Effects of leading-edge bevel angle on the aerodynamic forces of a non-slender 50° delta wing

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ABSTRACT

The aerodynamic performances of a non-slender 50° delta wing with various leading-edge bevels were measured in a low speed wind tunnel. It is found that the delta wing with leading-edge bevelled leeward can improve the maximum lift coefficient and maximum lift to drag ratio, and the stall angle of the wing is also delayed. In comparison with the blunt leading-edge wing, the increment of maximum lift to drag ratio is 200%, 98% and 100% for the wings with relative thickness $t/c = 2\%$, $t/c = 6.7\%$ and $t/c = 10\%$, respectively.

NOMENCLATURE

c	root chord length of the delta wing, cm
t/c	relative thickness of the delta wing
C_D	drag coefficient of the delta wing
C_L	lift coefficient of the delta wing
$C_{L\max}$	maximum value of C_L
C_{L0}	zero lift coefficient of the delta wing, the lift coefficient of the delta wing at zero angle-of-attack
ΔC_{L0}	zero lift coefficient increment of the delta wing relative to the blunt wing
C_L/C_D	lift to drag ratio of the delta wing
$(C_L/C_D)_{max}$	maximum value of C_L/ C_D
t	delta wing thickness, cm
α	angle-of-attack of the delta wing, deg
α_s	stall angle of the delta wing, deg
β	bevel angle, deg

1.0 INTRODUCTION

Since the wind tunnel experiments conducted by Werle(1) in 1954, the investigations on vortex formation, development and breakdown have attracted great attentions both experimentally and numerically for flow over delta wings, and the effects of angle-of-attack, thickness, sweep angle, leading-edge and trailing-edge cross-sections, Reynolds number and fuselage are involved. The detailed review may be found in Ashley *et al*(2), Rockwell(3) and Gursul(4).

As early as 1964, Earnshaw(5) pointed out that the leading edge cross-section was one of the key parameters which influenced the vortex breakdown position, and he suggested that great attention should be paid to this parameter. Afterwards, a lot of work have been done in this topic(6-15). Pelletier, *et al*(8) visualised the vortex breakdown positions for two 65° delta wings with the leading edge bevelled in different angles, their experimental results indicated that the vortex breakdown position advanced for the wing with its leading edge 20° symmetrical bevelled in comparison with the wing leading edge 45° windward bevelled. Based on the leading-edge suction analogy(9), Ericsson and King(10) proposed a method to estimate the aerodynamic forces of slender delta wing, which considered the effects of delta wing leading-edge shapes. They reported that the wing with blunt leading-edge stalls later than the wing with sharp leading-edge, and the wing with blunt leading-edge has higher lift before wing stalling.

For flow over non-slender delta wing, Miau *et al*(13) conducted the experimental study on 50° delta wing with relative thickness $t/c = 4\%$. Their results showed that, in comparison with the delta wing with leading-edge leeward and symmetrically bevelled, the leading-edge with 25° windward bevelled generated the strongest

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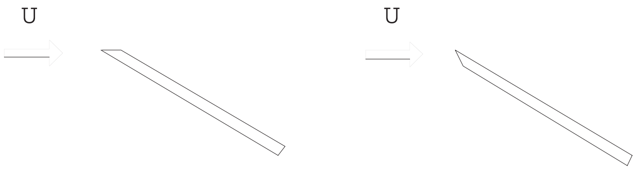
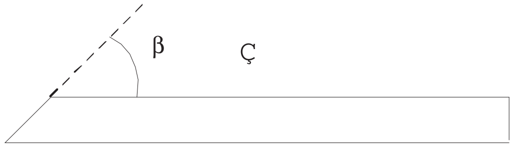


(a) Wing bevelled leeward. (b) Wing bevelled windward.



(c) Definition of the leeward bevel angle.

Figure 1. The sketch of wing bevel angle.

