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Technical Notes

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Small-Scale Vortical Structures in Crossflow Plane of a Rolling Delta Wing

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I. Introduction

THE flow on the suction, or leeward, side of a delta wing is dominated by the formation of a large-scale vortex. Previous experimental and numerical investigations have shown the existence of small-scale vortices on both stationary wings and wings moving at dimensionless timescales much longer than those of small-scale vortex formation. The experimental study of Gad-el-Hak and Blackwelder[1] revealed, using dye visualization, small-scale vortices feeding into the rollup process associated with the large-scale leading-edge vortex. In their study, the small-scale structures were attributed to vortex shedding from the leading edge. Further observations of Payne et al.[2] indicated locally stationary, small-scale vortical structures. In the experimental studies of Lowson,[3] Lowson et al.,[4] and Reynolds and Abtahi,[5] both unsteady and locally steady, small-scale vortical structures were observed. At relatively high Reynolds numbers, Washburn and Visser[6] deduced the existence of stationary, small-scale structures from time-averaged characterization of the shear layer from slender delta wings.

Gordnier and Visbal[7] undertook a numerical simulation of the shear layer leading to formation of the large-scale (primary) vortex, with emphasis on determining the origin of the instability causing the small-scale vortical structures. The frequencies of these instabilities were in general accord with those determined from linearized stability analysis. More recently, Gordnier and Visbal[8] and Visbal and Gordnier[9] have demonstrated the intimate relationship between the observed unsteadiness of the separated shear layer, which leads to the rollup process characteristic of small-scale vortical structures, and the eruption of the boundary layer from the leeward surface of the wing. In their studies, the coexistence of separated vorticity layers from the leading edge and the leeward surface of the wing is clearly evident. The importance of describing these types of aerodynamic flows using concepts of vorticity is emphasized by Lee and Ho[10] and Shih and Ho,[11] who interpret the lift characteristics of two- and three-dimensional wing configurations using vorticity balance principles.

To date, the possible coexistence and quantitative nature of organized concentrations of vorticity in the separated layers from both the leeward surface and the leading edge of the wing have not been addressed experimentally. The principal aim of this investigation is to interpret the system of vorticity layers and the primary leading-edge vortex using instantaneous representations of the sectional streamline topology and vorticity distributions, obtained via high-image-density particle image velocimetry. This approach allows quantitative identification and possible interaction of the small-scale vorticity concentrations in the separated layers.

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II. Experimental System and Techniques

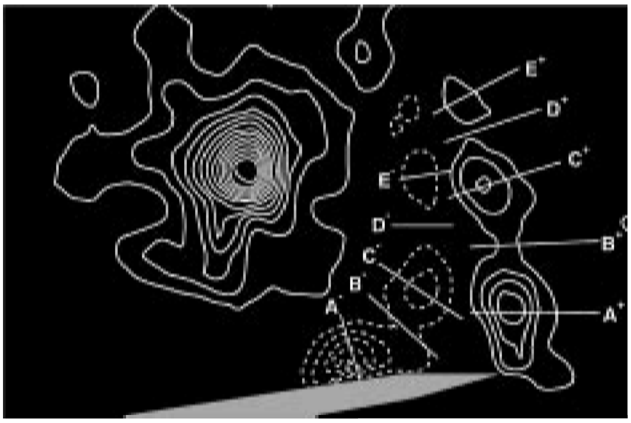
Experiments were performed in a large, open-surface water channel, with a test section approximately 1 m wide × 0.5 m deep. The freestream velocity was $U_\infty = 17.8$ cm/s, corresponding to a Reynolds number based on the centerline chord of the wing of 3.24×10^4. The delta wing used in the experiment had a sweep angle of 65 deg and a centerline chord $c_0 = 20.3$ cm; it was maintained at an angle of attack $\alpha = 30$ deg. Details of the wing configuration and experimental setup, including computer-controlled movement of the wing and the components of the image acquisition system, are given by Cipolla et al.[12] and Cipolla.[13]

The instantaneous velocity fields over an entire plane of the flow were obtained via scanning particle image velocimetry, as described by Rockwell et al.[14] A multifaceted (72) mirror rotates at 8.7 Hz to produce a 1-mm-thick laser sheet at an effective scanning rate of 626 Hz. The laser sheet was oriented perpendicular to the centerline of the delta wing at a location $x_L = 0.90c_0$ downstream of the apex. The images obtained as 35-mm film negatives were interrogated by a program that uses a single-frame cross-correlation method involving the application of two successive fast Fourier transforms.[15] A typical window size $d_I \times d_I$ of 0.72×0.72 mm was used with a 50% overlap, thereby satisfying the Nyquist criterion, i.e., the step size $\Delta\ell$ of the interrogation process did not exceed $0.5d_I$. The resulting grid size on the film was 0.36×0.36 mm, corresponding to 2.25×2.25 mm in the physical plane, with the magnification of the lens equal to 0.17. The uncertainties of velocity and vorticity are estimated to be within 1 and 6%, respectively.

