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An Experimental Investigation of the Structure of a Leading-Edge Vortex

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An Experimental Investigation of the Structure of a Leading-Edge Vortex

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Summary. An experimental investigation of one of the pair of vortices, produced above a delta wing at an incidence of 14·9 deg, has been made by means of a five-tube yawmeter head. Traverses through the axis of the vortex, at three stations along the wing, suggest that it may conveniently be regarded as divided into three regions. These comprise an outer and an inner region, in both of which scale effects are evident, and a region between these wherein the flow is effectively conical. Within the inner region, which is approximately 5 per cent local semi-span in diameter, the gradients of total head, static pressure and velocity are very high. Here also, circumferential velocities equal to free-stream velocity and axial velocities of over 2·3 times this were recorded.

1. *Introduction.* Most experimental studies of the flow around highly swept wings[1, 2, 3] have been confined to measurements of the distribution of total head within the vortices which form above, and inboard of, the leading edges. Until recently, the only attempt to obtain a complete distribution of the velocity vector and static pressure was that made by Kirby, whose results (unpublished) revealed high velocities—substantially greater than free-stream velocity—along the axis of such a vortex. More recently, and concurrently with the present investigation, this has been verified by Cox[4], who measured the movement of smoke filaments injected into the core of a vortex, and by Lambourne and Bryer[5], using pitot and static tubes.

Like Kirby, Lambourne and Bryer have also obtained fairly detailed distributions of velocity and pressure by means of a five-tube yawmeter head. In consequence, the relatively large-scale variations of velocity through the vortex field are reasonably well established. However, little is yet known about the fine structure of the vortices, which has been the main concern of the experiments described here.

There are two main sources of interest in the small-scale structure of the velocity field. The vortex is formed by the rolling up of a thin layer of vorticity which separates from the highly swept leading edge. This suggests that the significant lateral scale in the outer regions of the field is the distance between successive turns of the spiral layer. Consequently, there is some interest in establishing the extent to which the spiral convection of vorticity can be detected in the mean velocity distribution. Ultimately, of course, diffusion causes successive turns of the spiral to merge smoothly into each other. Also, surrounding the axis of the vortex, there is a second region with a very small

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lateral scale to which particular attention is drawn in a parallel theoretical investigation by Hall[6]. If we regard the core of the vortex as that region in which no significant evidence of spiral structure can be detected in the mean flow distribution, diffusion of vorticity is important only within a very much more slender viscous sub-core, according to Hall, provided that the Reynolds number based on distance along the axis of the vortex is large enough. Hence it is only in this region that the core structure would be expected to exhibit any marked scale effect.

The measurements reported here have accordingly been spaced more closely than in earlier work and have been confined to two mutually perpendicular traverses through the axis of the vortex, in each of three planes normal to the direction of the undisturbed stream. They have again been made using a five-tube yawmeter head. In order to obtain a well defined vortex field of reasonable size compared with the measuring instrument, it was thought desirable to use a rather large model set at high incidence. The flow may therefore have been subject to substantial constraint from the walls of the wind tunnel. But since the outer region of the vortex field was found to be nearly conical, the observed flow was taken, without correction, to be suitably representative of the flow regime in question.

2. *Apparatus and Tests.* The tests were conducted in the Royal Aircraft Establishment 4 ft × 3 ft Low Turbulence Wind Tunnel, at a speed of 100 ft/sec. The wing was a flat-plate delta of aspect ratio 1, made from 0·3 in. thick Duralumin, and had a centre-line chord of 56 in. The leading edges were chamfered on the pressure side at an angle of 30 deg in a plane at right angles to the leading edge. The tests were made, for the most part, at an incidence of 14·9 deg with the wing supported on three vertical, streamlined struts, braced by cross-wires, measurements being made in three planes at 30, 50 and 70 per cent of the centre-line chord measured downstream from the apex.

The tests were made using a remotely controlled five-tube Conrad type head, made from half-millimetre hypodermic tubing, mounted on a traversing rig such that vertical and horizontal traverses could be made in a plane at right angles to the free-stream direction. The angles of pitch and yaw were controlled by repeater motors and were recorded on mechanical counters geared to the transmitters. The local flow direction was determined by balancing the pressures in opposite pairs of the outer tubes, the difference between the mean of these readings and the total head giving a measure of the dynamic head. Calibration of the instrument was made in a uniform free stream and has been assumed to hold, without correction, within the vortex field.

