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Engineering Notes

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Unsteady Crossflow on a Delta Wing Using Particle Image Velocimetry

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Introduction

AT HIGH angle of attack, the well-known vortex breakdown phenomenon occurs on delta wings. Recent studies of delta wings undergoing pitching maneuvers to high angles of attack have revealed a delay in the response of the location of vortex breakdown relative to the wing motion. This substantial phase lag of the vortex breakdown position has been demonstrated previously for the case of sinusoidal motion of the wing.[1-3] Linear ramp-type pitching motion of the wing[4,5] has shown that the vortex breakdown response is typically an order of magnitude slower than the convective time scale; in essence, this means that the location of breakdown substantially lags that expected from quasistatic considerations. In view of these observations of the phase lag of vortex breakdown location, one expects the cross-sectional development of the leading-edge vortices to exhibit an analogous phase lag. Such lag has been demonstrated using qualitative flow visualization.[6] For this type of lag, the overall features of the velocity field during pitching maneuvers have been characterized separately.[5] Therein, the velocity field at several instants during the wing motion is compared with its quasistatic counterpart to show the consequence of the movement of the location of vortex breakdown through the plane of interest. The unsteady loading in relation to the foregoing features of the flow structure has been reviewed independently[7] and illustrates that corresponding phase lags and hysteresis of the unsteady forces are induced during a typical maneuver.

The emergence of particle image velocimetry (PIV) provides the potential for detailed characterization of the unsteady velocity field past a moving delta wing with an accuracy comparable to laser-Doppler anemometry (LDA) but without the necessity of phase referencing. This high-resolution optical method allows detailed definition of the flow structure at a given instant, thereby providing a more accurate representation of the flowfield than can be accomplished with phase-referencing techniques.

The objective of this note is to report on the first characterization of the unsteady flow structure past a pitching delta wing via particle imaging techniques and to reveal new features of the flow structure during pitch-up and pitch-down maneuvers. The major challenge of applying PIV to this class of flows is the inherent three dimensionality of the mean and unsteady flows. With this experimental approach, it is possible to address the crucial features of the cross-sectional flow structure for pitch-up and pitch-down motions of the wing, providing insight well beyond gross features such as the location of vortex breakdown.

Experimental Techniques

For this experiment, an open surface water channel is employed; its test section has a cross section 610 × 914 mm. The delta wing under study is fashioned of plexiglas to a sweep angle of 75 deg with an overall chord length of 242 mm. The lee surface is flat while the leading edges are beveled at 40 deg on the windward side. The Reynolds number based on chord is 9200.

Pitch-up and pitch-down ramp-type maneuvers between 25- and 50-deg angle of attack are conducted at nondimensional pitch rates ($\dot{A} = \dot{\alpha}C/2U_\infty$) between 0.025 and 0.15. This range of angle of attack is selected on the basis of observations of vortex breakdown at various static angles of attack. At the minimum angle, the static vortex breakdown location is downstream of the trailing edge, i.e., $\xi = x/C > 1.0$, while at the maximum angle, it is at $\xi = 0.15$, where ξ is the nondimensional chord location measured downstream of the apex. Values of angle of attack $\alpha = 45$ deg and chord location $\xi = 0.79$ are selected for observation of the flow during the pitching motion.

The particle tracking technique employed in this study involves seeding the flow with 4-μm particles and illuminating them by a scaning laser sheet. The laser sheet is produced by reflecting the continuous Argon-ion laser beam from a mirror mounted on a galvanometer scanner, which provides a highly repeatable angular displacement of the laser beam at a given frequency. Multiple images of each particle are visualized by driving the scanner with a ramp function at frequencies much higher than those of interest in the flow; the most suitable frequency in the present case is 100 Hz. The multiple images are captured on a single 35-mm photographic negative by synchronizing the laser scanning with the camera firing. The wing motion is controlled via a microcomputer so that the entire system is synchronized to fire the camera and scan the laser at the desired instantaneous angle of attack. In order to determine automatically the velocity field by computer, a known bias velocity is added to the entire photograph so that directional ambiguity is removed. The bias is introduced by reflecting the image of the laser sheet from a mirror mounted on a second galvanometer scanner. This technique deflects the field of view with a constant velocity.[8] After processing, this bias is subtracted to recover the original velocity field. Further details of the experimental configuration and technique are described elsewhere.[9]