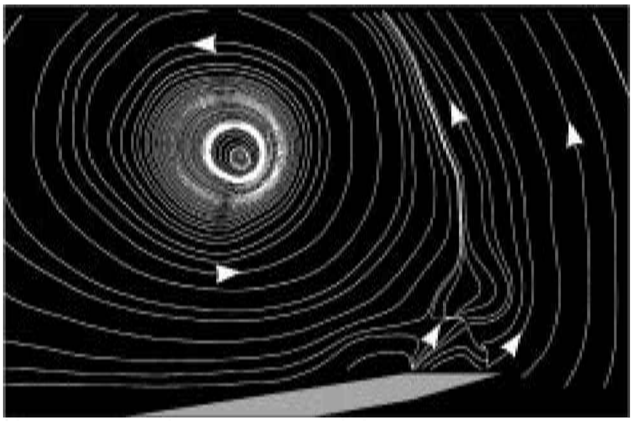
In this investigation, the structure of the flow past a delta wing harmonically oscillating in the rolling mode is studied to elucidate the evolution of the leading-edge vortices. The wing oscillates about its centerline chord at a reduced frequency $k \equiv \omega b/2U_\infty = 0.2$ and an amplitude $\Delta\phi = 10$ deg from an initial roll angle $\phi_0 = -12$ deg. This large value of ϕ_0 causes the location of vortex breakdown to be near the trailing edge on the starboard (right) side and near the apex on the port (left) side. In all plots of vorticity and streamlines in crossflow planes presented in Figs. 1–3, the flow is out of the page; positive vorticity ω_x (counterclockwise rotation) oriented normal to the crossflow plane is indicated by solid curves, and negative vorticity is indicated by dashed curves. The values of minimum and incremental vorticity, i.e., $\omega_{\min}$ and $\Delta\omega$, are ± 10 and 10 s^{-1}, respectively. The location of the delta wing cross section is shown in gray in each image. Arrows superimposed on the streamlines illustrate the local flow direction. The relative locations of vortex breakdown $(X_{vb} - X_L)/C_0$, with X_{vb} and X_L measured from the apex of the wing, for the starboard vortex are 0.1 (Fig. 1), 0.13 (Fig. 2), and −0.031 (Fig. 3).

III. Results and Discussion

Closeup views of instantaneous patterns of vorticity (Fig. 1a) and the corresponding streamline topology (Fig. 1b) are shown. This image represents an instant during an oscillation cycle, when the wing is rotating clockwise relative to this field of view. The primary (major) vortex is defined by the large-scale pattern of positive (solid

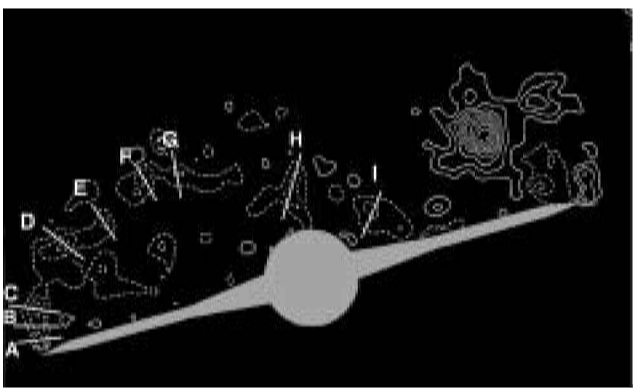


a) Vorticity contours

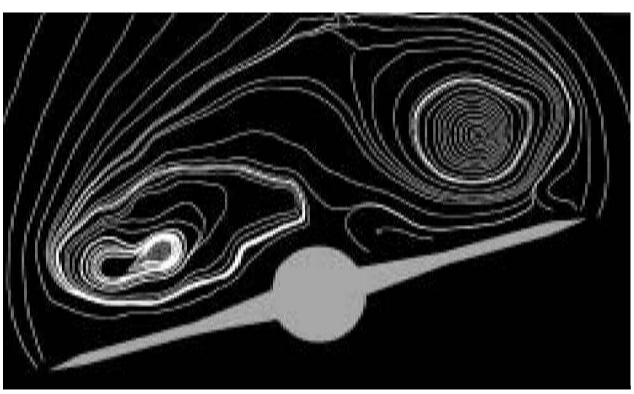


b) Sectional streamline patterns

Fig. 1 Typical instantaneous image ($\phi \cong -8$ deg) during oscillation cycle at $k = 0.2$, $\phi_0 = -12$ deg, and $\Delta\phi = 10$ deg.