3. *Results.* Fig. 1 shows a representative traverse of total head, static pressure and total velocity through the vortex centre. In spite of the relatively large size of wing, it can be seen that the yawmeter head is by no means small compared with the region of the vortex where the gradients are large (hereafter called the viscous sub-core) even at the 70 per cent chord position. In consequence, there are probably fairly large errors in readings, which may vary in a systematic manner as the size of the instrument varies relative to the diameter of the viscous sub-core. However, if the traverses at 30 and 70 per cent chord, for example, are compared (Fig. 2), it can be seen that the differences are most significant in the viscous sub-core. These differences are quite large and indicate a gradient of axial velocity and static pressure which is of the order of magnitude predicted by Hall and, in general, accords well with variations attributed elsewhere[5] to scale effect. It seems unlikely therefore that this variation could be accredited wholly to instrument error. Again there is no reason for the differences in the width of the viscous sub-core, shown in Fig. 2, to be suspect.

The total-velocity curve in Fig. 1 shows the two peaks which might be expected from the high circumferential velocity gradient shown in Fig. 4 together with the kind of streamwise-velocity distribution shown in Fig. 3, the presence or absence of these peaks being dependent on the relative size of the circumferential-velocity gradient to the curvature of the streamwise-velocity curve. It may be noted in Fig. 3 that the maximum value of streamwise velocity is registered at a different position to that for minimum total head, this being because streamwise velocity, and not velocity parallel to the axis of the vortex, is plotted.

Fig. 4 compares the vertical traverses of circumferential velocity at three stations. Apart from the overall displacement of the curves, probably due to tunnel constraint effects, this figure shows that deviation from the general characteristics of conical flow, outside of the viscous sub-core, is not serious in this plane, the worst deviation being at the outer vortex sheet which is more sharply defined at 70 per cent chord. This is to be expected if the diffusion of the spiral sheet follows a power law x^n where x is the streamwise distance and n is less than unity. The viscous sub-core shows a variation in diameter between the three streamwise traverses much as is predicted by Hall who suggests that it should approximately follow an $x^{1/2}$ law. Accordingly in Fig. 6 is plotted $(x/c_0)^{1/2}(d/s)$ where d represents the distance between the maxima on each side of the solid rotating core and is taken as a rough measure of the viscous sub-core diameter. Clearly this law holds within the experimental accuracy of the results.

Another feature of the curves plotted in Fig. 4 is the waviness apparent in the vortex core, outside of the sub-core. This has been attributed to the residual effects due to the spiral sheet of vorticity. Thus, if the circumferential velocity is replotted relative to the centre of the vortex in four quadrants on a rotating system of axes as in Fig. 6, alternate points of inflexion on these curves may then be taken as a rough indication of the trace of the spiral skeleton. These points were plotted in rectangular co-ordinates and the smooth curve, drawn through them, was replotted onto Fig. 6. Clearly, however, not enough experimental points were taken to give accurate values for the points of inflexion.

A rough traverse was made at a nominal incidence of 28 deg with one degree of yaw at a point 5 to 10 per cent chord upstream of vortex breakdown and a total velocity of $4 \cdot 4V_0$ was recorded together with a pressure coefficient of -24. This was not quite at the centre of the vortex and slightly larger numerical results should be obtainable.

4. *Conclusions.* The investigation suggested that, for this wing under the conditions obtaining in the test, the leading-edge vortex can conveniently be regarded as divided into three regions. These comprise:

(1) a vortex core, approximately 30 per cent local semi-span in diameter, wherein the traces of the vortex sheet produce only minor perturbations on the circumferential-velocity distribution. The flow within this region is essentially conical in nature except for a slender region along its axis, namely

(2) the viscous sub-core, approximately 5 per cent local semi-span in diameter, in which the gradients of total head, static pressure and velocity are very high. The vortex core as a whole has been treated theoretically by Hall who predicted the existence of a non-conical sub-core, the diameter of which would vary with $x^{1/2}$ where x is the streamwise distance. This variation has been verified here as also have the trends of variation of velocity.

(3) Outside of the vortex core is a region in which the trace of the vortex sheet is marked and here again Reynolds number effects may be detected in the definition of the sheet. Whilst it is true that viscous diffusion has effectively erased the sheet within the vortex core, nevertheless the remaining traces can be detected sufficiently well for the spiral structure to be determined well into this region.

