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 $1.87 \times 10^5$ 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 nondeterministic 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.

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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. 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 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 also pointed out from their studies that the chined forebody did not develop any side...
force and the vortex flow over the chined forebody was symmetrical at any angles of attack without sideslip. Tian et al. 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. 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. that the flow is asymmetric vortices flow.

Half 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. 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, was due to the sensitiveness of asymmetric vortices flow to minute perturbation on the nose. 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. Keener and Chapman 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 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., 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. 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 \( L_{aft}/D = 3 \) and a chined afterbody with a fineness ratio \( L_{aft}/D = 5.5 \). 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 \( -(z/h) + (y/a)^2 = 1 \) where \( b/a = 0.75 \) and the parabola equation of the bottom surface is \( (z/h) + (y/a)^2 = 1 \) 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 \( y = Y \) 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 \( Re = 1.87 \times 10^5 \) 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 \( x = 0^\circ \) to \( x = 70^\circ \) in \( 5^\circ \) 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 \( d_p = 0.6 \) mm was selected and fixed at axial location \( x_p = 1 \) mm and different circumferential locations \( \gamma \). 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 \( x \) at zero sideslip. As can be seen, no side force develops when \( x \leq 20^\circ \). 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 \( x \geq 20^\circ \). According to the previous studies, 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
vortices flow becomes asymmetric vortices flow due to the increase of angle of attack over the chined fuselage. However, the increase of angle of attack not only brings on asymmetric vortices flow, but also leads to vortex breakdown which will occur due to strengthening of adverse pressure gradient from the rear of the model. Phenomenon of asymmetric vortex breakdown over the chined body has already been observed by Refs. 2,4,11–13. Does asymmetric vortices flow mean the same flow as asymmetric vortex breakdown? Results of Refs. 6,7 indicated that asymmetric vortices appeared before vortex breakdown. In order to clarify this question, the vortical flowfield over the chined fuselage was investigated by 2D PIV.

Fig. 1 Sketch of experimental model and distribution of pressure taps.

Fig. 2 Sketch of artificial tip perturbation.

Fig. 4 gives the vorticity distributions $\omega$ in seven cross sections along the model at $\alpha = 35^\circ$ and $\alpha = 40^\circ$. Concentrated high vorticity area on the leeward side of the model indicates the existence of the forebody vortices and its disappearance indicates vortex breakdown. It is clearly observed that there is no vortex breakdown along the model at $\alpha = 35^\circ$ and vortex breakdown appears only for the right vortex (observed from the rear view) near the end of the model at $\alpha = 40^\circ$, which also indicates an asymmetric vortex breakdown of the leeward vortices. At the same time, the maximum vorticity of the leeward vortex is also extracted to illustrate vortex breakdown as shown in Fig. 5. The vorticity of the right vortex decreases sharply to a low level from $x/D = -6.0$ to $x/D = -8.0$ at $\alpha = 40^\circ$, which indicates a vortex burst according to the study in Ref. 22. But the vorticity decreases gradually along the model and keeps at a high level until the end of the model for the two leeward vortices at $\alpha = 35^\circ$, which means there is no vortex

Fig. 3 Side force vs angle of attack at zero sideslip.

Fig. 4 Vorticity distributions along the model.
Combining these two aspects, vortex breakdown appears when $\alpha > 35^\circ/C_176$.

Based on the above analysis, the leeward vortical flow over the chined fuselage is already asymmetric vortices flow before the appearance of vortex breakdown. Therefore, the asymmetric vortices flow is asymmetry of the forebody vortices but not asymmetry of vortex breakdown. According to the evolution of flow with angle of attack, the leeward vortical flow over the chined fuselage can be divided into three regimes, which are regime of symmetric vortices flow ($\alpha \leq 20^\circ/C_176$), regime of asymmetric vortices flow ($20^\circ < \alpha \leq 35^\circ/C_176$) and regime of asymmetric vortex breakdown ($\alpha > 35^\circ/C_176$), as illustrated in Fig. 6. In this paper, emphasis is laid on the regime of asymmetric vortices flow. Flow behavior in regime of asymmetric vortex breakdown still needs to be explored further in subsequent studies.

