THE COLLEGE OF AERONAUTICS
CRANFIELD

EXPERIMENTS ON A JET-FLAP DELTA WING
IN GROUND EFFECT

by

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Experiments on a Jet-Flap Delta Wing in Ground Effect

- by -


SUMMARY

Tests have been made on a 70° cropped delta wing with trailing edge slot blowing both with and without a fixed ground board. Jet deflections of 0° and 30° were used. The incidence range was \(-1° < a < 20°\) and height/root chord ratios varied between 0.12 and 0.22, the lowest height corresponding to touch-down at 15° incidence.

Lift increased steadily as the ground was approached due to the "baulking" of the airflow between the model and the ground. The effect of the trailing edge jet was small except when the jet impinged on the ground plate, causing some reduction in lift at the highest incidence. Drag was increased at a given incidence in ground effect, the increase being approximately equal to the increase in induced drag due to the increased pressure lift. In general, both the aerodynamic centre and centre of pressure moved rearwards as the ground was approached but moved forward very quickly when the jet impinged on the ground board.
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<th>Symbol</th>
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<tr>
<td>( \alpha )</td>
<td>geometric wing incidence</td>
</tr>
<tr>
<td>( c_0 )</td>
<td>Root chord = 3.33 ft.</td>
</tr>
<tr>
<td>( c_{\text{c}} )</td>
<td>aerodynamic mean chord = 2.60 ft.</td>
</tr>
<tr>
<td>( h )</td>
<td>distance between ground board and pivot point (0.68 ( c_o ))</td>
</tr>
<tr>
<td>( q )</td>
<td>main stream dynamic head</td>
</tr>
<tr>
<td>( S )</td>
<td>wing area = 3.60 sq. ft.</td>
</tr>
<tr>
<td>( m_j )</td>
<td>measured rate of mass flow slugs/sec.</td>
</tr>
<tr>
<td>( V_j )</td>
<td>final jet velocity assuming isentropic expansion to free stream pressure.</td>
</tr>
<tr>
<td>( C_{\mu} )</td>
<td>blowing momentum coefficient = ( \frac{m_j V_j}{q.S} )</td>
</tr>
<tr>
<td>( C_L )</td>
<td>lift coefficient = ( \frac{\text{Lift}}{q.S} )</td>
</tr>
<tr>
<td>( \Delta C_{L_p} )</td>
<td>pressure lift coefficient due to jet flap effect</td>
</tr>
<tr>
<td>( \Delta C_{L_G} )</td>
<td>lift increment due to ground effect</td>
</tr>
<tr>
<td>( C_D )</td>
<td>drag coefficient = ( \frac{\text{Drag}}{q.S} )</td>
</tr>
<tr>
<td>( C_{m} )</td>
<td>pitching moment coefficient = ( \frac{\text{pitching moment about 0.68} c_o}{q.S. \bar{\alpha}} )</td>
</tr>
<tr>
<td>( \eta )</td>
<td>trailing edge flap deflection</td>
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Suffices
- \( b \) indicates value obtained with T.E. blowing
- \( o \) indicates value obtained without T.E. blowing
1. Introduction

In the last decade a considerable research effort has been directed towards exploring the aerodynamic characteristics of slender wings. One aspect which seems to have been neglected, judging by the almost complete lack of published work, is the effect of ground proximity on these slender shapes. Another effect which has not been studied is the effect of jet exhaust when a powerful battery of jet engines is mounted at the rear of the aircraft.

Comprehensive experimental test programmes on the effect of ground proximity\(^{(1)}\) and the effect of jet configurations\(^{(2)}\) are currently in progress at the Royal Aircraft Establishment, but in order to obtain quickly some information on both ground and jet-induced effects a series of tests was made on a 70° cropped delta wing, both with and without full span trailing edge slot blowing. It was not possible to simulate a battery of round jets as in conventional aircraft and the tests are representative of a jet-flap delta wing, but it is possible to draw some tentative conclusions for more conventional slender wing aircraft.

