Exploratory Evaluation of Moving-Model Technique for Measurement of Dynamic Ground Effects

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A ground-based testing technique is under development for the measurement of dynamic or time-dependent ground effects that may be present during aircraft approach and landing. The technique utilizes a model that moves horizontally over an upwardly inclined ground plane to simulate rate of descent. This method contrasts with conventional wind-tunnel ground-effects testing techniques in which data are obtained for a model at several fixed heights above the ground and is, therefore, much more representative of actual flight conditions. A relatively simple and comparatively inexpensive method of simulating rate of descent involves the use of the NASA Langley Research Center Vortex Research Facility (VRF) to move a model horizontally over a ground plane comprised of an upwardly inclined ramp followed by a horizontal segment. The model motion over the inclined ramp simulates an approach flight path angle, and the combination of the forward speed of the model and the ramp angle determines the simulated rate of descent. Results were obtained in the VRF for a generic 60 deg delta wing and for an F-18 configuration, with and without thrust reversing, at forward speeds up to 100 ft/s. These same models and support hardware were also tested in the NASA Langley 14- × 22-ft Subsonic Tunnel at identical conditions (but without rate-of-descent) with and without a moving belt ground plane to obtain data for comparison.

Nomenclature

b	= wing span
ΔC_L	= increase in lift coefficient ($C_L = L/qs$). Subscript indicates the h/b used to obtain the reference C_L.
h	= height of the model over the ground board (referenced to the MAC/4)
$\dot{h}$	= rate of descent
L	= lift
MAC	= mean aerodynamic chord
NPR	= nozzle pressure ratio (p_j/p_∞)
p	= total pressure
q	= dynamic pressure
S	= wing area
V	= velocity
α	= angle of attack
δ_f	= flap deflection
δ_h	= horizontal stabilizer deflection

Subscripts

j	= jet
le	= leading edge
te	= trailing edge
∞	= freestream

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Introduction

FUTURE fighter/attack aircraft will almost certainly utilize some form of thrust vectoring to achieve enhanced takeoff and landing performance. Additionally, reducing the ground roll after landing will require the use of reversed thrust. Analyses have shown that, for thrust reversing to be most effective, the engines must be at a high power setting at touchdown so that reverse thrust may be applied immediately without waiting for engine spool-up. The configuration aerodynamics associated with the forward directed efflux of reversers will almost certainly be sensitive to ground effect, and accurate prediction of these effects is not always possible in wind tunnels, because the effects of power, floor boundary layer, and rate of descent may not be properly included.

Considerations of ground effects determined from wind-tunnel tests and flight tests[1] indicate that transient effects which occur in flight are not considered at all in typical wind-tunnel ground-effects testing. In particular, conventional wind-tunnel ground-effects tests (i.e. time-averaged tests of a stationary model at various ground heights) actually simulate an aircraft flying near the ground at a constant altitude rather than an aircraft descending through a given altitude, as is the case in approach and landing. As shown in Fig. 1, flight test results of an XB-70 in ground effect indicated less lift increase during approach than was predicted on the basis of wind-tunnel testing. Dynamic testing of an XB-70 model[2] determined that ground-effect characteristics measured so as to include the effect of rate of descent matched the flight test results much better than the conventional wind-tunnel data as can be seen in Fig. 1. Other flight test results using a Concorde aircraft[3] showed that constant-altitude, low-level flight results agreed very well with the ground effects predicted by wind-tunnel tests.

Another stimulus to perform ground-effects testing with a moving model arose from an investigation concerning a generic thrust reverser study, reported in Ref. 4. During the investigation, the thrust-reverser flowfield generated undesirable ground effects such as a severe lift loss and large rolling moments at ground heights above wheel touchdown. Questions arose as to whether the effects measured in these conventional static wind-tunnel tests would be encountered during an actual approach. That is, would the flowfield develop fully and interfere with the aircraft in the short period of time that the aircraft was in ground effect, or would the aircraft fly through (or ahead of) the flowfield and land before the ground could have a significant effect on the configuration's aerodynamic characteristics? Figure 2 illustrates some of the differences between conventional static wind-tunnel ground-effect testing and testing with a moving model. In the static technique, a model is set at a given height above the ground plane, the flowfield develops to a steady-state condition, then the aerodynamic characteristics are measured. The moving model method measures the aerodynamic characteristics of a configuration with the flowfield in a dynamic state, similar to conditions encountered during an actual approach. On a normal approach without thrust reversers operating, the differences may have little effect on the measured aerodynamic characteristics, but the plumes created by forward-blowing jets at low ground heights will react differently to the two test conditions. This can result in a substantial difference in measured aerodynamics between the two techniques. Not only are the plume dynamics different in the two methods of testing, but they also differ geometrically. If both methods are used to test a model at a given angle of attack, the moving model will be set at a lower angle of incidence to the ground board (reduced by the simulated glide path angle). This changes the impingement angle of the jet on the ground plane, resulting in distinctly different plumes.

