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CRANFIELD

Experiments on a Delta Wing Using Leading Edge Blowing to Remove the Secondary Separation

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CORRIGENDA

Page 2. Last line of paragraph 1 should read: "very close to the surface, without blowing, leave the leading edge."

Page 6. Ref. 6. should read: Alexander A.J. Experimental investigation on a cropped delta wing with edge blowing. College of Aeronautics Report No. 162.

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SUMMARY

It is found that the entrainment effect of a thin jet emerging from the leading edge of a delta wing is sufficient to remove the secondary separation. The minimum jet momentum required is small, but increases with incidence. Tests made without blowing, and with minimal blowing, include balance measurements, pressure plotting and tuft studies, over the range of incidence $\alpha = 0^{o} - 20^{o}$. It is concluded that the presence of the secondary separation does not affect the lift or the vortex height appreciably, but is at least partly responsible for the large discrepancy between theory and experiment with regard to the spanwise position of the vortex.

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LIST OF SYMBOLS

α	wing incidence
K	cotangent of leading edge sweep angle
c_o	root chord = 3.33 ft.
p	static pressure on wing surface
p_∞	free stream static pressure
p_B	static pressure on wing surface with L.E. blowing
p_o	static pressure on wing surface without L.E. blowing
q	mainstream dynamic head
s	wing local semi span
x	chordwise distance
y	spanwise distance
z	distance normal to wing
S	wing area
μ	measured total momentum ejected from L.E.
C_μ	blowing momentum coefficient $= \dfrac{\mu}{q.S}$
$C_{\mu crit}$	minimum value of C_μ required to remove secondary separation
C_L	lift coefficient $= \dfrac{\text{total lift}}{q.S}$
C_N	sectional normal force coefficient $= \dfrac{\text{normal force/unit chord}}{q.2s}$
C_p	pressure coefficient $= \dfrac{p - p_\infty}{q.S}$
ΔC_p	$\dfrac{p_B - p_o}{q.S}$

1. Introduction

The problem of the flow over a delta wing with leading edge separation has attracted a great deal of attention during the last decade. A large number of experimental investigations have been made and it may be said that the structure of the flow is fairly well understood. The fairly complete picture that has been built up has enabled various authors to perform theoretical studies incorporating the main features of the flow.

Although Legendre(1) and Kuchemann(2) have advanced theories, the works of Brown and Michael(3) and Mangler and Smith(4) are generally acknowledged to resemble most closely the actual flow field. Owing to the complicated nature of the problem, only a very simplified theoretical model is amenable to solution, and agreement between these theories and experimental results is generally not good. The discrepancies at subsonic speeds can be attributed to two causes. Firstly, none of the theories satisfy the Kutta-Joukowski condition at the trailing edge, and this leads to large differences between measured and predicted overall lifts. Compared on a section (spanwise) basis, measurements taken close to the apex of a delta wing agree rather better with theory. There is, at present, no adequate means of dealing with this problem. Secondly, the theories ignore the existence of the secondary separation, and it is usually assumed that this is the main cause of the discrepancy between theory and experiment in the region close to the apex of a delta wing, where even in subsonic flow reasonable agreement could be expected.

The extent of the influence of the secondary separation is impossible to assess unless either an allowance can be made for it in the theory, or a real flow can be produced in which it does not exist. No suitable theory has so far been produced, and since the secondary separation invariably accompanies the main leading edge vortex under normal circumstances, attempts were made to remove it by artificial means. Mention should be made here of the flow over the leeward side of a yawed delta wing (Ref. 5). At suitably large angles of yaw, the secondary separation seems to have disappeared and the vortex core moves outward from its unyawed position. At the same time the vortex core moves upward and the positions do not agree with theory. In view of the asymmetric nature of the flow, this is not surprising but it appears to be the only example of a leading edge vortex with no secondary separation occurring under "natural" conditions.

The secondary separation can be removed by artificial means, involving the use of some external power source, e.g. suction, and if these methods do not affect the flow appreciably in other ways, they could provide an insight into the influence of the secondary separation. In tests reported elsewhere (Ref. 6), leading edge blowing has been used to improve the characteristics of a delta wing and it was noticed that a relatively small amount of blowing was sufficient to remove the secondary separation, the entrainment action of the jet being sufficient to remove the slowly moving air in the separation region. A study of the flow field also showed that the flow with blowing resembled quite closely the theoretical flow pattern. A detailed study of this phenomenon was not made at the time, but it was noted that although the amount of blowing required to remove the secondary separation was small, it increased with incidence. Furthermore, the tests were made with the jet emerging normal to the leading edge and it was felt that under these conditions the direction of the flow close to the leading edge was very different from the direction without blowing.

