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Effects of a vectored trailing edge jet on delta wing vortex breakdown

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Abstract Flow visualization was used to study the effects of a vectored trailing edge jet on the leading edge vortex breakdown of a 65° delta wing. The experimental results indicated that there is little effect of the jet on the leading edge vortex breakdown when the angle of the vectored jet is less than 10°. With the increase of the vectored angle *β*, the effect of the jet on the flow becomes stronger, i.e., the jet delays the leading edge vortex breakdown in the direction of the vectored jet, and accelerates breakdown of the other leading edge vortex. Moreover, the effect of the jet control tends to be weaker with the angle of attack.

List of symbols

C	root chord length of delta wing
Ur	jet velocity normalized by the freestream velocity
Xp	increment in the leading edge vortex breakdown location due to blowing
ΔXp	difference between the two leading edge vortex breakdown locations
α	angle of attack
β	vectored angle of the trailing edge jet

1 Introduction

Leading edge vortices play a central role in delta wing aerodynamics, and trailing edge jet effects can modify vortex behavior. Trailing edge jets were utilized by Helin and Watry (1996) to control the leading edge vortex breakdown of a delta wing with a sweep angle of 60°. In their experiment, the two rectangular jets were located symmetrically at the trailing edge of the delta wing, and the jet direction was perpendicular to the trailing edge. In the normalized jet velocity range of $0 \le Ur \le 8$, the water tunnel flow visualization indicated that the jets delayed the leading edge vortex breakdown by about 0.18 C. Moreover, the trailing edge jets also delayed the appearance of the asymmetrical vortex of the delta wing, which is very useful to prevent the introduction of a roll moment to the delta wing. With a similar experimental model, Nawrocki (1995) investigated the effect of symmetric jets, differential jets, vectored symmetric jets, and vectored differential jets on the leading edge vortex breakdown. It was found that the vectored jets were much more efficient in controlling the leading edge vortex breakdown than unvectored jets. A maximum delay in vortex breakdown of 0.45 C was obtained for vectored jet at Ur=8. It was also found that the control effect was sensitive to the angle of the vectored jets. When the direction of the jet was inclined to the vortex core, the control effect was increased; in contrast, when the jets were directed away from the vortex core, the amount of the leading edge vortex breakdown delay decreased. Thus it appears that the trailing edge jets may improve the aerodynamic performance of a delta wing, and lead to lift enhancement and improved stability. In order to provide a technical basis for the design of high performance light aircraft with vectored jets, the flow visualization technique was used in this study to investigate the effect of a trailing edge vectored jet on the leading edge vortex breakdown over a 65° delta wing with a sharp leading edge. As we mentioned, the related previous work (Helin and Watry 1996; Nawrocki 1995) used twin jets, whereas the current work uses a single jet mounted on the centerline, because light fighters usually have a single engine.

2 Experimental instrument and equipment

The experiment was conducted in the water tunnel of the Fluid Mechanics Institute at the Beijing University of Aeronautics and Astronautics. The test section of the water tunnel is 0.4 m wide, 0.4 m deep, and 6.0 m long. A sharp leading edge delta wing with a sweep angle of 65° was used as the experimental model, with the underside of the model beveled at an angle of 60°(see Fig. 1). To facilitate the experimental observations, the planform of the delta wing was evenly divided into five portions along the root chord line, with the radial lines introduced from the wing apex with a spacing of 10°. A single trailing edge vectored jet was located at the center of the trailing edge with a rectangular nozzle exit of 2.4 cm×0.3 cm. The variations of the vectored jet angles were realized by installing different jet orifices into the trailing edge of the model as shown in Fig. 1. The freestream velocity was 6.0±0.2 cm/s as measured by laser Doppler velocimetry (LDV), resulting in a Reynolds number based on the root chord line of the wing