As a result of concern over the information gathered in the above investigations and observations, and the known sensitivity of powered configurations to ground boundary-layer modeling, it appeared that conventional ground-effect testing techniques should be reevaluated. The main emphasis in the present investigation was to determine the effects of sink rate by comparing the results of current static testing methods with results from a dynamic procedure in which a model would be moved toward an inclined ground plane to simulate rate of descent. A second objective of the study was to evaluate the need for using a moving-belt ground plane when testing configurations with thrust reversers in wind tunnels. Identical models and support systems were tested in both the NASA Langley 14- × 22-ft Subsonic Tunnel and the NASA Langley Vortex Research Facility (VRF) to minimize any effects of using different hardware in the two tests. The 14- × 22- ft Subsonic Tunnel was used for the static testing because it has both a boundary-layer removal system and a moving-belt ground plane. This paper presents the details of the dynamic testing technique and provides an assessment of the effects of both the moving-belt ground plane and the moving-model technique as they influence the development of aerodynamic ground effects.

Throughout this paper, the term "static" refers to results obtained in the 14- × 22-ft Subsonic Tunnel with a stationary model; "dynamic" refers to results obtained in the VRF while the model was moving over the inclined portion of the ground board to simulate rate of descent; and "steady state" refers to the results obtained in the VRF while the model was moving at a fixed height over the level portion of the ground board.

Models

Two models were tested in the investigation. The first model was a 36-in. span, 60 deg delta wing made from ⅜-in. clear acrylic sheet. The leading and trailing edges were beveled to sharp edges. As sketched in Fig. 3, a six-component strain-gage balance was mounted to the upper surface of the wing on the centerline of the model, 6 in. forward of the trailing edge. Two nonmetric circular jets were mounted at the trailing edge to exhaust forward at a 45 deg angle. The nozzle exits were 1 in. below the trailing edge of the wing and were spaced 4 in. apart. Simple convergent nozzles were used to insure uniform flow distribution at the exit plane.

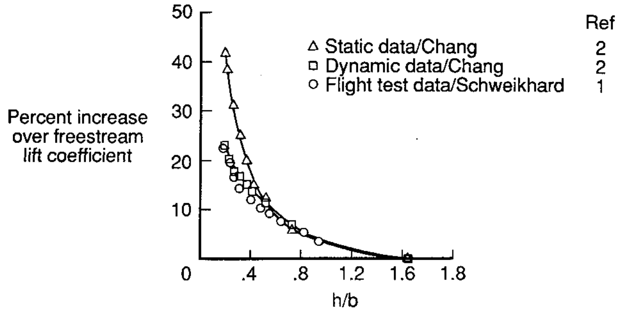

Fig. 1 Comparison of static, dynamic, and flight test data of an XB-70 at $\alpha = 9.3$ deg.

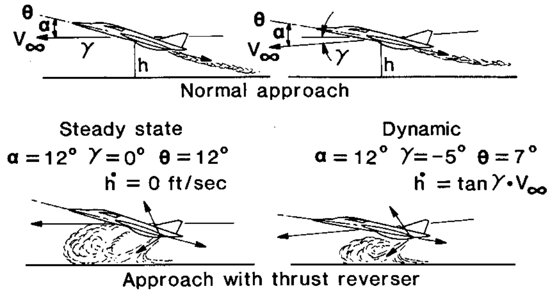

Fig. 2 Schematic of dynamic and steady-state ground effects.

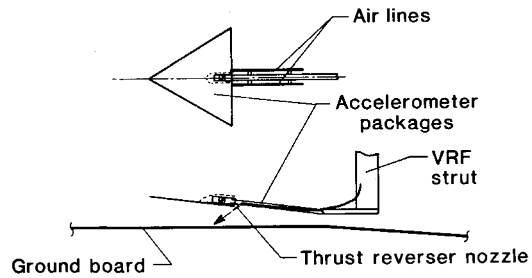

Fig. 3 Sketch of 60 deg delta wing mounted on the VRF strut.

