CHARACTERISTICS OF A RECTANGULAR WING
WITH A PERIPHERAL JET IN GROUND EFFECT

PART I

by

Karl Dau
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SUMMARY

Lift, drag, and pitching moment were measured on a rectangular wing with a peripheral jet in ground effect for various angles of attack and forward speeds at two heights above the ground. Low-pressure air was used for the peripheral jet for reasons of similitude. Efforts were made to make the jet velocity as uniform as possible along the peripheral slot. In addition to force measurements on the wing, flow-visualization tests on the ground board were also carried out in the wind tunnel.

The results show that there exist two flight regimes for the wing. At low forward speeds the wing behaves essentially like a hovering platform. As forward speed increases a gradually increasing part of the leading-edge jet is blown back so that the wing behaves like a jet flap at high forward speeds. The transition from one flight regime to the other is gradual rather than abrupt owing to the three-dimensional character of the wing. The results also show that a considerable fraction of the jet momentum flux is recovered as thrust at negative angles of attack and low forward speeds. The wing was also found to be statically unstable about the midchord for all angles of attack, forward speeds, and the two (small) heights above ground which were tested.
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### NOTATION

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<tr>
<th>Symbol</th>
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<tr>
<td>$A_i$</td>
<td>Area of air inlet on wing</td>
</tr>
<tr>
<td>$A_j$</td>
<td>Area of peripheral slot</td>
</tr>
<tr>
<td>$AL$</td>
<td>Lift augmentation, $\frac{L}{J}$</td>
</tr>
<tr>
<td>$AT$</td>
<td>Thrust augmentation, $\frac{F}{J \sin \alpha}$</td>
</tr>
<tr>
<td>$c$</td>
<td>Chord length</td>
</tr>
<tr>
<td>$C^*_L$</td>
<td>Modified lift coefficient, $\frac{L}{qS + J}$</td>
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<td>$C^*_D$</td>
<td>Modified drag coefficient, $\frac{D}{qS + J}$</td>
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<tr>
<td>$C^*_{Mc}$</td>
<td>Modified pitching moment coefficient, $\frac{M_c}{(qS + J)C}$</td>
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<td>$C^*_N$</td>
<td>Modified normal-force coefficient, $\frac{N}{qS + J}$</td>
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<tr>
<td>$C_J$</td>
<td>Blowing coefficient, $\frac{J}{qS}$</td>
</tr>
<tr>
<td>$D$</td>
<td>Drag</td>
</tr>
<tr>
<td>$h$</td>
<td>Height of wing above ground</td>
</tr>
<tr>
<td>$h_{cp}$</td>
<td>Dimensionless centre of pressure, measured from L.E.</td>
</tr>
<tr>
<td>$h_n$</td>
<td>Dimensionless neutral point, measured from L.E.</td>
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<tr>
<td>$H_h$</td>
<td>Horizontal reaction of struts on wing</td>
</tr>
<tr>
<td>$H_V$</td>
<td>Vertical reaction of struts on wing</td>
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<tr>
<td>$j$</td>
<td>Jet momentum flux per unit slot length</td>
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<td>$J_i$</td>
<td>Jet momentum flux through air inlet</td>
</tr>
<tr>
<td>$J^1_l$</td>
<td>$\int_{A_l} \rho \nu_i^2 dA$</td>
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<td>Jet momentum flux through peripheral slot</td>
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<tr>
<td>$k$</td>
<td>Calibration factor, $\frac{q_i}{q_{ic}}$</td>
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(iv)

Length of sting

Total lift,

\[ L' + \sum_j \left( \frac{A_i}{A_i} \right) \]

Lift as measured by balance

Pitching moment about midchord

Jet mass flow

Force normal to wing

Static pressure at end of ejector mixing tube

Static pressure at air-supply-tube exit

Average static pressure at air-supply-tube exit

Total pressure at centre of air-supply-tube exit

Reaction of support strut on sting

Dynamic pressure of tunnel flow

Dynamic pressure at air inlet

Average dynamic pressure at air inlet, \[ \sum_i \left( \frac{A_i}{A_i} \right) \]

Dynamic pressure at centre of air inlet

Dynamic pressure at the peripheral slot

Average dynamic pressure at the peripheral slot, \[ \sum_j \left( \frac{A_j}{A_j} \right) \]

Distance of pressure probe from centre of air-supply-tube exit

Distance between centre and wall of air-supply-tube exit

Distance along peripheral slot

Wing area

Slot width

Thrust
\( V \)  \hspace{1cm} \text{Forward speed}

\( v_i \)  \hspace{1cm} \text{Velocity at air inlet}

\( v'_i \)  \hspace{1cm} \text{Deviation from average velocity at air inlet}

\( v_j \)  \hspace{1cm} \text{Jet velocity}

\( v'_j \)  \hspace{1cm} \text{Deviation from average jet velocity}

\( z \)  \hspace{1cm} \text{Distance from pivot point to mean line of wing profile}

\( \alpha \)  \hspace{1cm} \text{Angle of attack}

\( \rho \)  \hspace{1cm} \text{Air mass-density}

\( \tau \)  \hspace{1cm} \text{Distance from inboard side of jet slot to pressure probe}
1. INTRODUCTION

Although a large part of the research effort in the field of ground effect phenomena is being applied to vehicles that are designed to stay close to the ground when in use, interest is also being shown in the idea of using the ground effect on aircraft, i.e. as a substitute for the undercarriage of an otherwise conventional aircraft. The wings of such an aircraft would be equipped with a peripheral jet, which would be used to create an air cushion only during take-off and landing. In cruising flight lift would be generated by the wings in the conventional way. Thrust would be furnished either by the trailing-edge jet directed backwards or by a separate propulsion unit. Efforts are being made to investigate the feasibility of this idea; and the experiments described in this report are part of this effort.

Specifically, the object of these experiments was to determine the lift, drag, and pitching moment characteristics of a rectangular wing equipped with a peripheral jet for various heights above ground, forward speeds, and angles of attack. In view of the fact that the wing would have to be efficient also in cruising flight remote from the ground, a planform with an aspect ratio of four was chosen rather than, say, a circular planform which would be more suitable for a conventional GEM.

The aerodynamic forces and moments, as presented in this report, do not include the forces associated with the air intake.
II. DESCRIPTION OF APPARATUS

2.1 Wind Tunnel and Balance

The principal experiments on the wing were carried out in the UTIA subsonic wind tunnel, shown in Fig. 1. The wind tunnel is of the closed-throat, single return type with an octagonal test section measuring 48 x 32 in. in the principal directions. The fan is driven by a 60 hp electric motor, which can bring the air speed in the test section up to about 200 fps.

