7

14A

GROUND INTERFERENCE EFFECTS

By Robert O. Schade

Langley Research Center

SUMMARY

L 1 4 1 6

A study has been made to determine the basic phenomena associated with the ground interference effects for VTOL aircraft in an attempt to arrive at some generalized conclusions regarding the effect of the ground on the various types of VTOL aircraft.

The results showed that helicopter and other rotor aircraft generally experience favorable ground effect. In the case of propeller VTOL aircraft the tilt-wing configurations will usually experience a small favorable ground effect. For the deflected-slipstream configurations a large detrimental ground effect is experienced at low angles of attack of the thrust axis but little or no ground effect at angles of attack of 25° or 30°. For buried-fan and jet configurations the ground effect can be favorable or unfavorable depending upon the geometry of the fans or jets and the airframe. For single-jet configurations the ground effects are detrimental and cannot be eliminated by fixes on the airplane. For these cases, a perforated landing platform appears to offer promise as a means of minimizing the adverse ground effect. Ground effects experienced in hovering flight tend to decrease with increasing forward speed and are rather small at airspeeds that might be of interest for STOL operation of the various VTOL configurations. The qualitative predictions of the ground effect for various VTOL aircraft configurations can be made with a fair degree of confidence, but it appears at the present time that the magnitude of the effect for specific configurations will usually have to be obtained from test data.

INTRODUCTION

Ground interference effects have not proved to be very significant for conventional airplanes but they have assumed major importance for VTOL aircraft because the slipstream or jet exhaust is directed straight down for vertical take-off and landing. These ground interference effects can be either favorable or unfavorable depending upon the configuration.

It is the purpose of this paper to cover ground interference effects for all types of VTOL aircraft, with descriptions of the phenomena

Preceding page blank

involved and indications of possible means of minimizing the unfavorable interference effects where they exist.

It should be pointed out that the term "ground interference effects" used in this paper refers to the effect of the ground on the aerodynamics of the aircraft. Other effects of the slipstream impingement, such as ground erosion, recirculation of dust and debris, and effects on objects surrounding the landing area are covered in the paper by Thomas C. O'Bryan.

The ground interference effects discussed in this paper can be broken down into two parts: the effect on the thrust of the propulsion source itself and the effect on the airframe. Basic phenomena associated with these two kinds of interference are indicated and experimental data for various VTOL configurations are presented. Some indication of the particular interference effect involved in each case is given.

L1416

SYMBOLS

D	diameter
h	height
L	lift
L_∞	lift at infinite distance above ground
M_α	variation of pitching moment with angle of attack
β	propeller blade angle
θ_T	angle of thrust line

GROUND EFFECT ON PROPULSION SOURCE

Figure 1 shows the lift augmentation of propellers and rotors. The sketch in the figure indicates that as the rotor approaches the ground the slipstream fans out; the result is an increase in pressure and a decrease in velocity in the slipstream. This change causes the well-known increase in lift on the rotor as it approaches the ground. A typical variation of lift augmentation for a propeller or rotor is shown by the curve in figure 1. The term L/L_∞ is the ratio of the amount of lift in ground effect to that out of ground effect. (Values above 1.0 indicate favorable ground effect.) The ratio h/D is the height above the ground divided by the diameter.

For jet engines there is a similar flow which also spreads out as the ground is approached, but in this case an increase in lift is not obtained. In fact, a decrease in lift or thrust might be experienced because the increased pressure in the jet exhaust results in back pressure on the engine. However, this effect for a jet is not a significant one because the tail pipes of jets are usually not very close to the ground in terms of tail-pipe diameter.

Figure 2 shows the effect of the ground on a ducted fan with two different blade angles. When the blade angle is set for optimum efficiency in hovering out of ground effect, there is a loss in lift as the ground is approached. This detrimental ground effect is attributed to the fact that the higher disk loadings associated with ducted fans require higher blade angles, and there is a tendency for the blades to stall as the ground is approached. This stalling tendency can be reduced by using lower blade angles, and if the blade angle is reduced to a very low value, a favorable ground effect can be obtained as indicated by the top curve. Of course, it must be realized that this change from an unfavorable to a favorable ground effect is accomplished at the expense of some hovering efficiency out of ground effect.

