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New Pair of Leading-Edge Vortex Structure for Flow over Delta Wing

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Visualization experiments show that a new flow structure of two pairs of leading-edge vortices exists on the upper surface of the 75-deg sweptback delta wings with leeward and symmetrical beveled leading edges. The wind-tunnel force measurement results indicate this new structure contributes much to the aerodynamic performance of the wing. Some discussion about this new observation is presented in this paper.

Nomenclature

BLx	=	streamwise vortex breakdown location normalized by root chord of delta wing, original from the vertex of delta wing
C_D	=	drag coefficient
C_L	=	lift coefficient
C_L/C_D	=	lift-to-drag ratio
α	=	angle of attack of delta wing
α_{eff}	=	effective angle of attack of delta wing
$\wedge$	=	sweepback angle of leading edge of delta wing

Introduction

DELTA wings are largely incorporated into many advanced, high-performance aircraft configurations today. It is well known that the cross-sectional shapes of leading edges affect the aerodynamic performance of delta wings. Kegelman and Roos[1] investigated systematically the effects of leading-edge profiles on the flow over delta wings with a sweepback angle of 70 deg. They concluded that the shapes of the leading edges significantly affect the burst of leading-edge vortices. Based on the force measurement results, Kegelman and Roos[1] found that the leading edge of a delta wing with positive camber generated greater vortex lift than that with the negative camber. Miau et al.[2] conducted similar research work on several 50-deg sweepback delta wings with the relative thickness of 4% of the root chord. Their investigation into nine leading-edge profiles showed that the leading edge, which was beveled windward at 25 deg, generated the strongest and the most concentrated vortices. The leading-edge vortices were also farthest away from the delta-wing surface. However, the reduction of leading-edge vortices strength, that is, lift reduction, happened when the wing leading edges were leeward and symmetrical beveled. Because the angles of attack were below 20 deg in their research, their investigation did not point out what the flow structures were at higher angles of attack with various leading-edge profiles. Lately, through-flow visualizations on a same-swept delta wing with 45-deg windward beveled leading edge and the relative thickness of 2.2%, Taylor et al.[3] found a very distinct flow structure. They attained a dual-vortex structure over the leeward wing surface and suggested that the structure resulted from the interaction of the secondary separated shear layer and the shear layer of the primary leading-edge vortices. Their study indicated that the structure was dependent on Reynolds number. Although there are many studies about the influence of leading-edge shapes on delta wings, such as Polhamus,[4] Pelletier and Nelson,[5] Ericsson and King,[6] and so on, the dual-vortex structure over low-sweepback delta wing is first reported in Gursul's work. In this research regime, most of the researchers did not consider the fact that the bevel directions of leading edges greatly influence the flow over delta wing. Ericsson[7] found that the blunt leading edges caused stalling delay and lift enhancement of delta wing rather than the sharp leading edges. Huang et al.[8] suggested that the effect of leading-edge bevels just related to the ratio of the bevel-surface width to the boundary-layer thickness before separation. They also did not care about the effects of bevel direction on the delta wings.

In view of these different opinions, more investigations into the effects of the cross-sectional shapes of leading edges are expected to clarify some doubt. In this paper, force measurements in wind tunnel and dye visualizations in water channel were conducted, and a new leading-edge vortex structure, that is, the dual-vortex structure, was observed in flow-visualization experiments. This is a new observation for the flow over highly swept delta wings, and the wind-tunnel experiments indicate that the vortex lift of the delta wing with leeward beveled leading edge is greater than those of the others. The present paper will make some elementary discussion, and further research work is needed to give insight into the subject.

Experiments

All of the models were flat-plate delta wings with different cross-sectional shapes of leading edges and the leading edges were beveled at 45 deg on the windward wing surface, leeward wing surface, and symmetrically on both surfaces, respectively, as shown in Fig. 1, which are denoted as WB, LB, and DB (defined as delta wing with windward beveled leading edge, leeward beveled leading edge, and double-side leading edge, respectively) in this paper, respectively. The sweepback angle of the delta wings $\wedge$ is 75 deg, and the thickness 5 mm, 2% of the root chord of the delta wings. The models used in force measurement experiment were as well as in visualization study.