The aerodynamic forces on the wing were measured on a six-component balance of UTIA design. The forces are transmitted to leaf springs, whose deflections are converted by differential transformers into voltage signals. An electrical null-method is used to read force measurements, i.e. the voltage signal corresponding to the force is balanced out manually by a displacement on a balancing transducer. This displacement, mechanically amplified and multiplied by a calibration factor, constitutes the force reading.

2.2 Wing

Figure 2 shows the wing on the preliminary test stand in the normal testing position, i.e. with its bottom surface up. Figures 3 and 4 show additional details of the wing and of its installation in the wind tunnel. The dimensions are as follows:

- Planform: Rectangular
- Span: 25 in.
- Aspect Ratio: 4.17
- Chord: 6 in.
- Profile: NACA 0015
- Length of either L.E. or T.E. slot: 24.5 in.
- Length of either tip slot: 5.69 in.
- Width of either L.E. or T.E. slot: 0.093 in.
- Width of either tip slot: 0.082 in.

All portions of the peripheral jet can be adjusted for width, whereas the direction of the jet can be changed at the L.E. and T.E. slots only. In all tests, however, the direction of the peripheral jet was kept perpendicular to the plane of the wing.

The wing is mounted upside down in the wind tunnel on two main struts and a tail strut extending through the tunnel floor to the balance underneath. The angle of attack of the wing can be changed by lowering or raising the tail strut.
2.3 Jet Air Supply

Low-pressure high speed air from an ejector (Ref. 1) is ducted through the central air-supply tube into the hollow wing, and is blown out through the peripheral slot. The air-supply tube is bolted to the tunnel floor and connected to the wing air inlet by an annular mercury seal, shown in Fig. 3. The mercury seal prevents transmission of forces between the wing and the air-supply tube, and allows relative movement between the two. Heavy oil floated on top of the mercury, and slotted seals of soft rubber installed on both sides of the mercury cup prevent the mercury from becoming entrained in either the internal or external air flow. Furthermore, an automatic safety device prevents the mercury seal from blowing out in case of over-pressurization by actuating a relief valve in the air supply line.

For reasons of similitude a low-pressure air supply with high mass flow rather than a high-pressure low-speed air supply for the peripheral jet was chosen. High-pressure supply air would have given rise to an overchoked peripheral jet and sonic exit velocities, whereas the air supply used produced jet exit speeds of the same order of magnitude as the maximum relative speed of the wing. Thus the flow around the wing is aerodynamically similar to that around a full-scale wing.

The high mass flow of low-pressure air was produced by an ejector utilizing the high-pressure laboratory air. The design of the ejector is described in Ref. 1.

The ground is simulated by a 44 in. x 32 in. plywood ground board suspended from the ceiling of the test section by four partly faired steel rods. It can be raised and lowered by a screw mechanism. The leading edge of the ground board has the shape of the front portion of an NACA 0020 airfoil.

III. EXPERIMENTAL PROCEDURE

3.1 Momentum Flux Along the Peripheral Jet

It was felt that the variation of the momentum flux per unit slot length, $j$, along the peripheral jet had a considerable effect on the behavior of the wing. Hence, efforts were made, firstly, to measure $j$, and secondly, to make it as constant as possible along the periphery.

For this purpose the wing was mounted on the preliminary test stand as shown in Fig. 2. Air from the ejector was ducted into the wing and exhausted through the peripheral jet into the atmosphere with the ground board removed. First the angle $\phi$ between the jet velocity vector and a chordwise plane perpendicular to the wing planform was measured at a number of points on the peripheral jet with a cylindrical
three-hole yaw probe. This test revealed an appreciable variation of $\phi$ with distance along the slot, which is shown in Fig. 5. No attempt was made to change this distribution.

Next, the maximum total head within a given plane across the peripheral jet was measured with a flat total-head probe at various positions along the peripheral jet. Care was taken to align the probe with the jet stream. A number of these traverses were made, one of which is shown in Fig. 6. This traverse was made for the wing as manufactured, i.e. possessing all its internal struts and having no internal screens. Figure 6 indicates that $j$ was far from constant along the peripheral jet.

To find the reason for this large variation in $j$ a flow-visualization study was made of the air flow inside the wing. The inside wing surfaces were painted with a mixture of kerosene and lampblack and the jet air was turned on. A sample of the resulting streak patterns is shown in Fig. 7. They showed the existence of large wakes behind the internal stiffening posts. Hence a third of these were removed. In addition to this, the following changes were made:

1) A 32 x 32 in$^{-1}$ mesh wire screen running the full span of the wing was installed across both L.E. and T.E. slots in the position shown in Fig. 4.

2) The remaining stiffening posts were faired.

After these changes were made a total-head traverse across the width of the slot was made for various positions along the peripheral jet. Representative samples of the dynamic-head profiles so obtained are shown in Fig. 8 in non-dimensional form. There were 36 in all.

The dynamic-head readings in the peripheral jet were made non-dimensional by dividing them by $p_e$, the static pressure at the end of the ejector mixing tube. Figure 9 shows that for some given point in the peripheral jet the dynamic pressure $q_j$ at that point, divided by $p_e$, remained practically constant within the range of experimental $p_e$. Hence any errors in $q_j$, resulting from fluctuations in $p_e$, were eliminated by dividing $q_j$ by $p_e$.

The local value of $j$ was found from graphical integration of the peripheral-jet profiles and plotted in non-dimensional form against spanwise distance. To eliminate the peaks in $j$ still present at some points the local slot width at those points was decreased by fairings on the slot sides. Furthermore, the width of the spanwise slots was reduced from about 0.12 in. to the values shown in Sect. 2.2. A final check of the maximum total-head variation along the peripheral jet was made when the wing had been installed in the wind tunnel. The final $j$-distribution is shown on Fig. 10.
3.2 Measurements at the Air Inlet to the Wing

Before wind tunnel testing could be started, the problem of measuring the momentum flow from the peripheral jet under the various test conditions had to be solved. This could not be done directly at the slot owing to instrumentation difficulties. It was therefore decided to calculate the jet momentum flow from measurements at the air inlet to the wing. Moreover, knowledge of the momentum flow and the static pressure at the inlet was required to eliminate their contribution to the aerodynamic forces on the wing. These considerations made measurements of the inlet flow quantities necessary.

For this purpose five static pressure probes were installed at the exit of the central air supply tube, four at the walls and one in the centre of the tube. The pressures at these points were measured when air was supplied to the peripheral slot, and found to vary not more than 4% from the average pressure. Hence the static pressure was assumed to be constant across the air tube exit.

