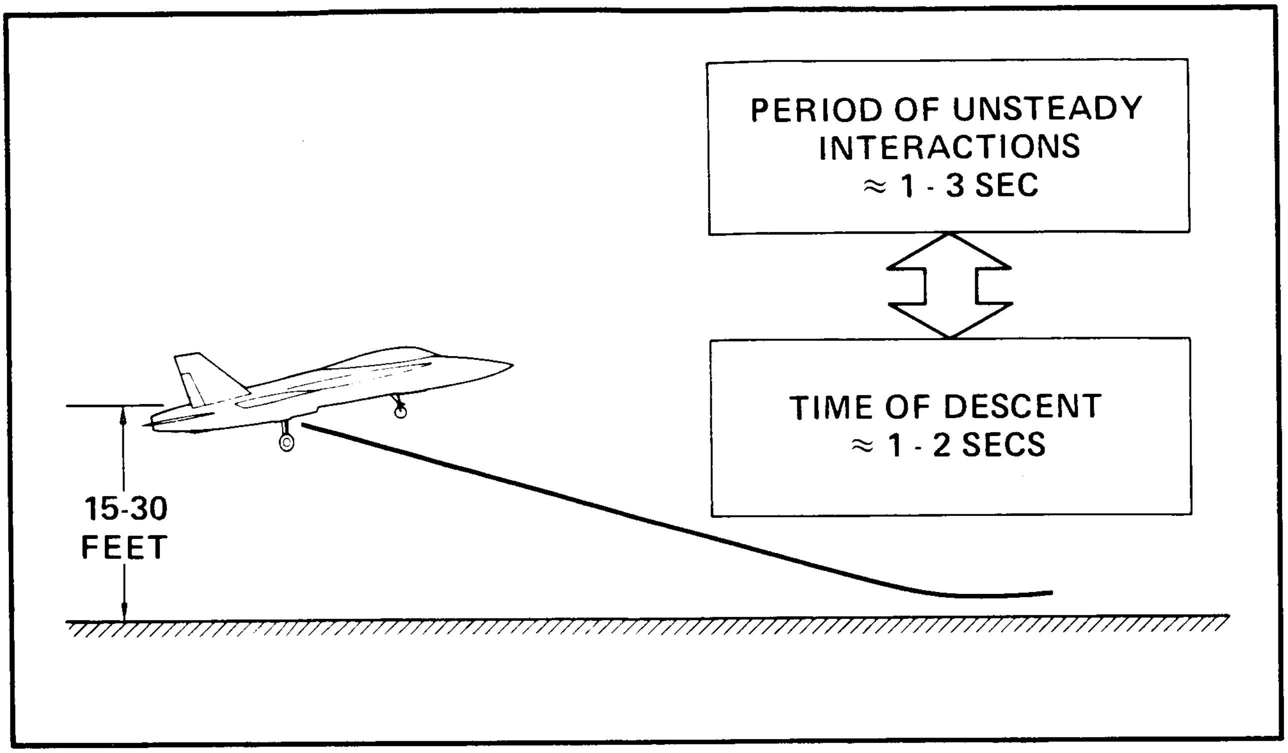

FIGURE 16. RATIONALE FOR SIMULATING RATES OF DESCENT IN GROUND EFFECT

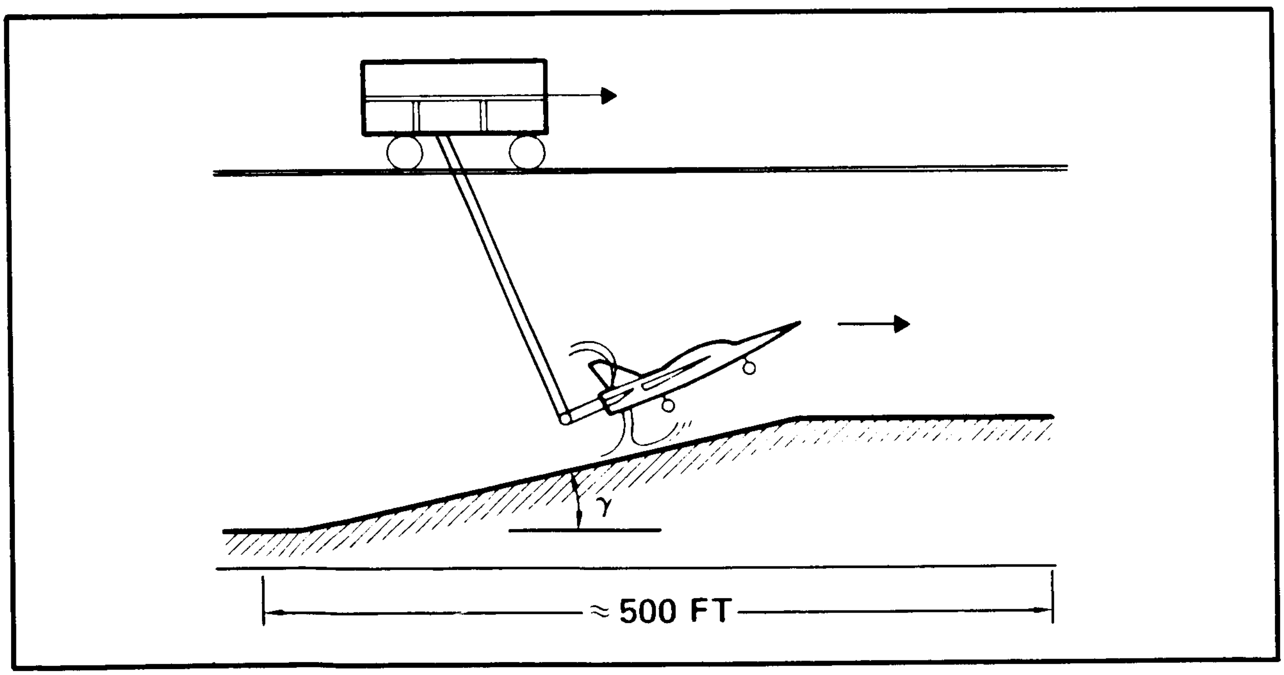

FIGURE 17. CONCEPT FOR NASA/NORTHROP/USAF