EFFECT OF SLIPSTREAM ON AIRFRAME

Two-Dimensional Patterns

The upper sketches of figure 3 illustrate the two basic flow patterns resulting from different arrangements of slipstreams with respect to airframe surfaces. The two lower sketches show a vertical cross section through the slipstream. The induced pressures resulting from the two flow patterns are shown by the symbols + and - indicating positive and negative changes in pressure, respectively. At the left-hand side of the figure the case of a single slipstream emerging from the bottom of a surface is shown. There is an induced flow around the edges and under the surface as indicated by the broken lines; this flow results in a decreased pressure and therefore an unfavorable ground effect. At the right-hand side the case of two slipstreams at the edge of a surface is shown. In this case the flow pattern is upward in the middle resulting in increased pressure on the surface between the slipstreams and thus in a favorable ground effect.

With actual airplane configurations, of course, there are variations and combinations of these two basic flow patterns. For example, if two jets are exhausting from some intermediate positions there will be both positive and negative induced pressures, and the ground effect can be either favorable or adverse depending on how much of the total surface area is between the jets.

Three-Dimensional Pattern

Figure 4 shows a three-dimensional slipstream pattern for a two-propeller tilt-wing configuration with the two columns, which represent the slipstreams from the two propellers, coming down and striking the ground. The lines with arrows indicate slipstream filaments as they flow radially outward. Because there is an equal and opposite flow along the ground at the plane of symmetry, the plane of symmetry effectively serves as a solid wall through which no flow can pass. Since the slipstream filaments cannot flow through the plane of symmetry, the slipstream must flow upward. This flow is straight upward directly between the propellers but goes upward at progressively smaller angles at greater distances ahead of and behind the propellers. This causes ground effect not only on surfaces between the propellers but also on surfaces all along the plane of symmetry. It should be emphasized that this discussion concerns only the idealized case where the flow is perfectly symmetrical and steady. Of course, in the practical case the recirculation is likely to be both unsymmetrical and unsteady particularly when flying in gusty air and over uneven terrain. Also, if the aircraft is banked, the upward flow instead of being in the plane of symmetry as shown here moves out along the span in the direction of the upgoing wing. The flow in these cases leads to random disturbances of the aircraft which can result in poor handling qualities when the aircraft is flying near the ground. This effect on handling qualities is discussed in the papers by John P. Reeder and by F. B. Gustafson, Robert J. Pegg, and Henry L. Kelley.

HELICOPTER AND ROTOR VTOL AIRCRAFT

For the helicopter and other rotor VTOL aircraft, the ground effect is for all practical purposes the ground effect on the rotor itself since the airframe is small relative to the rotor disk area. This effect of the ground on the rotor has already been discussed.

TILT-WING PROPELLER CONFIGURATIONS

The effect of the ground on two tilt-wing propeller configurations is shown in figure 5. Both of these configurations show an increase in lift as the ground is approached. The data for the four-propeller model indicate that part of the favorable ground effect is provided by the propellers themselves and part by the buildup of pressure on the bottom of the fuselage. The favorable ground effect is greater for the Hiller X-18 model because this model has a fuselage with a wide flat bottom. These are small-scale data, but the large favorable ground effect has been verified in the case of the Hiller X-18 by full-scale tests which showed favorable ground effect of about the same magnitude as that shown in this figure. Figure 6 shows some information on the effect of the ground on the stability and control of the Hiller X-18 model. The lower plot shows the effect of the ground on the static longitudinal stability or stability of attitude. For hovering flight out of ground effect, of course, all VTOL aircraft have neutral attitude stability. It can be seen that as the aircraft approaches the ground it becomes stable. This stabilizing effect is a direct result of the favorable ground effect on the fuselage. A nose-down attitude puts the nose closer to the ground resulting in an increased lift augmentation on the forward portion of the fuselage which tends to restore the fuselage to its original attitude. The upper plot shows the variation of yaw control with height. Shown here is the ratio of the control effectiveness in ground effect to that out of ground effect. In considering the variation of yaw control with height, it is pointed out that the ailerons on the trailing edge of the wing within the slipstream are used for yaw control on this configuration. The decrease in yaw control to approximately 50 percent of its original value as the ground is approached, as shown by the upper plot, is the result of the decrease in slipstream velocity over the ailerons.

