Forward-Speed Effects on Peripheral-Jet Ground Support Systems

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This paper presents a theory for the effect of forward speed on a two-dimensional peripheral-jet ground-effect support. New analytical models are proposed for the flow at the peripheral-jet nozzle exit and the cross flow underneath the support. Results are presented for the lower-surface pressure distribution as well as the lift and ideal pumping power. The theory is supported by a comprehensive experimental study conducted with a two-dimensional model in a moving-ground wind tunnel. The model was externally fed and had a flat bottom. At low subcritical speeds, the effect of forward speed is found to be adverse in the absence of upper-surface lift. The theory predicts the freestream dynamic pressure to be less than the average cushion pressure for this model at critical speeds. At high subcritical speeds performance improved such that lift-power requirements at critical speeds are 20–30% below those at hover. Throughout the subcritical speed regime there is general agreement between theory and experiment. Although not considered in the present work the theory can be extended for a limited range above critical speed and to three-dimensional supports.

Nomenclature

C_p = pressure coefficient (p/q_∞)
d = distance between jet curtains
F = pressure force
h = ground clearance
H = jet-curtain total pressure (gage)
l = lower-surface lift
M = momentum flux
p = static pressure (gage)
p = effective cushion pressure
P = nondimensional lift power
q = dynamic pressure
Q = flow rate
t = nozzle width
V = velocity
x, y = coordinates
θ = nozzle angle
ρ = density

Subscripts

c = cushion; cross flow
f = front jet curtain
j = jet curtain
n = nose
r = rear jet curtain
o = hover
∞ = ambient; freestream

Introduction

RECENT studies indicate that the high-speed mass transportation vehicles of the coming decade will most likely be fluid supported; e.g., the tracked air-cushion vehicle, the hovercraft, surface effect ships, etc.[1,2] Consistent with the variety of specific functions to be performed, the potential configurations of our future mass transport vehicles is large. It is expected that many of these vehicles will have ground-effect-support systems based on the peripheral-jet concept.

The flow phenomena associated with peripheral-jet ground-support systems in a balanced hovering state are well understood and theoretical predictions of hovering performance are in reasonable agreement with experiment. In comparison to hover, the flowfield surrounding a peripheral jet in forward flight is considerably more complex. In addition to the flow over the upper surface of the system, the air in the cushion region can no longer be considered stagnant.

Most of the previous studies have been limited to experiments for the effect of speed on over-all performance. Progress in the theoretical aspects of the forward-speed problem has been limited. For example, to date, a satisfactory explanation has not been given of the nonuniformities in cushion pressure which occur at speed. A coordinated investigation, combining theory and experiment, of speed effects which are common to all peripheral jet supported vehicles has not been attempted. This is due in part to the fact that specialized equipment is required to satisfactorily conduct experimental studies, e.g., a moving-ground wind tunnel.

The purpose of this work is to present a detailed study of the aerodynamic influence of forward speed on a peripheral-jet ground support, schematically illustrated in Fig. 1. The study includes both theoretical analyses and experimental tests. For simplicity, the study was restricted to a simple two-dimensional configuration; however the theoretical developments can easily be extended to three-dimensional configurations. Experiments to confirm the theory were conducted in the Rensselaer Polytechnic Institute 4-ft × 6-ft moving-ground wind tunnel using an appropriate two-dimensional model.

This article deals primarily with the flow underneath the support. An analysis of the upper-surface flow including efflux effects can be found in Ref. 3.

Analysis

The flow about a simple peripheral-jet support at forward speed is shown in Fig. 1. The flow details are based on previous flow-visualization studies; notably those of Gross and Powers.[4] With the exception of certain aspects of the

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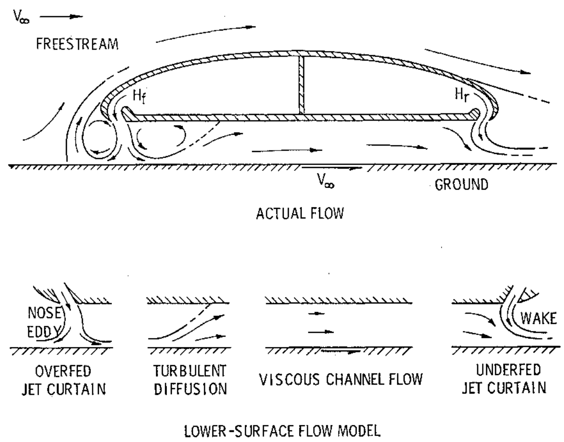

Fig. 1 Peripheral-jet support at subcritical speed.

flow over the upper surface, this figure is also applicable to the plane of symmetry of three-dimensional supports. It can be seen that the jet curtains at the front and rear are, respectively, overfed and underfed. (The term overfed is used when the momentum of the jet is sufficient to produce ground impingement and splitting. When the jet curtain is deflected and isolated from the ground by a cross flow, the term underfed is used. The borderline case between overfed and underfed is termed a balanced jet-curtain flow.) In the vehicle frame of reference, the ground plane moves in the downstream direction at the freestream speed, V_∞.

