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Influence of artificial tip perturbation on asymmetric vortices flow over a chined fuselage

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Abstract An experimental study was conducted with the aim of understanding behavior of asymmetric vortices flow over a chined fuselage. The tests were carried out in a wind tunnel at Reynolds number of 1.87×10^5 under the conditions of high angles of attack and zero angle of sideslip. The results show that leeward vortices flow becomes asymmetric vortices flow when angle of attack increases over 20°. The asymmetric vortices flow is asymmetry of two forebody vortices owing to the increase of angle of attack but not asymmetry of vortex breakdown which appears when angle of attack is above 35°. Asymmetric vortices flow is sensitive to tip perturbation and is non-deterministic due to randomly distributed natural minute geometrical irregularities on the nose tip within machining tolerance. Deterministic asymmetric vortices flow can be obtained by attaching artificial tip perturbation which can trigger asymmetric vortices flow and decide asymmetric vortices flow pattern. Triggered by artificial tip perturbation, the vortex on the same side with perturbation is in a higher position, and the other vortex on the opposite side is in a lower position. Vortex suction on the lower vortex side is larger, which corresponds to a side force pointing to the lower vortex side.

1. Introduction

Chined forebody is utilized by modern fighter planes, owing to its stealth, high-speed performance and some good aerodynamic characteristics, such as high lift and postponing stall of the wing. It should be emphasized that one of the most important performances of modern fighter is high maneuverability which is achieved through flight at high angles of attack. Thus vortices flow over chined forebodies at high angles of attack has been studied extensively over several decades.[1–13] But a problem still remains unsolved, which is whether vortices flow over chined body is symmetric or asymmetric at high angles of attack and zero angle of sideslip.

At first, Erickson and Brandon[1,2] have studied the flows over a chine-forebody slender-wing configuration carefully and found from flow visualization at zero sideslip that no asymmetric vortices could be observed until the flow phenomenon became asymmetric as the chine and wing vortices burst. Then, Roos and Kegelman[3,4] also pointed out from their studies that the chined forebody did not develop any side

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force and the vortex flow over the chined forebody was symmetrical at any angles of attack without sideslip. Tian et al.[11] have studied the vortices flow over a chined forebody at high angle of attack and zero angle of sideslip to explore whether vortices flow is symmetric or asymmetric. Their investigation was based on that the forebody vortices flow can evolve with the variation of tip perturbation if it is an asymmetric one.[14,15] They found the forebody vortices did not evolve with tip perturbation, therefore it was concluded that the vortices flow over the chined forebody was symmetric flow. However, it can be clearly found from Ref.[11] that the flow is asymmetric vortices flow.

Hall[6] conducted a study on stability of a generic fighter with a chined fuselage. It was found that there was no vortex bursting for either forebody or wing vortices up to maximum lift at zero sideslip, but nonzero values of side force and roll moment were observed. This indicated that the flow was already asymmetric when vortex burst appeared. It was also found that roll moment had multiple values near zero sideslip which manifested a lack of repeatability. Test results of Jouannet et al.[7] showed that the side forces were nonzero and unrepeatable at high angles of attack for two chined models manufactured in the same shape and size, which indicated that side force data were non-deterministic for two identical chined models. Even for one model tested upright and inverted, this phenomenon was also observed. Non-determinacy of side force for conventional slender bodies, which was called the effect of roll angles by some scholars,[16,17] was due to the sensitiveness of asymmetric vortices flow to minute perturbation on the nose.[14,15] Thus the non-determinacy of side force for the chined body might imply that the vortices flow was also asymmetric at high angles of attack. In addition, nonzero side force also appeared before vortex breakdown.

As is well-known, for slender bodies and wings, asymmetric vortices occur when angle of attack is large enough.[18–21] Keener and Chapman[20] concluded that asymmetric vortices occurred over slender bodies and wings as the fineness ratio increased to be bigger than approximately 2.5, and the vortex asymmetry was due to the hydrodynamic instability in the vortex flow field resulting from the crowding of the vortices. Polhamus[19] gave the asymmetry boundary of leading edge vortices for delta wings and found that asymmetric vortices could be generated for slender delta wings. Well then, is flow asymmetric vortices flow over chined body at high angles of attack?

