Investigation of the three-dimensional flow over a 40° swept wing

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ABSTRACT

Three-component laser Doppler anemometry (LDA) has been used to measure the complex flow distributions over the suction surface of a symmetrical 40° swept wing model at an angle of incidence of 9° and for the relatively low Reynolds number (based on the root chord) of 2.1 × 10^5. Emphasis was placed on the separation and reattachment of the boundary-layer flow, and the formation of vortical structures.

The experimental programme now described utilised a large wind tunnel and several advanced measurement techniques to produce an unusually detailed collection of results. Thus, data are presented here for the behaviour of the three-dimensional boundary layer developing on the suction surface at positions from 30% to 90% semi-span. These results show the spatial variations of the time-averaged mean and fluctuating velocity components in three orthogonal directions, including the distributions of the normal and shear stress levels. Further analysis has enabled the time-averaged vortical structures to be identified and compared with the results of surface flow visualisation.

Flow over a swept wing poses many challenges for the computational modeller. The underlying aim, here, therefore, was to produce a data archive for the validation of computer predictions. As will be shown, some of the experimental results have already been used in this way and the data base is available for use by other workers.

Nomenclature

- span, mm
- local chord, mm
- turbulence intensity, dimensionless
- Reynolds number, dimensionless
- tangential velocity, ms⁻¹
- time-averaged tangential velocity, ms⁻¹
- normal velocity, ms⁻¹
- time-averaged normal velocity, ms⁻¹
- spanwise velocity, ms⁻¹
- time-averaged spanwise velocity, ms⁻¹
- chordwise co-ordinate, mm
- co-ordinate normal to wing surface, mm
- spanwise co-ordinate, mm

Superscripts and subscripts

- time-averaged value
- instantaneous velocity fluctuation
- free-stream value
1.0 INTRODUCTION

1.1 Flow over a swept wing

The flow over the suction surface of a swept wing at incidence is characterised by complex interactions between the boundary layer, regions of separation and reattachment, and the strong vortical structures which appear as a result of these interactions. These vortical structures can take either a ‘closed’ or an ‘open’ form, depending upon the angle of sweep and the operating conditions. The extreme case of the ‘slender wing’, for which the angle of sweep is normally taken to exceed 65°, has been extensively studied, and the vortical flow structures over such a wing are well understood (e.g. Riley and Lawson[1], Gursul[2]). Recently, however, there has been increasing interest in the flow over ‘non-slimmer’ swept wings because of their wide application in combat aircraft and unmanned air vehicles (or UAVs). The experimental studies by Gursul[3], Ol and Gharib[4], Yaniktepe and Rockwell[5], Rockwell[6], Yaniktepe et al[7], and the computational studies by Li and Leschziner[8,9], and Hahn and Drikakis[10], for example, all deal with the flow behaviour around non-slimmer delta wings in the range 35° – 55°.

Being aware of this background, another factor in the choice of the 40° and 60° sweep angles used in the present study was the knowledge that the leading-edge separation from a non-slimmer wing is much more complex than that over a (highly swept) slender wing. For example, the experimental studies carried out by Yaniktepe and Rockwell[5], for a wing with an angle of sweep of 38.7°, revealed the existence of several distinct zones of flow behaviour over the suction surface, coupled with a complex vortex system. In contrast, much less complexity is encountered for a wing with a higher sweep angle – Rockwell[6]. Thus, sweep angles of 40° and 60° were chosen for the present study in order to embrace the boundary between the two flow zones, and provide a severe test case for the validation of any computational model.

1.2 Measurement techniques

From the viewpoint of the experimentalist, the complex flow conditions above a swept wing bring significant difficulties. Since the main objective was to produce a comprehensive database of high quality flow information, there was little alternative to the use of non-intrusive laser-based methods of measurement. Given the availability of a sufficiently large wind tunnel, this narrowed the choice to two techniques, namely three-component laser Doppler anemometry (3D-LDA) and three-component Particle Image Velocimetry (3D-PIV). Now, although 3D-PIV is well-established, and has many advantages, it is recognised that typical levels of accuracy for the cross-plane velocity component are sometimes poor[11] and measurements of the turbulence properties are, at best, questionable. In contrast, 3D-LDA offers an extremely accurate technique for measuring three orthogonal velocity components of the flow, on a point-wise basis. Unfortunately, collection of the data inevitably involves greater difficulty and longer time-scales. Salient factors, here, are that the beam intersection point (i.e. the measurement volume) must be located with great precision over the whole of the measurement space, and the velocity data must be collected intermittently at high speed, then processed and sample-averaged to derive the required information. In practice, 3D-LDA introduces many challenges and the difficulties increase if the measurements are to be performed in a large wind tunnel, with the emphasis on using a relatively small model to minimise tunnel wall effects and the flow closest to the model surface. Additionally, in the wing boundary layer regions, optical reflections from the wing surface are likely to be strongest and the concentration of the seeding particles (which determines the particle arrival rates) is invariably lower than in the free-stream.