As speed increases, a greater fraction of the front jet-curtain flow is forced into the cushion. The forward speed at which all of the front jet curtain is forced into the cushion is termed the critical speed. At still higher speeds, the freestream flow begins to pass beneath the support. This speed regime is termed supercritical. The present theory, while extendable for a limited range of supercritical speeds, is limited in this paper to the subcritical regime depicted in Fig. 1.

The theoretical approach is to divide the subcritical flowfield into regions in which the major flow phenomena can be delineated. Simple models are proposed for each region. The breakdown of the flowfield beneath the support into simple regions is indicated in Fig. 1.

Nozzle-Exit Flow

An important aspect of the analysis is the determination of flow conditions at the nozzle exit for both the overfed and underfed peripheral-jet curtain flows. In the present study, a new potential-flow theory was developed for determining these conditions. The question of flow conditions across the nozzle exit of peripheral-jet supports has received a great deal of attention in the past. The unconventional feature of this two-dimensional flow is that different pressures exist to either side of the nozzle at the exit. Approximations, such as assuming a uniform exit pressure equal to the average of the two pressures,[5] can lead to gross errors in the prediction of cushion pressure at low ground clearance. For example, cushion pressure (and therefore lift capability) for a support with vertical nozzles is overpredicted by a factor of 2 at $h/t = 0.0$ with the above approximation. Several relatively simple approximations have been found which do not lead to such a large error (e.g., Exponential theory[6] and Barratt theory[7]). More rigorous treatments are given by the potential-flow analyses of Strand,[8] Ehrich,[9] and others. The motivation behind the development of a new theory in the present study was that with respect to unbalanced jet curtains the above analyses were found either to be not applicable or to have uncertain accuracy.

The new theory involves a free streamline flow model and the use of conformal transformations to relate hodograph and potential planes. The details of this theory can be found in Refs. 3 and 10. It is considerably less complex than other potential-flow analyses[8, 9] and is applicable to both overfed and underfed jet curtains. More generally, the theory can be used to determine the exit-flow conditions (discharge coefficients, etc.) for two-dimensional nozzles or slots whenever different exit pressures exist to either side of the jet curtain. Both flow separation within the peripheral-jet nozzle and the difference in streamwise location of the inner and outer walls of the nozzle are factors in the analysis. Ground-boundary effects on the nozzle-exit flow were found to be insignificant even at the lowest ground-clearance-to-nozzle-width ratio considered ($h/t = 1.69$).

Analysis of the Unbalanced Jet Curtains

The principle interest in the study of unbalanced jet curtains is to determine the relation between cushion flow and the pressure difference sustained by the jet curtain. This is found by applying the momentum and continuity equations to a control volume which surrounds the jet curtain. The control volumes for the overfed and underfed jet curtains are shown in Fig. 2. The points S_1 and S_2 are located where the flow separates from the nozzle walls. The flow details within the control volumes are considered only in a qualitative sense. Except for the inclusion of certain minor details consistent with the height difference of the two separation points in the nozzle-exit flow, the control volumes selected are otherwise the same as in other unbalanced peripheral-jet studies (e.g., Ref. 7).

The pressures p_1 and p_2 along the vertical boundaries are assumed uniform and viscous stresses along the ground are neglected. The flow conditions along the vertical boundaries are fixed by the assumption that the jet-curtain flow has a uniform total pressure. Bernoulli's equation gives the velocity of the flow as it crosses the boundary of the control