2. Model and range of tests

The model is a 70° cropped delta wing having an aspect ratio of 0.73, with the tip chord equal to one third of the root chord. It is of rhombic cross section and has a 0.040 in. slot round the periphery which was sealed in these tests except for the trailing edge slot. Interchangeable brass edges enabled tests to be made with the trailing edge jet undeflected relative to the model and deflected downwards 30°. Excluding a small region at each end of the slot the variation in jet velocity was about ±5% but owing to the construction of the model it was difficult to improve on this figure. The blowing momentum coefficient, \(C_\mu = \frac{m_j}{q_j V_j}\), was measured directly using orifice plates and \(V_j\) was calculated, assuming isentropic flow from measured slot pressures to atmospheric pressure.

The tests were made in the College of Aeronautics 8 ft x 6 ft low speed wind tunnel with the model mounted on a Warden type six-component balance. The ground was represented by a large wooden plate eight feet square and two inches thick, stiffened by "L" shaped steel supports to ensure flatness. The plate had an elliptic leading edge and a chamfered trailing edge and was set at zero incidence relative to the tunnel stream. It projected forward about two feet ahead of the wing apex and could be positioned vertically by means of screw jacks.

Balance measurements were made in all the tests of lift, drag, and pitching moment for zero sideslip only. Corrections for pressure constraints on the balance are similar to those of Ref. 3. Conventional corrections for ground effect tests are small \(^{(4)}\) and none have been applied. Tests were made with the jet undeflected and deflected downwards 30° over the range of incidence \(\alpha = -10°\) to +20°. \(C_\mu\) values ranged between 0 and 0.2 approximately, thus covering the range for conventional supersonic transport type aircraft although due to pressure limitations in the model it was not possible to cover
the full jet-flap range. Ground clearances with the undeflected jet were
\( h/c_o = 0.122, 0.162, \) and \( \infty \), and with the 30° downward deflected jet
\( h/c_o = 0.140, 0.158, \) and 0.220, and \( \infty \), where \( h \) is the height of the pivot
point \((0.68 c_o)\) above the ground plate.

3. Discussion of Results

3.1. Lift

The variation of lift with incidence for the basic model configuration, i.e.
no blowing or ground, is shown in Fig. 2. The non-linear slope is typical of
slender wings and it is interesting to note that the deflection of a full span
trailing edge flap \((\Delta L = 0.040)\) gives a lift increment \( \Delta C_L \) of 0.15 which
is unchanged throughout the incidence range.

The effect of mounting the model close to a fixed ground board without blowing
is shown in Fig. 3, where lift increments due to ground proximity, \( \Delta C_{LQ} \), are
plotted against incidence for \( \eta = 0° \) and 30°. The lowest values of \( h/c_o \) tested
(0.122 for \( \eta = 0° \) and 0.140 for \( \eta = 30° \)) correspond to an 8 ft. trailing edge
clearance on an aircraft with a 200 ft. root chord at 15° incidence and represent
a practical minimum, i.e., touchdown conditions. At zero incidence with no
flap, the venturi effect between model and ground board actual gives rise to a
small reduction in lift but as incidence is increased the lift rises rapidly due to
the "baulking" of the flow under the model, reaching a maximum \( C_L \) of 1.07 at
\( \alpha = 20° \), an increase of almost 50% over the no ground case.

With the full span trailing edge flap deflected downwards 30°, the lift
increments due to ground proximity increase at low incidence but fall below the
undeflected flap case at higher incidence. As no pressure plotting was possible
on this model, the cause of this loss of lift due to flap deflection in ground effect
could not be determined but is probably caused by earlier separation on the wing
upper surface due to larger adverse pressure gradients at the rear of the wing.

In Figs. 4a - 4c the variation of \( C_L \) with \( C_{\mu \frac{1}{2}} \) for \( \eta = 0° \) is shown for
\( h/c_o = \infty, 0.162, \) and 0.122. The variation is linear in the range tested and
is similar to the trend observed on a low aspect ratio straight wing (5) and a 60°
Delta wing (6). The fact that \( C_L \) is constant in most cases up to \( C_{\mu \frac{1}{2}} \)
about one is a reasonable justification for extrapolating the present results to
higher values of \( C_{\mu \frac{1}{2}} \) if necessary. Even with an undeflected jet sheet there is
some increase in pressure lift due to the ability of the jet sheet to support a
pressure difference with the wing at incidence.