### 3.2. Determinacy of asymmetric vortices flow

Hall$^6$ pointed out in his study that roll moment had multiple values near zero sideslip which manifested a lack of repeatability. Jouannet et al.$^7$ also found that side force data were non-deterministic for two identical chined models. These indicate a non-determinacy of asymmetric vortices flow, but where does this non-determinacy come from?

According to studies on slender body of revolution,$^{14,15}$ asymmetric vortices flow is sensitive to perturbation on the nose tip, therefore it is triggered by the natural minute geometrical irregularities on the nose tip within machining tolerance. However, those irregularities caused by machining are randomly distributed and different for models manufactured in the same shape and size, so the response of the forebody asymmetric vortices appears random behavior and test results show no repeatability. Because there is only one test model, it fails to observe random behavior of asymmetric vortices in this research. But test results of Hall$^6$ and Jouannet et al.$^7$ have already revealed the problem.

The non-determinacy of asymmetric vortices flow will hinder the understanding of flow behavior of asymmetric vortices, thus it is important to find out how to obtain deterministic asymmetric vortices flow. Since the non-determinacy of asymmetric vortices flow is caused by tip perturbation, could deterministic asymmetric vortices flow be obtained by attaching artificial tip perturbation? Deng et al.$^{14,15}$ have proposed the technique of attaching artificial tip perturbation to make forebody asymmetric vortices flow determinacy for slender body of revolution, and the technique has been proved feasible. Therefore, artificial tip perturbation is applied to the case of chined fuselage model to study the determinacy of forebody asymmetric vortices over the chined forebody.

Fig. 7 presents $C_T$ data with artificial tip perturbation located at different circumferential locations. When $\alpha \leq 20^\circ$, $C_T$ is nearly zero and data is repeatable even for different perturbations. However, the case is completely different when $\alpha > 20^\circ$. $C_T$ develops but becomes dispersed under the influence of perturbation. These indicate that the leeward vortices flow is sensitive to tip perturbation until the angle of attack...
is above 20°. Even more remarkable, the appearance of the flow sensitivity to tip perturbation is simultaneous with the appearance of the asymmetric vortices flow indicated in Fig. 3. This flow sensitivity to tip perturbation provides a more powerful evidence of the appearance of the asymmetric vortices flow. Therefore, the asymmetric vortices flow can be triggered by tip perturbation and it changes with variation of tip perturbation.

In order to testify deterministic influence of artificial tip perturbation on the asymmetric vortices flow, repetitive experiments are conducted by re-attaching known and deterministic artificial tip perturbation. In order to make it distinct, results of only two perturbations are given. As illustrated in Fig. 8, test results show a good repeatability. Therefore, it is indicated that the influence of artificial tip perturbation on the asymmetric vortices flow is repeatable. Deterministic asymmetric vortices flow can be obtained by attaching known and deterministic artificial tip perturbation. Unfortunately, it fails to verify the deterministic effect of the same artificial tip perturbation on different models because there is only one experimental model, which will be investigated in subsequent research.

3.3. Response of asymmetric vortices flow to artificial tip perturbation

Deterministic asymmetric vortices flow can be obtained with the aid of artificial perturbation on the nose tip, so what is the effect of tip perturbation on the asymmetric vortices flow?

In order to find out the response of asymmetric vortices flow to perturbation, data are given in the form of variation of side force with circumferential location of perturbation at fixed angle of attack $\alpha = 35^\circ$ as illustrated in Fig. 9.

As shown in Fig. 9, $C_y$ value keeps changing with the circumferential location of perturbation and this indicates that perturbations at different locations lead to different asymmetry levels. When perturbation is located on the symmetry plane, $C_y$ is close to zero. And $C_y$ is positive for perturbations on the left side of the symmetry plane and negative for perturbations on the right side of the symmetry plane. Taking the cases with perturbations on the right side of the symmetry plane as an example, leeward perturbations ($\gamma = 225^\circ$ and $\gamma = 255^\circ$) lead to larger magnitude of $C_y$ than windward perturbations ($\gamma = 285^\circ$ and $\gamma = 315^\circ$), which indicates that leeward perturbations have stronger influence on the asymmetric vortices flow than the windward perturbations. Situation is the same for perturbations on the left side of the symmetry plane. Thus $C_y$ presents a single-cycle sine-shaped variation with circumferential location of perturbation.