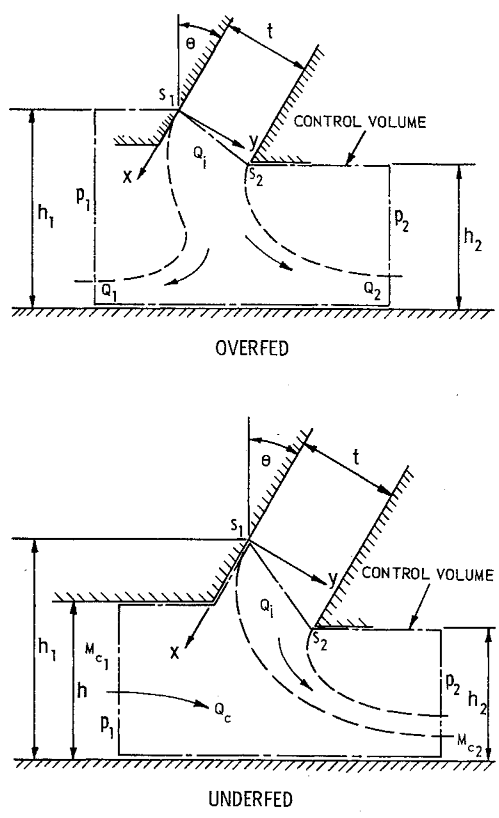

Fig. 2 Unbalanced jet-curtain flows.

volume. This velocity is constant across the thickness of the jet curtain. The same considerations apply to the cross flow for the underfed jet curtain. Although not considered here, increased accuracy can be obtained if a viscous analysis is used to determine the effects of entrainment and ground-board boundary layer on the velocity profiles at the vertical boundaries of the control volume.[11]

In the case of the overfed jet, the horizontal-momentum equation can be written as

$$[2\rho(H-p_1)]^{1/2}Q_1 - [2\rho(H-p_2)]^{1/2}Q_2 = (F_x + M_x)\sin\theta - (F_y + M_y)\cos\theta + p_2h_2 - p_1h_1 \quad (1)$$

where F_x, M_x, F_y, and M_y are the x and y components of pressure force and momentum flux for the control-volume boundary between S_1 and S_2. The continuity equation is simply

$$Q_1 + Q_2 = Q_j \quad (2)$$

Once the nozzle geometry and pressure difference across the jet curtain are prescribed, the quantities $F_x + M_x$, $F_y + M_y$, and Q_j are determined from an analysis of the flow at the nozzle exit. After determining the nozzle-exit flow, the flow rates Q_1 and Q_2 are found from Eqs. (1) and (2).

For the underfed jet, the cushion flow ahead of the jet curtain is regarded as fully diffused so that in general the lower-surface geometry and in particular the depth to which the lower surface is recessed above the end of the cushion-side nozzle wall is a factor in the analysis. The effect of a lower-surface recess is discussed further in Ref. 3. The lower surface of the experimental model was not recessed and thus recess effects are not considered in the following analysis. Another factor which complicates the analysis of an underfed jet is the magnitude of the pressure which acts on the cushion side of the nozzle-exit flow. In the present study, this pressure is assumed equal to the uniform static pressure, p_1, of the cross flow on the cushion side of the jet curtain.

When a uniform total pressure for the cross flow between the vertical boundaries of the control volume is assumed, the relation between the cross-flow momentum change, $\Delta M_c = M_{c1} - M_{c2}$, and the cushion flow rate, Q_c, is

$$\Delta M_c = \rho Q_c\{[2(p_1 - p_2)/\rho + (Q_c/h)^2]^{1/2} - (Q_c/h)\} \quad (3)$$

The horizontal momentum equation for the underfed jet is then written in the form

$$\Delta M_c = p_1h_1 - p_2h_2 - Q_j[2\rho(H-p_2)]^{1/2} - (F_x + M_x)\sin\theta + (F_y + M_y)\cos\theta \quad (4)$$

The third term on the right side of Eq. (4) is the final momentum of the jet curtain expressed in terms of its flow rate, Q_j. When the pressure difference across the jet curtain is specified and the nozzle-exit-flow problem solved, Eq. (4) gives an explicit determination of ΔM_c. The cushion flow rate Q_c can then be calculated directly from Eq. (3).

In the theoretical calculations of the present work, the underfed-jet analysis was worked in reverse. Both Q_c and p_2 were known and the cushion pressure p_1 was determined numerically from Eqs. (3) and (4) using standard iteration methods.

Cross-Flow Analysis

The cross-flow analysis is based on the assumption that the distance between the front and rear peripheral jets is an order of magnitude greater than the lower-surface ground clearance. The lower surface is assumed to be reasonably flat. The cushion may be recessed. Pitch angles are assumed to be small.

The cross flow is subdivided into two regions. The first of these is a small region adjacent to the overfed jet in which turbulent diffusion of the cross flow occurs. The second region lies between the diffusion region and the underfed jet curtain. It extends over most of the base and is considered to be a fully developed viscous channel flow.