The other model used in the study was a 0.07 scale F-18 model shown in Fig. 4. The model was mounted on a six-component strain-gage balance inside the fuselage, and it was equipped with adjustable leading- and trailing-edge flaps and a horizontal stabilizer. Reverse thrust simulation was supplied nonmetrically using a thrust reverser simulator described in Ref. 4. The simulator provided for variability in both longitudinal reverser angle and splay angle (the angle that the jets are inclined spanwise).

The models were tested at several rates of descent, forward speeds, and thrust reverser settings. Tests were run first in the VRF and then were run statically in the Langley 14 × 22-ft Subsonic Tunnel. The same sting and airlines were used for both tests to minimize differences in the support interference effects between the two facilities.

Test Facilities

The Vortex Research Facility (Fig. 5) at the NASA Langley Research Center was modified for the present study by installing a 150-ft-long ground plane assembly approximately in the center of the test section. The models were suspended on

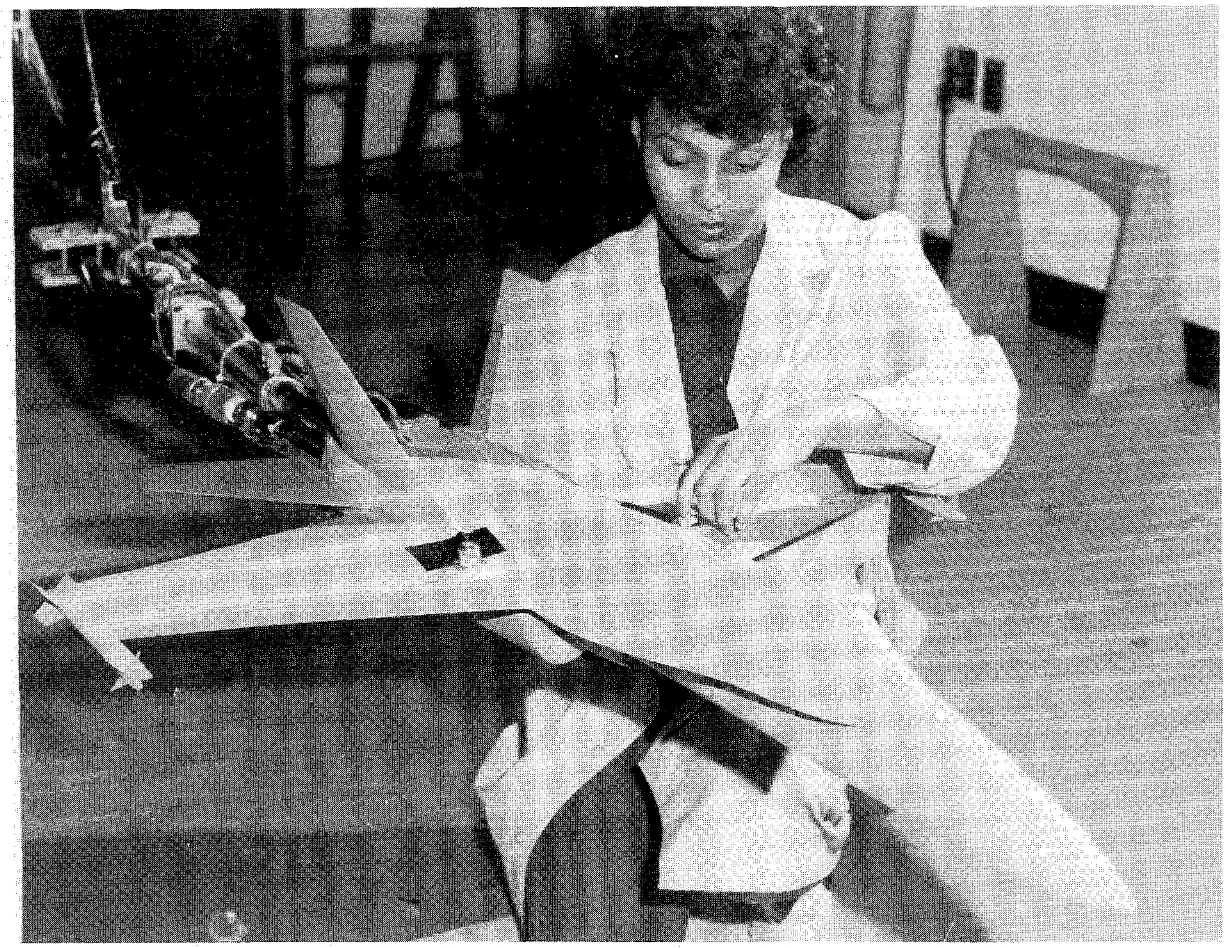

Fig. 4 F-18 model mounted in the VRF.