Force measurement experiments were conducted in an open-circuit low-speed wind tunnel in Beijing University of Aeronautics and Astronautics. The experimental velocity is 20 m/s, which results in a Reynolds number of 3.42×10^5 based on the root chord of the delta wings. The turbulent intensity of the incoming flow is less than 0.3% at the wind speed of 20 m/s. Visualization experiments were performed in a low-speed water channel with turbulent intensity of no more than 1%, and its test section is 0.6×0.6 m with length of 4.0 m. Experimental Reynolds number is 1.39×104 in water-tunnel experiments, and dye was injected at the vertex of delta wings to visualize the leading-edge vortices. Because the characteristics of the flow over a sharp leading-edge delta wing is insensitive to Reynolds Number tested,[9] it is reasonable to compare the results of force measurement with those of dye visualizations.

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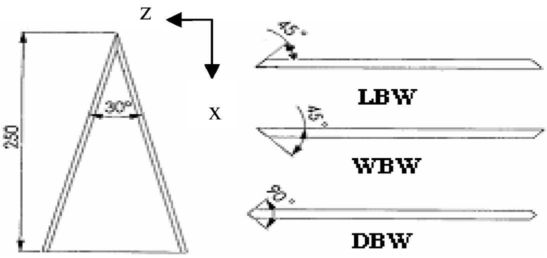

Fig. 1 Schematic graph of experiment models.

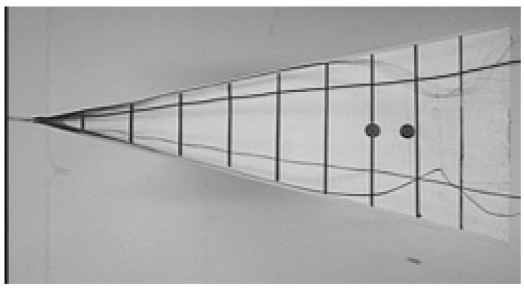

Fig. 2a Top view of double-pair leading-edge vortex structure for DB at α = 25 deg.

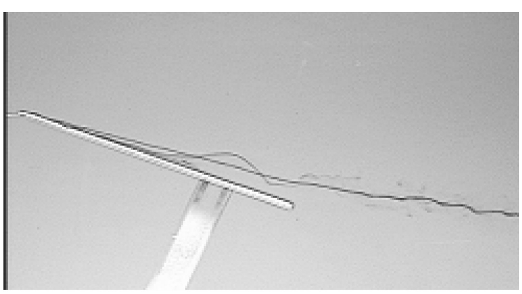

Fig. 2b Side view of double-pair leading-edge vortex structure for DB at α = 25 deg.

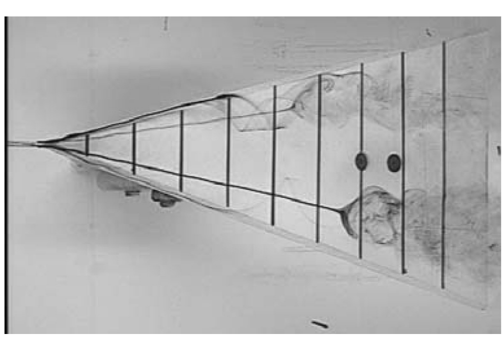

Fig. 2c Top view of double-pair leading-edge vortex structure for DB at α = 40 deg.