A sketch of the diffusion region is shown in Fig. 3. The boundaries of this region coincide roughly with the cross-flow vena contracta and the lower-surface reattachment point. Flow-visualization studies (e.g., Ref. 4) have indicated that the chordwise extent of the diffusion region is on the order of two to three times the cushion ground clearance. Diffusion of the overfed jet in this region is believed to account for much of the nonuniformity in cushion pressure which has been observed when peripheral jets are in an unbalanced condition; either in hover or at speed.[4, 7, 12]

It is recognized that turbulent diffusion of the overfed jet actually begins at the nozzle exit. The new consideration introduced in this study is that the diffusion process continues until the cross flow reattaches to the lower surface. It is contended that typically the major part of the diffusion takes place after the overfed jet curtain impinges upon the ground. Obviously, this assumption is less valid for very large clearance ground supports (i.e., when diffusion of the jet curtain on the cushion side is at an advanced state prior to ground contact).

The diffusion region is handled by a one-dimensional analysis which gives the diffusion pressure rise explicitly in terms of Q_c. The chordwise extent of the diffusion region and the associated loss of cushion lift are not considered. The analysis is basically that used in elementary treatments of sudden pipe expansions,[13] and simply consists of the application of the horizontal momentum equation to the control volume shown in Fig. 3, wherein viscous forces along the ground and lower surface are not considered. The pressures p_1 and p_2 are assumed to be uniform along the vertical boundaries. The result for the diffusion pressure rise is

$$p_2 - p_1 = \rho(Q_c/h)\{[2(H-p_1)/\rho]^{1/2} - (Q_c/h)\} \quad (5)$$

where the term $[2(H-p_1)/\rho]^{1/2}$ is the velocity of the cross flow at the upstream boundary. If both p_2 and Q_c are known, p_1 is easily found from Eq. (5). A significant cross-flow total-pressure loss accompanies the turbulent diffusion.

The balance of the cross flow is modeled as a fully established channel flow. The details of the theoretical analysis of this region are given in Refs. 3 and 10. They have been omitted here because the pressure change across this region was found to be small in comparison to the diffusion pressure rise for the ground clearances considered.

Solution of the Forward Speed Problem

The effect of forward speed on the lower-surface flow is found by combining the various elements just discussed. The upper-surface flow plays a primary role in determining the pressures which exist in the nose eddy and in the wake at the rear of the support. These regions bound the lower-surface flow elements. The variation of pressure with speed in these regions largely determines the effect of speed on the lower-surface flow conditions. The cushion flow induced by viscous action of the moving ground is a relatively minor effect.

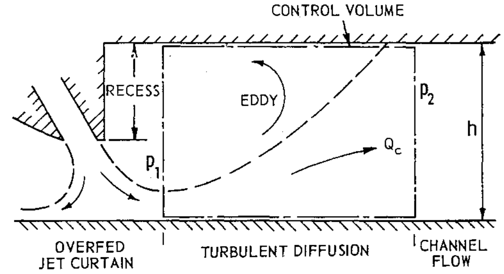

Fig. 3 Diffusion region.

The theoretical prediction of the nose eddy and wake pressures was not attempted in this study. In the theoretical calculations of the lower-surface flow, measured wake pressures and assumed values of the nose-eddy pressure coefficient, C_{p_n}, were used. As an approximation, C_{p_n} is assumed to be zero at low forward speeds and is assumed to be 1.0 at high subcritical speeds. Theoretical calculations of lower-surface-flow conditions were made using both limit values.

When the nose eddy and wake pressures are known, the lower-surface flow can be determined by an iterative process. If a value for Q_c is assumed, the cushion pressure adjacent to the underfed jet can be determined from Eqs. (3) and (4). The pressure change across the channel-flow region can also be determined. These steps establish the pressure just downstream of the diffusion region. Equation (5) is used to find the cushion pressure adjacent to the overfed jet. A new value of Q_c can then be determined from Eqs. (1) and (2). The process is continued until Q_c converges.

Experiment

The experiments were conducted with a two-dimensional airfoil-shaped model which has a working-section aspect ratio of 0.8. The model is symmetric about the mid-cord and has the dimensions indicated in Fig. 4. Pitot probes upstream of the peripheral-jet nozzles are used to measure the jet-curtain total pressures. The peripheral-jet nozzles have a 10° convergence and an average inward inclination of 30°.