In planning the experimental programme, it was known that alternatives to 3D-LDA have usually been preferred by previous workers. For example, Gleyze and Capbern[12] studied the flow over a straight two-dimensional wing (i.e. an un-swept aerofoil) in a wind tunnel. However, after some initial experiments with 3D-LDA to check the two-dimensionality of the flow in the central plane of the wing, they resorted to a (less-demanding) two-component (2D LDA) system for the majority of their experimental study. Other simplifications have also been a feature of many previous investigations.

1.3 Factors influencing the detailed design of the models

Some of the investigations mentioned previously used simplified flat plate wing models e.g. Gursul[13]. Unfortunately, these models could never be fully representative because the relatively crude nature of the models, and particularly the geometrical features of their leading edges, could be expected to cause a fixed separation of the flow at the leading-edge of the model.

Other workers have confirmed that the geometrical features of the leading-edge exert a considerable influence on the boundary layer behaviour and, particularly, the vortical structures which arise on the suction surface – see, for example, Ericsson and King[14]. These findings all help to emphasise that the wing model for an experimental study of this kind needs to reflect full-size practice, incorporating both the correct aerofoil section, the appropriate distribution of loading, and the correct wing-tip shape. The present investigation was founded, therefore, on an appreciation of the complexities of three-dimensional flows over swept wings and the not insignificant instrumentation demands for flow measurement in a large wind tunnel.

Complementary measurements for the flow created by a 60° delta wing, together with more extensive results obtained by flow visualisation and three-component PIV, will be presented in later publications. As stated, the overall aim has been to generate a comprehensive and fully-documented database for the swept wings, providing detailed experimental results against which computational predictions can be compared.

2.0 EXPERIMENTAL APPARATUS

2.1 Design of wing models

The aerodynamic design of the 40° and 60° swept wing models was undertaken by McParlin[15]. In particular, the 40° model was designed using an inviscid panel method, according to standard procedures employed in the aerospace industry. The wing was intended to have a plan-form, thickness/chord ratio and pressure distribution, which were reasonably representative of a transonic combat aircraft, without requiring the release of any information of a commercially or security sensitive nature. The wing was designed to have a 40% chordwise roof pressure distribution, combined with elliptic spanwise loading and a design lift coefficient of 0.2. Additionally, the camber and thickness were chosen to give appropriate distributions of the loading, and local lift coefficient, this being achieved by iterative twisting of the aerofoil sections about the straight trailing edge. A basic RAE 102 aerofoil section was used.

Both symmetrical full-span wing models were machined from solid aluminium, without a fuselage, to satisfy the constraints imposed by the cross-sectional dimensions of the Avro Wind Tunnel. Consequently, the 40° swept wing model had a full span of 650mm, a root chord of 303.3mm and a tip chord of 90.9mm, with a constant 6% thickness to chord ratio along the whole span. This relatively sophisticated wing model was twisted around its straight trailing edge, between 86% semi-span and the tip, producing a kink in the leading-edge and a 5:33° wash-out angle at the tip. The wing tip was machined parallel to the root chord plane, ending with a semi-circular section across the thickness.
2.2 Details of the wind tunnel and model support

Experiments were performed in the Avro Wind Tunnel at the Goldstein Laboratory, University of Manchester. The working section of this general-purpose, closed-circuit return, wind tunnel was nominally rectangular in section, being 2.7m in width and 2.2m in height. Corner fillets were used to minimise secondary flow generation, giving a cross-sectional area of 5.15m², and the length of the working section was about 4m. The upstream settling chamber, incorporating a honeycomb and damping screens to optimise the flow distribution and reduce the turbulence levels in the working section, was followed by an inlet contraction with an area ratio of 6:1. This arrangement produced relatively low free-stream turbulence levels, remaining below 1% for velocities in the range 10 to 60 ms⁻¹.

