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Engineering Notes

Dye Visualization of the Flow Structure over a Yawed Nonslender Delta Wing

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I. Introduction

STUDIES of aerodynamic structures and behaviors of the nonslender delta wings are invariably essential to develop a method to control the development of the vortex breakdown as well as the development of vortices. Unsteady aerodynamics of nonslender delta wings, consisting of shear layer instabilities, the structure of vortices, the occurrence of breakdown, and fluid/structure interactions were extensively reviewed by Gursul et al. [1]. They emphasized the sensitivity of the vortical flow structures varying the angle of attack α of the delta wing. Yavuz et al. [2] studied the vortical flow structure on a plane immediately adjacent to the surface of nonslender delta wing, $\Lambda = 38.7$ deg. Yaniktepe and Rockwell [3] performed experimental investigations on the flow structures at trailing-edge regions of diamond- and lambda-type wings. In both wings, vortical flow structures in the crossflow planes of trailing edge vary rapidly with the angles of attack α. Sohn et al. [4] visually investigated the development and interaction of vortices in crossflow planes at various locations on the delta wing with leading edge extension (LEX) using micro water droplets and a laser beam sheet. The range of angle of attack α was taken as $12 \leq \alpha \leq 24$ deg at yaw angles θ of 0, −5, and −10 deg. It was indicated that, by introducing yaw angle θ, the coiling, merging, and diffusion of the wing and LEX vortices increased on the windward side, whereas they became delayed significantly on the leeward side. Their study confirmed that the yaw angle θ had a profound effect on the vortex structures. Taylor and Gursul [5] visualized leading-edge vortices of a $\Lambda = 50$ deg sweep angle, having angles of attack as low as $\alpha = 2.5$ deg. Gursul et al. [6] report that combat air vehicles (UCAVs) and micro air vehicles have particularly dominant vortical flows having low sweep angles (25–55 deg), and future UCAVs are expected to be highly maneuverable and highly flexible. Yaniktepe and Rockwell [7] aimed at investigating the unresolved concepts, which included averaged structure of shear layer from the leading edge of the wing, unsteady features of separated layer adjacent to the surface of the wing, and control of flow structure by leading-edge perturbations. Elkhoury and Rockwell [8] have investigated to provide various measurements of the visualized dye patterns, including the degree of interaction of vortices, the onset of vortex breakdown, and effective sweep angle of the wing root vortex, as a function of both Reynolds number and angle of attack α. Elkhoury et al. [9] had investigated the Reynolds number dependence of the near-surface flow structure and topology on a representative UCAV planform.

The present investigation focuses on the formation and development of leading-edge vortices, vortex breakdown, and three-dimensional separation and stall of the complex and disorganized flow structure over the delta wing. The leading-edge sweep angle was $\Lambda = 40$ deg. The angle of attack was varied within the range of $7 \leq \alpha \leq 17$ deg and the yaw angle θ was varied within the range of $0 \leq \theta \leq 15$ deg.

II. Experimental System

Experiments were conducted on a large-scale circulating free-surface water channel. The internal dimensions of the water channel were $8000 \times 1000 \times 750$ mm, which was made from a 15-mm-thick transparent Plexiglas sheet with upstream and downstream fiberglass reservoirs. Before reaching the test chamber, the water was pumped into a settling chamber and passed through a honeycomb section and a 2:1 channel contraction. These reservoirs and honeycomb screen arrangements were used to maintain the turbulence intensity below 0.1%. The wing was initially maintained in a horizontal position by a slender support strut that extended vertically from the midchord of the wing. A fluorescent dye, which shined under the laser sheet, was used to create color change in the water to visualize flow characteristics over the delta wing during the dye experiments. Dye was injected in the near field of the delta wing trailing edge by plastic pipe, and dye was passed through a narrow and close channel in the delta wing to its apex. The video camera (Sony HD-SR1) was used to capture the instantaneous video images of the vortex flow structures. The delta wing had a chord length of $C = 140$ mm with a sweep angle of $\Lambda = 40$ deg. The schematic of the experimental arrangement, including laser sheet orientations and corresponding parameters, is presented in Fig. 1. The depth of the water in the test section was adjusted to 530 mm for the present experiments. The Reynolds number based on the delta wing chord was kept constant for all experiments as $Re_c = 10,000$, which corresponded to the freestream velocity of 72 mm/s for all experiments. The flow characteristics over the delta wing in the plan-view plane was presented for angles of attack such as $\alpha = 7$, 10, 13, and 17 deg, and yaw angles such as $\theta = 0$, 6, 8, and 15 deg. Dye visualization experiments in the crossflow plane were performed at locations of $X/C = 0.6$, 0.8, and 1. On the other hand, for the plan-view measuring planes, the laser sheet was located along the central axes of leading-edge vortices.

III. Results and Discussion

The behavior of flow structure of the delta wing in the side-view plane is presented for different angles of attack in Fig. 2. As seen in the first image, a coherent leading-edge vortex is formed very close to the delta wing surface, having an angle of attack of $\alpha = 7$ deg. As seen in the work of Ozgoren et al. [10] and Akilli et al. [11], the leading-edge vortex takes place further away from the surface of the slender delta wing compared to the present delta wing. In addition, the primary vortex structures are more coherent in the case of slender delta wings (Sahin et al. [12]). The location of vortex breakdown moves toward the apex of the delta wing rapidly when the angle of attack α increases slightly. For example, the vortex breakdown occurs at the delta wing apex at an angle of attack of $\alpha =$ 13 deg. In the present dye visualization, it was demonstrated that the vortex breakdown location shows significant fluctuations in the streamwise direction, as also stated by Ol and Gharib [13] and Taylor et al. [14]. A large-scale separation/stall is developed over the entire surface of the wing under a high angle of attack α presented in the third and fourth images of Fig. 2, as also stated by

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