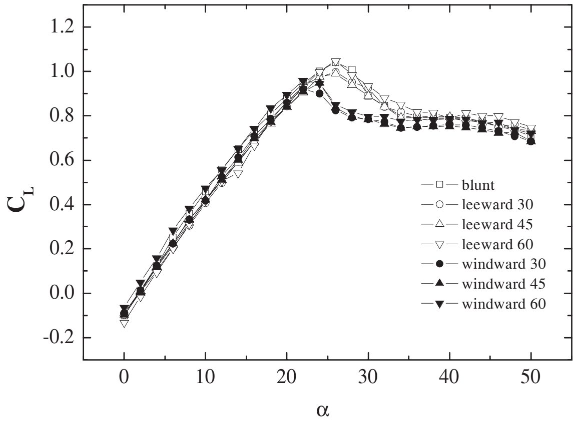
and the most concentrated vortices that were farthest away from the delta wing surface. Kawazoe *et al*(15) conducted the experiment to measure the pressure distribution and the velocity field for flow over a 45° thick delta wing with rounded leading-edge, they reported that the thick delta wing produces lower lift coefficient than the thin wing at small angles-of-attack, and stall is slightly delayed. They attributed it to the different sizes of the leading-edge vortex: the vortex of thin wing spread wider than the thick one, which may lead to stall phenomenon.

In this paper, the effects of leading-edge cross-section and the thickness on the aerodynamics were investigated and analysed for flow over non-slender 50° delta wing, and it is expected that the present research may farther our understanding of flow over low sweep delta wing.

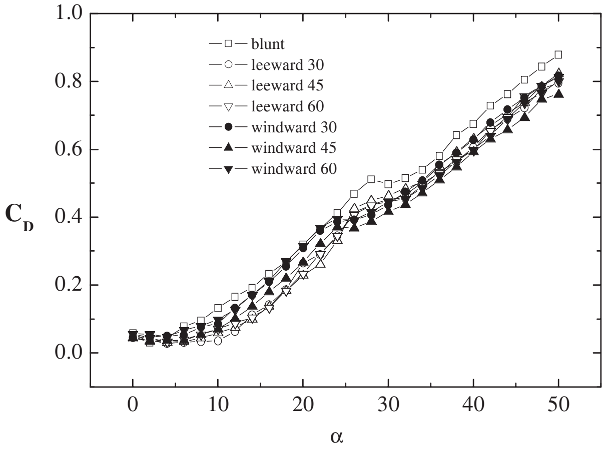
2.0 EXPERIMENTAL EQUIPMENT AND FACILITIES

The experiments were carried out in an open circuit low speed wind tunnel in Beijing University of Aeronautics and Astronautics, which has a 1·02 × 0·76m ellipse shaped test section with the length of 2·0m. The turbulence level of the in-coming flow is less than 0·3%, and the maximum velocity of this wind tunnel is $40ms^{-1}$. The tested models were 50° delta wings with blunt trailing edge, and different thickness and leading-edge bevel angles (Fig. 1). The thicknesses of the models were t = 3mm, 10mm, 15mm, and their root chord length had same value of c = 15cm, which result in the relative thickness t/c = 2%, 6·7% and 10%, respectively. Among them, the leading-edge of the 3mm delta wing was 30°, 45° and 60° windward and leeward bevelled; while 10mm and15mm delta wings were 15°, 30°, 45° and 60° windward and leeward bevelled. Besides, we also have three blunt wings with thickness of 3mm, 10mm and 15mm respectively in present investigation.

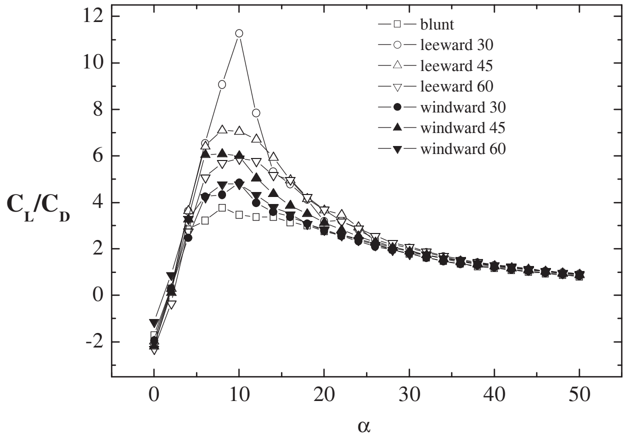
A six-component Aero-lab sting balance together with data acquisition and analysis system was used to measure the forces of the models. The model was pitched through a set angle-of-attack ranging from 0 to 50° with a step of 2°. The root chord length of the models were c = 15cm, and the free stream velocity was $20ms^{-1}$ in present experiments, so the Reynolds number was $2{\cdot}1 \times 10^5$ based on the root chord length of delta wing. The blockage of the model is only 2·4%, thus, no correction is made for the blockage interference.