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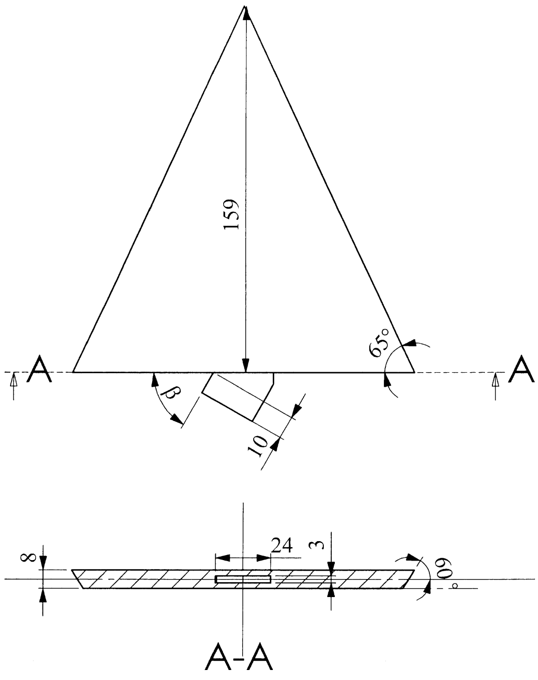

Fig. 1. Sketch of the experimental model (dimensions in mm)

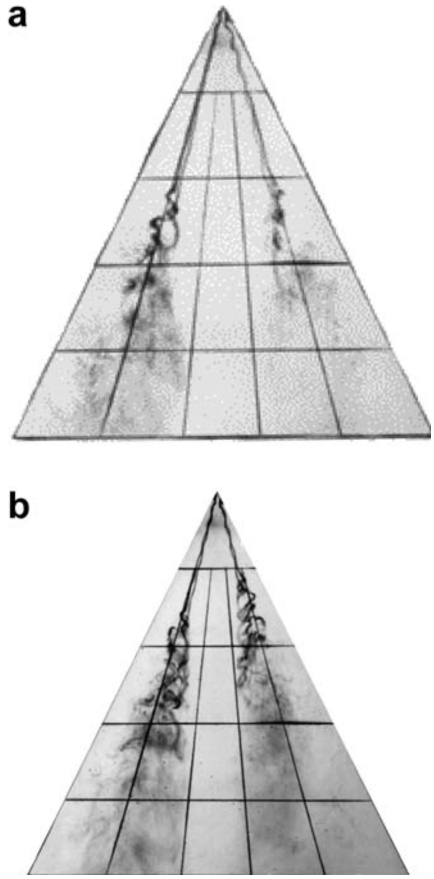

Fig. 2a, b. Typical flow patterns at different angle of attack (jet off). a Flow pattern of leading-edge vortex symmetric breakdown (α=25°). b Flow pattern of leading-edge vortex asymmetric breakdown (α=30°)

of 9.54×10^3. The effects of Reynolds number on the flow have not been considered in this paper.

In order to minimize flow disturbances, the experimental model was supported from underneath. The cross section of the support is 1.0 cm wide and 4.0 cm long with both the head and rear parts of a 1:3 semi-ellipse. The jet flow supply pipe was installed through the supports, and run through the body of the model to the trailing edge. A pump was used to generate the desired jet velocities, and the jet velocity was determined by dividing the flow discharge by the exit area of the jet. The accuracy of the resulting mean velocity is ±2%. Diluted ink dye injection pipes of diameter 1.0 mm were introduced into the apex of the model to visualize the leading edge vortex breakdown. A 35 mm camera together with a video recorder was utilized to record the flow patterns.

The model was installed carefully, so that the symmetrical flow patterns of leading-edge vortices showed that the model at small angle of attack was symmetrical with respect to the model centerline.