In order to maintain conical flow with blowing, it may be shown that it is necessary to increase the momentum ejected linearly from a zero value at the apex. This was achieved by the use of suitably grooved perspex strips (see Fig. 2), and by varying the angle of the grooves relative to the edge, a swept jet sheet could be obtained. In order to cause as little change as possible near the leading edge, it was decided to blow at an angle of 50° to the normal to the leading edge, this being approximately the angle at which the streamlines very close to the surface leave the leading edge.

2. Model and range of tests

The model is shown mounted in the wind tunnel (Fig. 1). It is a delta wing having a leading edge sweep of 70° with cropped tips, of chord equal to one third of the root chord, and has an aspect ratio of 0.73. There is a continuous blowing slot round the periphery (of constant width 0.040 in.) except close to the apex, but these tests were made with blowing from the swept leading edges only. The jet was ejected in a rearward direction (50° back from normal to leading edge) with the use of the small perspex strips shown in Fig. 2. Saw cuts in the perspex broke the jet sheet up into a large numbers of small jets, each capable of being directed at the desired angle to the leading edge. They merged into a continuous sheet within a very short distance.

Measurements of static pressure were made at thirty-six holes at each of three spanwise stations, x/c_o = 0.33, 0.49, 0.62. Most of the measurements were made at x/c_o = 0.49, but some measurements were made at the other stations to see if the flow remained conical over the forward swept part of the wing. Balance measurements of lift were also made for $C_\mu = 0$ and $C_\mu = C_{\mu crit}$. Corrections for balance constraint due to the compressed air feed pipes are described in Ref. 6. No suitable wind tunnel interference corrections for this type of test are available and none have been applied. Conventional corrections are small, $\Delta\alpha = 0.4^{\circ}$ at $\alpha = 20^{\circ}$

The blowing momentum coefficient C_μ $\left(\equiv \dfrac{\text{total momentum ejected}}{q.S}\right)$ was calculated from the measured thrust, wind off. In order to maintain conical flow with leading edge blowing, the momentum ejected should increase linearly from zero at the apex and the momentum distribution for a fairly low C_μ value is shown in Fig. 3. Except for a region near the apex, the momentum distribution approximates to a linear one. A fair amount of scatter in the points is to be expected, owing to the difficulty of measuring the total head of the very small jets. The direction of the jets was within one degree of the desired angle of ejection.

3. Experimental results

In Ref. 6 it was shown that leading edge blowing eliminated the secondary separation, but beyond the observation that the C_μ required was small and increased with incidence, no measurements of the actual values were made. The presence of the secondary separation is characterised by a region of roughly constant pressure outboard of the main vortex core, and its elimination shown by a reduction in pressure as the pressure distribution changes shape and the vortex core moves outboard.

In order to find the C_μ value necessary to remove the secondary separation, measurements of static pressure were made at the second pressure hole ($y/s = 0.92$). The variation of ΔC_p due to blowing with C_μ at $\alpha = 10^o$ is shown in Fig. 4. For C_μ values greater than that at which the change in slope occurred, the pressure distribution showed no trace of the constant pressure region and it was presumed that the secondary separation had been eliminated (see Fig. 5). Surface flow patterns supported this conclusion (see Fig. 6) except at the highest incidence, where there may have been a small secondary separation close to the leading edge. Values of $C_{\mu crit}$ were chosen, slightly greater than the C_μ value corresponding to the change in slope of the ΔC_p - C_μ curve. Values of $C_{\mu crit}$ for $\alpha = 5^o, 10^o, 15^o, 20^o$ were .006, .028, .044 and .059 respectively.

Most of the pressure readings were taken at $x/c_o = 0.49$ but the chordwise variation in the static pressure distribution is shown in Fig. 7 for $\alpha = 10^o$. Without blowing, $C_\mu = 0$, the flow is approximately conical to 62% of the root chord. At $C_\mu = C_{\mu crit}$, Fig. 7b shows that the flow is approximately conical to at least half chord. Since blowing only extended to $x/c_o = 0.66$, it is not surprising that the flow was not conical in the neighbourhood of $x/c_o = 0.62$.