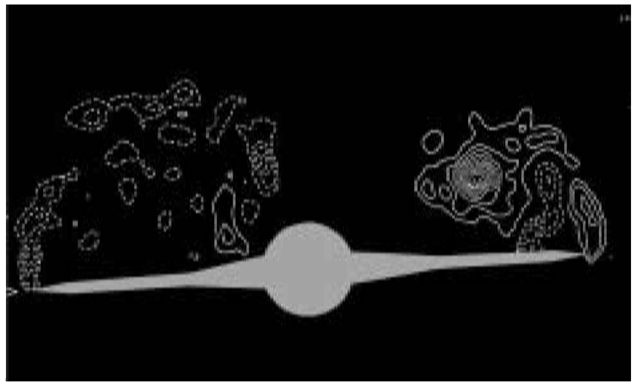


a) Vorticity contours

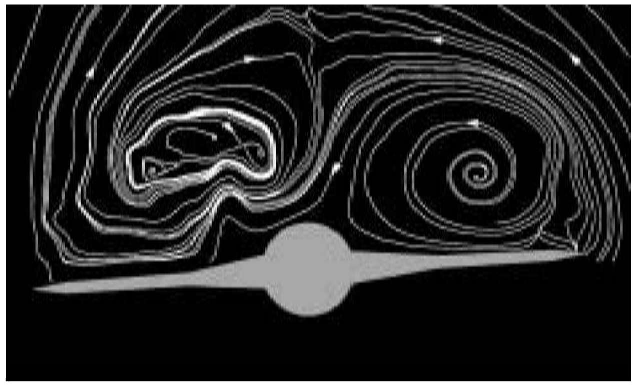


b) Sectional streamline patterns

Fig. 2 Instantaneous image at extreme value of roll angle $\phi \cong -14.6$ deg during oscillation cycle at $k = 0.2$, $\phi_0 = -12$ deg, and $\Delta\phi = 10$ deg.



a) Vorticity contours



b) Sectional streamline patterns

Fig. 3 Instantaneous image during clockwise roll of delta wing at reduced frequency $k = 0.2$ ($\phi = -2$ deg).

white) contour lines. The streamline pattern exhibits an inward spiral toward the center of the vortex until a limit cycle streamline is reached. On the interior of this limit cycle, the streamline pattern spirals outward, meaning that the limit cycle is stable. Moreover, we note that a very small-scale limit cycle is discernible at the center of the vortex pattern.

The focus of the present study is on 1) the separated layer of positive (solid white line) vorticity formed from the leading edge, having a sign compatible with the boundary-layer vorticity on the windward side of the wing; and 2) the negative (dashed white line) vorticity layer formed from the leeward surface. The streamline pattern indicates a nodal line immediately above the leading edge and separatices immediately above the leeward surface of the leading edge. Associated with this region is a pronounced concentration of vorticity intersected by line A^-. Well-defined vorticity concentrations intersected by segments C^- and E^- occur in a similar fashion as for a separated mixing layer. Separation from the leading edge of the wing gives rise to a pronounced vorticity concentration A^+, as well as concentrations C^+ and E^+. Remarkable is that the vorticity concentrations in these positive and negative layers appear to evolve in a coupled fashion, involving combinations A^+–C^-, C^+–E^-, and E^+ coupled with a neighboring, low-level concentration. The velocity in the region between these rows of positive and negative concentrations is low, and the entire system is, therefore, analogous to symmetrical, wake-like instability.

The small-scale concentrations of vorticity described in the foregoing have features in common with those occurring in shear layers separating from two-dimensional plates and bluff bodies. Although the present flow is three dimensional, scaling parameters are employed here in the spirit of defining the major features of the unstable pattern of small-scale vortex formation in the vorticity patterns of Fig. 1. The dominant frequency of the shear layer instability is characterized by evaluating the quantity $f\theta/W$, where f is the frequency of the shear layer instability; θ is the momentum thickness based on the variation of the velocity component w oriented normal to each of the line segments A^+, B^+, and so on; and W is the equivalent of the freestream velocity in the crossflow plane, again normal to lines A^+, B^+, and so on. The frequency f was determined by assuming that a concentration of vorticity travels in the crossflow plane at a velocity c corresponding to the value of velocity at the center of the concentration. Then, taking the wavelength λ to be the spacing between consecutive centers of vorticity concentrations, the frequency can be calculated as c/λ. Using values of these parameters at segment A^+ gives a dimensionless frequency value $f\theta/W = 0.029$. Strictly speaking, the results of purely two-dimensional stability theory[16] cannot be applied to predict the frequency of formation of these small-scale concentrations in the crossflow plane. Note, however, that the most unstable frequency for the instability of a two-dimensional mixing layer is $f\theta/W = 0.017$.