3 Experimental results and discussions

3.1 Baseline experiment (jet off)

The leading edge vortex breakdown over a clean delta wing with sharp leading edge was investigated first (Fig. 2). The flow visualization results indicated that the concentrated leading edge vortices were formed over a delta wing for $\alpha>10°$. These broke down symmetrically for $\alpha \le 25°$, typically with an angle between the root chord line and the projection of the vortex core of approximately 15°. When the angle of attack is greater than 25°, the leading edge vortex broke down asymmetrically. For $\alpha>40°$, the leading edge vortex broke at the apex of the delta wing, and the two vortex cores mixed strongly in an oscillatory manner.

For the baseline experiment mentioned, it can be seen that the leading edge vortex exhibited symmetric breakdown for $\alpha \le 25°$, and mixed fully for $\alpha>40°$. Thus, this experiment was conducted in the range of α=25°~40° with increments of 5°. The accuracy of the vortex breakdown location is in the range of about 3~5 mm.

3.2 The vectored jet experiment

There are two parameters that influence the effect of vectored trailing edge jet on the leading edge vortex breakdown, i.e., the velocity and the angle of the jet, and these two parameters can change the location of the leading edge vortex breakdown significantly. In this experiment, the jet velocity *Ur* varied from 0 to 10, and the jet angle of β was in the range of 0°–60° towards the left side of the model as viewed from above.

It is also found in the experiment that, when the jet angle β is less than 10°, the jet has little effect on the leading edge vortex breakdown. When the jet angle β is greater than 10°, the vectored jet causes a leading edge vortex breakdown delay in the left side of the model, but an earlier vortex breakdown on the right side (Fig. 3). Figure 4 shows the effect of the jet velocity on the relative

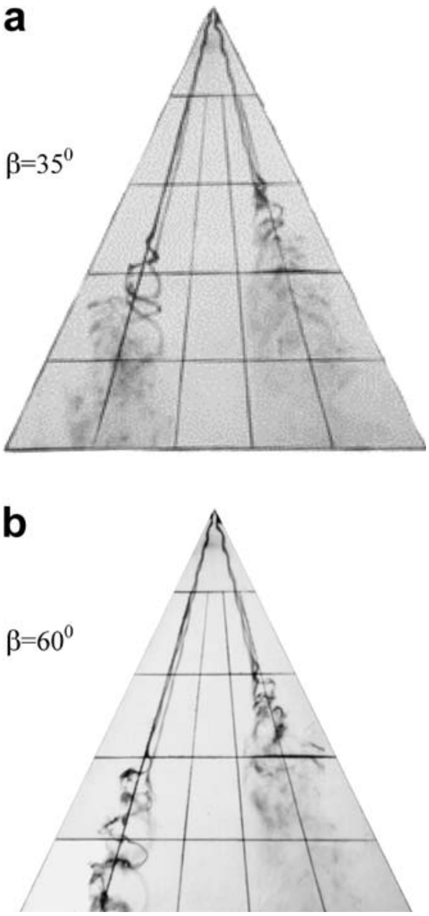

Fig. 3. Flow patterns at Ur=8 and α=25°

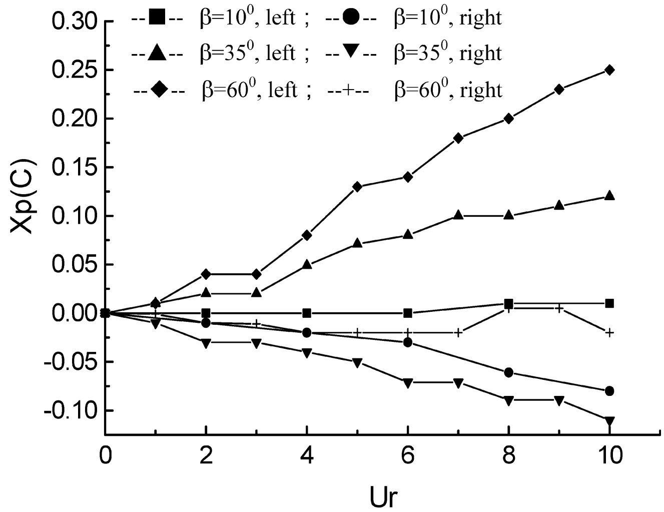

Fig. 4. The variation of the relative location of leading edge vortex breakdown with normalized jet velocity (α=25°). *Solid square* β=10°, left ; *solid circle* β=10°, right. *Solid triangle* β=35°, left; *inverted solid triangle* β=35°, right. *Solid diamond* β=60°, left; *plus* β=60°, right