The total-head distribution across the air tube exit was found by traversing the exit with a pitot-tube in several directions. Since the air-tube exit was inaccessible to the traversing probe with the wing in place, all traverses were made with the wing removed. To check whether the presence of the wing had any effect on the total-head distribution across the air-tube exit, the ground board was lowered into the position which the bottom surface of the wing normally occupied, and two traverses were repeated. Figures 11 and 12 show the results of these two traverses, together with the results from the traverses for which the ground board was removed. It can be seen in Fig. 12, for example, that the areas under the two curves are approximately equal, indicating that the removal of the wing for traversing purposes did not introduce an appreciable error in measurement. The results of the two remaining traverses are shown in Figs. 13 and 14. After completion of the traverses the central static-pressure probe was replaced by a total-pressure probe.

3.3 Wind Tunnel Tests

After the preliminary experiments described above the wing was mounted in the wind tunnel. Lift, drag, and pitching moment on the wing were then measured for various angles of attack, forward speeds, and two heights above ground. The following quantities were recorded:

\[ L', \text{ the lift measured by the balance,} \]
\[ H_h, \text{ the horizontal reaction at the main strut hinges,} \]
\[ P, \text{ the vertical tail-strut reaction at the sting,} \]
\[ \alpha, \text{ the angle of attack,} \]
\[ q, \text{ the forward-speed dynamic pressure,} \]
\[ h, \text{ the height above ground, as defined in Fig. 15,} \]
Pt, the total pressure at the centre of the air-tube exit,
Pw, the static pressure at the wall of the air-tube exit,
Pe, the static pressure at the end of the ejector mixing tube.

The jet mass flow was kept more or less constant for all tests except for high forward speeds where it was lowered to obtain a higher value of q/qj. All pressures were read by photographing a multiple manometer board, and reading the negatives on an optical comparator.

3.4 Flow Visualization Tests

In addition to the force measurements on the wing flow visualization tests were carried out on the ground board. The ground board was painted with a mixture of kerosene and lampblack, and both the tunnel and the peripheral jet were turned on. The resulting streak patterns were photographed and are displayed in Figs. 38 to 48.

IV. REDUCTION OF DATA

4.1 Lift, Drag, and Pitching Moment Coefficients

In converting the aerodynamic forces on the wing to non-dimensional coefficients the question arises: "What denominator would be the most meaningful one?". On one hand, the parameter J, the jet momentum, which is used for hovering vehicles, does not take into account the effect of forward speed on the behavior of the wing. On the other hand, the parameter qS would make the coefficients infinite at zero forward speed. Since both of these parameters play an important role in the aerodynamics of the wing under study, it was decided to use

\[ qS + J \]

as the non-dimensionalizing denominator. At zero forward speed the lift coefficient becomes the familiar lift augmentation factor \( A_L \). For high speeds all coefficients approach the value of the conventional coefficients \( C_L, C_D, \) and \( C_M \). The newly-defined coefficients are denoted by an asterisk to distinguish them from the former, and are thus:

\[
C_L^* = \frac{L}{qS + Jj} \\
C_D^* = \frac{D}{qS + Jj} \\
C_{M_{\parallel}}^* = \frac{M_{\parallel}}{(qS + Jj)c}
\]
4.2 Aerodynamic Forces

4.2.1 Lift

Figure 16 shows a free-body diagram of the wing. The aerodynamic forces on the wing are resolved into lift $L'$, drag $D$, and a pitching moment $M_{c/2}$ about the midchord. Also shown are the reactions of the supports on the wing, i.e. $H_V$, $H_h$, and $P$. By the law of statics,

$$L' = H_V - P$$

$L'$ is the lift for a wing with an inlet at the top wing surface, like the wing considered here. To eliminate the inlet forces, the inlet momentum and pressure contributions have to be added to the lift $L'$, i.e.

$$L = L' + J_i + \bar{p_i}A_i$$

or

$$L = H_V - P + J_i + \bar{p_i}A_i$$

(1)

4.2.2 Drag

Taking the sum of the horizontal forces from Fig. 16, we obtain

$$D = H_h$$

4.2.3 Pitching Moment

Taking moments about the midchord, we have from Fig. 16

$$M_{c/2}' - P(l \cos \alpha + z \sin \alpha) - H_h z \cos \alpha + H_v z \sin \alpha = 0$$

or

$$M_{c/2}' = Pl \cos \alpha + Pz \sin \alpha + Dz \cos \alpha - H_v z \sin \alpha$$

= Moment including the effects of the air inlet

The correction to the moment to allow for the inlet momentum flux is

$$\Delta M_{c/2} = -z \sin \alpha \cdot (J_i + \bar{p_i}A_i)$$

so that

$$M_{c/2} = M_{c/2}' + \Delta M_{c/2} = Pl \cos \alpha + Pz \sin \alpha + Dz \cos \alpha - (H_v + J_i + \bar{p_i}A_i) z \sin \alpha$$

(2)

= Moment corrected for effects of the air inlet
From Eq. 1

\[ H_v = L + P - (J_i + \bar{p}_i A_i) \tag{3} \]

Substituting Eq. 3 into Eq. 2 we get

\[ M_x = P \cos \alpha + Pz \sin \alpha + Dz \cos \alpha \]

\[ - [L + P - (J_i + \bar{p}_i A_i) + J_i + \bar{p}_i A_i] z \sin \alpha \]

or

\[ M_x = P \cos \alpha + Dz \cos \alpha - Lz \sin \alpha \]

\( H_v, H_h, \) and \( P \) were obtained from the balance measurements. \( J_i \) and \( \bar{p}_i \) were calculated from pressure measurements at the inlet as outlined below.

4.3 Inlet Momentum and Pressure

The inlet static pressure was assumed to be uniform across the air tube exit, its value being the average of the four static pressures at the wall (see Section 3.2).