Fig. 8 shows the variation of spanwise pressure distribution at $x/c_o = 0.49$ with incidence for $C_\mu = 0$, and Fig. 9 shows similar distributions for $C_\mu = C_{\mu crit}$. The change due to suppression of the secondary separation can be clearly seen. It is also apparent that the blowing affects only the vortex flow outboard of the attachment line on the upper surface. Pressures inboard of this line are scarcely affected by the blowing. In Fig. 10 the non-dimensional spanwise pressure distributions are compared with the theoretical values of Mangler and Smith for $\alpha = 20^o$ ($\alpha/K \simeq 1$). Agreement is not good, although the distribution with blowing is closer to the theoretical curve than the distribution for $C_\mu = 0$. Both with and without blowing, the experimental curves are seen to be wider and flatter than theory predicts.

Total lift was measured on the balance over the incidence range for $C_\mu = 0$ and $C_\mu = C_{\mu crit}$ and the results are shown in Fig. 11. The increase in total lift due to blowing shows a constant percentage increase, $C_{LB}/C_{Lo} = 1.14$. Experimental values of the normal force coefficient C_N/K^2 obtained from integration of static pressures are compared with the theories of R.T. Jones(7), Brown and Michael and Mangler and Smith, in Fig. 12. With blowing, very close agreement is obtained between the Mangler and Smith theory and experiment, although this is probably fortuitous. Without blowing, experimental points fall somewhere between the R.T. Jones and Mangler and Smith theories, as do most experimental values.

Fig. 13 shows the movement of the vortex core, both with and without blowing, compared with the Brown and Michael, and Mangler and Smith theories. The spatial variation of the vortex position with blowing ($C_\mu = C_{\mu crit}$) appears to follow the Mangler and Smith curve very closely (Fig. 13c), but Figs. 13a and 13b show that at a given incidence (or α/K) neither the height nor the spanwise position agree with the theory. The Brown and Michael theory predicts more closely the vortex height at a given incidence for both sets of experimental points, but the spanwise position is still greatly in error. Without blowing, the vortex core is much further inboard than either theory predicts.

4. Discussion of results

The two theories which represent most closely the flow over a delta wing with leading edge separation, are those of Brown and Michael[3] and Mangler and Smith[4]. Comparison of these theories with experimental results is usually inconclusive, since the experimental lift results show a scatter as wide as the difference between the theories (see Fig. 17, Ref. 4) and the vortex positions are dependent on the state of the boundary layer on the wing surface under the vortex core.

Comparison of the experimental vortex positions with theory can also be misleading. It is generally assumed that the Mangler and Smith theory gives better agreement with experiment and, when results are compared by plotting vortex height against spanwise position, this appears to be so. The experimental results obtained with blowing are a case in point; good agreement is apparently obtained with Mangler and Smith in Fig. 13c but Figs. 13a and 13b show that this is not so. However, when vortex height and spanwise position are plotted separately against α/K, Fig. 13 shows that the Brown and Michael theory gives better agreement with experiment up to a value of $\alpha/K = 0.5$. Experimental results are more difficult to obtain at low incidence and the tendency to compare results taken at high incidence, where accuracy is greater, with theories which are valid only for low values of α/K, has obscured this fact.

The Brown and Michael theory has the further advantage that it provides only one set of answers from the basic assumptions and not four, as in the theory of Mangler and Smith. Unfortunately Mangler and Smith only calculate one set of answers based on their preferred A+ boundary conditions but a single pressure distribution calculated for a value of $\alpha/K = 0.50$ for a slightly different boundary condition (pressure b.c. satisfied at mid point of vortex sheet instead of wing leading edge) shows a movement in the spanwise position of the vortex core of .035s. Fig. 13 shows that a change of α/K of about 25% would be necessary to achieve this movement for any given set of boundary conditions. The change in vortex height is not given.

Fig. 12 shows that good agreement is achieved between the Mangler and Smith theory and the experimental values with blowing, but this agreement is thought to be fortuitous since the effect of blowing is to increase the lift at constant incidence and when plotting the results in this way there is no means of allowing for the effective change of incidence due to blowing.

Some general conclusions may be drawn from the movement of the vortex cores with blowing. The effect of blowing is to increase the height of the vortex core by about .01 - .02 z/s and this is the order of increase which might be expected from considerations of the lift, i.e. the vortex core moves upward because the lift is increased and not because the secondary separation is removed. It seems fair to conclude that neither vortex height, nor the lift, are affected by the presence of the secondary separation.

Consider now the effect of the secondary separation on the spanwise position of the vortex core. An increase in lift corresponds to an inward movement of the vortex core, in this case about .01 y/s, but there is an actual movement of some .05 y/s <u>outwards</u> and this can only be attributed to the removal of the secondary separation.

5. Conclusions

Firm conclusions are difficult to draw from this experiment, in which an attempt was made to reproduce a flow similar to the model proposed by Mangler and Smith for the purpose of trying to assess the effect of the secondary separation on the flow over delta wings.