(a) Lift coefficient.



(b) Drag coefficient.



(c) Lift to drag ratio.

Figure 2. Effects of leading-edge bevels on delta wings with *t*/*c* = 2%.

3.0 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 The effect of bevel angle on *t/c* = 2% wing

For delta wing with t = 3mm (t/c = 2%), Fig. 2(a) shows the variation of C_L with α for the wings bevelled with different angles. In general, the leading-edge cross sections of the delta wings mainly influence C_L in the range from α_s to 34°. In comparison with the blunt wing, when the wing is bevelled windward, $C_{L\max}$ is decreased, and the corresponding α_s is advanced from 26° to 22~24°. For the wings bevelled leeward, their C_L curves are very close to the blunt wing, this means that $C_{L\max}$ and α_s are nearly the same for the blunt wing and the wings bevelled leeward.

Figure 2(b) presents the variation of C_D with α, it can be seen from this figure that, for all of the bevelled wings, C_D are less than the value of blunt wing. For $\alpha < 24°$, C_D are greater for the wings windward bevelled than the wings leeward bevelled.

It can be clearly seen from C_L/C_D curves shown in Fig. 2(c) that the leading-edge cross section significantly influences the wing aerodynamics. In spite of the wings bevelled windward or leeward, $(C_L/C_D)_{\max}$ are much greater than the blunt wing, and the wings bevelled leeward have the greatest value of $(C_L/C_D)_{\max}$, which is occurred at α = 8~10°. For the wing leeward 30° bevelled, $(C_L/C_D)_{\max}$ is about 11·4, which is increased by 200% compared with the blunt wing.

3.2 The effect of bevel angle on *t/c* = 6·7% wing

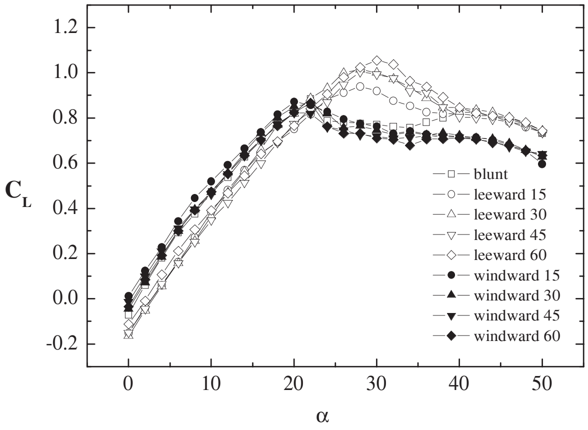
For the delta wing with t = 10mm (t/c = 6·7%), it can be seen from Fig. 3(a) that, when the leading-edges of the wing were windward bevelled, β has little influence on α_s and $C_{L\max}$. Moreover, the wing stalling occurs at α_s = 28~30° when the wings are leeward bevelled, which results in 8~10° delay of α_s, and $C_{L\max}$ increases with leeward bevelled angle. For the wing leeward 60° bevelled, the increment of $C_{L\max}$ is 20·5% compared with the blunt wing data. For the wing leeward bevelled 15°, 30° and 45°, this increment is 6·8%, 13·6% and 13·6%, respectively.

With regard to C_D, Fig. 3(b) indicates that, at small α, the wing with its leading-edge leeward 15° bevelled has minimum value, and C_D are lower for the wings with leading-edges leeward bevelled in comparison with the blunt wing. Based on the above analysis for C_L, it can be deduced that C_L/C_D will be enhanced for the wings with leading-edges leeward bevelled, and the maximum increment of $(C_L/C_D)_{\max}$ is 98% for the wing leeward 15° bevelled as shown in Fig. 3(c).