The inlet momentum was calculated by multiplying the dynamic-head reading of the centre probe in the air-tube exit by an experimentally determined calibration factor \( k \). This yields the average dynamic pressure over the air tube exit, i.e.

\[ \bar{q}_i = k q_{ic} \]

But

\[ J_i = 2 \bar{q}_i A_i = 2 k q_{ic} A_i \tag{4} \]

where

\[ \bar{q}_i = \int_{A_i} q_i \frac{dA}{A_i} \]

Now \( \bar{q}_i/p_e \) was determined by graphical integration of \( q_i/p_e \) over the tube exit area, and was found to be 1.19. The corresponding value of \( q_{ic}/p_e \) was 1.04. Therefore

\[ k = \frac{\bar{q}_i}{q_{ic}} = \frac{\bar{q}_i/p_e}{q_{ic}/p_e} = \frac{1.19}{1.04} = 1.14 \]

Substituting this value of \( k \) into Eq. 4, we obtain

\[ J_i = 2.28 q_{ic} A_i \]
4.4 Jet Momentum Flux

The jet momentum flux was calculated from the inlet momentum flux by applying the law of continuity between the air inlet and the peripheral slot. It was assumed that

\[ \rho_i = \rho_j = \rho = \text{constant} \]

over both inlet and slot area, since the Mach numbers

\[ M_i \approx M_j < 0.2 \]

With this assumption the resulting relationship between \( J_j \) and \( J_i \) is

\[ J_j = J_i \frac{1 - \frac{J_i'}{J_j'}}{1 - \frac{J_i'}{J_j}} \frac{A_i}{A_j} \]  \hspace{1cm} (5)

where

\[ J_i' = \int_{A_i} \rho v_i'^2 \, dA \]

\[ J_j' = \int_{A_j} \rho v_j'^2 \, dA \]

and

\[ v' = v - \bar{v} \]

Equation 5 is derived in detail in Appendix I. Equation 5 shows that \( J_j' \) and \( J_i' \) must be known in order that \( J_j \) may be calculated. Expressed in terms of experimentally measured quantities, \( J_i' \) becomes (see Appendix I)

\[ J_i' = 2 \int_{A_i} \left[ \sqrt{q_i} - \sqrt{q_i} \frac{dA}{A_i} \right]^2 \, dA \]  \hspace{1cm} (6)

The term \( J_i'/p_e \) was determined from Eq. 6 by graphical integration of the results from the air-tube-exit traverse, and was found to be 1.32 in.². The corresponding value for \( J_i'/p_e \) was 16.3 in.². Therefore

\[ \frac{J_i'}{J_i} = \frac{1.32}{16.3} = 0.08 \]
Jf'/\rho_e is a constant for a given jet slot area. On the other hand, Jf'/\rho_e varies with angle of attack, forward speed, and height above ground, since these variables change the shape of the dynamic-head profile of the peripheral jet appreciably. As a traverse across the peripheral jet was made for only one case, Jf' could only be estimated. The estimate was based on a representative dynamic-head profile from the traverse of the peripheral jet (see Fig. 8), and resulted in a value of Jf'/J of 14%. Another estimate of Jf'/J based on a fictitious triangular profile yielded a value of 11% for Jf'/J. Assuming an average value of

$$\frac{Jf'}{J} = 0.14$$

we have from Eq. 5

$$Jf = Ji \cdot \frac{1 - 0.08}{1 - 0.14} \cdot \frac{6.79}{5.50}$$

or

$$Jf = 1.32 \times Ji$$

V. DISCUSSION

5.1 Variation of Aerodynamic Coefficients with Forward Speed

It has been shown (Ref. 3 and 6) that there exist two flight regimes for a GEM in forward flight. At low forward speeds the GEM behaves essentially like a hovering platform. As forward speed increases the L.E. jet is blown back at a more or less well-defined forward speed, and beyond this speed the GEM behaves like a jet-flapped wing. In this flight regime the conventional lift coefficient CL would be a linear function of \( \sqrt{C_f} \).

Experimental evidence indicates that the UTIA wing behaves in a somewhat similar way. It can be seen in Fig. 17, for example, that C_L exhibits an essentially linear variation with \( \sqrt{C_f} \) for \( \sqrt{C_f} < 0.4 \) or \( q/q_j > 0.23 \), indicating that in this range the wing behaves like a jet-flapped wing. Evidence of a transition can also be found in the variation of the centre of pressure with forward speed, as shown in Fig. 32, where hcp exhibits a maximum at \( q/q_j = 0.15 \) to 0.2.

On the whole, however, the transition between flight regimes, if any, is not very pronounced. Examination of Figs. 18 to 29 shows that C_L, C_D, and C_Mc/2 vary smoothly rather than abruptly over the whole forward-speed range, except perhaps at high angles of attack. This contrasts with the results obtained by Poisson-Quinton (Ref. 3) from the study of a two-dimensional GEM. The transition speed is rather well defined for this GEM, as shown by the break in the graph of AL vs. q/q_j plotted in Fig. 51. The plots for the UTIA wing, on the other hand, do not show such abrupt variations.
The reason for the smoothness of transition in the case of the UTIA wing lies evidently in the three-dimensional character of the flow, and specifically, in the behavior of the L.E. jet, as illustrated by the ground board streak patterns in Fig. 38 to 43. They show that the centre part of the L.E. jet yields first at a value of \( \frac{q}{q_j} \) between 0.28 and 0.42. This centre part broadens with increasing forward speed, until most of the L.E. jet is blown back.

5.2 Variation of Lift with Height Above Ground

Figure 52 shows the variation of the lift augmentation with height above ground at zero forward speed and zero angle of attack for the UTIA wing and several other GEMs together with a theoretical relationship derived in Appendix II from inviscid thick-jet theory. Besides the values of \( A_L \) for the two heights investigated in this report, other values of \( A_L \), obtained at UTIA by J. M. Davis for the same wing, are also shown. Taking into account the fact that the other GEMs differ in planform (circular for NASA and Princeton) and flow characteristics (two-dimensional for Poisson-Quinton) from the UTIA wing, it can be seen that the agreement between the UTIA results and the other published results is good. The somewhat low values of \( A_L \) of Ref. 3 are due in part to an overestimation of \( J_j \), as stated in Ref. 3.

In contrast to the other data the lift augmentation curve for the UTIA wing does not exhibit a hump, but tends to level off at an h/c of about 0.45. It has been suggested (Ref. 7) that the existence of the hump at h/c = 0.5 is caused by the tendency of the ring vortex under the GEM to converge on itself at this height. Figure 48a shows that the flow under the UTIA wing hovering at h/c = 0.3 is somewhat different from that of a simple ring vortex, which might explain the absence of a hump in the augmentation curve.

All of the experimental values of \( A_L \) plotted in Fig. 52 are lower than those predicted by theory. Viscous losses in the air cushion are mainly responsible for this discrepancy, but part of it can also be traced to air leakage from the air cushion in the case of the UTIA wing. Examination of Fig. 38 shows that the stagnation lines of the peripheral jet, i.e. the lines at which the jet curtain impinges on the ground, do not extend to the four corners of the wing. This indicates that the jet curtain at the corners is separated from the ground by high-pressure air flowing out of the air cushion. The explanation for this phenomenon is that the jet curtain is inherently weaker at sharp bends in the peripheral slot than at straight portions.