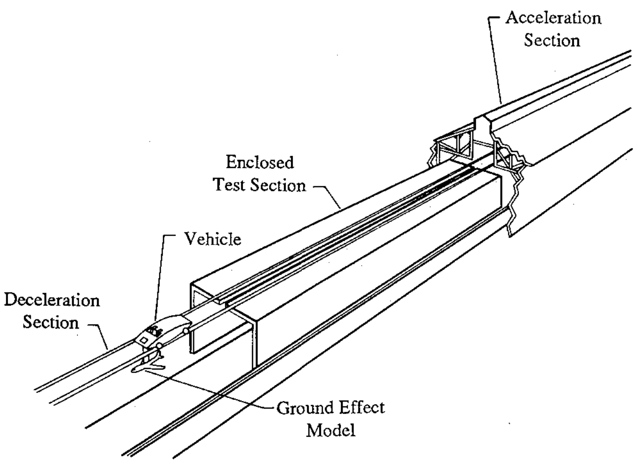

Fig. 5 Schematic diagram of the VRF.

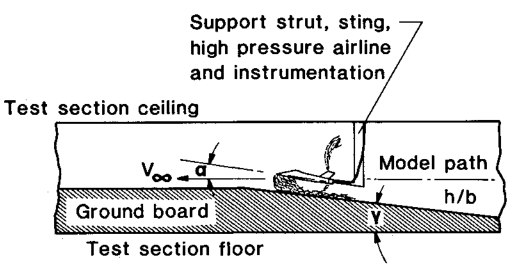

Fig. 6 Model passing through the test section in the VRF.

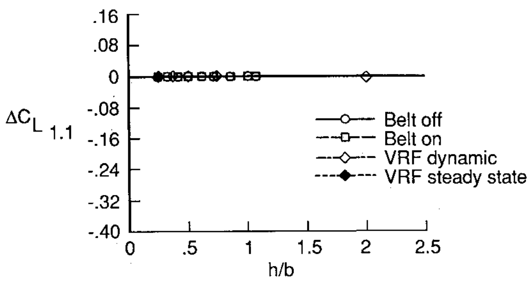

Fig. 7 Effect of height on the lift coefficient of a 60 deg delta wing at $\alpha = 1.5$ deg and NPR = 1.0.

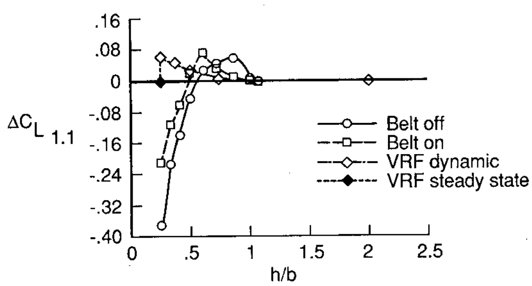

Fig. 8 Effect of height on the lift coefficient of a 60 deg delta wing at $\alpha = 1.5$ deg and NPR = 1.8.

a variable-length strut extending from the bottom of the gasoline-engine powered cart. The strut supported the model, sting, and airline assembly as well as the instrumentation. It also provided a means for adjusting the minimum height over the level portion of the ground board. Angle of attack was changed by pitching the entire strut, sting, and model assembly at the point where the strut was attached to the cart. Velocity was controlled by a cruise-control system on the cart. High-pressure air bottles on the cart provided compressed air for the jets.

The ground board consisted of two parts: a ramp that inclined upward 4 deg for a distance of 100 ft, followed by a horizontal section that extended an additional 50 ft. As the model moved over the inclined portion, the height of the model above the ground board reduced, thereby simulating an approach along a glide slope of 4 deg. Rate of descent was dependent on the test velocity as given by the equation:

$$\dot{h} = V_\infty \tan 4 \text{ deg}$$

After moving across the ramp, the model pased over the horizontal section to simulate rollout or constant altitude flight (see Fig. 6).

The static ground effects of the models were measured in the Langley 14 × 22 ft Subsonic Tunnel, which has a suction ground boundary-layer removal system and a relatively large test section. The boundary-layer removal system is located at the beginning of the test section and is followed by a moving-belt ground plane that is used to minimize boundary-layer development in the test section.