The negative is automatically interrogated using an established technique[10,11] in which a helium-neon laser beam passes through the negative and an objective lens to create a Young's fringe interference pattern in the far field. This optical Fourier transform is digitized and analyzed by autocorrelation to determine the direction and spacing of the fringes. The fringe direction is normal to the velocity vector and the spacing is inversely proportional to the velocity. An x-y traverse moves the negative to various locations, thereby generating a grid

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of velocity vectors that represents the flowfield. Typical grid sizes for the present study are 80 × 80, resulting in 6400 vectors with a spatial resolution of 1 mm in the flow.

Occasionally, the interrogation produces obviously "bad" vectors but these are removed before the data is further processed. Also, local regions of low particle density in the negative produce regions of data dropout in the velocity grid. A bilinear interpolation technique[12] is implemented to interpolate the regions of data dropout. The result is a continuous grid of vectors representing the instantaneous velocity field within the resolution of the scanning technique.

Experimental Results

The instantaneous velocity field at $\alpha = 45$ deg acquired during a pitch-up maneuver (from $\alpha_i = 25$ deg to $\alpha_f = 50$ deg at $\text{Å} = 0.15$) is shown in Fig. 1. There is clear indication of a concentrated vortical flow. In contrast, as shown in Fig. 2 for a pitch-down maneuver (from $\alpha_i = 50$ deg to $\alpha_f = 25$ deg) with an identical ramp rate ($\text{Å} = 0.15$) and at the same angle of attack $\alpha = 45$ deg, there is evidence of gross separation and stall with only a weak rotational flow. It is important to note that, in both cases, the instantaneous line of separation from the leading edge, as shown by instantaneous streamlines overlaying the velocity fields, forms a boundary between the leading-edge flow and the flow around the wing; the two regions are instantaneously isolated. Moreover, the stall-like flow corresponding to pitch-down in Fig. 2 protrudes significantly farther outboard of the wing than the concentrated vortical flow of Fig. 1 corresponding to the pitch-up case.

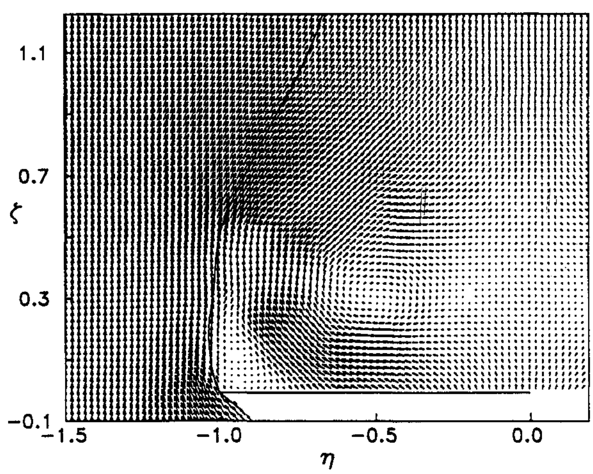

Fig. 1 Instantaneous crossflow velocity field at $\alpha = 45$ deg: pitch-up from $\alpha_i = 25$ deg to $\alpha_f = 50$ deg, $\xi = 0.79$, and $\text{Å} = 0.15$.

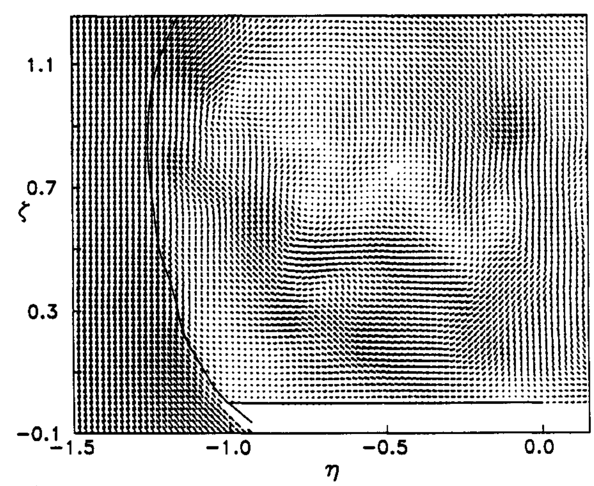

Fig. 2 Instantaneous crossflow velocity field at $\alpha = 45$ deg: pitch-down from $\alpha_i = 50$ deg to $\alpha_f = 25$ deg, $\xi = 0.79$, and $\text{Å} = 0.15$.