TEST OF UNSTEADY THRUST REVERSER EFFECTS IN GROUND PROXIMITY

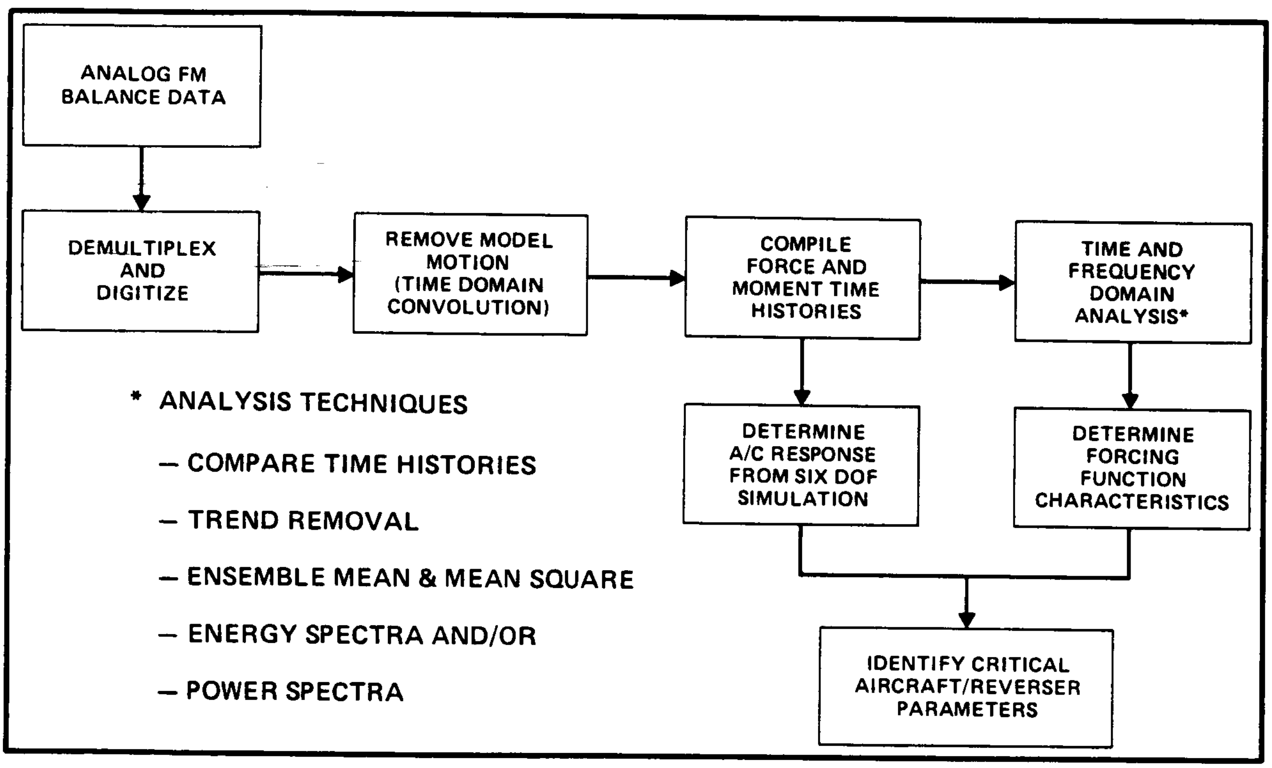

FIGURE 18. SCHEMATIC OF DATA ANALYSIS SCHEME FOR NORTHROP/NASA/USAF TRANSIENT GROUND EFFECTS TEST