Consider a jet sheet issuing straight down from a slot with a 90° bend, as shown in Fig. 49. Then the momentum flux from a section \( y \) of the bend is

\[
J_s = j_s v_s y
\]
and the momentum flux in the same streamtube where it is tangent to the ground is

\[ J_g = j_g r_g y \]

Assuming now that \( J_s = J_g \) we have

\[ j_s r_s y = j_g r_g y \]

or

\[ \frac{j_g}{j_s} = \frac{r_s}{r_g} \]

But

\[ r_g - r_s = h \]

or

\[ r_g = h + r_s \]

Therefore

\[ \frac{j_g}{j_s} = \frac{r_s}{h + r_s} \]  \( (7) \)

Equation 7 shows that \( j_g \) goes to zero as \( r_s \) goes to zero. Thus, if \( r_s \) is small enough, the jet curtain at the bend will not be strong enough to prevent the air in the air cushion from escaping.

5.3 Thrust and Drag

At negative angles of attack and low forward speeds (Fig. 24, \( \dot{q}/\dot{t} \) < 0.2), the drag becomes negative, i.e. thrust, which increases rapidly with decreasing speed. The rather large values of thrust and drag at hovering and low speeds suggest that the horizontal component of the base pressure is not the only mechanism giving rise to these horizontal forces at non-zero angles of attack. If the resultant force on the wing were perpendicular to the plane of the wing, \( \beta \) (as defined in Fig. 50) would equal \( \alpha \). A plot of \( D/L = \tan \beta \) against \( \alpha \) (Fig. 35) shows, however, that \( \beta \neq \alpha \) for hovering and low forward speeds, suggesting the existence of suction peaks at the trailing or leading edges. For \( h/c \) of 0.062 at negative angles of attack, and hovering \( \beta/\alpha = 1.40 \), which means that the total thrust is 40% higher than that accounted for by the sum of base pressure and jet reaction. The reason for these large values of thrust and drag is probably an asymmetry in the flow around the wing due either to a non-zero angle of attack or to a difference in the momentum.
fluxes from the L.E. and T.E. slots. This could give rise to a larger
downstream momentum flow, for instance, resulting in a net thrust. No
attempt was made to determine experimentally what detailed flow phenome-
one at the wing caused these forces. They could be due to suction peaks
at the edges of the wing caused by entrainment of outside air into the jet
curtain; or they could be due to pressure peaks caused by the flow inside
the wing.

5.4 Pitching Moment and Centre of Pressure

The plots of $C_{M_{z}}$ against $\alpha$ on Figs. 26 and 27 have posi-
tive slopes for the most parts, indicating that the wing is unstable about
the midchord for most angles of attack, and forward speeds at both heights.
At high speeds and positive angles of attack the slopes do not change very
much, having a value of about 0.01 per degree for both heights. At zero
angle of attack and hovering the wing is out of trim, i.e. it has a nose-up
pitching moment, as shown in Fig. 26 and 27. The reason for this is
probably that the momentum flux from the L.E. slot is larger than that
from the T.E. slot. This would also explain the non-zero drag for the
same case, because if the momentum flow from the L.E. jet were larger
it would appear as a higher upstream momentum flow after being turned
by the ground. This would give rise to a net drag.

Since no measurements of the pressure distribution along
the chord of the wing were made it is rather difficult to predict the be-
havior of the pitching moment. When the angle of attack is changed from
zero to a positive value, for instance, ideal fluid theory predicts an in-
crease in the base pressure at the trailing edge, which would be required
to maintain the smaller radius of curvature of the T.E. jet. The result
is a stabilizing moment, which does not agree with experimental results.
On the other hand, Ref. 3 shows that a vortex is present in the ground
cushion near both of the jet curtains of the two-dimensional GEM. This
vortex causes a suction peak to appear on the ground, which moves toward
the wing edge as the height above ground is decreased. The movement of
this suction peak is probably duplicated by a suction peak on the base of
the GEM, when the wing edge approaches the ground owing to a change in
angle of attack. This would cause an unstable pitching moment, which
agrees with the experimental observations on the UTIA wing. A study of
other GEMs (Ref. 4 and 5) shows that these are unstable for moderate
heights, but stable for low heights above ground. The two GEMs in
question, however, have additional jets blowing into the ground cushion,
which would probably decrease the size of the interior vortices if they
exist there. A comparison with these GEMs is therefore not conclusive.

There exists the possibility that the wing might be stable for
a proper choice of moment centre (i.e. the c.g. of an actual aircraft).
For neutral stability we must have
\[ C_{M_\alpha}^* = 0 \]

Now
\[ C_{M_\alpha}^* = C_N^* (h^* - h_{cp}) \approx C_L^* (h^* - h_{cp}) \]

where \( h^* c \) = distance from the L.E. to the moment centre.

Therefore
\[ C_{M_\alpha}^* = C_{L\alpha}^* (h^* - h_{cp}) - C_L^* \frac{\delta h_{cp}}{\delta \alpha} \quad (8) \]

Thus, we have for neutral stability
\[ C_{L\alpha}^* (h_n - h_{cp}) - C_L^* \frac{\delta h_{cp}}{\delta \alpha} = 0 \]

(8)

(9)

Figures 31 and 19 show that \( h_{cp} \) is always negative and \( C_L^* \) is always positive, but that \( C_{L\alpha}^* \) can attain positive, zero, and negative values as the angle of attack increases. The position of the neutral point is therefore influenced to a large degree by \( C_{L\alpha}^* \), approaching infinity as \( C_{L\alpha}^* \) approaches zero. Figures 53 and 54 show the variation of the neutral point with forward speed for three angles of attack at \( h/c = 0.062 \). To find the regions of stability on this plot we substitute \( h_{cp} \) as given in Eq. 9 into Eq. 8, i.e.
\[ C_{M_\alpha}^* = C_{L\alpha}^* (h^* - h_n) + \frac{C_L^*}{C_{L\alpha}^*} \frac{\delta h_{cp}}{\delta \alpha} = C_{L\alpha}^* (h^* - h_n) \quad (10) \]

As indicated by Eq. 10, the static margin \( h^* - h_n \) does not, by itself, determine the stability of the wing, since \( C_{L\alpha}^* \) is not constant. Therefore the condition for stability becomes
\[ C_{L_\alpha}^* > 0 \quad \text{for} \quad h^* < h_n \]

or

\[ C_{L_\alpha}^* < 0 \quad \text{for} \quad h^* > h_n \]

Applying this criterion we can see, for example, that at an angle of attack of 3° and \( h/c = 0.062 \) the wing is stable in two disconnected regions of forward speed as shown in Fig. 53.