Results and Discussion

Flow-Visualization Results

The results of flow-visualization experiments show that the flow structure over the delta wing with the leeward beveled leading edge is similar to that over the delta wing with the symmetrical beveled leading edge, but different from that of the windward beveled delta wing. When the angle of attack is greater than 15 deg, the double-pair leading-edge vortices appear over DB and LB as shown in Figs. 2a and 2b. In flow-visualization experiments, dye was injected into flow near the vertices of delta wings. Although this injection method is recommended to visualize the core of leading-edge vortices, it hardly shows the secondary vortices. So it is a new pair of leading-edge vortices that locates outside the primary leading-edge vortices (LEV), rather than the secondary leading-edge vortices. The new pair of leading-edge vortices develops along the beveled surface rotating in the same direction to the primary leading-edge vortices, it is called a sub-leading-edge vortex (SLEV) in this paper. The core of SLEV is slower than that of LEV. When α is greater than 35 deg, LEV becomes asymmetrical, and it is slightly difficult to visualize SLEV, as shown in Fig. 2c. For the same angle of attack, the breakdown location of the leading-edge vortex is delayed for DB and LB in comparison with WB as shown in Fig. 3.

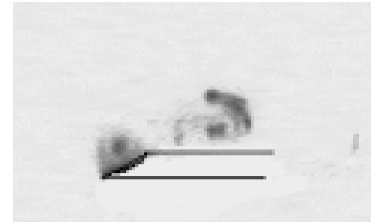

Fig. 2d Cross-sectional patterns of double-pair leading-edge vortex structure for LB at 60% of root chord location at α = 25 deg.

Based on the results of dye, hydrogen bubble, and fluorescence visualizations, it is suggested that the double-pair leading-edge vortex structure is related closely to the cross-sectional shapes of the leading edges of delta wings. This new structure can be characterized as follows: SLEV rotates in a same sense to LEV. Hydrogen-bubble flow-visualization study indicates that LEV is developed from the shear layer separated at the intersection between the beveled surface and the windward wing surface. For LB and DB, there exists the flow that moves downward along the beveled surface with sufficient width; therefore, this part of the flow is rolled up as a result of the induction of the LEV. Finally, a new pair of leading-edge vortex (SLEV) forms near the beveled surface with the same sense of rotation as the primary leading-edge vortex. When SLEV develops along the beveled surface, it is uplifted gradually until it touches the shear layer of LEV and then it entangles into LEV. The structure is quite different from that observed previously over delta wings. Figure 2d shows the cross-sectional pattern of the structure obtained in fluorescence visualization.

Miau et al.[2] did not observe the double-pair leading-edge vortex structure. For the delta wing with sweepback angle of 50 deg, the flow mainly attaches on the wing surface, and vortices are weaker when angles of attack are below 20 deg. They suggested that the leading-edge vortices were derived from intersection of the beveled surface and leeward wing surface, so that it was nearer to wing surface. Different from their view, the present paper suggests that the flow separation at the intersection of the bevel surface and windward wing surface forms LEV, based on the experiment observation. The beveled surface and LEV are necessary to the formation of SLEV. The entanglement of SLEV into LEV can increase the LEV's shear-layer energy, thereby delaying the leading-edge vortex breakdown to further downstream.

Analysis of Local Two-Dimensional Flow Around the Profile of Leading Edges

On the view of the effective angle of attack, some difference of the flow around the leading edges of LB and WB can be found. The analysis can help to explore the mechanism of SLEV.

Considering the influence of sweepback leading edge only, the effective angle of attack is calculated as follows:

$$a_{\text{eff}} = \tan^{-1}\left(\frac{\tan a}{\cos \wedge}\right)$$

Based on the calculating results shown in Table 1, the flow over the different cross-sectional shapes of the leading edges of the delta wings could be analyzed deeply.

For the flow over the wedge of LB as shown in Fig. 4a, $\alpha < 15$ deg corresponds to an effective angle of attack below 45 deg. In this case, the flow approaches the beveled surface at negative angle of attack, so that it attaches on the beveled surface. When $\alpha = 15$ deg, the flow still attaches to the beveled surface. For $\alpha > 15$ deg, the flow

Table 1 Effective angle of attack[a]

α	5	10	15	20	25	30	35	40	45	50
α_{eff}	18.68	34.27	45.99	54.58	60.97	65.85	69.71	72.86	75.49	77.75
$\alpha_{\mathrm{W\_BEVEL}}$[b]	63.68	79.27	90.99	99.58	105.97	110.85	114.71	117.86	120.49	122.75
$\alpha_{\mathrm{L\_BEVEL}}$[c]	−26.32	−10.73	−0.99	9.58	15.97	20.85	24.71	27.86	30.49	32.75

[a]Units in degrees. [b]$\alpha_{\mathrm{W\_BEVEL}}$ = incoming flow angle to windward beveled surface. [c]$\alpha_{\mathrm{L\_BEVEL}}$ = incoming flow angle to leeward beveled surface.