Figs. 5a - 5d give similar results for \( \eta = 30° \) and \( h/c_o = \infty, 0.220,\)
0.158 and 0.140. Again the variation of \( C_L \) with \( C_{\mu \frac{1}{2}} \) is linear above a certain
critical \( C_{\mu \frac{1}{2}} \) value, say \( C_{\mu \frac{1}{2}} \) below which the jet has no appreciable effect.
\( C_{\mu \frac{1}{2}} \) is about 0.004 for the no-ground case for all the incidences tested. The
critical value of \( C_{\mu \frac{1}{2}} \) needed to suppress flow separation over the flap for the
no-ground case was about 0.030 and was roughly independent of incidence.
This value is rather high for a flap deflection of only 30° but is due to the fact
that the blowing slot is located at the trailing edge well behind the separation
line.
With \( \eta = 30^\circ \), \( \alpha = 0^\circ \), and no ground, the slope \( \frac{C_L}{C^\frac{1}{2}} = 0.60 \) and the corresponding value in Ref. 5, on an aspect ratio 2.75 is 1.40. Despite the difference in wing shape and section, the change in slope can still be largely accounted for with a simple aspect ratio correction \( \frac{A_1}{A_1 + 2} \rightarrow \frac{A_2}{A_2 + 2} \) even for these very small aspect ratios.

A breakdown of the overall lift into its various component parts is given in Figs. 6a, and 6b, for \( \eta = 0^\circ \) and \( 30^\circ \) respectively at \( \alpha = 15^\circ \). The lower boundary at \( C_L = 0.49 \) is the lift obtained with neither blowing, flap, nor ground. To this is added the lift due to flap deflection, where appropriate, the direct jet lift component, and the jet induced pressure lift to give the lift with blowing but without ground. The upper boundary is the lift with blowing, flap \((\eta > 0)\) and ground.

Using Figs. 6a, and 6b, a tentative method of estimating ground effect on low aspect ratio jet-flap wings, if the unblown test results are available, has been developed.

Aerodynamic lift without ground or blowing is known, and also the lift increment due to ground which is assumed independent of \( C \mu \). The jet reaction lift can be calculated at the appropriate \( C \mu \) value and the only unknown is the jet induced pressure lift. This cannot be calculated with any accuracy from Spence's 2 D result \((7)\) modified by Maskell and Spence's three dimensional jet flap correction \((8)\) since the A.R.'s considered here are too low. However, from Spence's theory we may obtain the ratio \( \frac{C_L \text{ with blowing & flap}}{C_L \text{ no blowing or flap}} \) which is almost independent of aspect ratio for the small values of \( C \mu \) considered here, although the appropriate correction could be applied for large \( C \mu \) values.

The "theoretical" value for pressure lift coefficient due to flap and blowing is now taken to be:\[
\Delta C_{L_p} = \left( \frac{C_L \text{ with blow & flap}}{C_L \text{ no blowing or flap}} - 1 \right) \text{theoretical} \times C_L \text{ no blowing or flap, experimental}.
\]

These "theoretical" values are plotted in Fig. 7 and compared with experimental values of \( \Delta C_{L_p} \left\{ = \left( C_L B - C_L o - C \mu \sin \alpha \right) \right\} \)

The theory might be expected to overestimate the lift somewhat since it is linear, although good agreement with experiment was obtained \((8)\) for aspect ratios as low as 2.75.

It is then assumed that total lift in ground effect is made up of the following components:

\[ C_L \text{ no flap, blow, or ground} + \Delta C_{L_G \text{ no blow}} + C_\mu \sin \alpha + \Delta C_{L_p} \]
The first two terms are known from tests with an unblown model, the third term depends on two terms which can be postulated, and the fourth term can be calculated from Spence's blown flap theory. For $a = 15^\circ$ and $C = 0.2$, this method predicted the lift to within 5% of the measured lift.

It is not known whether predictions of total lift could be made with confidence outside the range of the present tests, but it is suggested as an empirical method until more information, both theoretical and experimental, is available.

3.2 Drag

Comparison of the measured and theoretical thrust is made in Fig. 8, both with and without a main stream flow out of ground effect. In still air the theoretical $C_L$ exceeds the measured thrust by about 2%, and with wind on by about 6%, both values being comparable to those obtained elsewhere.