VI. EXPERIMENTAL ERROR

6.1 Random Error

To check whether the aerodynamic coefficients depend on \( q/\bar{q}_j \), rather than on \( q \) or \( \bar{q}_j \) separately, and to check the repeatability of the tests a test run was repeated twice for \( h/c = 0.062 \) and \( \alpha = 1.5^\circ \) and varying \( q/\bar{q}_j \). The two repeat runs were different from the corresponding standard run in that \( q \) was now kept constant and \( \bar{q}_j \) was varied. The results of the two repeat runs and the corresponding standard run were plotted on the same graph and are shown in Figs. 55 to 57. Repeatability is seen to be good for lift, but not as good for drag and pitching moment, especially for hovering, where the scatter amounts to as much as \( \pm 12\% \). The reason for this can be attributed to the fact that the forces involved in the measurement of drag and pitching moment are much smaller than the lift forces, especially at hovering, making the percentage error in drag and pitching moment higher than that for lift.

6.2 Systematic Error

The largest systematic error is probably produced in the calculation of the jet momentum \( J_j \) from the inlet momentum \( J_i \), owing to the uncertainty in the shape of the dynamic-head profile at the jet slot for various test conditions. The uncertainty in the mean-square deviation there was estimated to be \( \pm 5\% \). To this must be added an error of about \( \pm 5\% \) in the calibration constant which is used in the calculation of the inlet momentum. This would result in an error of \( \pm 10\% \) in the aerodynamic coefficients for the hovering case, where the denominator contains only \( J_j \). With increasing forward speed the error in the denominator decreases rapidly.

The balance readings are felt to be correct within \( \pm 2\% \) on the average.
VII. CONCLUSIONS

Analysis of the results shows that there seem to exist two flight regimes for the wing. At low forward speeds the wing behaves essentially like a hovering platform, whereas at high speeds the wing exhibits the characteristics of a jet-flapped wing. This observation agrees with the results of other researchers. There seems to exist a significant difference in the behavior of three-dimensional GEMs, such as the UTIA wing, and two-dimensional GEMs in that the transition from one flight regime to the other is more gradual for three-dimensional GEMs, extending over a wider forward-speed range, than for two-dimensional GEMs. The reason for this difference in behavior seems to be that the centre part of the L.E. jet of the UTIA wing is blown back first and broadens gradually as forward speed increases, whereas the L.E. jet of a two-dimensional GEM is blown back as a whole within a comparatively narrow speed range.

The variation of lift augmentation with height above ground is comparable to other published results, a difference being that the lift augmentation curve does not exhibit a hump near h/c = 0.5. A more detailed investigation of the flow field under the wing would show whether the absence of the hump is due to the absence of a ring vortex.

Although viscous losses in the air cushion are probably mainly responsible for the discrepancy in experimental and theoretical values of $A_L$, part of this discrepancy can be traced to leakage of air from the air cushion at the four corners of the peripheral slot, as shown by flow visualization tests. This situation could be remedied by installing semi-circular slots at the wing tips, or by inclining the peripheral jet inwards at sharp bends in the peripheral slot.

At low forward speeds the thrust augmentation $A_T$ is higher than the lift augmentation by a considerable amount (up to 40%) indicating that some of the downward jet momentum flow is recovered as thrust after being turned backwards by the ground. It was not established whether the increase in thrust is due to suction peaks on the wing edges, say, or pressure on the inside of the wing. Further experimentation should clear this point up.

The wing was found to be unstable about the midchord for all angles of attack and forward speeds at the two heights investigated. Even with a suitable choice of moment centre (i.e. centre of gravity) the wing, at positive angle of attack, can be made stable only for limited regions of angle of attack and forward speeds. The boundaries of these regions of stability themselves vary with forward speed and angle of attack.

No definite conclusions have been drawn as to the cause of the instability of the wing. A detailed investigation of the flow field around the wing would do much to shed light on this problem.
<table>
<thead>
<tr>
<th>Reference</th>
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<tbody>
<tr>
<td>1</td>
<td>Design and Calibration of an Air Ejector to Operate Against Various Back Pressures.</td>
<td>Chisholm, R. G. A.</td>
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</tbody>
</table>
The jet momentum flux is given by

\[ J_j = \int_{A_j} \rho_j v_j^2 dA_j = \rho_j \overline{v_j^2} A_j \]  \hspace{1cm} (11)

assuming \( \rho_j \) is constant across \( A_j \).

The corresponding mass flow is given by

\[ M_j = \int_{A_j} \rho_j v_j dA_j = \rho_j \overline{v_j} A_j \]

Now the deviation, \( v'_j \), from the average velocity is defined by

\[ v'_j = v_j - \overline{v_j} \]

Then

\[ v'_j^2 = \overline{v_j^2} + 2 \overline{v_j} v'_j + v'_j^2 \]  \hspace{1cm} (12)

Substituting Eq. 12 into Eq. 11, we get

\[ J_j = \rho_j \overline{v_j^2} A_j = \int_{A_j} \rho \overline{v_j^2} dA + \int_{A_j} \rho (2 \overline{v_j} v'_j) dA + \int_{A_j} \rho v'_j^2 dA \]

\[ = \rho_j \overline{v_j^2} A_j + 0 + \rho_j \overline{v_j^2} A_j \]  since \( \int v'_j dA = 0 \)

where

\[ \overline{v_j^2} = \int_{A_j} v_j^2 dA / A_j \]

Therefore

\[ \overline{v_j^2} = \overline{v_j^2} + v'_j^2 \]

or

\[ v'_j = \overline{v_j^2} - \overline{v_j^2} \]  \hspace{1cm} (13)
Similarly
\[ \overline{V_i^2} = \overline{V_i'^2} - \overline{V_i^2} \]  

(14)

We can assume that \( \rho_i = \rho_j = \rho \), since \( M_i \approx M_j < 0.2 \)

Now by continuity
\[ A_j \overline{V_j} = A_i \overline{V_i} \]  

(15)

By squaring and rearranging Eq. 15 we have
\[ \overline{V_j^2} = \overline{V_i^2} \left( \frac{A_i'}{A_j} \right)^2 \]  

(16)

Substituting Eq. 13 and 14 into Eq. 16 we have
\[ \overline{V_j^2} - \overline{V_j'^2} = \left( \overline{V_i^2} - \overline{V_i'^2} \right) \left( \frac{A_i'}{A_j} \right)^2 \]  

(17)