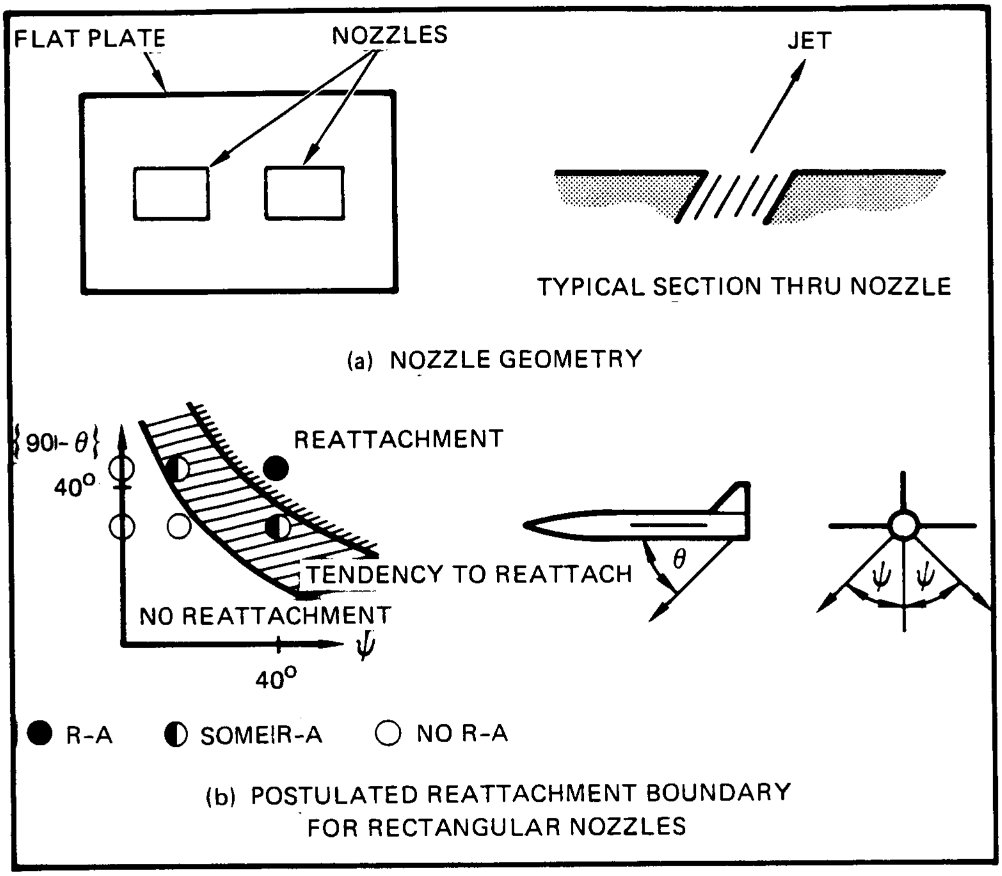

FIGURE 19. JET REATTACHMENT TO A FLAT SURFACE

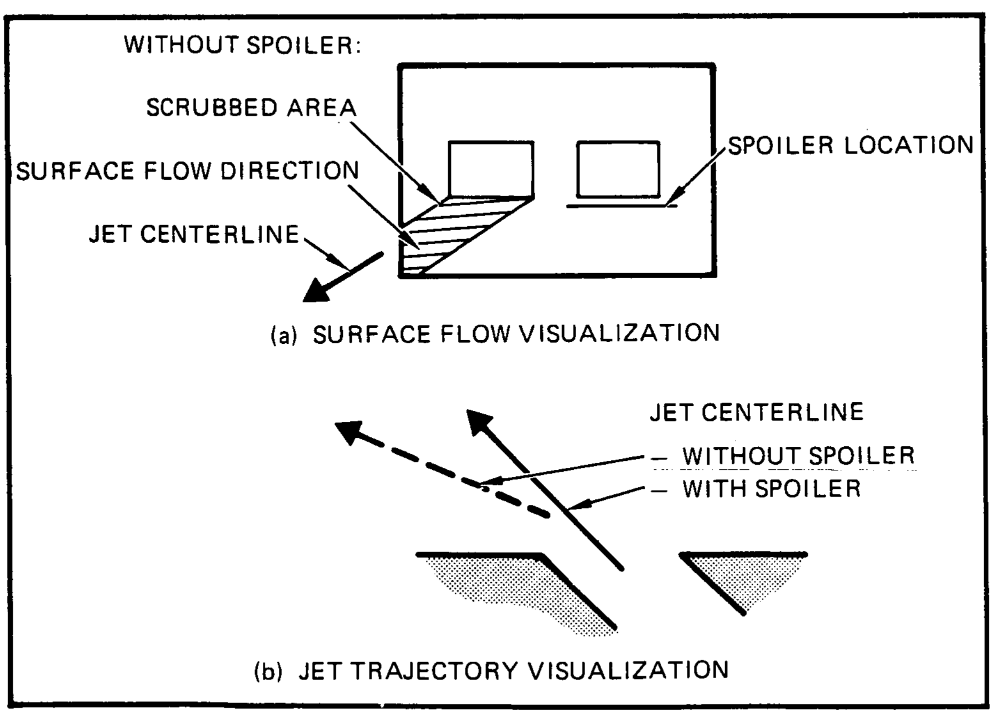

FIGURE 20. EFFECT OF SPOILER ON JET REATTACHMENT