The peripheral-jet air is brought into the model via ducts at either end so as not to disturb the two-dimensional flow over the center. A number of internal vanes and screens are incorporated to achieve uniform jet-curtain conditions across the span. A feature of the model is that each jet curtain is fed independently; thus it was possible to establish different ratios of front-to-rear supply pressure, and measure (with orifice meters) the flow rate of each jet curtain.

The tests were run in the Rensselaer Polytechnic Institute 4-ft by 6-ft moving-ground wind tunnel.[14] The model was mounted rigidly between channel boards. Forces were determined indirectly by integration of measured surface-pressure distributions.

Results

The support-system performance parameters considered here, both in hover and at forward speed, are lift and air-supply pumping power. Lift is composed of two components, the upper-surface lift which accounts for the external pressure distribution everywhere outside the jet curtains, and the lower-surface lift, l, which includes the reaction lift associated with the jet curtains. (Reaction lift was roughly 5% to 10% of the lower-surface lift both in hover and at speed over the range of test conditions in this study.) The lower-surface lift is expressed in terms of an effective cushion pressure, p_l, defined by

$$p_l = l/d \tag{6}$$

In characterizing performance, p_l can be considered a function of the weight and size of the craft. When the upper-surface lift is neglected, p_l is a constant independent of ground clearance and speed. The ideal lift power, $H_fQ_{jf} + H_rQ_{jr}$, is nondimensionalized using p_l. When $H_f = H_r = H$ the nondimensional power is defined by

$$P = \{(Q_{jf} + Q_{jr})/[2(2p_l/\rho)^{1/2}t]\}/(p_l/H) \tag{7}$$

The interrelation between lift, pumping power, and air-supply flow such that only two are independent is evident from Eq. (7).

Unbalanced Hover

Cushion pressure distributions for a series of unbalanced hover tests at $h/t = 3.38$ are shown in Fig. 5. The unbalanced conditions were established by testing at various front-to-rear-jet supply-pressure ratios. The pressures in the external regions bordering the jet-curtain flows are ambient. Since the theory does not attempt to account for the chordwise extent of the diffusion process, the lengths shown for the theoretical curves have been kept to a minimum consistent with a clear presentation. A major feature of Fig. 5 is the diffusion region. The magnitude of the diffusion pressure rise is predicted quite well by theory. For the most unbalanced case, the cushion pressures in the diffusion region are seen to be less than ambient. Cushion pressure is essentially uniform for the balanced case in Fig. 5.

More extensive results for the cushion pressures in unbalanced jet-curtain operation are shown in Fig. 6. The cushion pressure, p_c, and cushion flow rate, Q_c, are nondimensionalized by the corresponding supply pressure, H, and jet-curtain flow rate, Q_j. In the overfed region, two curves are shown for each ground clearance. They reflect the pressures before and after the diffusion process. Since Q_c was not directly measured, the experimental results for p_c/H, in the overfed region, are plotted versus the theoretical estimate for Q_c/Q_j. The quantity Q_c/Q_j, in the underfed region, is determined by multiplying the overfed result by the measured ratio of jet-curtain flow rates. The associated inaccuracy of the experimental curves is considered small because of the good agreement between theory and experiment seen in Fig. 6.

At the largest ground clearance tested ($h/t = 5.91$), Fig. 6 also shows the predicted cushion pressure levels based upon a viscous-flow theory.[11] This theory does not consider the diffusion pressure rise associated with overfed jets. For the balanced and underfed cases, the viscous theory is more accurate than the present theory at large ground clearances.

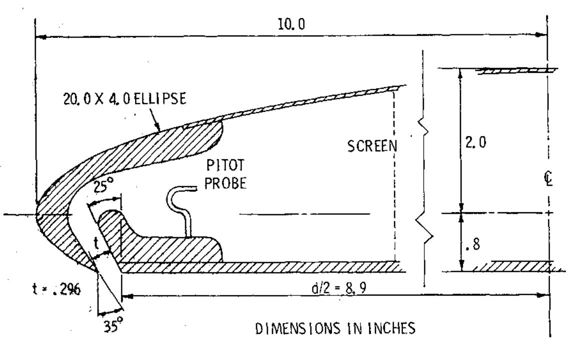

Fig. 4 Model geometry.