Multiplying Eq. 17 by \( \rho A_j \) we obtain
\[ J_j - J_j' = \left( J_i - J_i' \right) \frac{A_i'}{A_j} \]  

(18)

where
\[ J_i' = \rho \overline{v_i'^2} A_i = \int_{A_i} \rho v_i'^2 \, dA \]
\[ J_j' = \rho \overline{v_j'^2} A_j = \int_{A_j} \rho v_j'^2 \, dA \]

Rearranging Eq. 18, we finally obtain
\[ J_j = J_i \frac{1 - \frac{J_j'}{J_i'}}{1 - \frac{J_j'}{J_j}} \frac{A_i}{A_j} \]  

(19)

For the calculation of \( J_i' \) and \( J_j' \) these terms must be expressed in terms of experimental quantities. By definition of \( J_i' \)
\[ J_i' = \int_{A_i} \rho v_i'^2 \, dA \]
Now

\[ v_i = \sqrt{\frac{2}{\rho}} q_i \]  

(21)

and

\[ \bar{v}_i = \int_{A_i} v_i \frac{dA}{A_i} \]  

(22)

Therefore, combining Eq.'s 20, 21, and 22, we have

\[ J'_i = \int_{A_i} \rho \left[ \sqrt{\frac{2}{\rho}} q_i - \int_{A_i} \sqrt{\frac{2}{\rho}} q_i \frac{dA}{A_i} \right]^2 dA \]

or

\[ J'_i = 2 \int_{A_i} \left[ \sqrt{q_i} - \int_{A_i} \sqrt{q_i} \frac{dA}{A_i} \right]^2 dA \]  

(23)

Similarly

\[ J'_j = 2 \int_{A_j} \left[ \sqrt{q_j} - \int_{A_j} \sqrt{q_j} \frac{dA}{A_j} \right]^2 dA \]  

(24)
APPENDIX II

Derivation of $A_L = A_L(h/c, t/c)$ for Inviscid, Thick-Jet Flow

The following assumptions are made:

1. The flow is two-dimensional and inviscid.
2. The static pressure in the air cushion is constant.
3. The streamlines in the peripheral jet are circular arcs with a common centre of curvature.
4. The stagnation pressure in the jet flow is a constant.
5. The static pressure on the top surface of the GEM is atmospheric.

For the definition of terms see Fig. 58.

For the flow inside the jet

\[
\frac{dp}{2 \rho V^2} = \frac{dp}{\rho_t - \rho} = \frac{2 dR}{R} \tag{25}
\]

Integrating Eq. 25 yields

\[
\int_{p_a}^{p_t} \frac{dp}{\rho_t - p} = \int_{R_a}^{R} \frac{2 dR}{R}
\]

or

\[
\ln \frac{\rho_t - p_a}{\rho_t - p} = \ln \left( \frac{R}{R_a} \right)^2
\]

Therefore

\[
\frac{\rho_t - p_a}{\rho_t - p} = \frac{q_a}{q} = \left( \frac{R}{R_a} \right)^2 \tag{26}
\]

or

\[
q = q_a \left( \frac{R_a}{R} \right)^2 \tag{27}
\]

Now

\[
J = 2 \ell \int_{R_a}^{R_b} q dR \tag{28}
\]

where \( \ell \) = length of the slot.
Substitution of Eq. 27 into Eq. 28 yields

\[ J = 2L \int_{R_a}^{R_b} q_a \left( \frac{R_a}{R} \right)^2 dR \]

\[ = 2L q_a R_a^2 \int_{R_a}^{R_b} R^{-2} dR \]

\[ = 2L q_a R_a^2 (-1) \left[ \frac{1}{R_a} - \frac{1}{R_b} \right] \]

or

\[ J = 2L q_a R_a^2 \left[ \frac{1}{R_a} - \frac{1}{R_b} \right] \quad (29) \]

Now from Eq. 26

\[ p_r - p_b = (p_r - p_a) \left( \frac{R_a}{R_b} \right)^2 \]

Therefore

\[ p_b - p_a = (p_r - p_a) \left[ 1 - \left( \frac{R_a}{R_b} \right)^2 \right] \]

\[ = q_a \left[ 1 - \left( \frac{R_a}{R_b} \right)^2 \right] \quad (30) \]

But the lift due to base pressure, \( L_b \), is

\[ L_b = (p_b - p_a) S_b \quad \text{where} \quad S_b = \text{base area} \]

Therefore, using Eq. 30

\[ L_b = q_a S_b \left[ 1 - \left( \frac{R_a}{R_b} \right)^2 \right] \quad (31) \]

Neglecting the contribution of the static pressure across the slot to the lift, the total lift is

\[ L = L_b + J \]

and the lift augmentation is

\[ A_L = \frac{1}{J} = \frac{L_b}{J} + 1 \quad (32) \]
Substitution of Eq. 29 and 31 into Eq. 32 yields

\[ A_L = \frac{q_a S_b \left[ 1 - \left( \frac{R_a}{R_b} \right)^2 \right]}{2 \ell q_a R_a^2 \left( \frac{1}{R_a} - \frac{1}{R_b} \right)} + 1 \]  

\[ = \frac{S_b}{2 \ell} \frac{R_b + R_a}{R_a R_b} + 1 \]

From Fig. 58,

\[ R_b = h' \]

and

\[ R_a = R_b - t = h' - t \]

Therefore, from Eq. 33 and 34

\[ A_L = \frac{S_b}{2 \ell} \frac{2 h' - t}{(h' - t)h'} + 1 \]

\[ = \frac{S_b}{2 \ell} \frac{2 - \frac{t}{h'}}{h' - t} + 1 \]

\[ = \frac{S_b}{2 \ell h'} \frac{2 - \frac{t}{h'}}{1 - \frac{t}{h'}} + 1 \]

or

\[ A_L = \frac{S_b}{2 \ell c} \frac{1}{\frac{t}{h'}} \left[ 1 + \frac{1}{1 - \frac{t}{h'}} \right] + 1 \]
FIG. 2  WING ON PRELIMINARY TEST STAND
FIG. 3 SCHEMATIC CROSS-SECTION OF BLOWING WING AS INSTALLED IN WIND TUNNEL
FIG. 4  MECHANICAL DETAILS OF WING
FIG. 5 VARIATION OF SPANWISE JET ANGLE WITH DISTANCE ALONG PERIPHERAL SLOT.
FIG. 6 VARIATION OF MAXIMUM JET TOTAL PRESSURE VERSUS DISTANCE ALONG SLOT (BEFORE INSTALLATION OF WIRE SCREENS)
CYLINDRICAL STIFFENING POSTS

FIG. 7 STREAK PATTERN ON INSIDE WING SURFACE
FIG. 8 REPRESENTATIVE DYNAMIC-PRESSURE PROFILES ACROSS THE PERIPHERAL JET.
FIG. 9 VARIATION OF $q_j/p_e$ WITH EJECTOR BACK PRESSURE, $p_e$
FIG. 10 VARIATION OF $j$ ALONG L.E. AND T.E. JETS.
FIG. 11  DYNAMIC-PRESSURE PROFILES ACROSS AIR-TUBE EXIT.