In view of the high data density in Figs. 1 and 2 corresponding to $\text{Å} = 0.15$, it is desirable to show only one-fourth of the vectors, as illustrated in Figs. 3a and 3b. For comparison, the case of $\text{Å} = 0.025$ is shown in Figs. 4a and 4b for pitch-up and pitch-down cases, respectively. It is evident that the striking difference in the flow structure between pitch-up and pitch-down maneuvers extends to relatively low pitching rates. Note, however, that the central, core portion of the vortex appears to be partially stalled, or broken down, during the pitch-up motion represented in Fig. 4a. This means that the onset of instantaneous vortex breakdown is approaching the chordwise location of the laser sheet from downstream. Moreover, for the pitch-down motion of Fig. 4b, a similar but less coherent pattern means that the instantaneous location of vortex breakdown is upstream of the laser sheet.

Discussion

These results show that preservation of the leading-edge vortex structure is possible for angles of attack substantially exceeding that for which stall or gross vortex breakdown occurs on the stationary wing. Moreover, this effect occurs even for ramp rates as low as $\text{Å} = 0.025$, as illustrated in Fig. 4a, although the vortex is less concentrated than for the case of $\text{Å} = 0.15$ in Fig. 3a. Most remarkable is the fact that this preservation of a coherent leading-edge vortex can be attained without inward spiralling of the feeding sheet from the leading edge; rather, it corresponds to an outward-spiralling motion of the central part of the vortex.[13] .

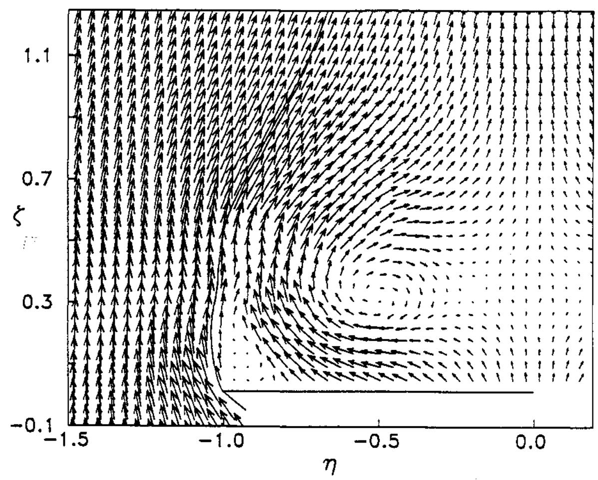

Fig. 3a Instantaneous crossflow velocity field at $\alpha = 45$ deg: pitch-up from $\alpha_i = 25$ deg to $\alpha_f = 50$ deg, $\xi = 0.79$, and $\text{Å} = 0.15$. Vector density 1/4th actual.

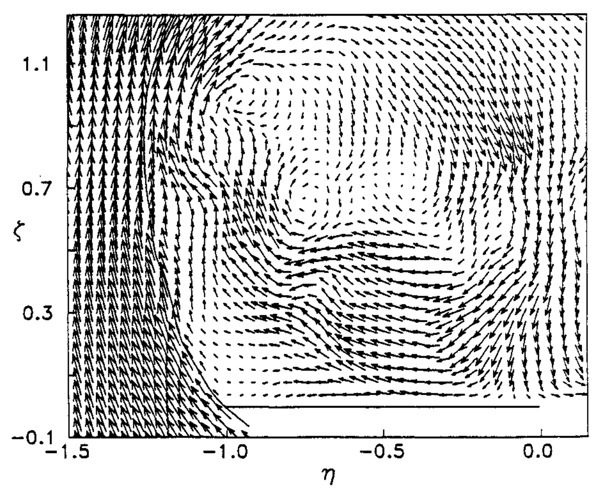

Fig. 3b Instantaneous crossflow velocity field at $\alpha = 45$ deg: pitch-down from $\alpha_i = 50$ deg to $\alpha_f = 25$ deg, $\xi = 0.79$, and $\text{Å} = 0.15$. Vector density 1/4th actual.