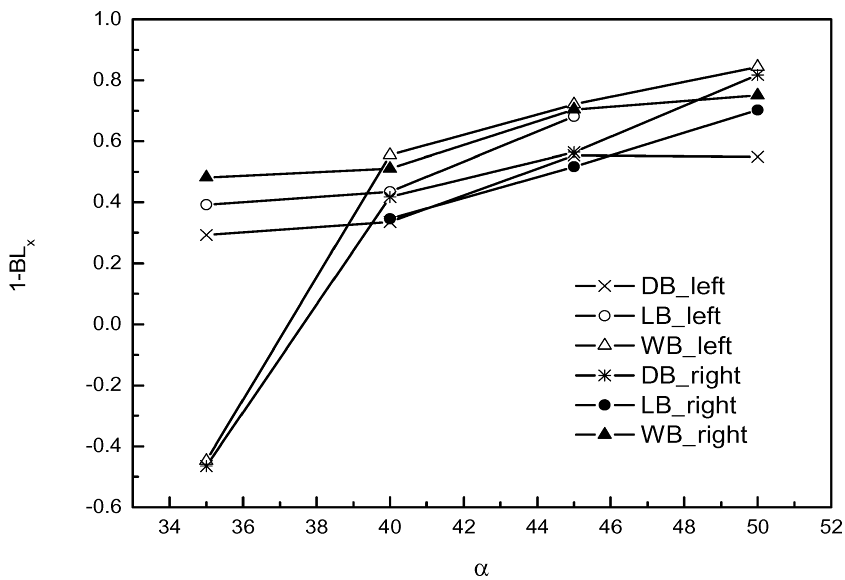

Fig. 3 Vortex breakdown location vs angle of attack.

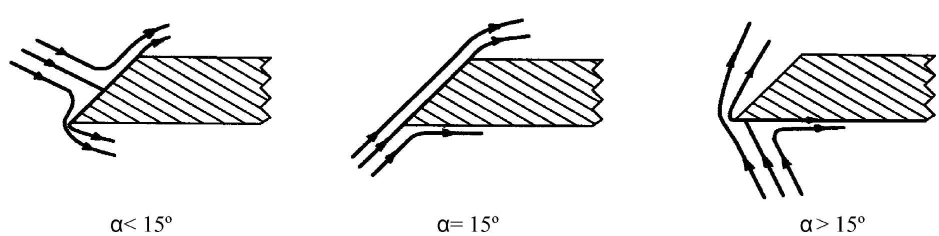

Fig. 4a Schematic graph of flow around leading-edge profile for LB.

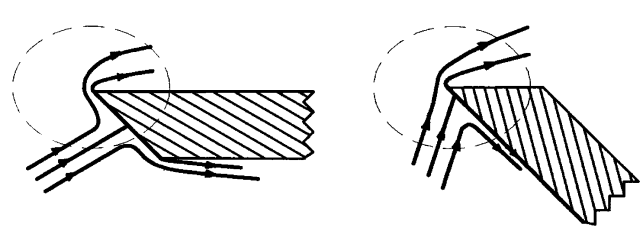

Fig. 4b Flows around leading-edge profiles for LB and WB.

approaches the beveled surface at positive angles of attack, and the stagnation point locates on the windward wing surface, thus the flow separation occurs at the vertex of the wedge.

For the wedge of WB as shown in Fig. 4b, the flow approaches the beveled surface at positive incidences under all experimental angles of attack. Thus the flow separation always occurs at the vertex of the wedge. If the flow over the leading-edge profile is two-dimensional, the incoming flow angle of LB is less than that of WB at the same angle of attack (Table 1).