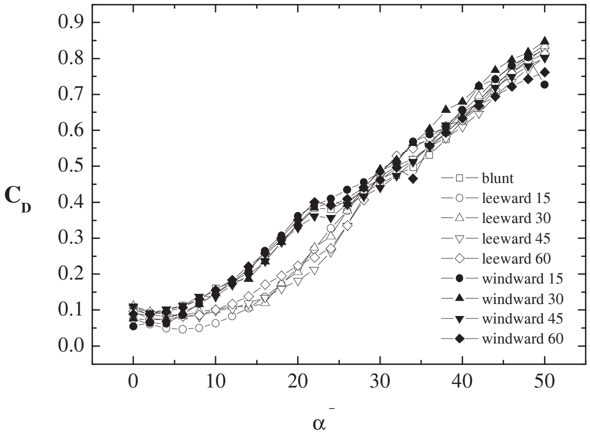
3.3 The effect of bevel angle on *t/c* = 10% wing

In this case, the relative thickness of the wing is t/c = 10%. In comparison with the two cases mentioned above, the leading-edge cross section much significantly influences the aerodynamics of this thick delta wing. Figure 4(a) shows that the wing with leading-edge bevelled windward nearly does not influence the stall angle of the wing, but the difference between the C_L is evident. For the wing with leading-edge leeward bevelled, their α_s are shifted from 20° to about 30°, and $C_{L\max}$ increases with β. This increment of $C_{L\max}$ is 29·5% for the wing with leading-edge 60° leeward bevelled.

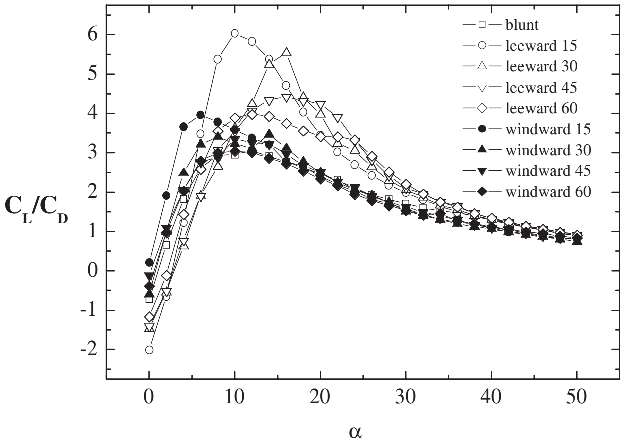
Figure 4(b) shows the variation of C_D with α, it is evident that C_D is smaller for the wing with leading-edge leeward bevelled than the blunt wing, so large C_L/C_D is expected for the leeward bevelled wings. Figure 4(c) shows that the leading-edge cross section remarkably influences C_L/C_D, and $(C_L/C_D)_{\max}$ is increased for the wing both leeward and windward bevelled in comparison with the blunt wing, a maximum increment of $(C_L/C_D)_{\max}$ is approximate 100% for the wing 15° leeward bevelled.



(a) Lift coefficient.

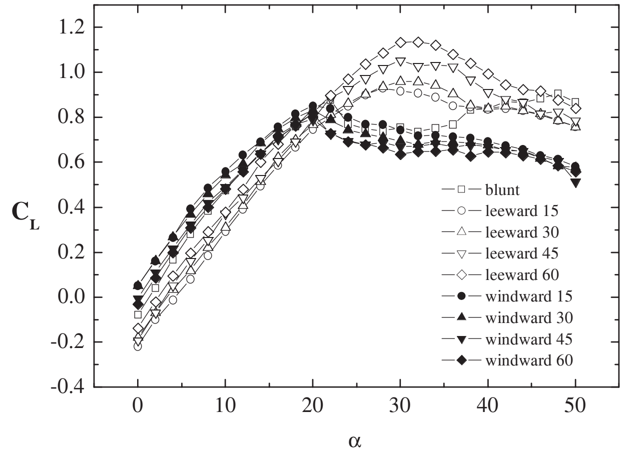


(b) Drag coefficient.

