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Engineering Notes

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Wing-Tip Vortex in the Near Field: An Experimental Study

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Introduction

FLOW close to the wing tip is of importance for both low– and high–aspect ratio wings. Indeed, induced drag could be significantly affected by spanwise lift distribution, because there is an introduction of energy that is concentrated at the wing tip. Furthermore, even small errors in the prediction of flow close to the wing tip can significantly affect the evaluation of the structural loads acting on the wing.

Knowledge of the physical behavior of the fully developed tip vortex is well established. However, experimental evidence shows, for the initial roll-up of the wing-tip vortex, complex behavior that is not adequately described by existing empirical models of the near-field flow. In fact, the tip vortex evolves from a complex three-dimensional separated flow, and the resultant motion of the trailing vortices is highly unsteady. This implies that the core of the vortex fluctuates in time, and this meandering behavior causes the time-averaged Eulerian point measurement to be an average that is weighted both in time and in space. It is thus evident that the unsteadiness of the flow represents a significant challenge for both numerical and experimental analysis.

Current knowledge of tip vortex flows is not adequate, and remains essentially qualitative, especially regarding the details of the mechanism of vorticity transport from the near-surface viscous layers into the trailing concentrated vortex. To achieve a better understanding of the initial phase of the tip vortex development an experimental study was performed, and its main results are described here.

Experimental Setup

The tests were performed in the 2-m wind tunnel of Defencetek of Pretoria. This facility is an open-circuit wind tunnel with test section diameter 1.7 m and length 2.55 m. The speed range is 3 to 33 m/s, with a turbulence intensity of 0.6% at 28 m/s. The model is an unswept half-wing (0.7 m half-span) with an aspect ratio of 5.7, a taper ratio of 0.4, a NACA 0012 cross section, and a bluff tip. The origin of the reference system is the trailing edge of the wing tip; the x direction is the asymptotic flow direction and the y direction is spanwise (positive moving from the root to the tip). The mean geometric chord, c, is assumed as reference length.

A "direct" measurement of the vorticity, using the probe described in Ref. 1, which is based on the theoretical concepts described by Freestone,[2] was made. The vorticity probe is basically composed of four yaw meters that measure the circulation around a circuit, which is 3.9 mm in diameter. The vorticity probe has the significant advantage of directly measuring the circulation, and it is preferred although it is not as small as other measurement probes. Additionally, the uncertainties associated with the evaluation of vorticity from velocity measurements in flows with high gradients and significant degrees of unsteadiness are reduced.

The output of the vorticity probe is a pressure difference, which, when referenced to the freestream dynamic pressure, can be expressed by the relation (see Ref. 1 for details)

$$\xi = K\rho U\Gamma/q_\infty$$

where the constant K depends on the probe geometry. The nondimensional quantity ξ is a measure of the vorticity at the center of the circuit centered on the probe.

The pressure measurements were made using a Scanivalve differential pressure transducer, with a 0.1% full-scale (2500 Pa) accuracy. The freestream velocity is 28 m/s, which corresponds to a Reynolds number of 4.5×10^5 based on the mean geometric chord. The results presented in this Note are mainly for an angle of attack $\alpha = 12$ deg and are obtained at 11 streamwise positions in the range $-0.4 \leq x/c \leq 3$. The measurements in the y–z plane are made at points 2 mm apart; at each point 8192 data points are sampled at a frequency of 1000 Hz.

Analysis of the Results

The vorticity maps in the y–z plane around the tip vortex, at eight streamwise locations, are shown in Fig. 1. At the position $x/c = -0.4$, on the wing, a small core in close proximity to the corner of the tip is seen (Fig. 1a). Further downstream, at $x/c = -0.2$ (Fig. 1b), a double core structure appears, with a primary vortex inboard of the corner and a secondary vortex, of the same sign, that is located closer to the tip corner. This suggests that the secondary vortex forms and develops following a mechanism that is similar to that of the primary vortex. The maximum vorticity in the secondary vortex is about 0.58 of the maximum vorticity in the primary vortex. Immediately downstream from the trailing edge ($x/c = 0.02$, Fig. 1c), the double-core vortex structure is still evident, although the secondary vortex is less pronounced.

At 0.10 chords downstream from the trailing edge (Fig. 1d) the two distinct cores are no longer seen. Negative values of vorticity (shown as dotted lines in the contour plots) are measured and indicate the presence of counter-rotating structures in the flow. The maximum vorticity in the counter-rotating structures is 0.14 of the maximum vorticity in the primary vortex.

At $x/c = 0.18$ (Fig. 1e), the vortex exhibits an irregular shape in the central core, indicating that the merging process is incomplete; regions of negative vorticity are still present. The vortex begins to show an axisymmetric form at $x/c = 0.33$ (Fig. 1f); a small zone of negative vorticity is still present, but with very low values, suggesting that the negative vorticity is almost completely absorbed by the main vortex.