Special Corrections

An inherent problem with moving-model testing is that model accelerations caused by cart and strut vibrations will contaminate the balance aerodynamic force data with inertial loads. These loads must be removed from the balance output in order to identify the aerodynamic data contained in the balance output. The strut and cart were therefore instrumented with several accelerometers to measure the vertical and lateral accelerations of the sting and the vertical, lateral, and longitudinal accelerations of the cart near the strut connection point.

As a first-order approximation of the inertial loads, the total mass of the model and all mounting hardware forward of the balance strain gages was multiplied by the measured vertical and lateral accelerations of the sting. The resulting loads were then subtracted from the normal and side force outputs of the balance, respectively, to obtain the aerodynamic loads on the model.

Results

60 Degree Delta Wing

The results of tests on the 60 deg delta wing are presented in Figs. 7–14 in terms of the change in lift coefficient due to ground proximity relative to the lift coefficient measured at the highest ground height common to all three test techniques. Each figure shows the moving-model results and static wind tunnel results obtained with and without the moving-belt ground plane. All moving-model results were obtained at a nominal sink rate of 6.3 ft/s. For the power-off case (Fig. 7), there are virtually no differences in measured ground effects between the different test techniques. However, when the thrust reversers were operated (Fig. 8) the results were quite different. At NPR = 1.8 the static data indicate a marked loss in lift, or "suckdown," at heights below $h/b = 0.75$ without the moving-belt ground plane. Eliminating the ground boundary layer by using the moving-belt ground plane delayed suckdown until $h/b = 0.6$. In sharp contrast to the static test data, the moving-model data from the VRF indicate that, even at a ground height of $h/b = 0.25$, there was no lift loss until the flow reached steady-state conditions over the horizontal portion of the ground board. Even for the VRF steady-state case, however, there was no lift loss relative to the reference lift coefficient; the favorable lift increase due to ground effect was offset by the suckdown from the reverser jets. At this time it is not understood why the steady-state thrust reverser results from the VRF do not exactly match the static data from the wind tunnel.

Increasing thrust to NPR = 2.0 showed no essential differences in the data trends, as can be seen in Fig. 9. There was a net loss in lift for the VRF steady-state case at $h/b = 0.25$ for this power setting indicating that suckdown has increased from the case of NPR = 1.8, as would be expected.

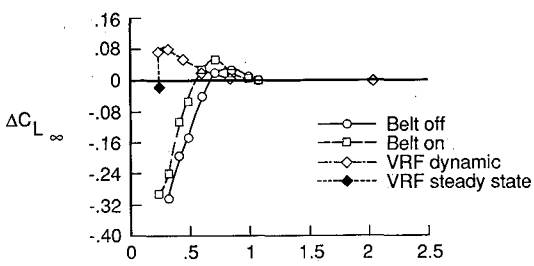

Fig. 9 Effect of height on the lift coefficient of a 60 deg delta wing at $\alpha = 1.5$ deg and NPR = 2.0.

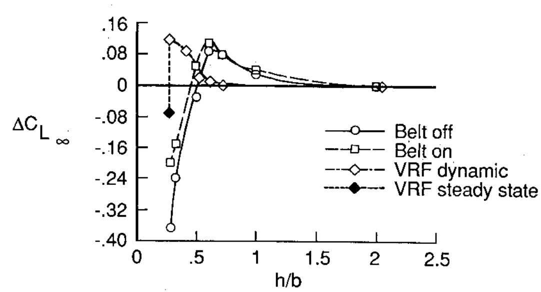

Fig. 11 Effect of height on the lift coefficient of a 60 deg delta wing at $\alpha = 10$ deg and NPR = 1.6.

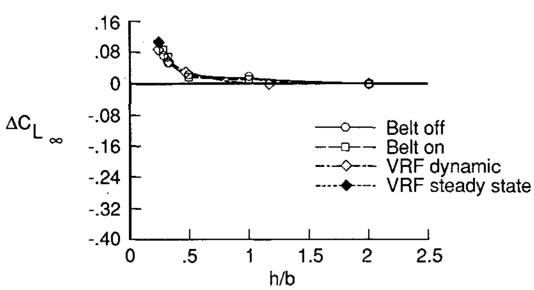

Fig. 10 Effect of height on the lift coefficient of a 60 deg delta wing at $\alpha = 10$ deg and NPR = 1.0.