1. It is possible, by means of leading edge blowing to remove the secondary separation. A certain minimum blowing value, $C_{\mu crit}$, is necessary and this increases with incidence. The jet entrains the slowly moving air between the main vortex and the leading edge and produces a flow which resembles the theoretical flow patterns.

2. The main effect of removing the secondary separation, using the minimum amount of blowing, is to move the leading edge vortex outboard some 5% of the semi-span from its unblown position. Since blowing increases the lift, the vortex core might have been expected to move inboard.

3. With $C_{\mu} = C_{\mu crit}$, the height of the vortex increases by about .015 z/s, roughly equivalent to the increase expected due to the increased lift. This strongly suggests that neither the lift nor the vortex height is affected by the presence of the secondary separation.

4. Good agreement is obtained between the normal force coefficient of Mangler and Smith and experimental values obtained by pressure plotting with $C_{\mu} = C_{\mu crit}$. This is to some extent fortuitous, since the way in which the results are plotted does not show the effective change of incidence due to blowing.

In general it would seem that the existence of the secondary separation has an important influence on the spanwise position of the main leading edge vortex, although it has very little influence on the vortex height and lift. There would seem to be considerable scope for improving the theory, even in its present form but undoubtedly some representation of the secondary separation is necessary if agreement betwen theory and experiment in this field is to approach that obtained in other branches of the subject.

6. References

1. Legendre, R. — Flow in the neighbourhood of the apex of a highly swept wing at moderate incidences. A.R.C. Report 16,796, 1954.

2. Kuchemann, D. — A non-linear lifting surface theory for wings of small aspect ratio with edge separations. R.A.E. Report Aero. 2540, 1955.

3. Brown, C.E., Michael, W.H. — On slender delta wings with leading edge separation. J.Aero.Sci., Vol.21, 1954, p.690, also NACA TN. 3430, 1955.

4. Mangler, K.W., Smith, J.H.B. — A theory of slender wings with leading edge separation. Proc. Roy. Soc., London, Ser.A Vol.251, 1959, p.200. Also R.A.E. Report Aero. 2593, 1957.

5. Harvey, J.K. — Some measurements on a yawed slender delta wing with leading edge separation. A.R.C. R. & M. 3160, 1958.

6. Alexander, A.J. — Experimental investigation on a cropped delta wing with edge blowing. Unpublished C.o.A. Report.

7. Jones, R.T. — Properties of low-aspect ratio pointed wings at speeds above and below the speed of sound. NACA Report 835, 1946.