In fact, the two-dimensional flow does not exist for the flow over the delta wings. However the present analysis might be helpful to explore some difference between LB and WB. When the flow separates at the vertex of the wedge, the flow goes through different geometry for LB and WB, which can lead to the different flow characteristics. As just mentioned, further exploration is necessary to give satisfied explanation for the double-pair leading-edge vortex structure.

Force Measurement Results

The results of force measurement indicate that the lift coefficients of DB and LB are enhanced at higher angles of attack, especially near the stalling angle. This is consistent with the result of Kegelman and Roos.[1] The stalling angle also increases as shown in Fig. 5, which indicates that the leeward bevel is benefit to the delta-wing lift characteristics. Kegelman and Roos[1] suggested that the positive camber of the leeward beveled leading edge changes the characteristic of the separation near the leading edge and the strength of the leading-edge vortices, so that the vortex lift increases. Here, the increase of the lift can be closely related to the double-pair leading-edge vortex structure. SLEV can increase the suction level above the tip of the upper-wing surface in comparison with the case without SLEV, resulting in the lift increment. However, no other data are available to support our suggested mechanism. Further research is needed to provide much more precise data to understand the flow well. Figure 6 shows the variation of lift-to-drag ratio vs angle of attack, which illustrates the effects of the cross-sectional shapes more clearly. The leeward-bevel delta wing increases lift-to-drag ratio of about 50% compared with the windward-bevel one. This favorable effect is surprising, and so great attention should be paid to the leading-edge profiles of delta wings.

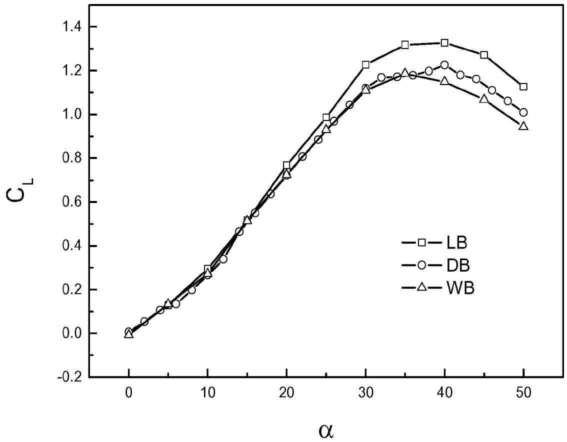

Fig. 5 Lift coefficient vs angle of attack.

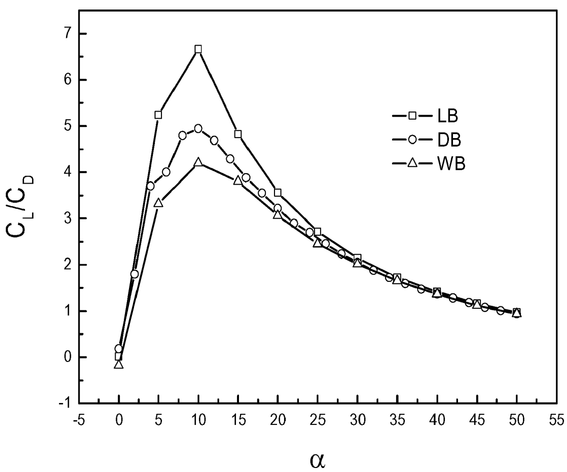

Fig. 6 Lift/drag ratio vs angle of attack.

Conclusions

1) Force measurement results indicate that the leeward beveled leading-edge enhances the lift of the delta wing and improves its characteristic of stalling, increase the lift-to-drag ratio.

2) The structure of the double pairs of leading-edge vortices is observed on the delta wings with leeward and symmetrical beveled leading edges in flow visualizations. The new leading-edge vortex structure might contribute much to the favorable effects of leeward and symmetrical beveled leading edges.

3) The beveled surface and LEV are necessary to the formation of SLEV. The flow downstream along the beveled surface is induced by the separated shear layer of LEV forming SLEV.

Acknowledgment

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