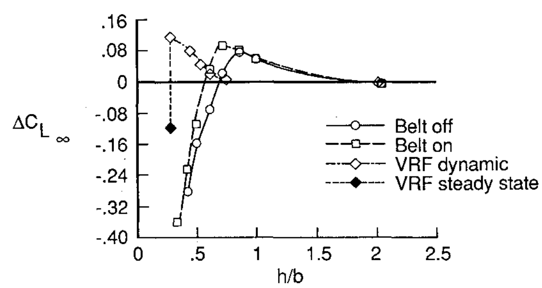

Fig. 12 Effect of height on the lift coefficient of a 60 deg delta wing at $\alpha = 10$ deg and NPR = 2.0.

The power-off data obtained at the angle of attack of 10 deg are shown in Fig. 10 and are relatively consistent among the three test procedures. The effect of power shown in Figs. 11 and 12 is essentially the same as measured for $\alpha = 1.5$ deg. The moving-model results show that not only was the lift loss delayed, but also that there was a slightly greater increase in lift coefficient at moderate heights than was observed in the wind-tunnel results.

Another interesting result was observed at $\alpha = 14$ deg as shown Fig. 13. The static ground effects measured in the wind tunnel for the power-off case began to be evident at a relatively large h/b, near 2.0, with or without the moving-belt ground plane in operation. In the VRF, however, the power-off ground effects observed with the moving-model technique did not become apparent until a much lower h/b of about 0.80 had been reached. The steady-state VRF data obtained over the horizontal portion of the ground board, however, did correlate well with the static wind-tunnel data. Similar results were obtained in the study reported in Ref. 3, which shows good correlation between wind-tunnel data and constant-altitude fly-over tests of a nonthrust reversing delta-wing aircraft. The effect of ground proximity at NPR = 2.0 (Fig. 14) was similar to the effect observed at lower angles of attack, but more pronounced. The steady-state lift loss was much less than was observed in the wind tunnel, and the dynamic ground effects resulted in a lift increase down to $h/b = 0.42$.

F-18 Model

The results of the 0.07 scale F-18 model tests show trends similar to those observed for the 60 deg delta wing model tests. For this model a nominal sink rate of 7.0 ft/s was used. As can be seen in Fig. 15, all three techniques showed little ground effect at an angle of attack of 1.5 deg when the thrust reversers were not operating. At NPR = 1.45 and 1.95, (Figs. 16 and 17) the onset of lift loss in ground effect can be seen to occur at lower ground heights for the moving-model VRF technique than for the wind-tunnel techniques. It is important to note that no data were obtained for heights greater than $h/b = 0.74$ for the moving ground belt tests or heights greater than $h/b = 0.9$ for the fixed ground plane wind-tunnel tests. Therefore, all increments in lift coefficient have been referenced to the values at $h/b = 0.74$. Also, the moving-model data were obtained at a lower minimum ground height and the steady-state VRF data correlates well with the lift loss that would be expected to occur in the wind tunnel results at the lower heights.

As noted previously, the thrust reverser simulator used with the F-18 model had provisions for varying the splay angle of the reverser jets. Figure 18 presents data for the reverser jets deflected 40 deg outward toward the wing tips. When these data are compared with Fig. 16, it is apparent that blowing forward parallel to the centerline of the F-18 model caused a severe lift loss that was avoided when the jets were blown spanwise. Also of interest in Fig. 18 is the fact that the

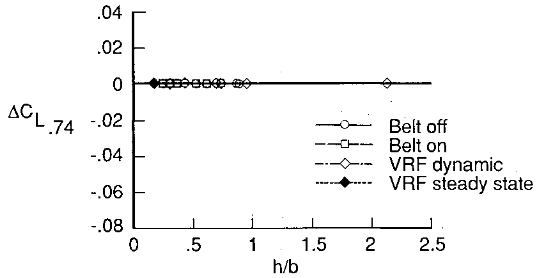

Fig. 15 Effect of height on the lift coefficient of an F-18 model at $\alpha = 1.5$ deg and NPR = 1.0. Clean configuration.

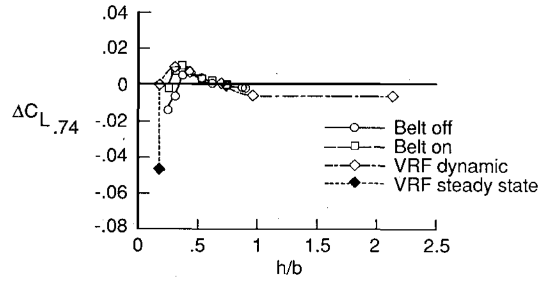

Fig. 16 Effect of height on the lift coefficient of an F-18 model at $\alpha = 1.5$ deg and NPR = 1.45. Clean configuration.