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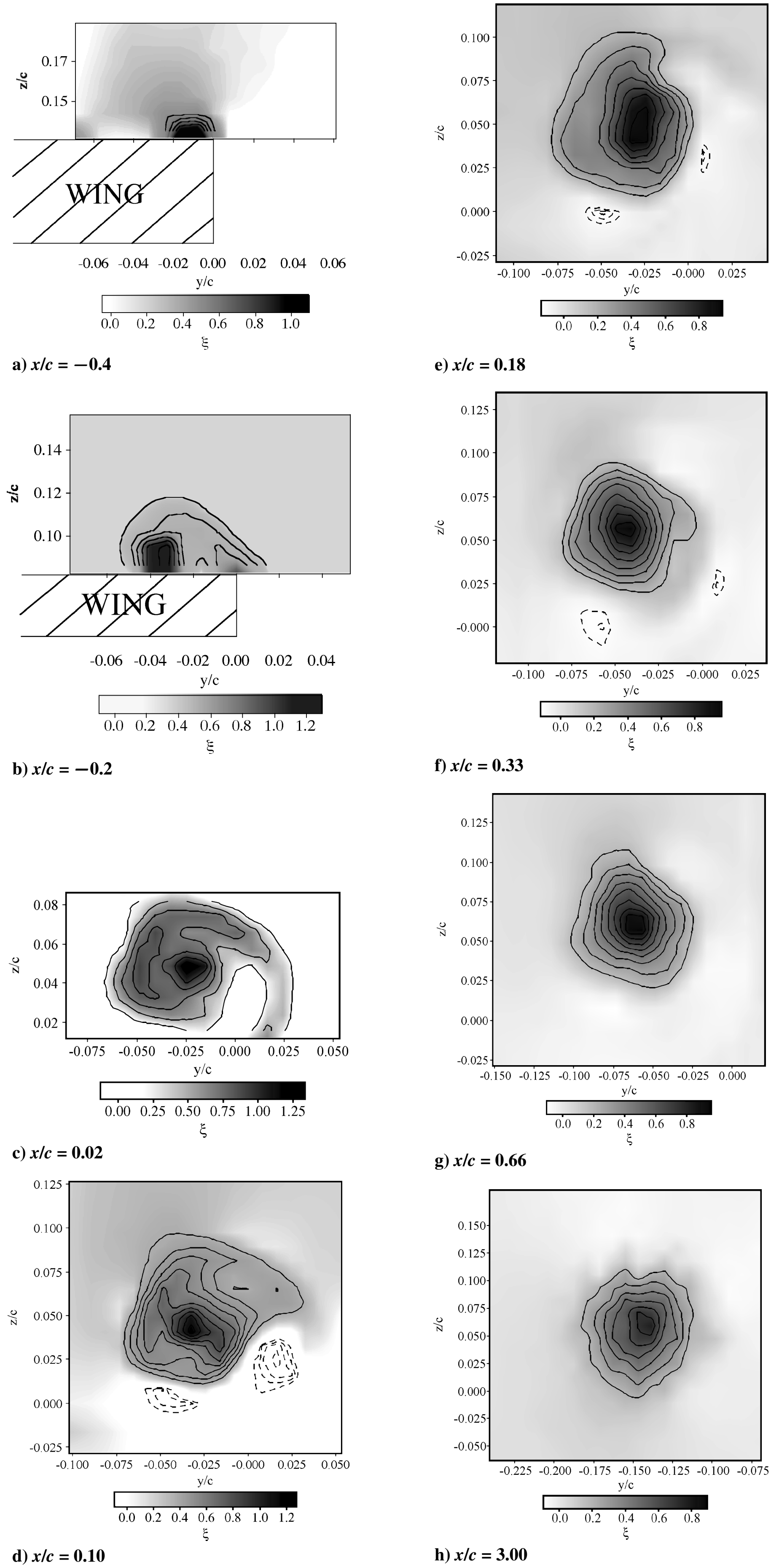


Fig. 1 ***y–z*** **plane vorticity maps at different streamwise positions.**

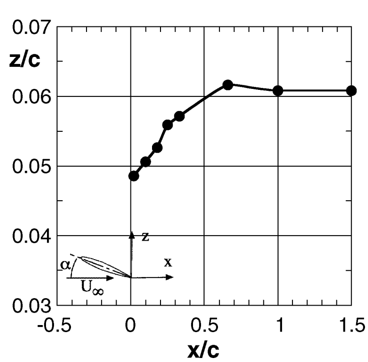
Further downstream, at $x/c = 0.66$ (Fig. 1g), the vortex exhibits an axisymmetric shape and no regions of negative vorticity are seen. Similar shapes are observed up to 2 chords downstream from the trailing edge; that is, once the roll-up phase is completed, the vortex maintains its shape and dimensions as it evolves downstream. At $x/c = 3.00$ the vorticity map is similar to that at $x/c = 0.66$ (Fig. 1h). The smaller values of vorticity arise due to the diffusion and the meandering of the vortex.

