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Effect of low dorsal fin on the breakdown of vortices over a slender delta wing

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ABSTRACT

Previous theoretical and experimental works show that the originally steady symmetric vortices over a flat-plate delta wing at zero side slip but high angles of attack are destabilized by the addition of a low dorsal fin, which renders the separation vortices asymmetric, unsteady, or non-conical. This paper examines the effect of the dorsal fin on the onset of vortex breakdown. A sharp-edged flat-plate delta wing with a 7.5 deg semi-apex angle is tested in a low-speed wind tunnel. The unsteady velocity and vorticity fields are mapped out at the 60% wing root chord location to quantify the vortex burst process caused by the addition of the low dorsal fins by using the laser Particle-Image-Visualization (PIV) technique. Two fin heights with the ratio of the local fin height to the local wing semi-span 0.3 and 0.6 are tested. The results demonstrate that the loss of global stability of the vortex configuration due to the addition of the low dorsal fin accelerates the onset of vortex breakdown and causes one of the vortices in the pair to burst periodically. The frequency and size of the burst are related to the height ratio of the fin.

1. Introduction

An increase in angle of attack over a certain value causes the symmetric separation vortices over slender bodies at zero roll and yawing angles to become asymmetric, resulting in large side forces in the case of slender bodies or large rolling moments in the case of swept wings. At higher angles of attack, vortex breakdown may appear, which leads to sudden loss of lift. The transition of the vortex pattern over symmetric bodies under symmetric flow conditions from being symmetric to asymmetric is an intriguing fluid dynamics issue and is of importance for both the performance and control of high maneuverability flight vehicles. For example, the undesirable flight condition of wing rocking is related to the appearance of asymmetric vortex flows [1,2]. Excellent reviews on this subject have been produced [3–5].

Cai et al. [6] introduced a vortex stability theory for slender conical bodies. Through analytical methods, they demonstrated that vortices over a flat-plate delta wing at zero side-slip are conical, symmetric and stable for all angles of attack. However, the addition of a low dorsal fin destabilizes the vortices, thus rendering the original symmetric vortices asymmetric or non-conical, or both. Only when the fin height is increased to a critical level, the flow will recover symmetry.

Meng et al. [7–11] performed a series of experimental tests on a sharp-edged flat-plate delta wing with a 7.5 deg semi-apex angle with and without a dorsal fin at angles of attack up to 32 deg. The ratio of the local fin height to local wing semispan, h_L/s, varies from 0.3 to 1.5. Smoke laser-sheet visualization, particle image velocimetry (PIV), and force measurement results were obtained and presented. The results indicate that at high angles of attack and zero side-slip the vortices over the delta-wing alone are steady, stable and symmetric prior to vortex breakdown. However, these symmetric vortices are rendered asymmetric when a low dorsal fin is added. These results support the prediction of the stability theory of Cai et al.

It should be noticed that the theory of Cai et al. [6] assumes two concentrated vortices in a steady, incompressible, inviscid flow. Small arbitrary perturbations of the positions of the two vortices are decomposed into the sum of symmetric and anti-symmetric perturbations with respect to the vertical center plane of a slender conical body. The stability of the vortices is then investigated by determining eigenvalues of the dynamic system that governs the time evolution of the motion of the two vortices. As such this theory only pertains to the global stability of assumed vortex configurations and thus is not applicable for the prediction of vortex breakdown.

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Understanding and prediction of vortex breakdown remain a challenging theoretical and engineering problem for the past 50 years [12–22]. Despite the absence of complete theory and prediction tools, flow control techniques have been used to delay the occurrence of breakdown [23–26].

Although the vortex stability theory of Cai et al. [6] is not capable for predicting the onset of vortex breakdown, we demonstrate experimentally in this paper that the loss of symmetry, steadiness, or conicity of the pair of concentrated separation vortices behind a delta wing due to the addition of a low dorsal fin as predicted by the stability theory promotes the onset of breakdown of the vortices. We set up an experiment of a wing-alone model for which the vortices are steady, symmetric, and without breakdown at a given high angle of attack. By adding a fin of two different heights we demonstrate by PIV measurements that the vortices become asymmetric and unsteady accompanied by the periodic burst of one of the vortices above the delta wing. We use the PIV technique to determine the velocity field, vorticity field, and the location and size of the vortex cores in order to characterize the unsteady vortex breakdown process.

The following section introduces the experimental setup. This is followed by the presentation and discussion of the experimental results. Lastly, the conclusions are presented.

2. Experimental setup

PIV experiments were performed at Beijing University of Aeronautics and Astronautics in a low-turbulence, low-noise and closed-circuit wind tunnel with an open test section of 1.5 m × 1.5 m. The free-stream conditions for the test model are free-stream flow velocity $U_\infty = 35$ m/s, Reynolds number $Re = 2.33 \times 10^6$, and angle of attack $\alpha = 35$ deg. The free-stream turbulence intensity is 0.08%. The non-uniformity of the incoming horizontal and vertical flow angles are within 0.5 deg.