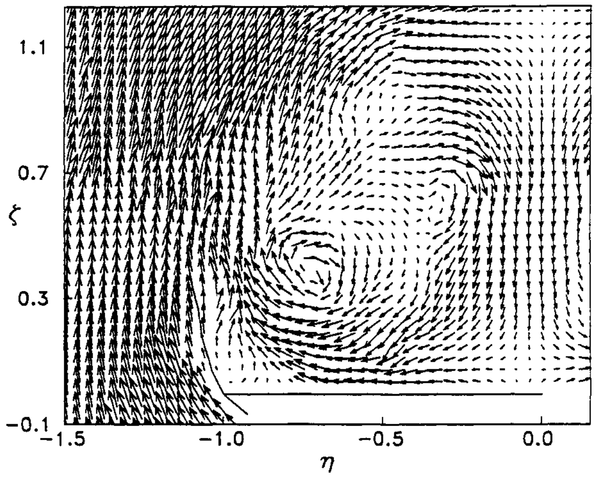

Fig. 4a Instantaneous crossflow velocity field at $\alpha = 45$ deg: pitch-up from $\alpha_i = 25$ deg to $\alpha_f = 50$ deg, $\xi = 0.79$, and $\mathring{A} = 0.025$. Vector density 1/4th actual.

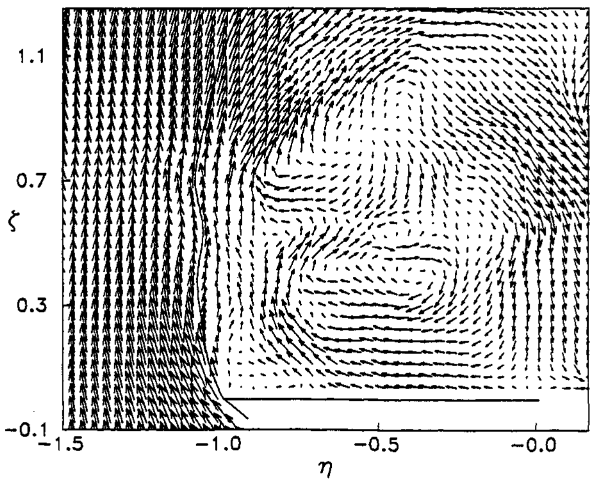

Fig. 4b Instantaneous crossflow velocity field at $\alpha = 45$ deg: pitch-down from $\alpha_i = 50$ deg to $\alpha_f = 25$ deg, $\xi = 0.79$, and $\mathring{A} = 0.025$. Vector density 1/4th actual.

This preservation of the vortex structure correlates well with the location of instantaneous vortex breakdown. As shown by Magness,[9] with a geometrically similar delta wing in a pitch-up maneuver from $\alpha_i = 30$ deg to $\alpha_f = 55$ deg at $\mathring{A} = 0.15$, the location of vortex breakdown at $\alpha = 45$ deg is downstream of the trailing edge ($\xi > 1.0$) in contrast to its location at $\xi = 0.22$ for the stationary wing. For the present pitch-up case at $\alpha = 45$ deg, the implication is that vortex breakdown has not moved upstream of the $\xi = 0.79$ location as a direct result of the dynamic motion.

Furthermore, irrespective of whether the vortex is highly coherent (Figs. 3a and 4a) or essentially nonexistent (Figs. 3b and 4b), the locus of the separation streamline implies that, in the instantaneous sense, no flow is entrained into the leading-edge vortex.[13] It therefore appears that the vorticity feeding the vortex originates from leading-edge separation at upstream locations during these pitching maneuvers.