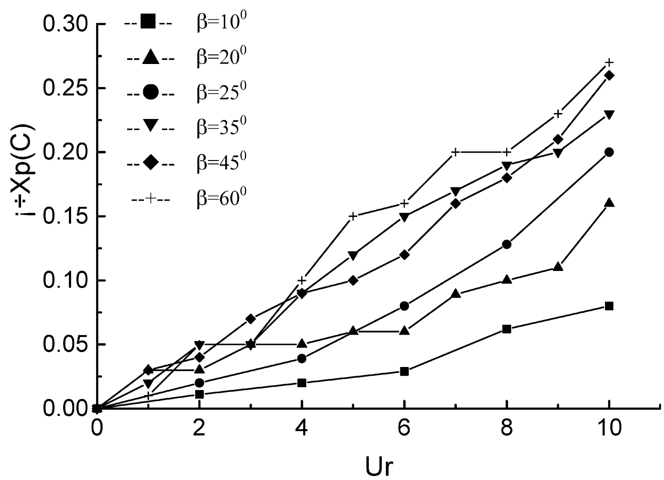

Fig. 5. The variation of the difference between the two leading edge vortex breakdown locations with normalized jet velocity (α=25°). *Solid square* β=10°; *solid triangle* β=20°; *solid circle* β=25°; *inverted solid triangle* β=35°; *solid diamond* β=45°; *plus* β=60°

location of the leading edge vortex breakdown for β=10°, 35°, and 60°. It can be seen that with the increase of the vectored jet angle β the influence of the vectored jet on the leading edge vortex breakdown becomes more and more significant, which results in the increase (decrease) of vortex breakdown delay for the left (right) side vortex. Figure 5 shows the effects of vectored angles on the relative difference of the two leading edge vortex breakdown locations. It is obvious from this figure that, for a given normalized jet velocity, Ur, the distance between the breakdown positions of the two leading edge vortices generally increases with the vectored jet angle β. It can be seen that the difference between the two leading edge vortex breakdown locations increases monotonically with jet velocity. A possible explanation is offered for this phenomenon. When the vectored jet is towards the left side of the model, it causes the flow to move towards this side. Thus, the left side leading edge vortex is enhanced, and a delay in the vortex breakdown location is obtained. On the other hand, this left side flow decreases the strength of the right side leading edge vortex, which leads to the vortex breakdown earlier than the jet-off situation.

The results for an angle of attack of α=30° are shown in Fig. 6. In comparison with the result obtained at α=25°, the increase of angle of attack from α=25° does not change the variation tendency of the leading edge vortex breakdown location. Only the value of the relative breakdown location is changed, in that the effect of the vectored jet on controlling the vortex breakdown appears to become weaker with the increased angle of attack (Fig. 7). This may be attributed to the fact that with the increased angle of attack the leading edge vortex breakdown location moves towards the apex of the delta wing. Thus the distance between the vortex breakdown location and the trailing edge vectored jet increases, which reduces the effect of the trailing edge jet on the leading edge vortex breakdown delay. Thus, in comparison with the relative small angle of attack case, a larger vectored jet velocity is needed for high angle of attack in order to achieve a similar vortex breakdown delay as for the case of lower angle of attack.