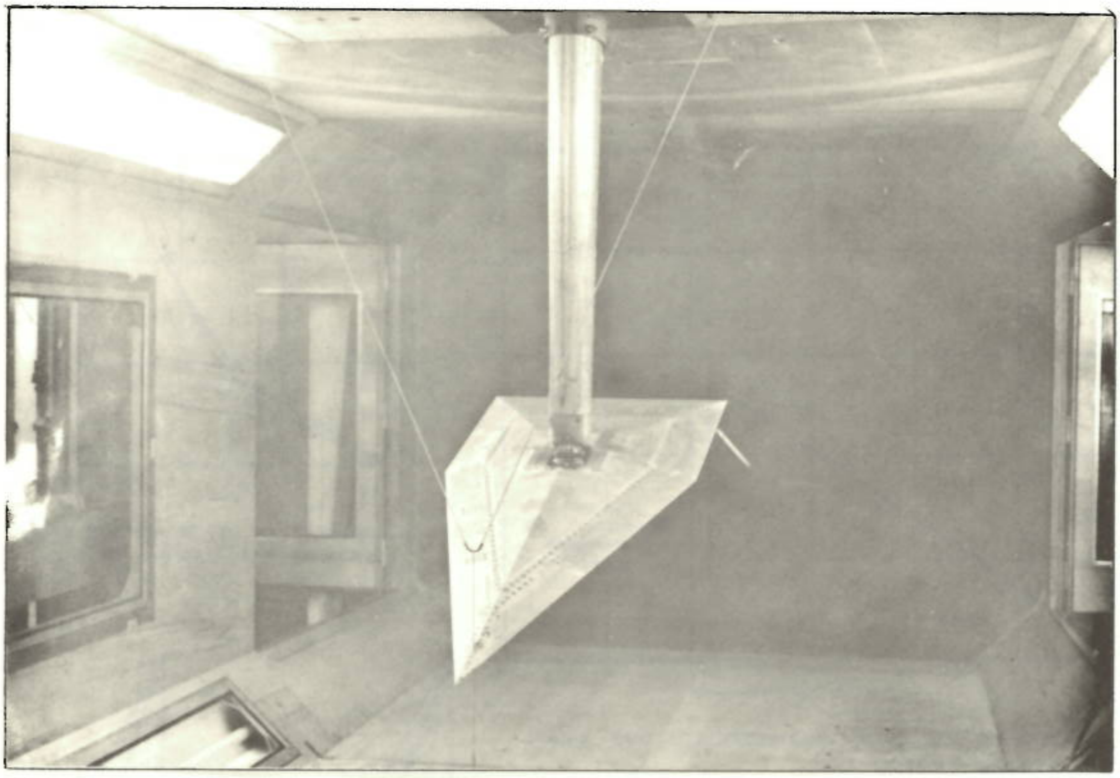

FIG. 1. MODEL MOUNTED IN WIND TUNNEL

FIG. 2. PERSPEX STRIPS FOR DIRECTING JET

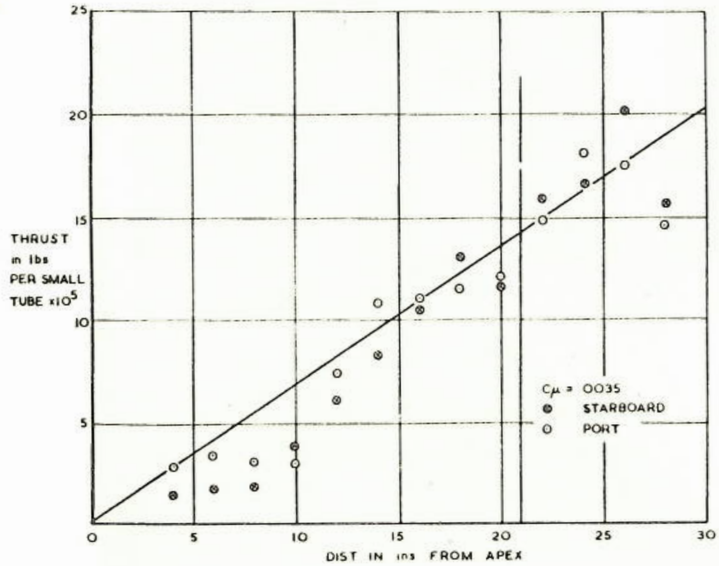

FIG. 3. BLOWING MOMENTUM DISTRIBUTION ALONG SWEPT LEADING EDGES

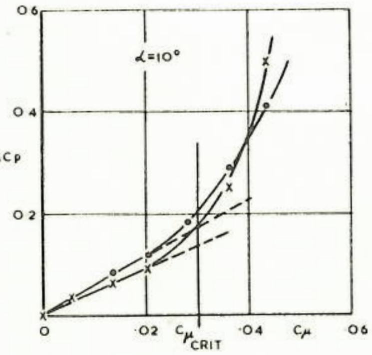

FIG. 4. VARIATION OF UPPER SURFACE STATIC PRESSURE WITH BLOWING. Y/s = 0·92

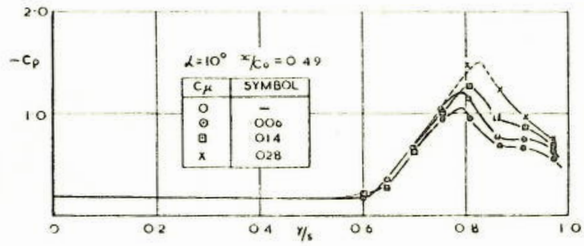

FIG. 5. VARIATION OF UPPER SURFACE STATIC PRESSURE DISTRIBUTION WITH BLOWING.

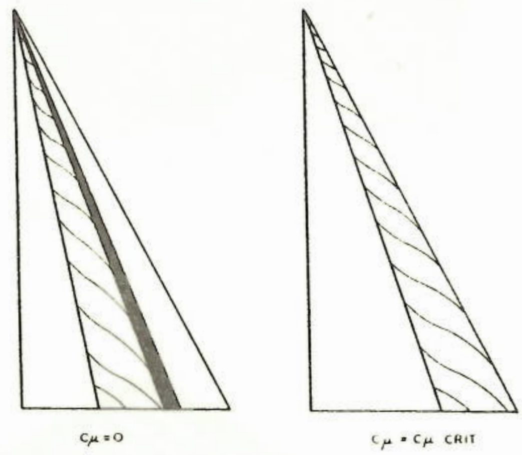

FIG. 6. SURFACE FLOW PATTERNS

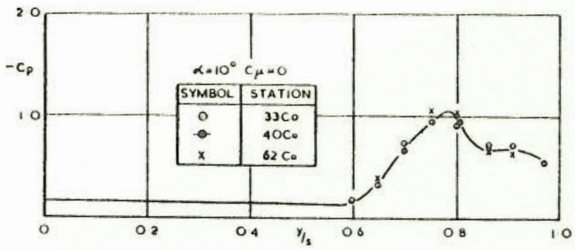

FIG. 7a. CHORDWISE VARIATION OF UPPER SURFACE SPANWISE PRESSURE DISTRIBUTIONS.