As mentioned by Jouannet et al.[7], non-determinacy of side force implies non-determinacy of asymmetric vortices, which makes it difficult to reveal flow behavior correctly. Then, how to get a deterministic asymmetric vortices flow? For slender body of revolution, deterministic asymmetric vortices flow could be obtained by fixing a known and deterministic perturbation on the nose tip.[14,15] So could this be the same for chined body? Furthermore, what is the response of asymmetric vortices flow to perturbation? In this paper, issues mentioned above are studied and discussed in sequence. Artificial perturbation is utilized in order to get a better understanding of the vortices flow behavior over the chined fuselage.\

2. Experimental setup and techniques

The chined fuselage has a length of $L = 680$ mm, base width of $D = 80$ mm, and base height of $H = 70$ mm. As illustrated in Fig. 1, the experimental model consists of a chined forebody with a fineness ratio $L_{\text{fore}}/D = 3$ and a chined afterbody with a fineness ratio $L_{\text{after}}/D = 5.5$. All transversal cross sections of the fuselage are similar in shape. The cross-sectional geometry is a parabola. The parabola equation of the top surface is $-(z/b) + (y/a)^2 = 1$ where $b/a = 0.75$ and the parabola equation of the bottom surface is $(z/b) + (y/a)^2 = 1$ where $b/a = 1$. The model is equipped with 22 pressure taps distributed in one section at $x/D = -3.0$. The pressure taps are equally spaced along the Y direction. The spaces for the taps at the top and bottom surfaces are 5.71 mm and 8.57 mm, respectively. A definition of coordinates is also given to express spanwise locations of pressure taps in Fig. 1, where $d = 40$ mm is half width of the model and y is Y coordinate in the body axis system.

Experiments were conducted in the D4 low-speed open-return wind tunnel at Beihang University. The test section is 1.5 m wide by 1.5 m high by 2.5 m long, and the freestream turbulence level is 0.08%. The tests were carried out at wind velocity $V = 35$ m/s, which corresponds to a Reynolds number $Re_{\text{D}} = 1.87 \times 10^5$ based on the width of the model D4. The model was sting mounted on a supporting mechanism and tested at fixed angles of attack from $\alpha = 0°$ to $\alpha = 70°$ in 5° increments under the conditions of zero sideslip.

Side force was measured by an internal six-component strain-gauged force balance with a measurement uncertainty of 0.3%. The output signals of the balance were recorded using an industrial PC with a 16-bit data acquisition card NI PCI-6143. The pressure data acquisition system primarily consists of a DTC Initium and an ESP module with a pressure transducer accuracy of 0.1% F.S. (Full Scale, ± 1 psi), which were both from PSI Company. The FlowMap DPIV system from the Dantec Corporation was used to measure sectional spatial velocity and vorticity field through the 2D particle image velocimetry (PIV) method. The spatial resolution used in this study was 3.1 mm.

The artificial tip perturbation was a spherical bead. A sketch of the artificial tip perturbation is given in Fig. 2. Perturbation with diameter $d_{\text{p}} = 0.6$ mm was selected and fixed at axial location $x_{\text{p}} = 1$ mm and different circumferential locations γ. Ten circumferential locations were tested respectively to investigate the influence of the tip perturbation.

3. Results and discussion

3.1. *Asymmetric vortices flow over chined fuselage at zero sideslip*

In order to investigate asymmetric vortices flow, side force was obtained by force measurement, which can just reflect flow asymmetry. Fig. 3 gives the variation of side force C_Y with the increase of α at zero sideslip. As can be seen, no side force develops when $\alpha \leqslant 20°$. Once angle of attack is increased beyond 20°, however, a highly nonlinear side force develops. This nonzero and nonlinear side force just indicates that the leeward vortices flow over the chined fuselage becomes asymmetric when $\alpha > 20°$.

According to the previous studies,[18,19] asymmetric vortices appear when angle of attack is large enough for slender bodies of revolution and slender delta wings. The case is the same for the chined fuselage, as illustrated in Fig. 3. Thus the leeward