The delta wing has a root chord $c_0 = 0.99$ m and a semi-apex angle $\epsilon = 7.5$ deg. The aspect ratio A is 0.53, which is the ratio of the square of the wingspan to the wing area. The model is made of a 15 mm-thick aluminum alloy plate. In order to make the leeward side wing perfectly flat, edges at the windward side of the wing are 20 deg beveled (see Fig. 1). The fins are of 2.0 mm thickness and are made of an aluminum alloy plate. Both sides of the fin leading edges are sharpened symmetrically to achieve a 45 deg angle on either side. The tip portion up to 160.0 mm from the apex is made separately for the three models, i.e., the wing-alone model and the wing models with 0.3s and 0.6s fins, respectively. A vertical fixed fin is mounted on the upper surface of the wing in its symmetry plane. To minimize the aerodynamic influence of the support to the model, the model is attached to the support on the lower surface of the wing and very close to the wing trailing edge.

Two dorsal fins, $h_L/s = 0.3$ and 0.6, are tested in the present study. With the prediction of Cai et al. [6], these two fin heights belong to the 'low' height range, which destabilizes the original symmetric vortices over the slender delta wing with the semi-apex angle of $\epsilon = 7.5$ deg. In previous experimental work, Meng et al. [11] corroborated the theoretical prediction in reference [6] that such low dorsal fins render the original vortices asymmetric, nonconical, and unsteady at the same angle of attack before vortex breakdown occurs.

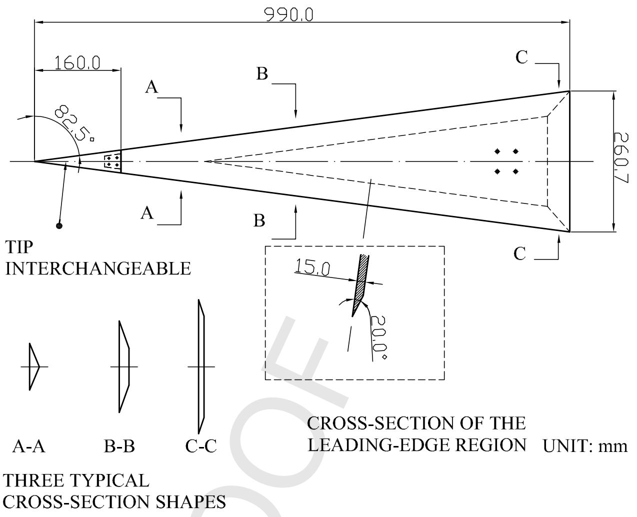

Fig. 1. Delta wing model without fin.

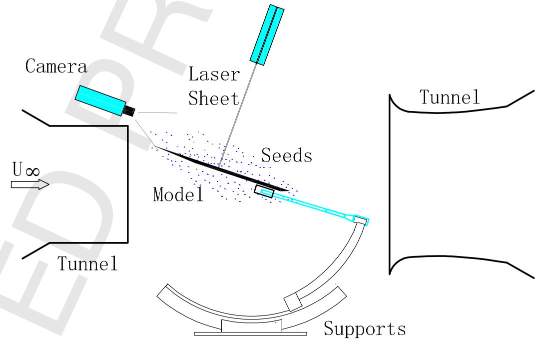

Fig. 2. PIV experimental setup.

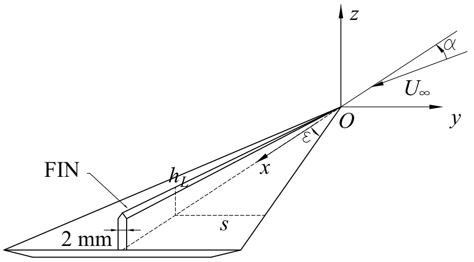

Fig. 3. Coordinates and dimensions of wing with low dorsal fin.

A DANTEC 2-D PIV system was employed in the present study and the PIV experimental setup is shown in Fig. 2. The Nd-YAG laser, PIV-350 by LABest Company, emits double pulses with 350 mJ energy. The laser sheet with a thickness of about 5 mm is set perpendicular to the root chord of the wing. One typical cross-section at the station $x/c_0 = 0.6$ is chosen. The flow is seeded with smoke particles that are approximately 1 μm in diameter. A cross-flow window of 2048 × 2048 pixels is recorded using a CCD camera. For each test case, a dual-pulse separation of 30 μs is used and 50 pairs of images are recorded at the rate of 2 Hz. The exposure time of a single frame is 8 ns, which is determined by the duration time of laser pulse.

For the PIV study, the wing-body coordinates (x, y, z) are introduced. The coordinates and the dimensions of the wing with dorsal fin are illustrated in Fig. 3. The location of the wing apex is the origin, the x-axis is parallel to the root wing chord and points downstream. The y-axis and z-axis point towards the wing starboard and upward, respectively.

The FlowManager software is used to analyse the dual-pulse images to produce instantaneous cross flow velocity distribution (v, w). The (v, w) distribution is used to calculate the instantaneous axial vorticity component ω_x. Time-averaged values are calculated from the 50 instantaneous velocity readings.

Convergence calculations show that 50 readings are sufficient for the data presented here. The relative error for the averaged quantities using 50 samples is within 1% for averages with more

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