The values of dimensionless circulation for the vorticity concentrations intersected by segments A^+, C^+, and E^+ are $\Gamma/U_\infty b =$ 0.087, 0.050, and 0.017, respectively, giving a value for the total dimensionless circulation in the layer from the leading edge of $\Gamma/U_\infty b = 0.15$. Calculating the circulation of the vorticity concentrations in the layer from the leeward surface, intersected by segments A^-, C^-, and E^-, gives values of $\Gamma/U_\infty b = -0.077$, -0.037, and -0.005. Thus, the total dimensionless circulation in the layer from the surface, i.e., $\Gamma/U_\infty b = -0.12$, is approximately equal to the total in the shear layer from the edge. However, the primary vortex has a value of dimensionless circulation $\Gamma/U_\infty b = 0.67$, over four times the values in the layers from the leading edge and the leeward surface. This higher value reflects that the primary vortex contains vorticity accumulated along the entire length of the leading edge.

The foregoing focuses on the sectional flow patterns at a location upstream of the onset of vortex breakdown. Well downstream of breakdown, the sectional flow pattern exhibits a highly stalled region on the port side, as shown in Fig. 2, corresponding to a typical instantaneous image at the position of the rolling motion in the clockwise direction. Patterns of contours of constant vorticity (Fig. 2a) and sectional streamlines (Fig. 2b) are shown.

Small-scale vorticity concentrations A–I are readily identifiable in Fig. 2a. Summing the contributions to the circulation from each individual concentration of negative vorticity in the shear layer from the leading edge on the port side gives a value of total dimensionless circulation $\Gamma/U_\infty b = -0.69$, where b is the full wing span. On the starboard side, the small-scale positive vorticity concentration in the shear layer separating from the leading edge and the adjacent negative vorticity concentration in the layer separating from the surface have values of $\Gamma/U_\infty b = +0.069$ and -0.098, respectively. Finally, the primary vortex on the starboard side has a value $\Gamma/U_\infty b = +0.71$, which is about 10 times the value in the shear layer feeding into it.

Finally, Fig. 3a shows contours of constant vorticity and Fig. 3b sectional streamlines for an instantaneous image obtained during oscillation, when the wing is rotating clockwise, just prior to reversing direction. Figure 3a shows the separation of the vorticity layers from the port and starboard leading edges. The vorticity layer rolls up into a coherent concentration of vorticity on the starboard side; vortex breakdown occurs just upstream of the field of view. The vorticity pattern on the port side of the wing is at a lower level and more dispersed, characteristic of a region of fully stalled flow. Also, a concentration of negative vorticity originating from the leeward surface of the wing is visible beneath the primary vortex on the starboard side. This concentration of vorticity erupts from the surface and occupies the region between the shear layer and the primary vortex.

In Fig. 3b, it is evident that the streamline topology on the starboard side is dominated by a large outward spiral from the core of the primary vortex. Note that the streamline separating from the leading edge is entrained into the flow on the opposite side of the wing. Finally, observe the streamline separating from the starboard surface of the wing, associated with the earlier noted upsurge of the concentration of secondary vorticity into the primary vortex. Remarkably, this streamline is entrained into the primary vortex.

Note that the peak vorticity levels on the starboard side are higher than those for the corresponding stationary wing, when the location of vortex breakdown is the same. The maximum vorticity of the starboard vortices in Fig. 3a is up to 64% higher than that of the stationary wing.[13] Movement of the leading edge affects the local pressure gradient and causes increased production of vorticity at the surface, leading to an increase in peak vorticity in the primary vortex.[10] Further comparison of the patterns of vorticity for stationary and rolling cases shows that the secondary vorticity beneath the primary vortex is much stronger when the wing is rolling.[13]

IV. Conclusions

The instantaneous patterns of vorticity and streamline topology on a rolling delta wing reveal, for a location upstream of the onset of vortex breakdown, the existence of remarkably ordered patterns of small-scale vorticity in the coflowing layers formed from the leading edge and the leeward surface of the wing. The spatial development of these layers, at a given instant, exhibits concentrations of vorticity of opposite sense, arranged in a pattern analogous to the symmetrical mode of a wake-like instability.

On the other hand, well downstream of the onset of vortex breakdown, the existence of a large-scale, stall-like zone above the leeward surface of the wing is dominated by the vorticity layer along its periphery, originating from the leading edge of the wing. Along the entire edge of the separated shear layer, the sectional concentrations of vorticity show a remarkably coherent form and consistent values of dimensionless circulation.

Acknowledgments

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