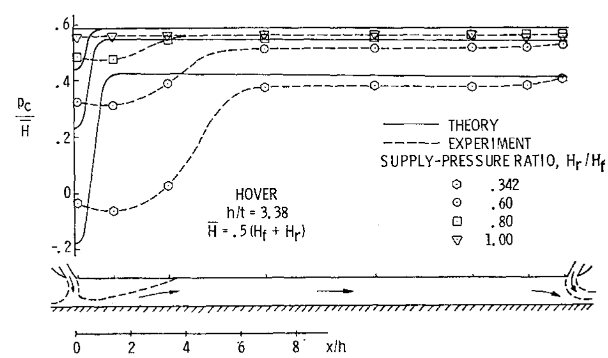

Fig. 5 Cushion pressure distributions for unbalanced hover.

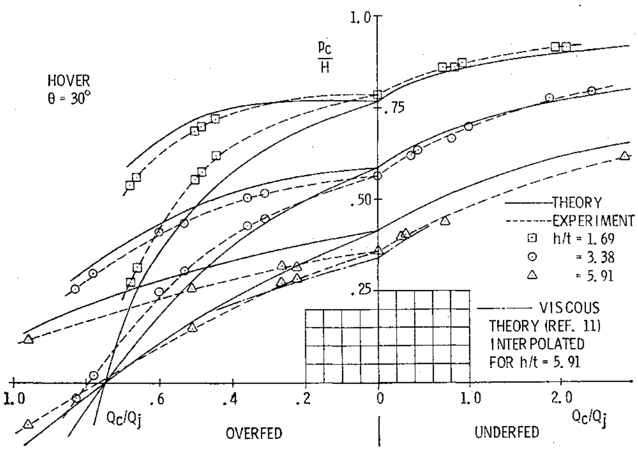

Fig. 6 Variation of cushion pressure with cushion flow for an unbalanced jet.

Because of the uncertainties associated with the diffusion region, the viscous theory is less accurate in the overfed case.

The jet-curtain flow rate Q_j as a function of the cushion pressure adjacent to the jet curtain is shown in Fig. 7. The theoretical curve is generated from the nozzle-exit-flow theory noted earlier. The experimental points are for several ground clearances and for both overfed and underfed-jet conditions. The points where p_c/H is negative are points where subambient pressures in the diffusion region occurred. The fact that all experimental data falls on one curve supports the assumption that ground-boundary effects on the nozzle-exit flow are negligible for the clearance range considered. The theoretical overestimation of the flow rate for low cushion pressures is a direct result of neglecting the nozzle boundary layer and the nozzle convergence. At large p_c/H, the theoretical underestimation of flow is believed related to an inaccurate estimate of the point within the nozzle at which flow separation occurs. It is important to note that the applicability of this figure (as well as Fig. 6) can be extended to forward speed by regarding both p_c and H as being referenced to the pressure in the external region rather than referenced to ambient.

Forward Speed

The forward-speed results to be presented here are limited to the case where the front and rear supply pressures are equal (i.e., $H_f = H_r = H$). Additional results for unequal supply pressures and for nonzero pitch attitudes can be found in Ref. 3. Since forward-speed performance is largely

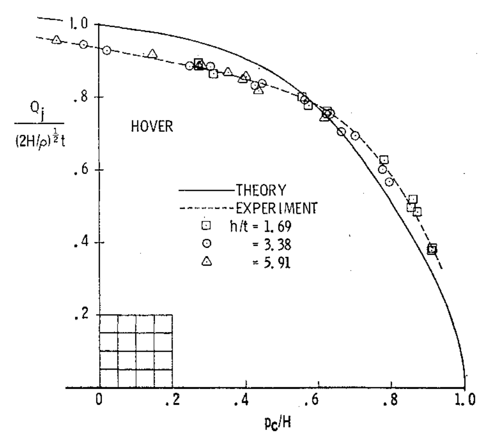

Fig. 7 Variation of jet-curtain flow with cushion pressure.

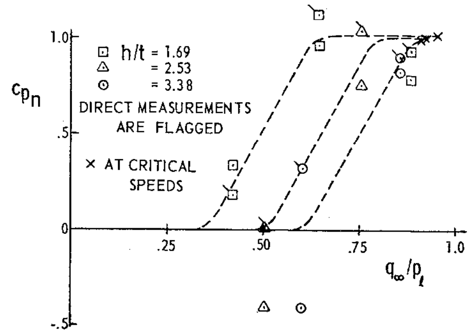

Fig. 8 Effect of forward speed on C_{p_n}.

dependent on the nose eddy and wake pressures which develop, results for these pressures are presented first.