Figure 1 shows how the 40° and 60° models were supported by attaching them to a 1.5m long support sting pointing upstream into the flow. In turn, the sting was mounted on a mechanical traversing mechanism that could be controlled remotely in pitch, yaw, roll and height. With this arrangement, the apex of the model was considered to be sufficiently far upstream of the traversing mechanism for any blockage effects associated with the model support to be ignored.

Since the intention was to make the experimental results available for the validation of CFD predictions, it was considered acceptable (and computationally convenient) to set the free-stream velocity to the relatively low level of 10 ms⁻¹. This corresponded to a Reynolds number of 2.1 x 10⁵ for the 40° wing, based on the free-stream velocity level and the root chord. Following a preliminary series of experiments to define the aerodynamic performance of each wing, involving visualisation and measurements with a force balance, the experiments were restricted to a single angle of incidence for reasons of expediency, recognising the very long time periods needed to calibrate the 3D-LDA system and collect sufficiently detailed data. For the 40° swept wing model, therefore, all the experiments with LDA were undertaken at a fixed incidence of 9° (based on the root chord). For this incidence, the wing was observed to operate in the pre-stall condition, with the expected region of reversed flow close to the wing tip, as will be discussed later. Similar measurements were made for the 60° delta wing model although these results will only be referred to briefly in this paper.

2.3 The LDA system

Measurements were made using a Dantec three-component LDA system, set-up in the cross-coupled coincidence mode to obtain instantaneous values of the velocity components in three orthogonal directions across the suction surfaces of the models. In this advanced system, a Coherent N90 5W argon-ion laser was operated at a power level of 2W in the all-lines mode to generate a single laser beam. This collimated laser beam was separated by the optical transmitter (Dantec 60X41) into three pairs of coloured coherent beams (in the green 512nm, blue 488nm and violet 476nm wavelengths). The beam pairs were transmitted along single mode fibre-optic cables to reach the two optical transmission probes (capable of one and two-dimensional measurement, respectively). These directed the three converging beam pairs into the wind tunnel working section, and collected the light scattered by the seeding particles moving through the measurement volume. A frequency shift of 40MHz was applied to one beam in each colour-separated pair to allow measurements to be made in regions of flow reversal.

The two optical transmission probes were mounted on a horizontal beam carried by a second three-axis mechanical traversing unit (supplied by Dantec), thereby providing an included angle of approximately 40° between the transmitted and receiving directions. This computer controlled traversing mechanism was an essential element in the measurement system, providing accurate positioning of the measurement volume and a minimum displacement between successive measurements of 0.25μm in the three orthogonal directions. The optical system, incorporating beam expansion and large diameter (2m focal length) transmission lenses, enabled 112mm separation of the three pairs of laser beams ‘at the front lens’. In turn, this yielded a measurement volume with dimensions of approximately 200μm in each of the three orthogonal directions and calibration factors of 8.93, 8.48, 9.83MHz/ms⁻¹ for the three (green, blue and violet) channels of the cross-coupled LDA system. Velocity bias in the data was removed by using the individual particle transit times to correct the sample mean values. Analysis has shown that the statistical uncertainty in the averaged velocity component was approximately 1% near the wall and less than 0.04% in the free stream.

The two LDA transmitting and receiving probes, mounted on the traversing mechanism, were located in an enclosed laser safe area underneath the wind tunnel working section. During operation, the three pairs of laser beams were transmitted upwards through a window in the floor of the working section and brought to an intersection in the flow. For convenience, each wing was aligned in the vertical plane for the LDA experiments, and improved access was obtained to the flow developing across the curved suction surface by inclining the optical beams so that the beam pairs approached the wing models from below the working section at an angle of approximately 8° to the vertical plane. These geometrical details were accounted for during numerical processing of the experimental results by the incorporation of an appropriate co-ordinate transformation.