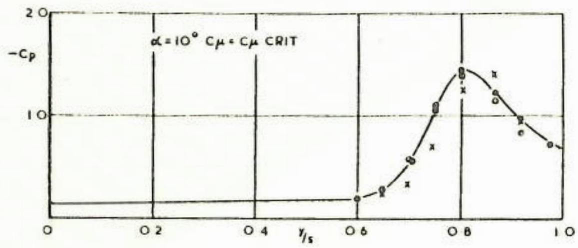

FIG. 7b.

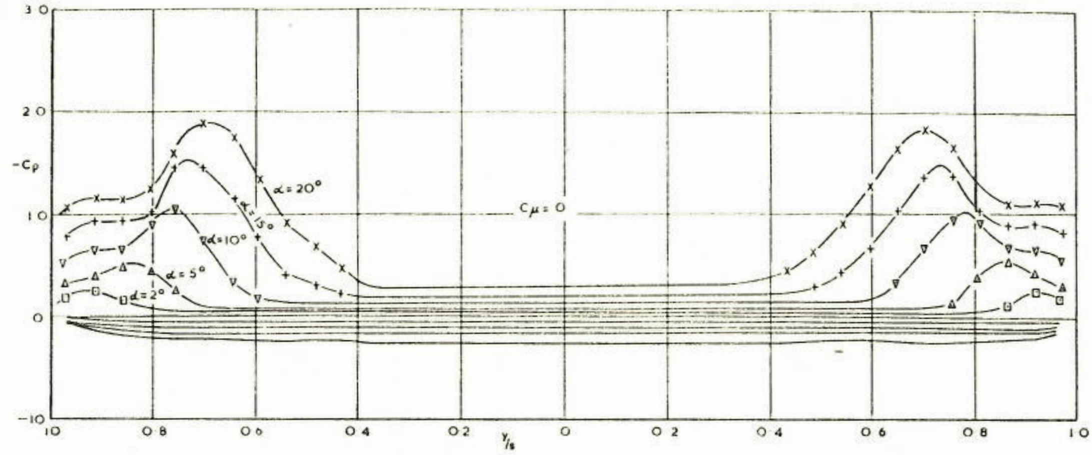

FIG. 8. SPANWISE VARIATION OF UPPER AND LOWER SURFACE STATIC PRESSURE DISTRIBUTIONS. $x/C_0 = 0{\cdot}49$.

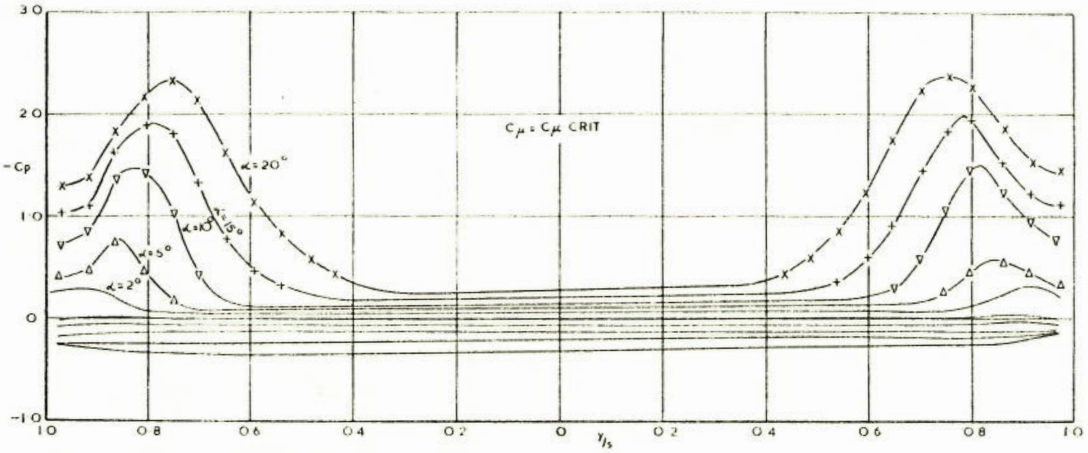

FIG. 9. SPANWISE VARIATION OF UPPER AND LOWER SURFACE STATIC PRESSURE DISTRIBUTIONS $x/C_0 = 0{\cdot}49$.