Fig. 9 Effect of circumferential location of perturbation on side force, $\alpha = 35^\circ$.

According to test data and analysis above, the state of asymmetric vortices flow is completely decided by the state of perturbation on the nose tip. Since the influence of artificial tip perturbation on asymmetric vortices flow has been illustrated by the response of side force to perturbation, what about the corresponding flow structure? Therefore, artificial tip perturbations on the leeward side of chine edge ($\gamma = 105^\circ$ represented by left position (LP) and $\gamma = 255^\circ$ represented by right position (RP)) which have the most prominent effect on the asymmetric vortices flow, are chosen to present flow behavior at $\alpha = 35^\circ$.

Fig. 10 Effect of perturbation on pressure distributions at $x/D = -3.0, \alpha = 35^\circ$.

According to PIV experiments, the normal vortex position is extracted and illustrated in Fig. 11. Under the conditions with LP, the suction on the right leeward side is larger than the one on the left leeward side. The contrary situation is presented under conditions with RP. According to PIV experiments, the normal vortex position is extracted and illustrated in Fig. 11. Under the conditions with LP, the normal position of the left vortex is higher than the one of the right vortex. However, this difference of the normal vortex position is reversed under the conditions with RP.

According to the normal vortex position, the definition of asymmetric vortices flow patterns is given as follows. If the

Fig. 10 gives the corresponding pressure distributions of the asymmetric vortices flow at $x/D = -3.0$, $C_p$ is pressure coefficient. Under the conditions with LP, the suction on the right leeward side is larger than the one on the left leeward side. The contrary situation is presented under conditions with RP. According to PIV experiments, the normal vortex position is extracted and illustrated in Fig. 11. Under the conditions with LP, the normal position of the left vortex is higher than the one of the right vortex. However, this difference of the normal vortex position is reversed under the conditions with RP.
right vortex of the asymmetric vortices is in the lower position while the left one is in the higher position when the flow is observed from the rear view, the flow pattern is right vortex pattern (RVP). The opposite flow pattern is left vortex pattern (LVP). Therefore, RVP is presented when perturbation is LP and LVP is presented when perturbation is RP, as illustrated in Fig. 12.

When the leeward vortical flow is asymmetric vortices flow, the vortex on the same side with perturbation is in the higher position, and the leeward vortex suction is lower on that side, which creates a side force pointing to the other side. Thus the influence of perturbation on asymmetric vortices flow pattern can be easily observed. It can be speculated that the influence of perturbation on flowfield near the nose tip is the key. However, it is still unclear how perturbation affects the flowfield near the nose tip and how the flow near the nose tip determines the development of the entire asymmetric vortices flow.

4. Conclusions

An extensive experimental investigation has been conducted to explore behavior of the asymmetric vortices flow over the chined fuselage.

(1) When $\alpha \leq 20^\circ$, the flow exhibits symmetric characteristic. Due to the increase of angle of attack, asymmetric vortices flow presents when $\alpha > 20^\circ$. Vortex breakdown appears when $\alpha > 35^\circ$ and it is asymmetric. Therefore, the asymmetric vortices flow is asymmetry of the forebody vortices but not asymmetry of vortex breakdown.

(2) The leeward vortical flow over the chined fuselage can be divided into three regimes according to the evolution of flow with angle of attack, which are regime of symmetric vortices flow, regime of asymmetric vortices flow and regime of asymmetric vortex breakdown.

(3) Deterministic asymmetric vortices flow can be obtained by attaching known and deterministic artificial perturbation on the nose tip of the chined fuselage.

(4) The state of asymmetric vortices flow pattern is decided by the state of perturbation on the nose tip. Side force presents a single-cycle sine-shaped variation with circumferential location of artificial tip perturbation. Under the influence of perturbation, the vortex on the same side with perturbation is in the higher position, and the vortex suction is lower on that side, which creates a side force pointing to the other side.

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References


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