Since interest centres on the flow behaviour in the boundary layer, the local surface of the model must be located with great precision in measurements of this type. Here, the intensity of the laser light reflected from the models, monitored using the photo-multiplier (PM) tubes in each colour-discriminated channel, enabled the relative distance between the centre of the measurement volume and the wing surface to be determined with considerable accuracy. One practical check on this spatial accuracy was that the velocity data (for each orthogonal component) should satisfy the no-slip condition when extrapolated back to the model surface – see, for example, the data presented in Fig. 4. Subsequently, each measurement traverse across the boundary layer was usually started at a distance of 0.2mm from the model surface to achieve a reasonable data rate, and the flow velocity was measured at 32 positions (extending to 80mm from the surface) for each traversing position, moving along the local normal to the wing surface – see Table 1 and Fig. 2. To ensure that satisfactory time mean values were obtained, at least 2,000 discrete velocity values (or realisations) were collected in each measurement position. This was achieved by fixing the sample time at 150s, irrespective of the particle arrival rate, and operating the LDA (Burst Spectrum Analyser) signal processing equipment in the validation mode.
In complex flow situations of this type, alignment of the optical system is particularly important if a high data rate and reliable data are to be obtained. The laser beam pairs were therefore aligned with the aid of a CCD sensor system, which enabled the six beams to be adjusted and brought to an accurate intersection in the working section (Jaryczewski(15)). Locating the positions of the six beams, in two planes separated by a known distance along the optical axis, yielded a coordinate transformation, from which the measured velocity components (relative to the three optical axes defined by the pairs of beams) could be converted into three orthogonal velocity components, corresponding to the local coordinate directions at each measurement position above the surface of the swept wing model – see Fig. 2.

3.0 MEASUREMENT PROGRAMME

LDA measurements have been made along the lines normal to the local aerofoil section, for each of the starting positions on the wing surface defined in Table 1. For further clarification, it may also be convenient to refer to Fig. 2.

### Table 1
**Measurement grid on the suction surface of the 40° swept wing**

| Spanwise stations z/h | 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 |
| Streamwise stations x/c | 0.1, 0.3, 0.5, 0.7, 0.9 |

NB $b$ denotes the semi-span and $c$ denotes the local chord.

Post-processing of the LDA data produced information on the mean flow and turbulence characteristics in the boundary layer. As mentioned, three orthogonal velocity components were initially obtained along the lines normal to the local aerofoil section. The derived results were then transformed into the aerofoil co-ordinate system, yielding the time averaged values of the local tangential velocity component $U$ along the $x$-direction (positive velocity implying flow in the streamwise direction), the normal velocity $V$ along the $y$-direction (positive when directed outwards from the wing surface), and the spanwise velocity component $W$ in the $z$-direction (with $W$ positive when directed towards the wing root). These measured mean velocity values were averaged and converted into a non-dimensional form by dividing each component by the free-stream value (leading to $U/U\infty$, $V/U\infty$, $W/U\infty$), as shown in Fig. 3. The corresponding non-dimensionalised turbulent fluctuations $\sqrt{U^2/U\infty}$, $\sqrt{V^2/U\infty}$, $\sqrt{W^2/U\infty}$, as well as the turbulent shear stresses $(u'v'/U_{\infty}^2)$, $(w'v'/U_{\infty}^2)$, $(w'v'/U_{\infty}^2)$, were also determined. Finally, the turbulence intensity, defined by the expression $I = \sqrt{(u'^2 + v'^2 + w'^2) / 3U_{\infty}}$, could be calculated – see Schlichting and Gersten(16).

4.0 EXPERIMENTAL RESULTS

4.1 Flow visualisation

Initially, surface flow visualisation was carried out by smearing a mixture of paraffin and paint pigment onto the wing surfaces. The two models were then exposed to a constant velocity flow of approximately $20\text{ms}^{-1}$. This caused the liquid to evaporate, leaving behind a record of the shear stress direction and, hence, the direction of the flow adjacent to the wing surface. The resulting tracer patterns were then photographed, leading to images of the type shown in Fig. 3. Note that typical results for the $60°$ delta have been included here simply to confirm that a relatively more simple surface flow structure was indeed observed for this slender wing.

Careful study of the visualisation images enables the complex three-dimensional nature of the flow in the boundary layer to be understood. However, it is worth observing that some of the flow details were revealed with greater clarity in video recordings of the oil film movements, before the paraffin had dried. The LDA and PIV techniques were then employed to explore some of these features. Although the whole visualisation study will be reported separately, it was felt that at least a mention of the basic findings was needed here because the results provide such a convenient check on the measured velocity distributions.