The variation of C_{p_n} with forward speed is shown in Fig. 8. The data points are based on two independent experimental measurements. The flagged symbols are from direct measurements of the surface pressure on the model midway between the nose and the front jet curtain. Measurements of the cushion pressure before and after the diffusion process, when used with Fig. 6, provide the second estimate of C_{p_n}. As discussed in Ref. 3, neither method is very satisfactory since considerable uncertainty is associated with each. Nevertheless, there is some degree of correlation between the two different sets of measurements. The results indicate that for the present model C_{p_n} is near zero at low forward speeds, and after a somewhat abrupt transition C_{p_n} is approximately 1.0 at and near critical speeds.

For the theoretical calculations, the wake pressure was equated to that measured for the given speed and ground clearance. Wake pressure coefficients averaged about −0.2. Further details are given in Ref. 3.

Figure 9 shows theoretical results for the ratio of cushion-to-front-jet-curtain flow rate as a function of speed. The broken curves show the calculated values corresponding to nose-eddy pressure coefficients of 0.0 and 1.0. The single composite theoretical curve for each ground clearance is constructed by fairing the $C_{p_n} = 0.0$ and $C_{p_n} = 1.0$ characteristics together. Figure 8 is used to locate the transition between the two limiting curves. The points at which Q_c/Q_{jf} is equal to 1.0 establishes critical forward speeds. A direct experimental determination of critical speeds (e.g., by flow visualization) was not attempted.

The variation of q_∞/H with the speed parameter q_∞/p_l is shown in Fig. 10. Reasonably good agreement exists between theory and experiment. The linearity between q_∞/H and q_∞/p_l reflects the fact that p_l/H is not a strong function of forward speed. Because the theory does not account for the lift loss associated with lower cushion pressures in the diffusion region, the theoretical prediction of critical speeds in terms of the parameter q_∞/H are considered more accurate than those in terms of q_∞/p_l. Critical-speed points for the experimental curves (including Fig. 8) were determined from

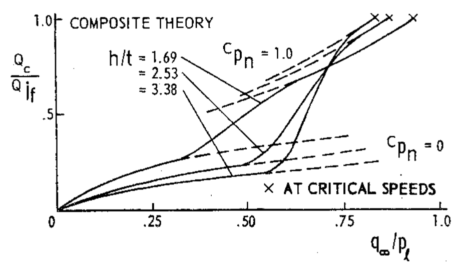

Fig. 9 Cushion flow induced by forward speed.

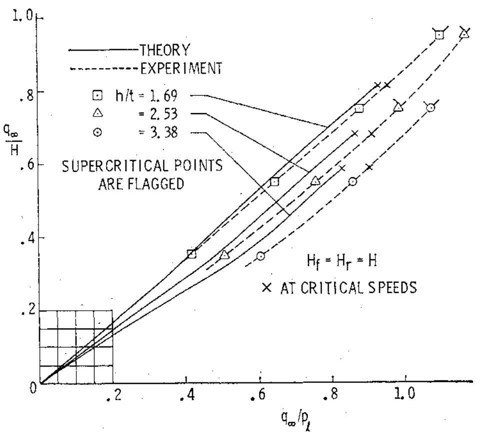

Fig. 10 Relation between q_∞/H and the speed parameter q_∞/p_l.

Fig. 10 with the assumption that the critical value of q_∞/H, as determined from theory, may be accurately applied to the experiments.

Figure 10 indicates that critical speeds for the conditions considered occur when the ratio q_∞/p_l is less than 1.0. More detailed results, not presented here, show that q_∞ at critical speeds was even less than the average cushion pressure. This result is in conflict with earlier theories (e.g., Ref. 15) which do not consider nonuniformities in cushion pressure. The low critical speeds are due in part to the flat-bottom design used in the present study. If the cushion is recessed, higher critical speeds, where q_∞ is greater than p_c, can be expected.

Cushion-pressure distributions at different forward speeds for $h/t = 3.38$ are shown in Fig. 11. The theoretical curves for the low and high subcritical speeds correspond, respectively, to values of 0.0 and 1.0 for C_{p_n}. General agreement between theory and experiment occurs. The fact that the theory predicts slightly higher cushion pressures than measured, both in hover and at speed, is due in part to viscous phenomena as noted earlier. The lift loss associated with lower pressures in the diffusion region can be seen to be relatively small in comparison to the total cushion lift. In the channel-flow region, a slight pressure rise in both the theoretical and experimental results can be seen. This is associated with the friction-pump effect of the moving ground. The experimental supercritical pressure distribution does not differ qualitatively from those at subcritical speeds.

The effect of forward speed on lower-surface lift is summarized in Fig. 12. The results are referenced to the conditions at hover. The curves show the variation of lift with speed for constant supply pressure. Alternatively, this figure gives the supply pressure required to maintain ground clearance in the absence of upper-surface lift.