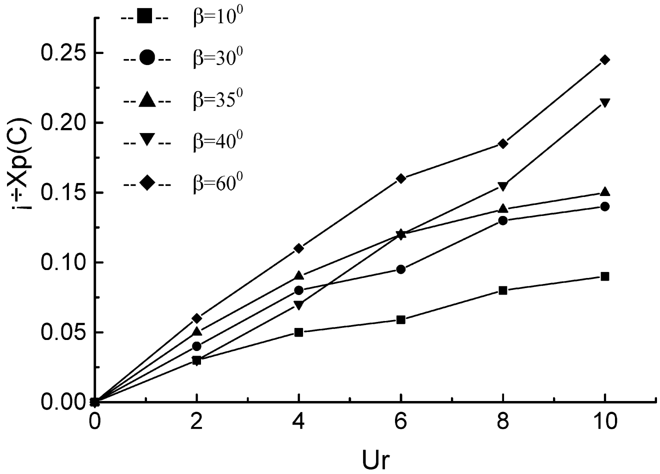

Fig. 6. The variation of the difference between the two leading edge vortex breakdown locations with normalized jet velocity (α=30°). *Solid square* β=10°; *solid circle* β=30°; *solid triangle* β=35°; *inverted solid triangle* β=40°; *solid diamond* β=60°

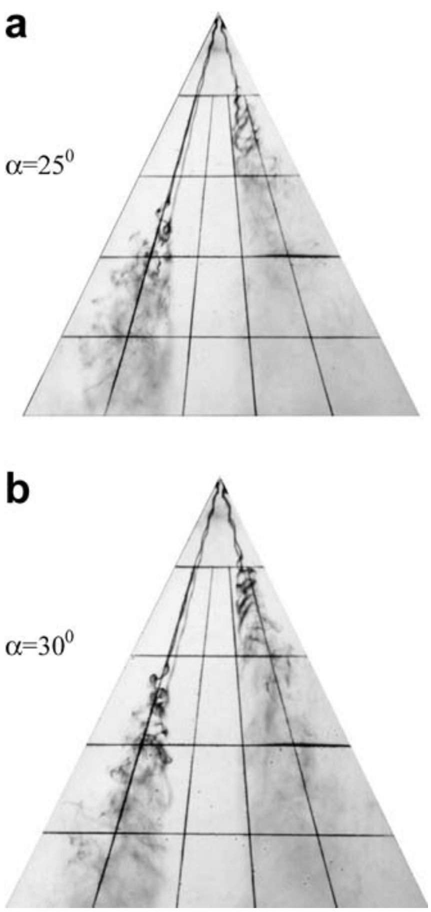

Fig. 7a, b. Flow patterns for β=60° and *Ur*=8

For α=40° in the jet-off case, the vortex breakdown starts at the apex of the delta wing. The two leading edge vortices mix strongly, and the combined vortex cores oscillate laterally. The vectored trailing edge jet can evidently make the oscillating vortex core change into steady vortex, but only on the side in the blowing direction.

These results suggest that, in order to fly at a high angle of attack in practice, the vectored trailing edge jet technique may be useful for stabilizing the leading-edge vortices. In this experiment, for a jet vector angle of 60° and an angle of attack of α=40°, the maximum delay of the leading edge breakdown reaches 0.36 C at *Ur*=10. When there is no vectored trailing edge jet, the leading edge vortex breaks down at 0.20 C.

4
Conclusions

- The effect of the vectored trailing edge jet on leading edge vortex breakdown is not significant for a jet angle of less than 10°. For a given angle of attack and jet velocity, the vectored jet generally causes a delay in the vortex breakdown on the side in the direction of the jet, and an advance in the breakdown for the vortex on the opposite side. This effect increases with increasing jet angle.
- For the same jet velocity and vectored jet angle, the effect of the vectored trailing edge jet on the leading edge vortex breakdown trends to decrease with the angle of attack.
- When the angle of attack is greater than 40°, the leading edge vortices interact and oscillate. The vectored trailing edge jet can cause the oscillating leading edge vortex to become steady on the side in the direction of the jet.

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