After the initial (primary) separation at the leading-edge, the flow re-attaches (shown by the dashed line) and more complex flow patterns appear near to the tip, leading to regions of reversed flow and two saddle points (denoted by SP) – see Fig. 3(b). One component of the reattached flow proceeds downstream in the chordwise (i.e. streamwise $x$) direction, while the other component turns back towards the leading-edge and separates at the secondary separation line. A separation bubble can be observed between the primary separation line and the reattachment line, with one dominant helical vortex within this bubble, as indicated in Fig. 3(b). Furthermore, due to the relatively low static pressure on the suction surface, flow occurs from the pressure surface to the suction surface around the tip and the outer part of the trailing-edge. This creates another flow separation region indicated by the dashed line at the trailing-edge.

4.2 LDA data reduction and representation

LDA made it possible to measure the velocity components of the flow at a distance of 0.2mm from the surface (i.e. $z/b = 0.0006$). In turn, this information revealed the flow directions. Referring to Fig. 3(b), it is seen that the flow directions so obtained are entirely consistent with the surface flow visualisation. For example, the arrows correctly follow the complex flow patterns close to the secondary separation line at the leading edge. Similarly, two-dimensional flow after the re-attachment line is revealed by the streamwise streaks in the visualisation photograph, between the root and 50% semi-span, and the comparatively high streamwise near-wall velocity components obtained by LDA measurement. In contrast, significantly lower velocity levels are observed near the wing tip and inside the separation bubble, upstream of the secondary separation line. Especially small velocities are observed near the saddle points, where the flow becomes highly three-dimensional. Moreover, both the velocity vectors and the surface visualisation patterns confirm the existence of a region of reversed flow near to the wing tip. The excellent agreement between the LDA results and the flow visualisation was taken as an indication that the properties of the time-averaged flow could be measured with satisfactory accuracy using the 3D-LDA system, even as close as 0.2mm to the aerofoil surface. Refer to Section 2.3 for a discussion of the experimental errors.

Figure 4 shows the boundary layer distributions of the three velocity components, presented in the tangential, normal and spanwise directions, in the chordwise plane at 30% semi-span.
Examination of the distributions of the normal velocity component in Fig. 4(b) reveals that the developing boundary-layer flow retains a velocity component directed towards the surface over most of the chord length, helping to explain how the flow remains attached and follows the curvature of the wing in the plane at $z = 0.3b$. Again, the flow distributions closest to the leading-edge show different trends to all the rest. Combining the distributions for the three velocity components with the high peak levels of turbulence indicates the strongly three-dimensional nature of the flow around the curved leading-edge of the swept wing – see also Fig. 3(b).

Finally, the distributions of the spanwise velocity component are presented in Fig. 4(c). These results confirm the highly three-dimensional nature of the flow in this plane at 30% chord ($x/c = 0.3$). In particular, there are large spanwise velocity components of $z = 0.3b$). Each component has been normalised by the free-stream velocity. The fourth graph shows the variation of the turbulence intensity in the boundary layer. These results are given here for five chordwise locations (Fig. 3 and Table 1) and a single Reynolds number of $2.1 \times 10^5$.

In Fig. 4(a), the local tangential component is seen to vary smoothly within the wing boundary layer, reaching a maximum value of 1.3 times the free-stream velocity close to the leading edge, presumably due to movement of the flow from the compression to the suction surface in this small region. Moreover, the level of the tangential ($x$-direction) velocity component at the outer edge of the boundary layer reduces gradually with increasing distance downstream. This finding is in agreement with the experimental results of other workers – see, for example, Gleyzes and Capbern.

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Figure 5. Distributions of the three normalised mean velocity components and the turbulence intensity, for the boundary layer at 80% semi-span ($z/b = 0.8$).

Figure 6. Distributions of the Reynolds stresses within the boundary layer – obtained at 80% chord for a Reynolds number $2.1 \times 10^5$. 
about 0.7 $U_\infty$ towards the wing root near the surface, changing to a component of 0.35$U_\infty$ spanwise towards the wing tip at a distance of 0.02$b$ from the surface. In the inner region, between 30% and 90% chord, the flow becomes nearly two-dimensional and, beyond 50% chord, the spanwise velocity falls to very low levels and, certainly, below 10% of the free-stream velocity.