FIG. 12  DYNAMIC-PRESSURE PROFILES ACROSS AIR-TUBE EXIT.
FIG. 13  DYNAMIC-PRESSURE PROFILE ACROSS AIR-TUBE EXIT.

FIG. 14  DYNAMIC-PRESSURE PROFILE ACROSS AIR-TUBE EXIT.
FIG. 15 DEFINITION OF $h$, HEIGHT ABOVE GROUND

FIG. 16 FREE-BODY DIAGRAM OF WING
FIG. 17 VARIATION OF $C_L^*$ WITH $\sqrt{C_J}$ FOR h/c = 0.062
FIG. 18 $C_L^*$ VERSUS $\alpha$ FOR $h/c = 0.031$
FIG. 19 $C_L^*$ VERSUS $\alpha$ FOR $h/c = 0.062$
FIG. 20  $C_L^*$ VERSUS $q/\bar{q}_j$ FOR $h/c = 0.031$
FIG. 21 \( C_L \) VERSUS \( q/q_j \) FOR \( h/c = 0.062 \)
FIG. 22 $C_D^*$ VERSUS $\alpha$ FOR $h/c = 0.031$
FIG. 23 $C_D^*$ VERSUS $\alpha$ FOR $h/c = 0.062$
FIG. 24  $C_D^*$ VERSUS $q/q_j$ FOR $h/c = 0.031$
FIG. 25  $C_D^*$ VERSUS $q/\bar{q}_j$ FOR $h/c = 0.062$
FIG. 26  \( \frac{C_{Mc}^*}{2} \) VERSUS \( \alpha \) FOR \( h/c = 0.031 \)
FIG. 27  $C_M^* \text{ VERSUS } \alpha$ FOR $h/c = 0.062$
FIG. 28 \( \frac{C_{Mc}}{2} \) VERSUS \( q/\bar{a}_j \) FOR \( h/c = 0.031 \)
FIG. 29 $C_{M_c}^*$ VERSUS $q/q_j$ FOR $h/c = 0.062$
FIG. 30 \( h_{cp} \) VERSUS \( \alpha \) FOR \( h/c = 0.031 \)
FIG. 31 $h_{cp}$ VERSUS $\alpha$ FOR $h/c = 0.062$
FIG. 32  \( h_{cp} \) VERSUS \( q/q_j \) FOR \( h/c = 0.031 \)
FIG. 33  $h_{cp}$ VERSUS $q/q_j$ FOR $h/c = 0.062$
FIG. 34  D/L VERSUS $\alpha$ FOR $h/c = 0.031$
FIG. 35  D/L VERSUS $\alpha$ FOR $h/c = 0.062$
FIG. 36  D/L VERSUS q/\bar{q}_j  FOR h/c = 0.031
FIG. 37 D/L VERSUS q/\bar{q}_j FOR h/c = 0.062
FIG. 38 to 48

GROUND BOARD STREAK PATTERNS FOR VARIOUS HEIGHTS ABOVE GROUND, ANGLES OF ATTACK, AND FORWARD SPEEDS. (THE DARK AREAS REPRESENT REGIONS OF LOW-SPEED FLOW)
FIG. 40  $h/c = 0.062$, $\alpha = 0$, $q/q_j = 0.21$
FIG. 41  \( h/c = 0.062 \), \( \alpha = 0 \), \( q/q_j = 0.28 \)
FIG. 42  \( h/c = 0.062, \alpha = 0, q/\bar{q}_j = 0.42 \)
FIG. 43  \( h/c = 0.062, \, \alpha = 0, \, q/q_j = 0.98 \)
FIG. 44  \( h/c = 0.1, \; \alpha = -4.5^\circ, \; q/q_j = 0.28 \)
FIG. 45   \( h/c = 0.1, \ \alpha = -3.0^\circ, \ q/\bar{q}_j = 0.29 \)
FIG. 46   $h/c = 0.1$, $\alpha = +3.0^\circ$, $q/\bar{q}_j = 0.30$
FIG. 47 \( h/c = 0.1, \ \alpha = +4.5^\circ, \ q/\bar{q}_j = 0.30 \)
FIG. 48  h/c = 0.1,  \( \alpha = +7.5 \),  \( q/\sqrt{\dot{q}} = 0.29 \)
FIG. 48a  \( h/c = 0.3, \; \alpha = 0, \; q/q_j = 0 \)

(DARK SPOTS NEAR WING CORNERS ARE OIL SPOTS)
PLAN VIEW OF BEND IN PERIPHERAL JET

SECTION A-A
FIG. 50 DEFINITION OF $\beta$
FIG. 51 A_L VERSUS q/q_j FOR h/c = 0.031

REF. 3, POISSON-QUINTON, (h/c = 0.047, \( \alpha = 0 \))
\[ A_L = \frac{S_k}{2l_c} \frac{l}{\ell} \left[ 1 + \frac{1}{1 + \frac{h'}{\ell}} \right] \]

\[ h' = h + 0.15 \text{ in.} \]

FIG. 52 \( A_L \) VERSUS \( h'/c \) FOR HOVERING AT \( \alpha = 0 \)

- POISSON-QUINTON (REF. 3)
- NASA (REF. 6)
- PRINCETON (REF. 7)
- UTIA
FIG. 53 VARIATION OF NEUTRAL POINT WITH FORWARD SPEED FOR h/c = 0.062
FIG. 54 VARIATION OF NEUTRAL POINT WITH FORWARD SPEED FOR \( h/c = 0.062 \)
FIG. 55  CHECK ON REPEATABILITY OF RESULTS.  $C_L^*$ VERSUS $q/q_j$ FOR $h/c = 0.062$
FIG. 56  CHECK ON REPEATABILITY OF RESULTS.  $C_D^*$ VERSUS $q/\bar{q}_j$ FOR $h/c = 0.062$
FIG. 57  CHECK ON REPEATABILITY OF RESULTS. $C_{\frac{\text{Mc}}{2}}^*$ VERSUS $q/\bar{q}_j$ FOR $h/c = 0.062$
FIG. 58  TWO-DIMENSIONAL THICK JET NEAR THE GROUND