Within the viscous sub-core, circumferential velocities almost equal to free-stream velocity and axial velocities of over $2 \cdot 3$ times this were recorded at an incidence of $14 \cdot 9$ deg. Unfortunately, no information is as yet available on the behaviour of the instrument in these gradients and until measurements by other techniques are obtained, nothing can be said about the absolute accuracy of the investigation.

LIST OF SYMBOLS

c_0	Centre-line chord of wing
d	Diameter of viscous sub-core
H	Total head
p	Static pressure
p_0	Free-stream static pressure
r	Radial distance from centre of vortex
s	Local semi-span
u	Velocity component in free-stream direction
v_r	Circumferential-velocity component
V_0	Free-stream velocity
x, z	Rectangular co-ordinates in a vertical streamwise plane
ρ	Air density

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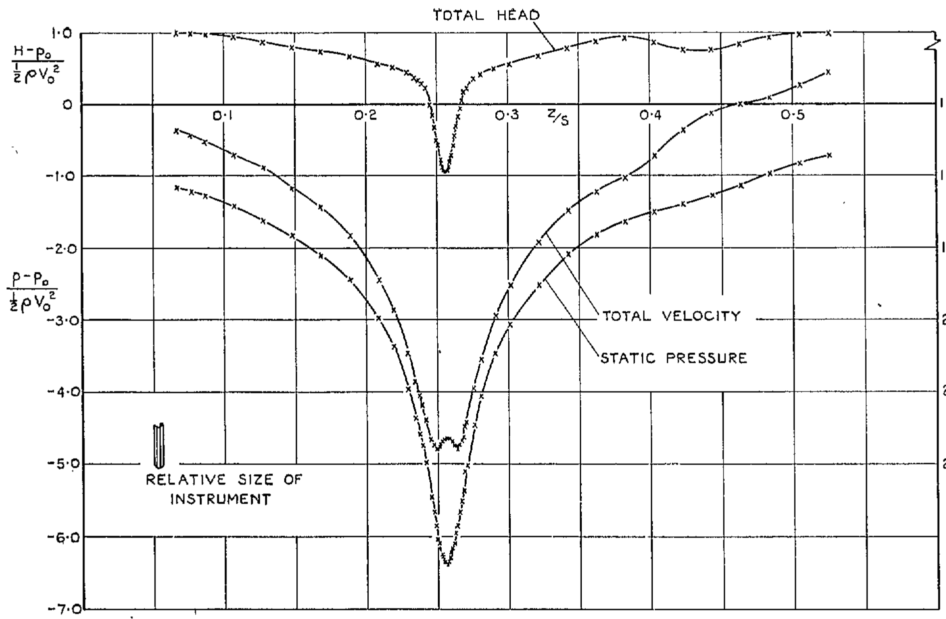

FIG. 1. Vertical traverse of total head, static pressure and total velocity through the axis of the vortex at 70 per cent chord.