L-1416

DEFLECTED-SLIPSTREAM PROPELLER CONFIGURATIONS

Figure 7 shows the effect of angle of the thrust line on the variation of lift augmentation with height for various deflected-slipstream propeller configurations. The research-model data were obtained at various angles of the thrust line from 0° to 24°, whereas the data on the Fairchild and Ryan research aircraft were obtained at angles of 25° and 30°, respectively. For an angle of 0°, large detrimental ground effects were obtained, but as the angle of the thrust line was increased, the detrimental effect became smaller until at angles around 25° or 30° the ground effect was negligible, as shown by the data on the Ryan and Fairchild machines. This effect can be explained as follows: As the wing-flap configuration approaches the ground, an adverse pressure gradient builds up over the upper surface of the wing tending to cause separation and loss of lift. This effect is apparently more pronounced for the 0° angle case where the wing-flap combination must turn the slipstream 90°; the slipstream is therefore likely to be partially separated even out of ground effect. For an angle of 30°, of course, the slipstream need only be deflected 60° rather than 90° so there is better flow over the wing and less tendency to separate.

FAN-IN-WING ARRANGEMENT

The effect of the ground on the fan-in-wing arrangement is shown in figure 8. For the case of the wing and fans alone there is a detrimental ground effect shown by the lower curve. This effect apparently results from a negative pressure buildup under the outboard portion of the wing that is greater than the positive pressure buildup between the fans. The magnitude of this effect will, of course, vary with wing and fan geometries. The upper curve shows that a beneficial effect can be obtained by adding a fuselage below the wing. In this case the effect is rather large at the low values of h/D because the fuselage is flat and is almost touching the ground. It may be noted that the reversal in the slope of the upper curve indicates an unstable variation of power with height which would make it difficult for a pilot to maintain constant altitude when flying at this height. Of course, this same situation exists for all heights when the ground effect is adverse.

L
1
4
1
6

MULTIPLE-JET CONFIGURATIONS

Shown in figure 9 is the effect of the ground on multiple-jet configurations. For the two-jet arrangement there is a detrimental ground effect, shown by the long-dashed line. When four vertical fences are placed along the fuselage between the jets to form an open-bottom box to trap the recirculated jet exhaust, a beneficial ground effect is obtained but there is still some adverse ground effect at the intermediate heights.

With the four-jet configuration there is only a small negative ground effect. In this case, more of the jet exhaust is trapped between the jets resulting in a greater buildup of pressure in this region which almost balances out the losses caused by negative pressure under the remainder of the airframe. If this approach is followed to the extreme and if jets are placed all around the perimeter of the airframe, it is possible to end up with a very beneficial ground effect as has been shown in work with ground-effect machines. Incidentally, an attempt is being made to take advantage of this principle in the GETOL, ground-effect take-off and landing, machines currently being studied.

SINGLE-JET CONFIGURATIONS

In figure 10 the effect of the ground on single-jet configurations is shown. For the research model as shown by the dashed curve there is negative ground effect because of the negative pressure produced under the airframe by the single jet. A similar effect was obtained on the Bell X-14 as shown by the solid line. Attempts to minimize this negative effect by fixes on the aircraft itself have not been too successful. For the Bell X-14, some improvement was obtained by lengthening the landing gear and effectively moving up along the curve. Another method proposed for minimizing the adverse ground effect of jet configurations is the use of a perforated landing platform a short distance above the ground. The principal effect of the perforated plate is to provide a barrier between the high-energy jet exhaust which flows along the ground and the air above that it tries to entrain. This method reduces the induced negative lift. With the use of this perforated plate on the research model the losses are reduced to almost zero for normal landing-gear heights.