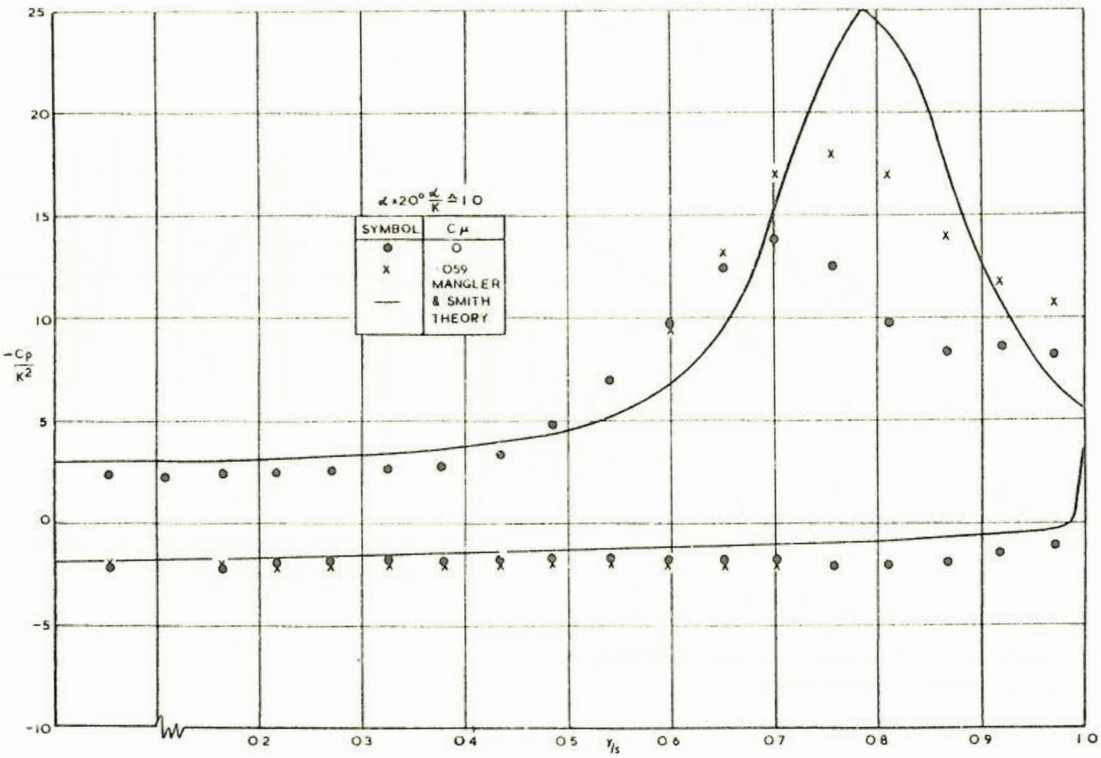

FIG. 10. COMPARISON OF THEORETICAL AND EXPERIMENTAL STATIC PRESSURE DISTRIBUTIONS.

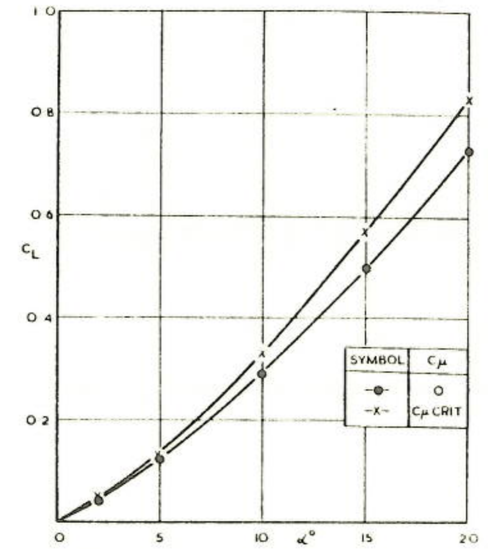

FIG. 11. VARIATION OF LIFT WITH INCIDENCE.