The presence of negative vorticity during the roll-up phase is thought to be related to the interaction between the wake and the outer layers of the vortex core. The regions of negative vorticity suggests an unsteady mechanism, which is associated with the generation of counter rotating structures that are transported by the primary vortex. These counter-rotating structures interact with the primary vortex and the rolling spiral arm, with which they subsequently merge.

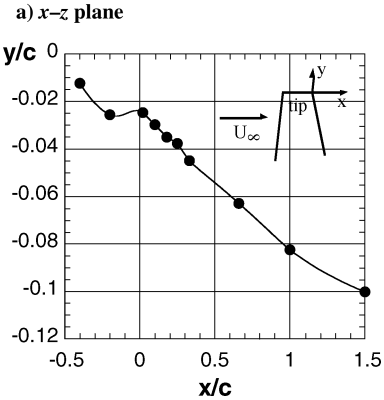
The presence of a double core structure, such as that measured in the present work, was previously observed by Engel[3] using helium bubble flow visualization. Moreover, in Ref. 3 evidence of two core edges was found in the tangential velocity profiles for angles of attack higher than 3.75 deg, suggesting that the vorticity associated with a secondary vortex, at the end of the merging process, could become wrapped into an annulus around the main vortex core. The vorticity maps in the present work agree with this hypothesis, because several streamwise stations show counter-rotating structures that subsequently merge into a single core structure that is typical of a fully developed wing-tip vortex.

The double-core structure initially forms on the suction side of the wing tip. The secondary vortex rotates around the primary vortex and subsequently merges with it. The mixing process occurs over a finite distance, and the axisymmetric shape is formed when the mixing of the two cores is complete.

The trajectories of the vortex centers can be examined to gain additional insight into the near-field flow physics. In the x–z plane the trajectory of the vortex center (Fig. 2a) is initially directed toward



a) ***x–z*** **plane**



b) ***x–y*** **plane**

Fig. 2 Vortex trajectories in the near field.

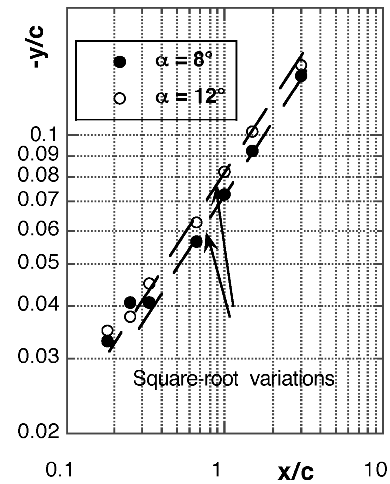


Fig. 3 Spanwise position of the vortex center.

the positive z-direction at a nearly constant angle. Downstream from $x/c > 0.5$ the vortex is aligned with the asymptotic flow direction. In the x–y plane (Fig. 2b), the vortex center moves inboard and is inclined at 2.5 deg with respect to the x-axis.

The vorticity contours show that the roll-up phase is complete about 0.5 chords downstream of the trailing edge. It is therefore of interest to examine the spanwise vortex movement. In Fig. 3, the vortex trajectories are shown on a logarithmic scale for both the 8- and 12-deg angle-of-attack cases. It is seen that the spanwise position of the vortex varies as the square root of streamwise distance; this same result is found in Ref. 4. The results of the present work indicate that this square root trajectory occurs also in the near field and persists until the roll-up process is about to be completed.

Once the roll-up is complete, the vorticity is concentrated in a core with radius 0.040–0.045 c. This result is in good agreement with Ref. 4. Ramaprian and Zheng,[5] on the other hand, studied the tip vortex on a low–aspect ratio rectangular wing. They found that the vortex radius was 0.1–0.15c and for the spanwise trajectory it varied as x 0.75. The difference between the present work and Ref. 5 is possibly due to the different wing geometries.

Conclusions

An experimental study of the initial formation of the wing-tip vortex was conducted. The vorticity was directly measured using a vorticity probe, whose experimental uncertainties are smaller than those of other measurement probes. The measurements document, over a small streamwise distance, the formation of a double-core vortex structure that subsequently merges into a single vortex. The spanwise position of the primary vortex core varies as the square root of the streamwise distance; this is in good agreement with previous studies.

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