L
1
4
1
6

EFFECT OF FORWARD SPEED ON GROUND EFFECT

So far, only ground effect in hovering flight has been considered. The effect of forward speed on the ground effect for three different VTOL configurations is shown in figure 11. In this figure lift augmentation is plotted against forward speed. The curves are for a helicopter with its favorable ground effect, for a deflected-jet configuration with its unfavorable ground effect, and for a deflected-slipstream configuration in the condition in which it experiences the most unfavorable ground effect - that is, at an angle of the thrust line of 0°. As discussed previously, this large unfavorable ground effect with the deflected-slipstream configuration in hovering can be eliminated by increasing the angle of the thrust line. This case is used only to illustrate the effect of forward speed on a very large detrimental ground effect. The data were obtained under conditions corresponding to a running take-off - that is, with the wheels on the ground. This information is therefore applicable to short take-off and landing, or STOL, operation. The main point to be obtained from this figure is that the ground effects, both favorable and unfavorable, generally tend to disappear as forward speed is increased and are rather small for airspeeds that might be of interest for STOL operation with the various configurations.

CONCLUDING REMARKS

From a study of ground interference effects on VTOL configurations the following conclusions were made:

Helicopter and other rotor aircraft generally experience favorable ground effect.

For propeller VTOL aircraft the tilt-wing configurations usually experience a small favorable ground effect. For the deflected-slipstream configurations a large detrimental ground effect is experienced at low angles of the thrust line but little or no ground effect is experienced at angles of 25° or 30°.

For buried-fan and jet configurations the ground effect can be favorable or unfavorable depending upon the geometry of the fans or jets and of the airframe.

For single-jet configurations the ground effects are detrimental and cannot be eliminated by fixes on the airplane. For this case, a perforated landing platform appears to offer promise as a means of minimizing the adverse ground effect.

L
1
4
1
6

Ground effects experienced in hovering flight tend to decrease with increasing forward speed and are rather small at airspeeds that might be of interest for STOL operation of the various VTOL configurations.

And, finally, although the qualitative predictions of the ground effect for various VTOL aircraft configurations can be made with a fair degree of confidence, the magnitude of the effect for a specific configuration will generally have to be obtained from test data.