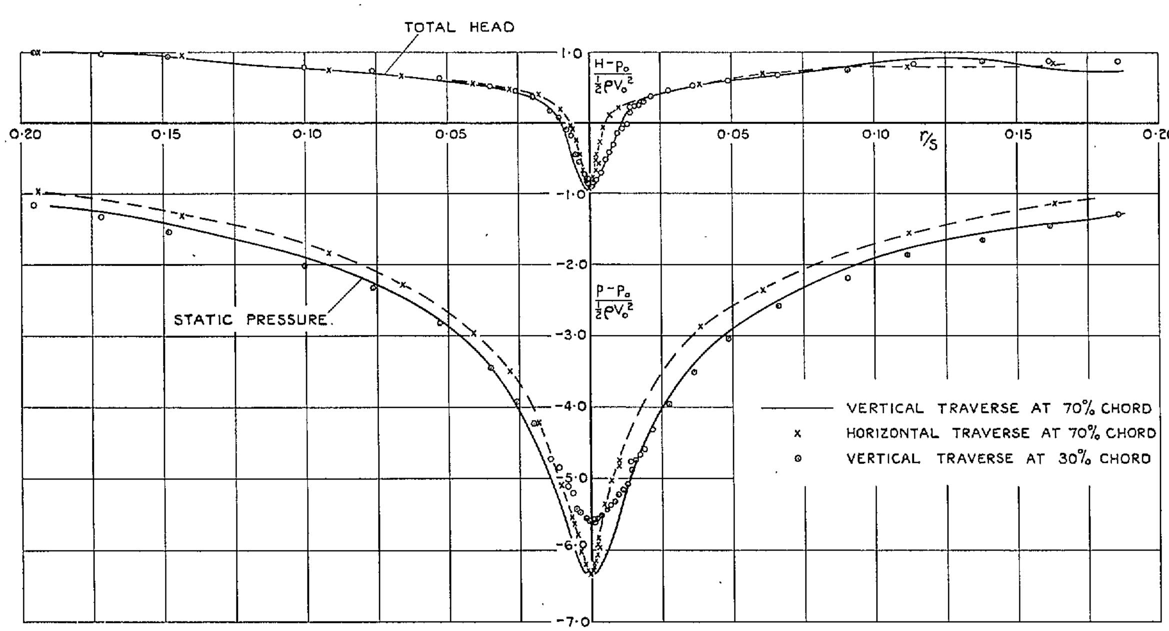

FIG. 2. Comparison of total-head and static-pressure traverses.

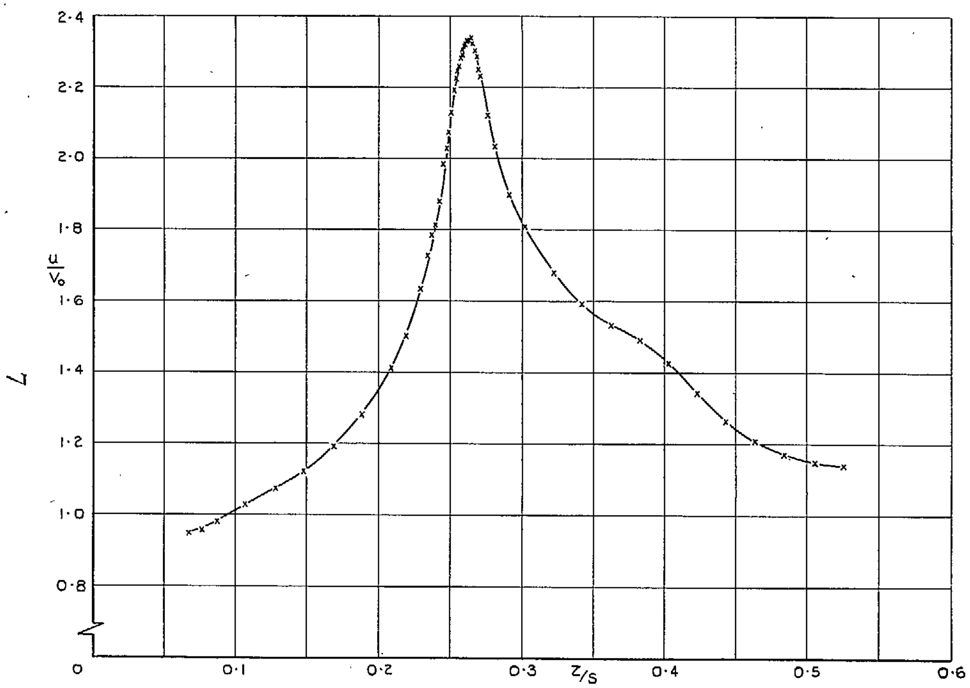

FIG. 3. Vertical traverse of streamwise component of velocity at 70 per cent chord.