The turbulence intensity levels for the various traverse positions reach a maximum of around 10% at the wing surface, reducing to the 1% level at a wall distance of $y/b = 0.03b$. However, due to flow separation from the leading-edge, the turbulence intensity for the boundary layer measured at 10% chord ($x/c = 0.1$) reaches almost 30% at a distance from the wing surface $y/b = 0.14$.

Moving to the measurement plane at 80% semi-span, it is apparent from the distributions of the tangential velocity intensity presented in Fig. 5(d), the region of the flow corresponding to the elevated shear stresses becomes wider as it moves downstream. Moreover, the shear stress distributions have a similar shape in all the downstream stations, the term $-\overline{u'v'}$ (acting in a plane $z = \text{constant}$) has the largest value of the three shear stresses, presumably due to the large mean velocity gradient $\partial U/\partial y$ across the thickness of the boundary layer – see Fig. 5(a). Examination of the data in Fig. 6(b) shows that the shear stress $-\overline{u'w'}$ (acting in a plane $y = \text{constant}$) tends to a negative value in the near wall region, possibly associated with the vortex observed in the plane $z = 0.8b$. Finally, it is noted that the shear stress $-\overline{w'v'}$ (acting in a plane $x = \text{constant}$) was the smallest of the three shear stress components, despite the rotational motion in the transverse plane above the suction surface.

Figure 7 shows the transverse velocity vector fields, calculated as the vector resultant of the spanwise and normal components, superposed on the contours of the tangential velocity component appearing in the boundary layer at 10% chord ($x/c = 0.1$) are consistent with flow separation at this location.

In Fig. 5(c), due to the vortical structures that develop over the suction surface, high spanwise velocity components, ranging from $-0.3U_\infty$ to $0.2U_\infty$, appear very near to the wing surface (at a distance $y/b = 0.01$). Moreover, on the wing surface ($y/b = 0$) beyond 30% chord ($x/c = 0.3$), the flow direction is towards the wing tip, as indicated by the negative spanwise velocities. Conversely, the flow is directed towards the wing root at 10% chord, possibly due to the flow reversal inside the separation bubble, as indicated by the surface visualisation image – see Fig. 3.

Finally, Fig. 5(d) reveals that the maximum value for successive distributions of the streamwise turbulence intensity level moves progressively away from the wing surface as the distance from the leading-edge increases i.e. moving in the chordwise ($x$) direction. A maximum intensity of approximately 25% is reached at 70% chord. These changes are associated with the developing boundary layer and the presence of the wing tip vortices.

Figure 8 shows the distributions of the three turbulent shear stresses and the streamwise normal stress, for the five stations in the spanwise plane at 0.8$b$. As observed for the distributions of the turbulence intensity presented in Fig. 5(d), the region of the flow corresponding to the elevated shear stresses becomes wider as it moves downstream. Although the shear stress distributions have a similar shape in all the downstream stations, the term $-\overline{u'v'}$ (acting in a plane $z = \text{constant}$) has the largest value of the three shear stresses, presumably due to the large mean velocity gradient $\partial U/\partial y$ across the thickness of the boundary layer – see Fig. 5(a). Examination of the data in Fig. 6(b) shows that the shear stress $-\overline{u'w'}$ (acting in a plane $y = \text{constant}$) tends to a negative value in the near wall region, possibly associated with the vortex observed in the plane $z = 0.8b$. Finally, it is noted that the shear stress $\overline{w'v'}$ (acting in a plane $x = \text{constant}$) was the smallest of the three shear stress components, despite the rotational motion in the transverse plane above the suction surface.

For the planes at 30% chord and beyond (Figs 7(b) to 7(e)), the boundary layer remains attached and there is a significant flow velocity towards the wing tip. The separated shear layer is distinguishable in all five planes, becoming thicker and moving away from the wing surface as it moves downstream. Moreover, the reversed flow region reduces in size as the flow moves downstream.
Alternatively, Fig. 8 shows the time-averaged streamlines and contours of the turbulence intensity at the same five spanwise (fixed chord) planes for a Reynolds number of $2 \times 10^5$. The results at 10% chord, which are shown in Fig. 8(a), indicate that the separated shear layer effectively divides the flow across the wing surface into two regions. An up-wash flow appears above the shear layer, while the flow below the shear layer is moving along the surface, with a strong inclination to move towards the wing tip.