LIFT AUGMENTATION OF PROPELLERS AND ROTORS

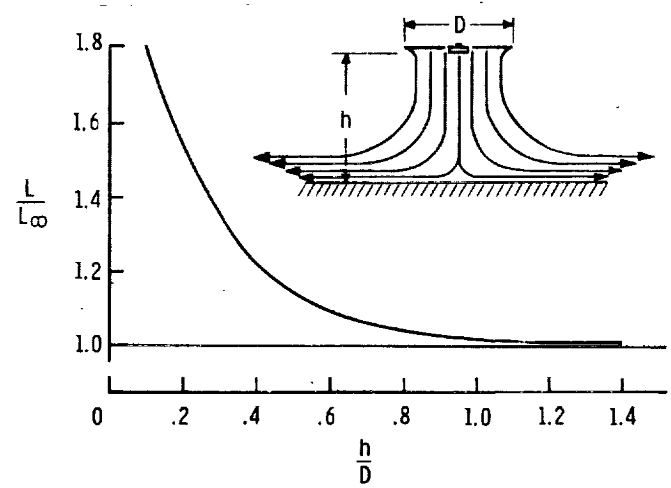

Figure 1

DUCTED FAN IN REGION OF GROUND EFFECT

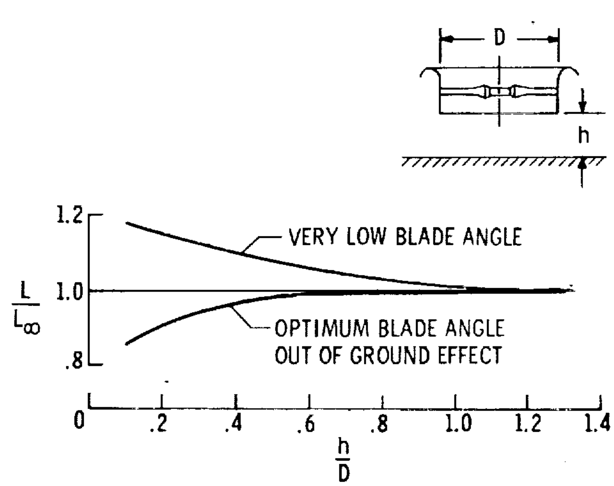

Figure 2

SLIPSTREAM PATTERNS

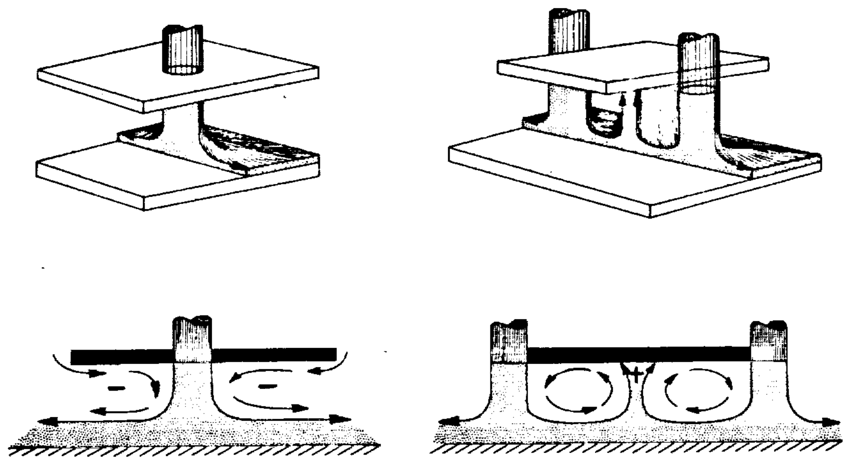

Figure 3

THREE-DIMENSIONAL SLIPSTREAM PATTERN

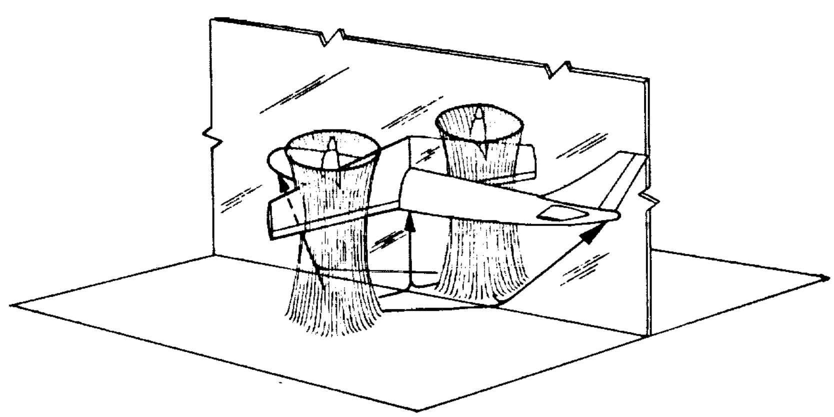

Figure 4