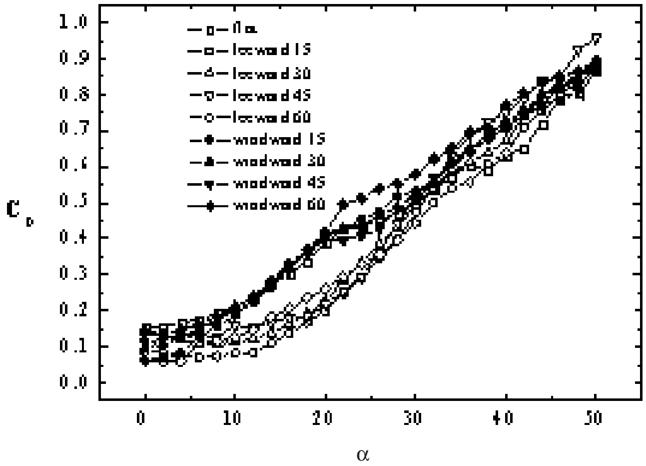


(c) Lift to drag ratio.

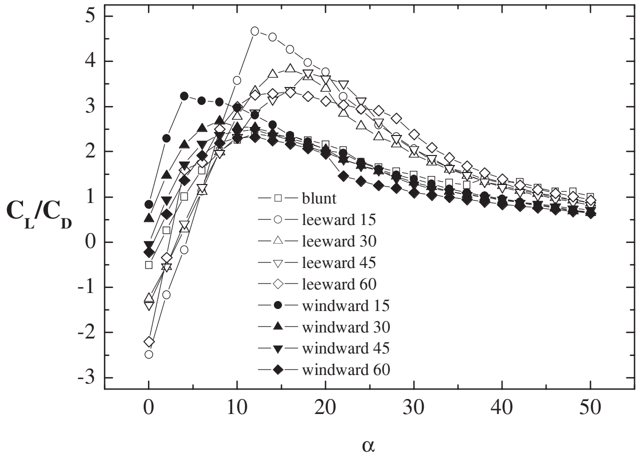
Figure 3. Effects of leading-edge bevels on delta wings with t/c = 6·7%.



(a) Lift coefficient.



(b) Drag coefficient.



(c) Lift to drag ratio.

Figure 4. Effects of leading-edge bevels on delta wing with $t/c = 10\%$.

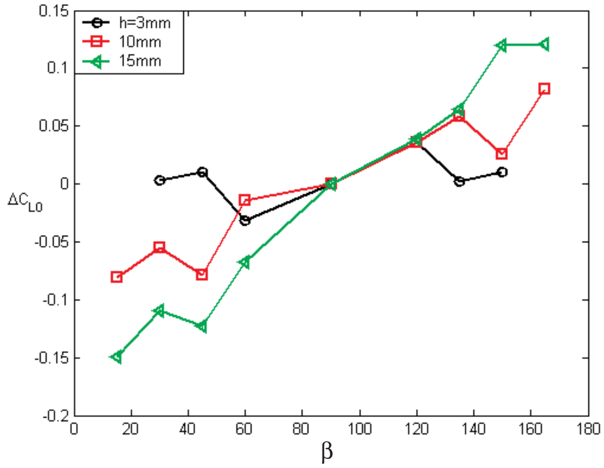


Figure 5 The variation of ΔC_{L0} with wing bevel angles β.

3.4 Discussion

From that mentioned above, it may be concluded first that, irrespective of the wing thickness, the wings have high C_L when they are bevelled windward before stall. This is in accordance with Miau *et al*'s$^{(13)}$ visualisation results, they pointed out that, the leading-edge vortex of delta wings with leading-edge windward bevelled not only forms at relative small α but also has strong strength, which may results in the vortex lift increment at relative small α, thus C_L is increased totally before stall.