In summary, by application of the PIV technique, it is possible to identify the instantaneous nature of both the coherent vortical structure and the structure of regions of gross stall on a pitching delta wing. The occurrence of these extreme classes of flow structure is linked to the dynamic hysteresis of vortex breakdown location on the wing. Existence of a stall region can result in large outward displacement of the instantaneous separation streamline at the cross section of observation. In cases where the coherent structure of the vortex is preserved, it is not necessary for the feeding sheet to exhibit an inward-spiralling motion.

Acknowledgment

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References

[1]Wolffelt, K. W., "Investigation of the Movement of Vortex Burst Position with Dynamically Changing Angle of Attack for a Schematic Delta Wing in a Water Tunnel with Correlation to Similar Studies in Wind Tunnels," AGARD CPP-413, 1986.

[2]Rockwell, D. O., Atta, R., Kuo, C. H., Hefele, C., Magness, C., and Utsch, T., "On Unsteady Flow Structure from Swept Edges Subjected to Controlled Motion," *Proceedings of the Second Workshop on Unsteady Separated Flow*, U.S. Air Force Systems Command, Frank J. Seiler Research Lab. Rept. FJSRL-TR-88-0004, Sept. 1988, pp. 299–312.

[3]Atta, R., and Rockwell, D., "Leading-Edge Vortices Due to Low Reynolds Number Flow Past a Pitching Delta Wing," *AIAA Journal*, Vol. 28, June 1990, pp. 995–1004.

[4]Reynolds, G. A., and Abtahi, A. A., "Instabilities in Leading-Edge Vortex Development," AIAA Paper 87-2424, 1987.

[5]Magness, C., Robinson, O., and Rockwell, D., "Control of Leading-Edge Vortices on a Delta Wing," AIAA Paper 89-0999, 1989.

[6]Gad-el-Hak, M., and Ho, C. M., "The Pitching Delta Wing," *AIAA Journal*, Vol. 23, Nov. 1985, pp. 1660–1665.

[7]Ashley, H., Katz, J., Jarrah, M. A. M., and Vaneck, T., "Unsteady Aerodynamic Loading of Delta Wings for Low and High Angles of Attack," *International Symposium on Nonsteady Fluid Dynamics*, edited by J. A. Miller and D. P. Telionis, Vol. 92, ASME Fluids Engineering Div., 1990, pp. 61–78.

[8]Adrian, R. J., "An Image Shifting Technique to Resolve Directional Ambiguity in Double-Pulsed Laser Velocimetry," *Applied Optics*, Vol. 25, 1986, pp. 3855–3858.

[9]Magness, C., "Unsteady Response of the Leading-Edge Vortices on a Pitching Delta Wing," Ph.D. Dissertation, Lehigh Univ., Bethlehem, PA, 1991.

[10]Meynart, R., "Instantaneous Velocity Field Measurements in Unsteady Gas Flow by Speckle Velocimetry," *Applied Optics*, Vol. 22, 1983, pp. 535–540.

[11]Lourenco, L., Krothapalli, A., Buchlin, J. M., and Riethmuller, M. L., "A Noninvasive Experimental Technique for the Measurement of Unsteady Velocity and Vorticity Fields," *Aerodynamic and Related Hydrodynamic Studies Using Water Facilities*, AGARD CPP-413, June 1987, p. 23.

[12]Landreth, C. C., and Adrian, R. J., "Measurement and Refinement of Velocity Data Using High Image Density Analysis in Particle Image Velocimetry," *Applications of Laser Anemometry to Fluid Mechanics: Proceedings of the 4th International Symposium*, ASME, Springer-Verlag, New York, 1989, pp. 484–497.

[13]Magness, C., Robinson, O., and Rockwell, D. "Flow Structure on a Pitching Delta Wing." *Bulletin of American Physical Society*, 1990, Abstract KE5, page 2335.

Time-Average Loading on a Two-Dimensional Airfoil in Large Amplitude Motion

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Introduction

REFERENCE 1 describes the results of an analytical study of the performance of a hypothetical dynamically "aug-

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