EFFECT OF THE GROUND ON TWO TILT-WING CONFIGURATIONS

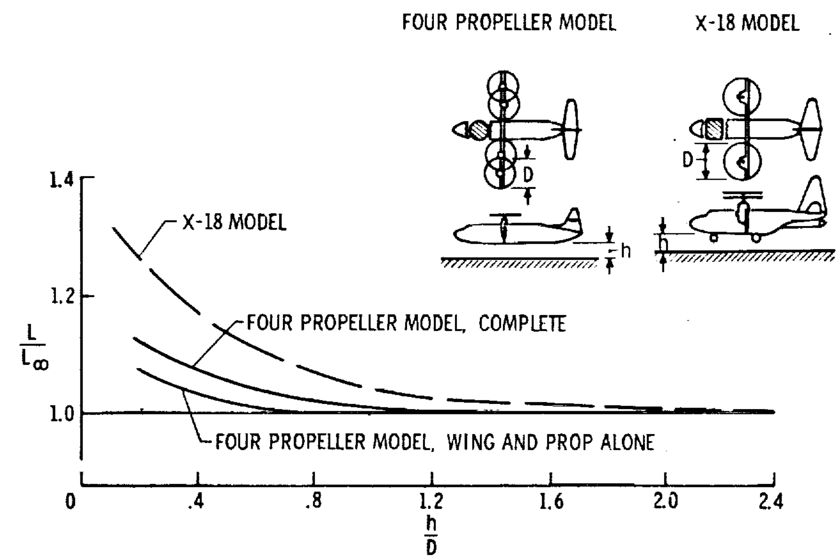

Figure 5

STABILITY AND CONTROL OF X-18 MODEL IN REGION OF GROUND EFFECT

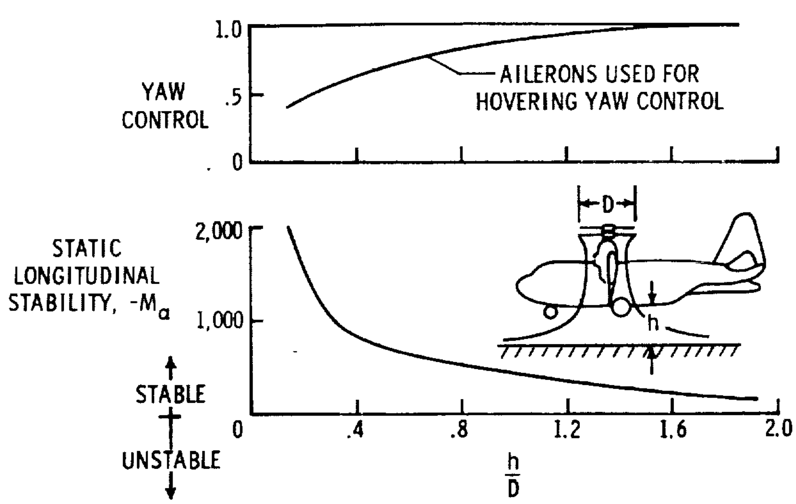

Figure 6

EFFECT OF THE GROUND ON DEFLECTED-SLIPSTREAM CONFIGURATIONS

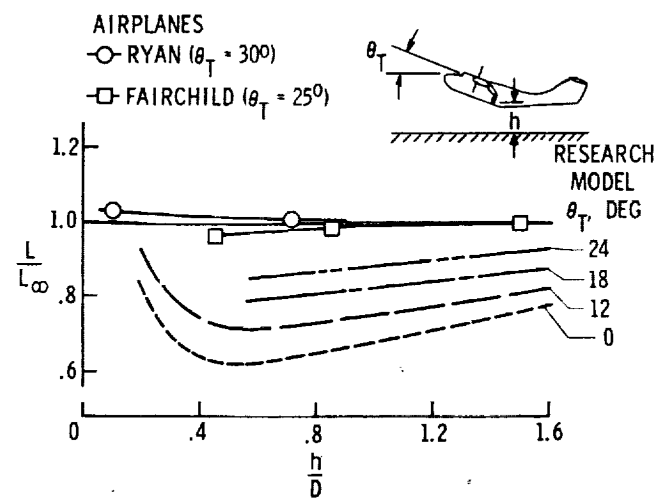

Figure 7

EFFECT OF THE GROUND ON FAN-IN-WING ARRANGEMENT