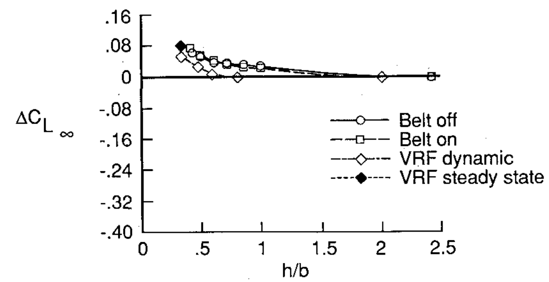

Fig. 13 Effect of height on the lift coefficient of a 60 deg delta wing at $\alpha = 14$ deg and NPR = 1.0.

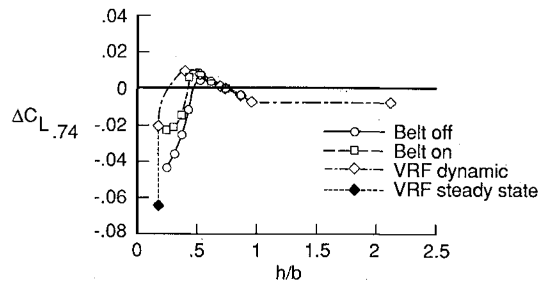

Fig. 17 Effect of height on the lift coefficient of an F-18 model at $\alpha = 1.5$ deg and NPR = 1.95. Clean configuration.

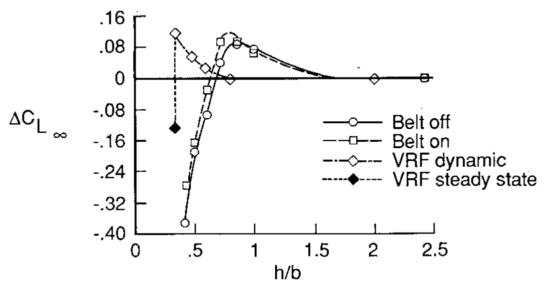

Fig. 14 Effect of height on the lift coefficient of a 60 deg delta wing at $\alpha = 14$ deg and NPR = 2.0.

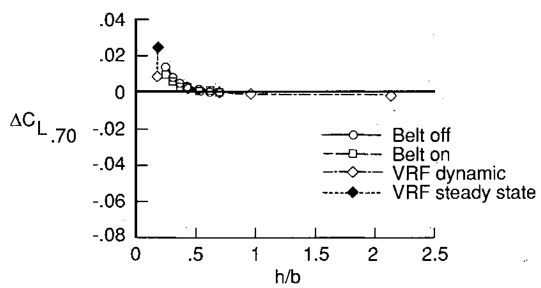

Fig. 18 Effect of height on the lift coefficient of an F-18 model at $\alpha = 1.5$ deg and NPR = 1.5. Clean configuration with 40 deg splay.

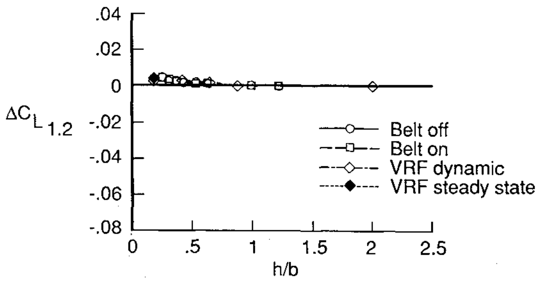

Fig. 19 Effect of height on the lift coefficient of an F-18 model at $\alpha = 1.5$ deg and NPR = 1.0. High lift configuration.

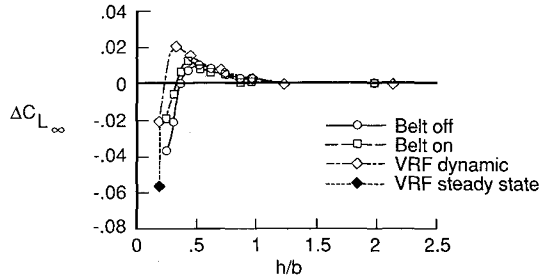

Fig. 22 Effect of height on the lift coefficient of an F-18 model at $\alpha = 8.4$ deg and NPR = 1.5. High lift configuration.