Drag is plotted against lift for $\eta = 0^\circ$ in Figs. 9a - 9c. Drag is reduced at a given lift as the ground is approached due to the smaller induced drag, but at a given incidence, which is of more practical interest, there is an increase in drag of about $a \Delta C_{L_G}$, where $\Delta C_{L_G}$ does not include the direct jet lift component. Similar trends are observed for $\eta = 30^\circ$ (Figs 10a - 10d) except for large values of $C_\mu$ & $a$, where the jet impinges on the ground plate.

3.3 Pitching Moments

The pitching moments presented here are as measured about the pitching axis at 0.68$c_o$ and thus have a positive slope, the aerodynamic centre being well forward of this point.

For $\eta = 0^\circ$ (Figs. 11a - 11c) the variation of $C_m$ with $C_L$ is linear. At zero incidence, the venturi effect created close to the ground giving the small negative lift referred to in § 3.1 also gives rise to a small nose up pitching moment. At a given lift, with $C_\mu$ constant, the pitching moment is reduced on approaching the ground, but at a given (moderate) incidence the change is very small. Since the pivot point (0.68) is close to the centre of area for this model, it suggests that the 'baulked' flow under the model produces a roughly constant pressure rise over the whole of the lower surface.

With $\eta = 30^\circ$ (Figs. 12a - 12d) the pitching moment at a given lift with $C_\mu$ constant is also reduced on approaching the ground, but at constant (moderate) incidence ground proximity increases the pitching moment. This tendency agrees with the trend observed in § 3.1, where the cause of lower values of $\Delta C_{L_G}$ with flap deflected at moderate incidence was said to be due to increased flow separation on the upper surface as the ground was approached.

The movement of the aerodynamic centre and the centre of pressure with height and blowing is shown in Fig. 13 for $a = 15^\circ$ and $\eta = 0^\circ$ and $30^\circ$. These values are typical for all moderate incidences. With $\eta = 0^\circ$ there is a steady rearward movement of both aerodynamic centre and centre of pressure as the ground is approached. This is in line with an increase in pressure on the undersurface acting near to the centre of the area, and indicates an increase in static stability as the ground is approached.
With the flap deflected 30°, the aerodynamic centre is only slightly forward of the undeflected flap position and without blowing, hardly moves as the ground is approached. With blowing, as soon as the jet impinges on the ground, the aerodynamic centre moves forward very rapidly and the model becomes unstable. The centre of pressure is also virtually fixed without blowing, and moves forward only a small amount with blowing. With the flap deflected it is likely that flow separation on the upper surface counteracts to some extent the effect of increased pressure on the lower surface.

4. Conclusions

These tests were made in order to obtain some idea of the effect of ground proximity on a delta wing both with and without a jet flow. Blowing was from a full span trailing edge slot and the results are strictly applicable only to a jet-flap delta configuration, but tentative conclusions are drawn of the probable effects of round jets on conditions close to the ground.

At zero incidence there was a small reduction in lift; the pressure on the wing lower surface was reduced slightly by the venturi type flow between the wing and the ground. At most positive incidences, however, there was a substantial increase in lift at small ground heights. The maximum increase in lift without blowing and zero flap deflection at the highest incidence (20°) and the smallest clearance, corresponding to touch-down conditions was \( \Delta C_L/G = 0.35 \), an increase of almost 50% over the free-air value. With the flap deflected 30° downwards and \( C_{\mu} = 0 \), the lift at low incidences was greater than with the flap undeflected, but for high incidences close to the ground there was a small adverse effect which was attributed to earlier flow separation on the upper surface caused by the increased adverse pressure gradient at the rear. The effect of the presence of the jet close to the ground was small except when impingement occurred, resulting in some loss of lift.

The effect of ground proximity on drag at a given incidence was to increase the drag by an amount equal to the induced drag increment based on \( \text{pressure lift increment due to ground} \). Without flap, at moderate incidences, both the aerodynamic centre and the centre of pressure moved backwards as the ground was approached and this movement was not changed by the presence of the jet. With flap deflected corresponding movements were very small until the jet impinged on the ground plate when both centres moved forward.