Second, the wing with leading-edge bevelled leeward can delay α_s up to 10° for the two thicker wings, this is due to the delay of leading-edge vortex breakdown in this case$^{(14)}$. In order to further analyze the bevel angle effect, Figure 5 shows the influence of β on ΔC_{L0}, where $\beta > 90°$ means that the wing is bevelled windward. In comparison with the blunt wing, ΔC_{L0} of the bevelled wing is antisymmetric about the blunt wing. It is evident that the negative ΔC_{L0} is produced when the wing leading-edge bevelled leeward, and a positive ΔC_{L0} is obtained for the wing bevelled windward. Moreover, this influence becomes more significant with wing thickness, and β nearly does not influence C_{L0} for the thin wing tested in present study. Thus, from the viewpoint of lift enhancement before stall, the leading-edge of the wings should be bevelled windward, especially for the thick wings; whereas, from the viewpoint of increasing $C_{L\max}$ and delaying α_s, the wing leading-edge should be bevelled leeward.

Third, the wings have low C_D when they are bevelled leeward, and this C_D reduction is much prominent at small leeward bevel angle, which results in the significant increment of C_L/C_D. This increment is mainly due to the drag reduction in this case.

4.0 CONCLUSIONS

- From the viewpoint of lift enhancement before stall, the leading edge of the wings should be bevelled windward, especially for the thick wings. Whereas, from the viewpoints of increasing $C_{L\max}$ and delaying α_s, the wing leading edge should be bevelled leeward.
- The thicker wing will lead to larger C_D, which results in lower maximum value of C_L/C_D. Thus, the thin delta wing performs excellent aerodynamic characteristics.

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REFERENCES

1. WERLE, H. Quelques resultants experimentaux sur les ailes en fleches, aux Faibles vitesses, obtenus en tunnel hydrodynamique, *La Recherché Aeronautique*,1954, **41**.
2. ASHLEY, H., KATZ, J., JARRAH, M.A. and VANECK, T. Survey of research on unsteady aerodynamic loading of delta wings, *J Fluid and Structures,* 1991, **5**, pp 363-390.
3. ROCKWELL, D. Three-dimensional flow structure on delta wings at high angle-of-attack: experimental concepts and issues, 1993, AIAA Paper 93-0550.
4. GURSUL, I. Review of unsteady vortex flows over delta wings, 2003, AIAA Paper 2003-3942.
5. EARNSHAW, P.B. Measurements of vortex-breakdown position at low speed on a series of sharp-edged symmetrical models, November 1964, ARC CP 828.
6. BARTLETT, G.E. and VIDAL, R.J. Experimental investigation of influence of edge sharp on the aerodynamic characteristics of low aspect ratio wings at low speed, *J Aero Sci*, 1955, **22**, (8).
7. KEGELMAN, J. and ROOS, F. Effects of leading-edge shape and vortex burst on the flowfield of a 70 deg sweep delta wing, January 1989, AIAA Paper, pp 1989-0086.
8. PELLETIER, A. and NELSON, R.C. An experimental study of static and dynamic vortex breakdown on slender delta wing planforms, 1994, AIAA Paper 94-1879-CP.
9. POLHAMUS, E.C. Predictions of vortex lift characteristics by leading-edge suction analogy, *J Aircr*, 1971, **8**, pp 193-199.
10. ERICSSON, L.E. and KING, H.H.C. Effect of leading-edge cross-sectional geometry on slender wing unsteady aerodynamics, January 1992, AIAA Paper, pp 1992-0173.
11. HUANG, X.Z., SUN, Y.Z. and HANFF, E.S. Further investigations of leading-edge vortex breakdown over delta wings, AIAA Paper, 1997, pp 1997-2263.
12. WANG, J.J. and ZHAN, J.X. A new pair of leading-edge vortex structure for flow over delta wing, *J of Aircr*, 2005, 2005, **42**, (3), pp 718-721.
13. MIAU, J.J., KUO, K.T., LIU, W.H., HSIEH, S.J., CHOU, J.H. and LIN, C.K. Flow developments above a 50-deg sweep delta wings with different leading-edge profiles, *J of Aircr*, 1995, **32**, (4), pp 787-794.
14. LU, S.F. Experimental Investigations on Vortex Structures and Aerodynamics for Flow over 50 deg Sweep Delta Wings, Master thesis, Beijing University of Aeronautics and Astronautics, 2005.
15. KAWAZOE, H., NAKAMURA, Y., ONO, T. and UMHIMARU, Y. Static and total pressure distributions around a thick delta wing with rounded leading-edge, 1994, AIAA Paper, pp 1994-2321.