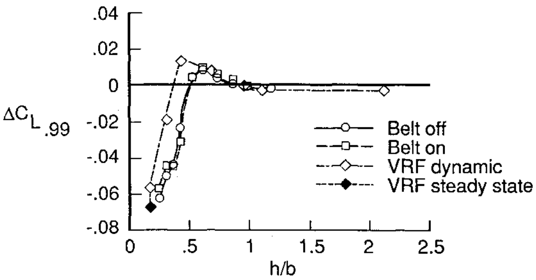

Fig. 20 Effect of height on the lift coefficient of an F-18 model at $\alpha = 1.5$ deg and NPR = 2.0. High lift configuration.

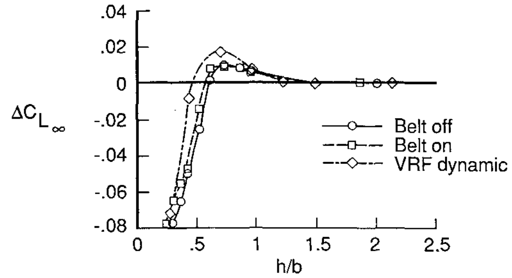

Fig. 23 Effect of height on the lift coefficient of an F-18 model at $\alpha = 8.4$ deg and NPR = 2.5. High lift configuration.

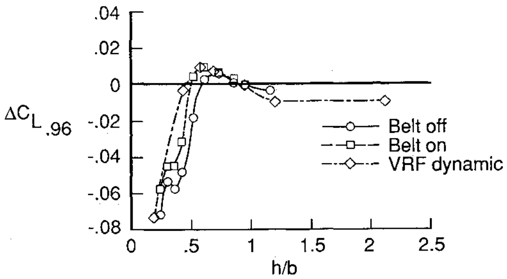

Fig. 21 Effect of height on the lift coefficient of an F-18 model at $\alpha = 1.5$ deg and NPR = 2.5. High lift configuration.

steady-state data taken with the moving model seems to be in general agreement with an extrapolation of the wind tunnel data to $h/b = 0.18$.

Data obtained with the leading and trailing edge flaps deflected are illustrated in Figs. 19–23. With the model unpowered and at a low angle of attack, all three techniques produced very similar ground effects. At NPR = 2.0 (Fig. 20) the ground effect trends for all three techniques were similar to the previously discussed case with underflected flaps. That is, lift loss associated with close ground proximity was delayed with the moving-model as compared to conventional tests. When thrust reverser power was increased to NPR = 2.5, the moving-belt wind tunnel data were in fairly good agreement with the VRF results, as seen in Fig. 21. This would indicate that the time-dependent effect is a funciton of the time necessary for the plume to develop in front of the model. High-powered jets penetrate further and impinge on the floor at a higher ground heights than low-powered jets. Once the jet impinges, it will separate into a forward-moving wall jet and an aft-moving wall jet. The forward-moving wall jet then develops into the plume or ground vortex, that affects the model aerodynamics. With better penetration, the jets can begin the formation of the plume sooner, perhaps reducing the effect of sink rate.

At $\alpha = 8.4$ deg and NPR = 1.5, the data of Fig. 22 show the typical delayed suckdown in the VRF as compared to the static wind-tunnel results. On the other hand, results at NPR = 2.5 (Fig. 23) show good agreement among all three techniques in the value of h/b for the onset of good agreement among all three techniques in the value of h/b for the onset of suckdown as was noted earlier at a high power setting. It should be noted, however, that neither the level of suckdown nor the increment in lift coefficient before suckdown are well matched between the wind tunnel and the VRF data.

Concluding Remarks

The moving-model technique has been shown to be a unique, informative method for evaluating the aerodynamic ground effects of powered and unpowered models. The implications of the results obtained appear to be especially significant for STOL-type configurations with thrust reversers. Moving models having no thrust simulation showed different levels of ground effects than levels measured by conventional static wind-tunnel tests; but, the data follow similar trends at higher angles of attack. Models with thrust reversers, on the other hand, have been shown to exhibit dramatically different trends in the aerodynamics associated with ground effects. The data also show that, while the use of a moving-belt ground plane can improve the correlation of static ground effects data to some extent, the results are still considerably different from those measured on a moving model.

For the purpose of this exploratory, limited investigation it was not necessary to address the problem of scaling the results of the dynamic test technique to full scale. However, for this method to be useful in obtaining aerodynamic design data that problem must eventually be addressed. A follow-up test is planned that will concentrate on the effect of varying rate of descent and jet velocity. In addition, measurements will be made of the higher-frequency variations in the configuration aerodynamics.

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