In view of the almost total absence of information on this subject, a very tentative method of predicting lift in ground effect with a jet-flap from unblown results is suggested, and over the range of tests covered here would seem to agree with experiment to about ±5% accuracy.

Although it was not possible to test a round jet configuration, the results obtained with an undeflected jet-flap suggest that, in this case, jet-induced effects will be negligible and only the increase in lift due to the vertical jet component need be considered.
5. References


FIGURE 1  MODEL MOUNTED IN WIND TUNNEL
FIG. 2. VARIATION OF LIFT WITH INCIDENCE.
\[ C_{\mu} = 0, \quad \frac{h}{c_0} = \infty. \]
FIG. 4a. VARIATION OF LIFT WITH $C_{\mu}^{1/2}$, $\eta = 0^\circ$

FIG. 4b. VARIATION OF LIFT WITH $C_{\mu}^{1/2}$, $\eta = 0^\circ$

FIG. 4c. VARIATION OF LIFT WITH $C_{\mu}^{1/2}$, $\eta = 0^\circ$, $\frac{h}{C_D} = 0.162$. 
FIG. 5a. VARIATION OF LIFT WITH $\frac{C}{C_0}$, $\eta = 30^\circ$, $h = \infty$.

FIG. 5b. VARIATION OF LIFT WITH $\frac{C}{C_0}$, $\eta = 30^\circ$, $h = 0.220$.

FIG. 5c. VARIATION OF LIFT WITH $\frac{C}{C_0}$, $\eta = 30^\circ$, $h = 0.158$.

FIG. 5d. VARIATION OF LIFT WITH $\frac{C}{C_0}$, $\eta = 30^\circ$, $h = 0.140$. 
FIG. 6a. VARIATION OF LIFT INCREMENTS DUE TO BLOWING AND GROUND EFFECT. $\alpha=15^\circ$, $\eta=0^\circ$.

FIG. 6b. VARIATION OF LIFT INCREMENTS DUE TO BLOWING AND GROUND EFFECT. $\alpha=15^\circ$, $\eta=30^\circ$.

FIG. 7. COMPARISON OF THEORETICAL AND EXPERIMENTAL JET-INDUCED PRESSURE LIFT. $\alpha=15^\circ$, $C_D=\infty$.

FIG. 8. COMPARISON OF MEASURED AND THEORETICAL THRUST.
**Fig. 9a. Variation of Drag with Lift.** \( \eta = 0^\circ, \ \frac{h}{C_D} = \infty \).

**Fig. 9b. Variation of Drag with Lift.** \( \eta = 0^\circ, \ \frac{h}{C_D} = 0.162 \).

**Fig. 9c. Variation of Drag with Lift.** \( \eta = 0^\circ, \ \frac{h}{C_D} = 0.122 \).
FIG. 10a. VARIATION OF DRAG WITH LIFT. $\eta = 30^\circ$, $h/c_0 = 0.00$.

FIG. 10c. VARIATION OF DRAG WITH LIFT. $\eta = 30^\circ$, $h/c_0 = 0.158$.

FIG. 10b. VARIATION OF DRAG WITH LIFT. $\eta = 30^\circ$, $h/c_0 = 0.220$.

FIG. 10d. VARIATION OF DRAG WITH LIFT. $\eta = 30^\circ$, $h/c_0 = 0.140$. 
FIG. IIa. VARIATION OF PITCHING MOMENT ABOUT O-68 \( c_0 \) WITH LIFT.

\( \eta = 0^\circ, \frac{h}{c_0} = \infty \).

FIG. IIb. VARIATION OF PITCHING MOMENT ABOUT O-68 \( c_0 \) WITH LIFT.

\( \eta = 0^\circ, \frac{h}{c_0} = 0.162 \).

FIG. IIc. VARIATION OF PITCHING MOMENT ABOUT O-68 \( c_0 \) WITH LIFT.

\( \eta = 0^\circ, \frac{h}{c_0} = 0.122 \).
FIG. 12a. VARIATION OF PITCHING MOMENT ABOUT 0.68 \( c_0 \) WITH LIFT.
\( \eta = 30^\circ, \frac{b}{c} = \infty \).
FIG. 13. MOVEMENT OF CENTRE OF PRESSURE AND AERODYNAMIC CENTRE WITH HEIGHT $\alpha=15^\circ$