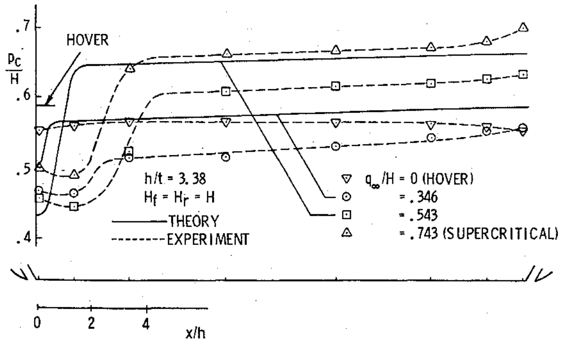

Fig. 11 Cushion pressure distributions at forward speed.

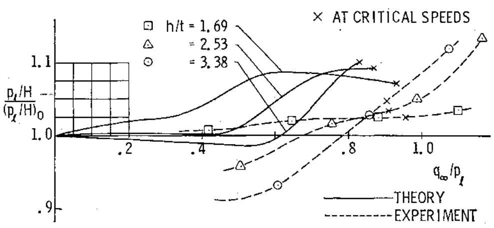

Fig. 12 Effect of speed on lift.

Figure 13 shows the effect of speed on ideal lift power required to maintain ground clearance. Ram pressure recovery and the power required for momentum drag are not taken into account. The experimental results for P are obtained from the measured jet-curtain flow rates and Eq. (7). It may be seen that the initial effect of speed is adverse. However, as critical speeds are approached, the lift power required to maintain clearance is 20–30% less than it is at hover.

Conclusions

The effect of forward speed on the performance of a peripheral-jet ground support has been analyzed by subdividing the flow into elements, each of which is handled by a relatively simple analysis. Experimental measurements tend to confirm the validity of each of the individual elements, as well as to corroborate a proposed theory based on their combination. In the absence of the contribution to lift by the upper surface, forward-speed performance was found to deteriorate at low speeds. At higher speeds performance improved, so that at critical speeds substantially less pumping power was required than at hover.

Some details were not considered in the theory and these represent areas in which further work should be undertaken. The most important aspect not considered was an analytical treatment of the nose region; in particular, a prediction of an effective nose-eddy pressure coefficient is needed. The experimental measurements indicate that the assumption $C_{p_n} = 1.0$ (Ref. 5) can not be applied at low sub-critical speeds. A theoretical analysis of the nose region has been made by Hsu[16] but it is not in quantitative agreement with results found here. It is clear that both nose shape, ground clearance, and possibly the additional efflux of peripheral-jet air at the nose if the front jet is overfed, are major factors which influence the nose pressure. It should also be noted that the more extensive results of Ref. 3 indicate the possibility of nose-eddy pressure coefficients appreciably less than zero under certain conditions.

Another detail not considered is the chordwise extent of the diffusion process. In the diffusion region, the streamwise pressure gradient will play a role in determining the diffusion process as well as being a product of it.

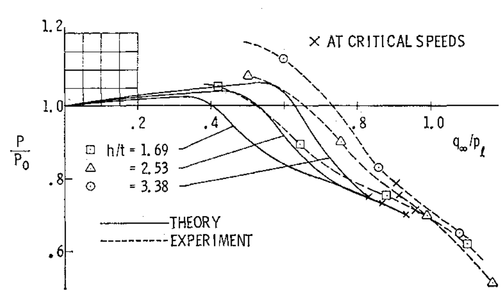

Fig. 13 Effect of speed on lift power.

The analysis of the unbalanced jet-curtain flows can be improved with better estimates of flow separation within the nozzle and by taking into account entrainment and ground boundary-layer effects. The basic considerations with respect to the latter have been given in Ref. 11.

Two-dimensional balanced peripheral-jet theories have been found applicable to three-dimensional supports when the planform radius of curvature is large compared to the ground clearance of the support (this is typically the case). The implication is that the assumption of local two-dimensional flow is reasonable under these conditions. Because of this, the present unbalanced jet-curtain theory including the diffusion model should also be applicable to three-dimensional supports. At subcritical speeds the external flow differs appreciably between two and three dimensions. With a blunt nose however, the freestream will still stagnate ahead of the front jet curtain at critical speeds and the cushion flow should be qualitatively the same. Thus, the relation between critical speed and cushion pressure is expected to be approximately the same for a three-dimensional support as was determined here for a two-dimensional support.

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