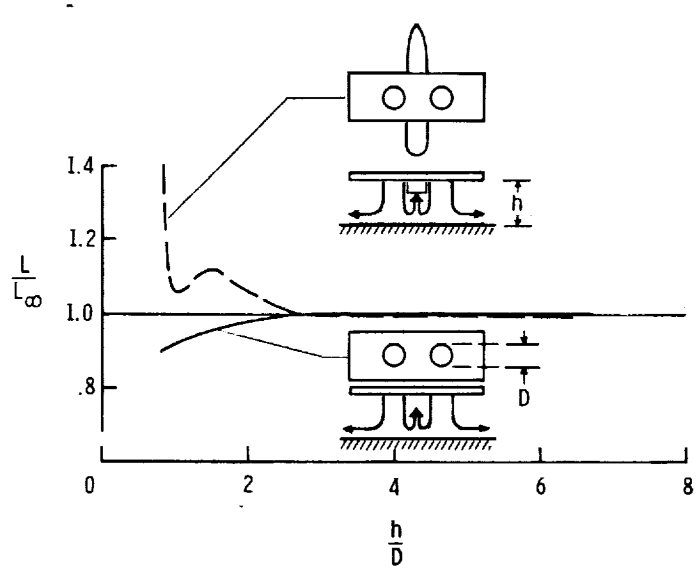

Figure 8

EFFECT OF THE GROUND
ON MULTIPLE - JET CONFIGURATIONS

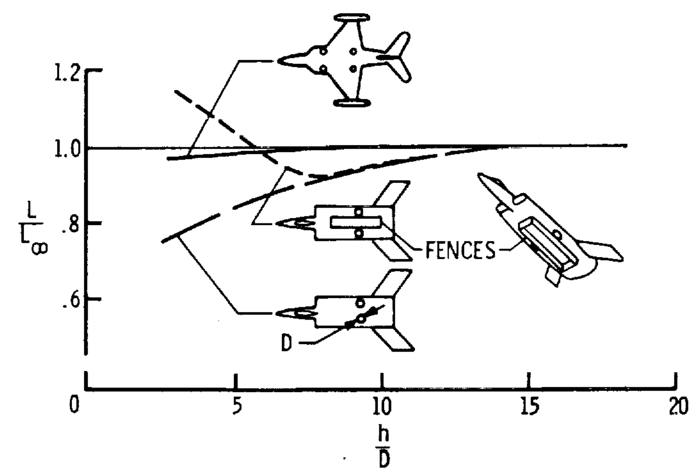

Figure 9

EFFECT OF THE GROUND ON SINGLE-JET CONFIGURATIONS

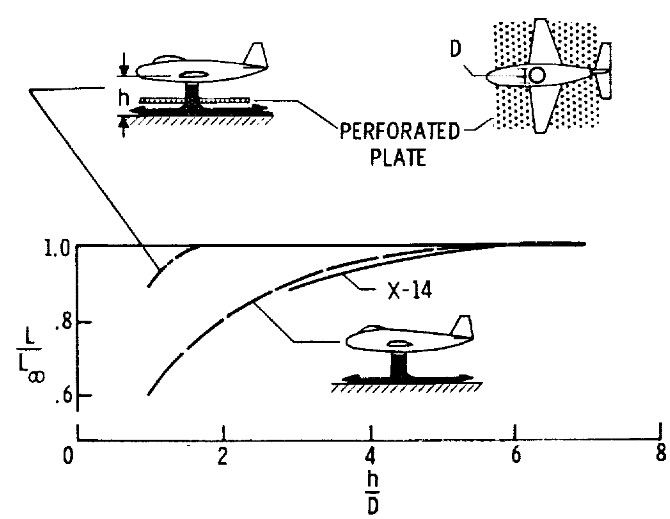

Figure 10

EFFECT OF FORWARD SPEED ON GROUND EFFECT

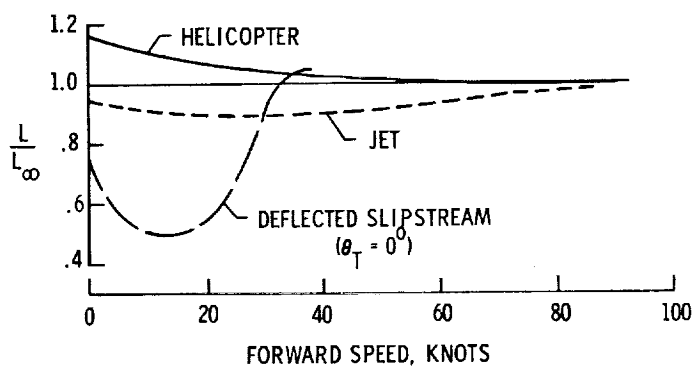

Figure 11