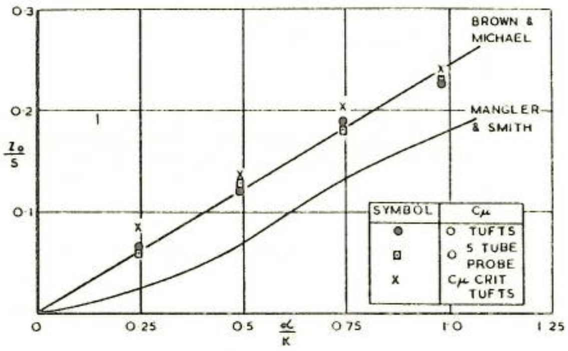

FIG. 13a. VARIATION OF VORTEX HEIGHT WITH INCIDENCE.

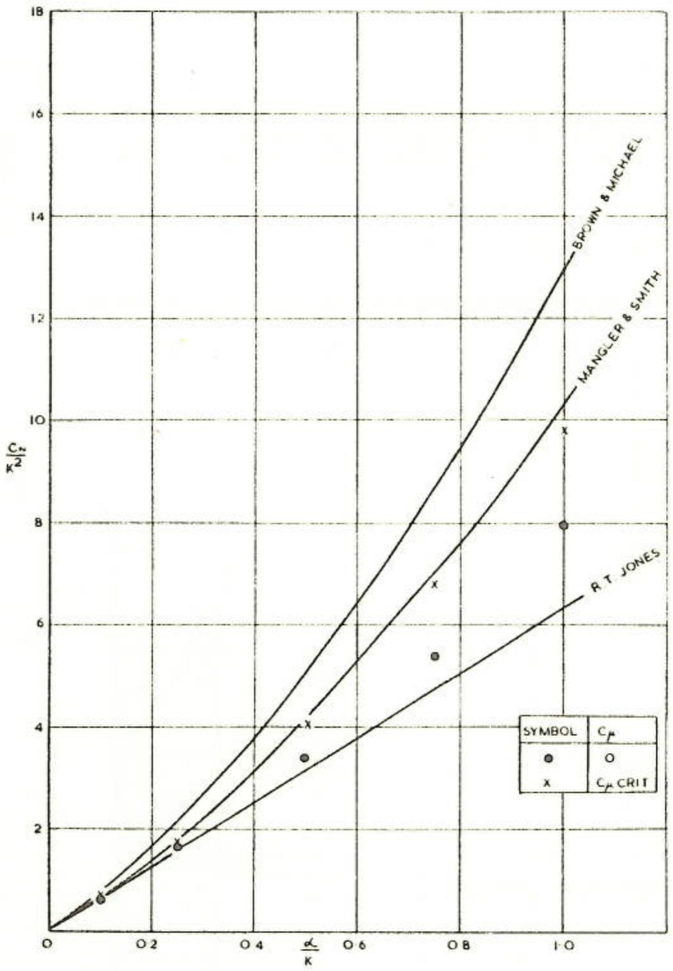

FIG. 12. COMPARISON OF THEORECTICAL AND EXPERIMENTAL NORMAL FORCE COEFFICIENTS.

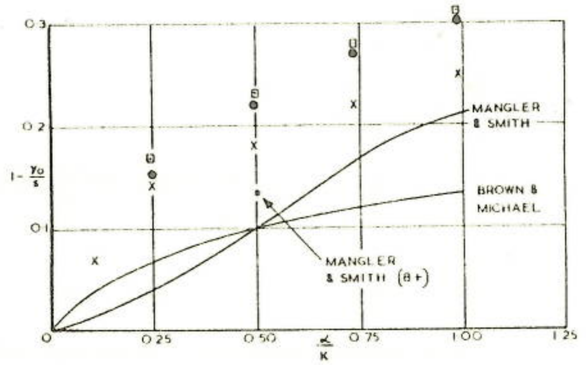

FIG. 13b. VARIATION OF SPANWISE POSITION OF VORTEX WITH INCIDENCE.

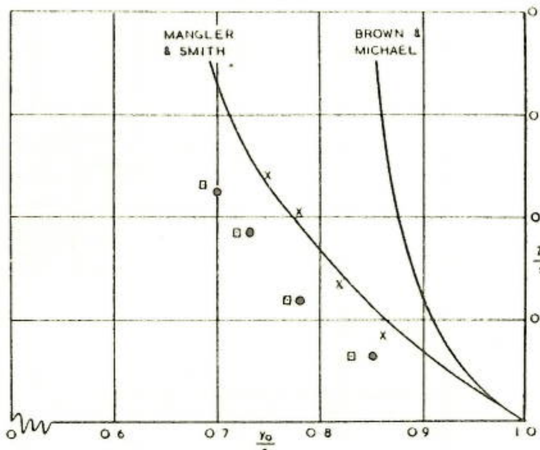

FIG. 13c. VARIATION OF VORTEX HEIGHT WITH SPANWISE POSITION.