Based on the time mean velocity distributions in the transverse planes, i.e. ignoring the streamwise component for this purpose, it was possible to calculate the distribution of the streamlines. These mean streamlines reveal another important feature of the flow over the suction surface, which can be identified in each of the five measurement planes. In Fig. 8(b), for example, the mean streamlines in the transverse plane at 30% chord indicate the presence of a well-defined vortical structure. From comparison with the distributions in Fig. 7(b), it is apparent that this vortical structure is bounded by the separated shear layer referred to previously. Subsequently, the results for successive planes show how this vortex grows as the flow moves downstream – see Figs 8(c) to 8(e). The contours show that the turbulence levels were highest in the core of the vortex and in the shear layer separation region close to the wing tip.

4.3. Vortical structures over the suction surface

The line representing the locus of the vortex core can be compared with the results of the surface flow visualisation – see Fig. 9. As expected, the vortex core was located approximately mid-way between the reattachment and the secondary separation lines (indicated by lines (i) and (iii) in Fig. 9(a)). Considering, next, the height of the vortex core above the wing surface, the results in Fig. 9(b) indicate that the vortex core moved steadily away from the surface in successive measurement planes up to perhaps 50% chord. Thereafter, it lifted more rapidly off the surface as it approached the trailing-edge. This vortex behaviour induced strong three-dimensional flow components and was probably responsible for the reversed flow pattern observed at the trailing edge – see Fig. 3. The more detailed information obtained using PIV confirmed these findings and will be published in due course.

Location of the vortex core made it possible to determine the variation in the spanwise and normal velocity components within the vortex, as shown in Fig. 10. Although these profiles were obtained on planes defined normal to the aerofoil surface in the chordwise plane, they still show the evolution of the vortex as it develops downstream. Assuming that the effective diameter of the vortex can be defined by the distance between the maximum (positive) and minimum (negative) values of the spanwise velocity, it is seen that this diameter increases from around 5mm at 30% chord to more than 40mm at 90% chord. Again, this agrees with the surface flow visualisation results presented in Fig. 9. In addition, for a forced-vortex core flow, the circumferential velocity should vary linearly with distance from the centre. The position of this centre, corresponding to a zero velocity level, is indicated by the symbol ⊗.

5.0 CREATING A DATABASE OF THE EXPERIMENTAL RESULTS

The conditions to be satisfied by any database intended for validation purposes have been discussed by Schaeffler and Jenkins(17). The essential requirements are that the experimental details, including all the test procedures and any limitations of the apparatus and the instrumentation, should be recorded in complete detail. The experimental errors must also be estimated so that these can be included in any assessment of the validity of the computational procedures.

The nature of LDA measurement in a large wind tunnel raises several potential sources of error, all of which need to be addressed with care so that their eventual contribution to the accuracy of the measured data can be determined. A definitive paper on this subject by Edwards(16) offers useful guidance, and there have been several others, for example, by Bremhorst and Hollis(18).

The authors were mindful of these requirements while performing this experimental programme so that subsequent users of the database might make the best use of the information it contains.

Finally, it is noted that the database for the 40° swept wing model has already been used, with some success, to validate a number of RANS and LES computational codes (Li and Leschziner(19), and Hahn and Drikakis(20)).

6.0 CONCLUSION

Three-component LDA measurements have been performed in the complex three-dimensional boundary layer flow above the suction surface of a 40° swept wing model. Detailed quantitative information has been obtained about the development of the strongly three-dimensional flow created by this swept wing. The time averaged and turbulence data provide information about the development of the separating shear layer, the creation of vortical
structures above the swept wing, and the formation of a trailing vortex system.

In parallel, oil-film surface flow visualisation was used to investigate the developing three-dimensional boundary layer. This visualisation revealed the existence of boundary layer separation and reattachment, a separation bubble near to the leading-edge, strong spanwise flows near the wing tip, and the generation of a trailing vortex. The main features shown by the LDA measurements were therefore confirmed by the flow visualisation.

In other experiments, still to be reported, 3D PIV measurements will be described that provide another basis for comparison and further evaluation of the LDA data.

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REFERENCES
18. EDWARDS, R.V. Report of the special panel on statistical particle bias problems in laser anemometry, ASME, Transactions, J Fluids Engineering (ISSN 0099-2202), June 1987, 109, p 89.