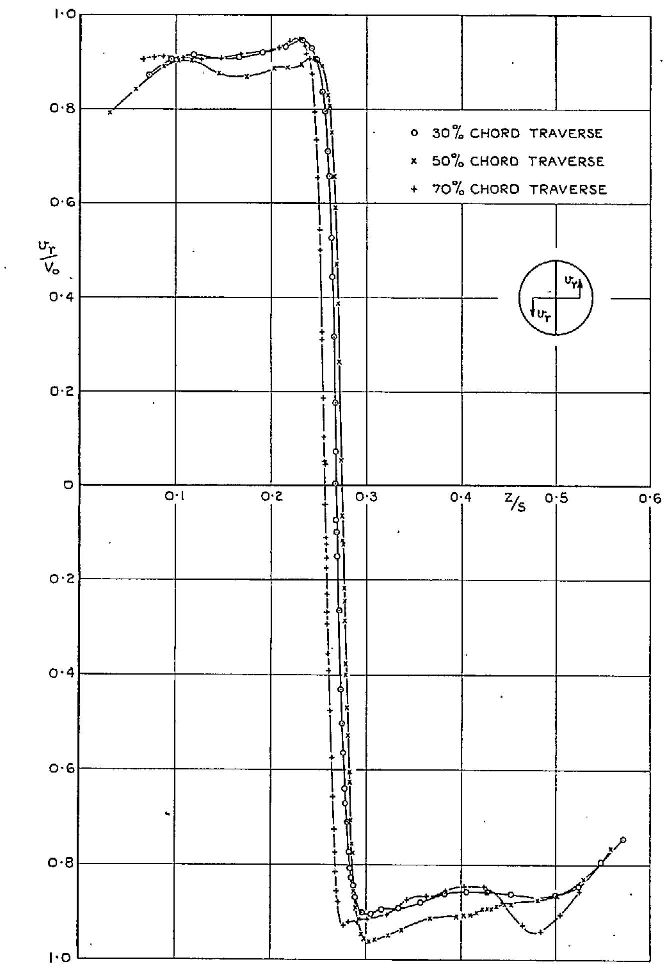

FIG. 4. Vertical traverses of circumferential velocity at three stations.

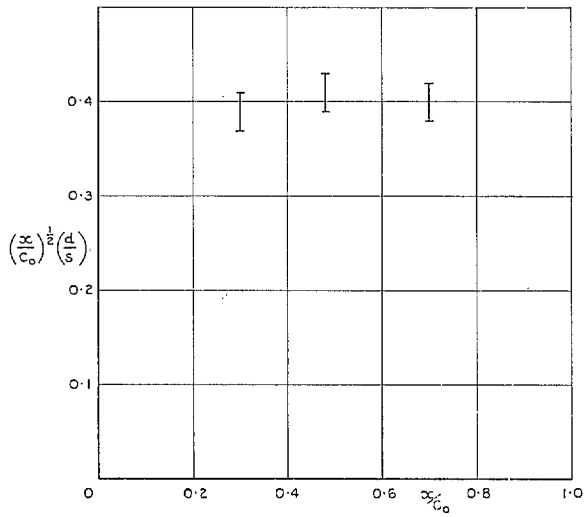

FIG. 5. Variation of viscous sub-core diameter with streamwise distance.

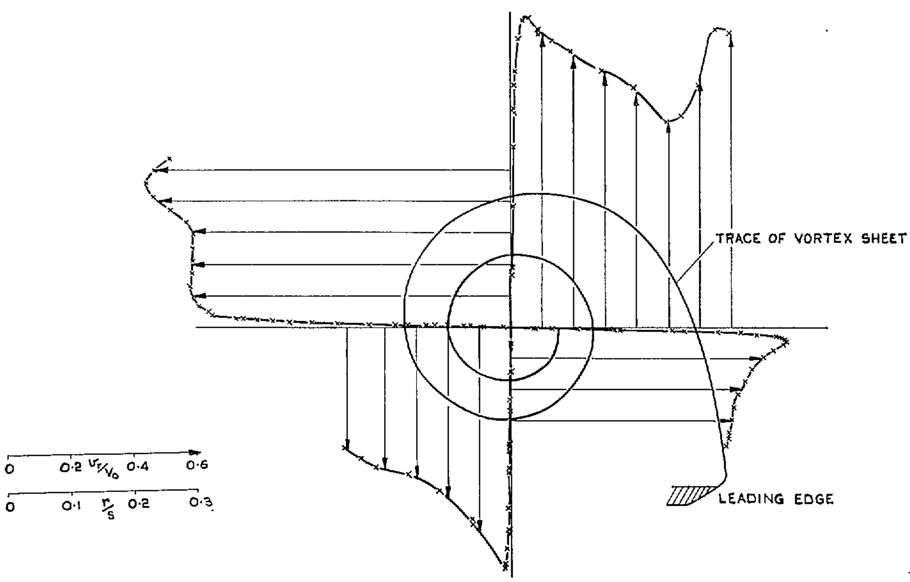

FIG. 6. Variation of circumferential velocity with radius in four quadrants.

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