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Experimental Study on Gurney Flap and Apex Flap on a Delta Wing

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The effects of Gurney flaps and apex flaps on the longitudinal aerodynamic performance of a delta wing with 70-deg sweepback angle were investigated in low-speed wind tunnel at a Reynolds number of 3.16×10^5 based on the root chord of the delta wing. The experimental results indicate that the increment of lift coefficient can be obtained efficiently for different ranges of angle of attack with Gurney flaps and apex flaps, respectively. The study first tested the application of Gurney flaps together with an apex flap on the highly swept-back delta wing. The results show that they, used together, can greatly improve the longitudinal aerodynamic performance of the delta wing, and in this case the apex flap contributes much to the gains. The maximum lift-to-drag ratio can be achieved when the drooping angle of the apex flap is nearly equal to the angle of attack.

Nomenclature

B	=	drooping angle of apex flap
C_D	=	drag coefficient
C_L	=	lift coefficient
C_M	=	pitching-moment coefficient
Cr	=	root chord length of delta wing
H	=	height of Gurney flap
α	=	angle of attack of delta wing
α_e	=	effective angle of attack of delta wing

Subscripts

A	=	apex flap
G	=	Gurney flap

Introduction

DELTA wings have long been effective configurations for modern flight aircrafts. Leading-edge vortex (LEV), as the main feature of the flow over delta wings, domains the distinct aerodynamics of delta wings at high speed and high angles of attack. In past decades, various devices aiming at controlling LEV and enhancing aerodynamics of delta wings have been tested. These were detailed in Ref. 1. Gurney flaps and apex flaps are very effective as well as simple devices for delta wings' performance gains.

A Gurney flap is a thin small flat plate attached to the trailing edge perpendicular to the airfoil chord line on the pressure side of an airfoil. The previous studies such as Liebeck,[2] Neuhart and Pendergraft,[3] Storms and Jang,[4] and so on showed that Gurney flaps increase the maximal lift coefficient, reduce zero-lift angle of attack, and delay vortex breakdown (VBD). Its favorable effects attracted much research interesting. In recent years, numerous researches were conducted to investigate the effects of Gurney flap on delta wings and to explore a proper physical explanation to these effects. Giguere et al.[5] found that a beneficial Gurney flap for the best lift-to-drag performance should be submerged within the local boundary layer, based on his test on airfoils. Traub and Galls̀[1] later investigations on Gurney flaps on delta wings indicated that a Gurney flap improves lift-to-drag ratio for the same lift coefficient at moderate-to-high lift coefficients. However, it has a marginal effect on VBD position and spanwise position of LEV except that it draws LEV closer to the upper surface of delta wings. Their statement that a Gurney flap mainly affects the attached flow over delta wings might explain the result of Giguère et al.[5] Jang et al.,[6] based on the computational results, suggested that a Gurney flap changed the adverse pressure gradient near the trailing edge of an airfoil, thus enhancing the suction level on the upper surface. Myose et al.[7] tested Gurney flaps with various heights on single-element, multi-element airfoils and wings, drawing the similar conclusion as previous work that a Gurney flap positioned properly achieved performance gains. Buchholz[8] compared the effects of Gurney flaps and leading-edge fences on a delta wing with 60-deg swept angle. He found that a Gurney flap increased lift-to-drag ratio but advanced VBD. He suggested that the effect is caused by the increase of swirl angle of LEV. Li and Wang[9,10] also conducted much research work on Gurney flaps over delta wings giving complement for the researches on Gurney flaps.

An apex flap is another kind of flap, which affects the leading-edge vortices over a delta wing to improve the aerodynamic performance of the delta wing. The effective camber of a delta wing affects the pressure gradient along leading-edge vortices, thus domains the characteristic of the flow over the delta wing such as suction level, vortex breakdown. The drooping apex flap brings a positive camber resulting in the delay of vortex breakdown; thus, an apex flap could be used to control the position of vortex breakdown on a delta wing. Based on flow visualization in water channel and pressure measurement in wind tunnel, Lowson and Riley[11] found that a small apex flap could provide about 1% chord movement in vortex breakdown position for a 1-deg change in the drooping angle of the apex flap. Through visualization, velocity, and surface-pressure measurement, Klute et al.[12] found that a drooping apex flap, rotating around an axis located 40% Cr, could delay VBD by an angle of several degrees beyond the steady flow breakdown angle of attack, for fixed and dynamic pitching 75-deg swept delta wings. Xu et al.[13] and Zhan et al.[14] through force measurement manifested the aerodynamic benefit of apex flaps on a 70-deg swept delta wing.

As aforementioned, either a Gurney flap or an apex flap is a promising effective device with a simple form on delta wings. A Gurney flap mainly affects the attached flow or wake, whereas an apex flap affects LEV. They control different characteristics of the flow over delta wings. It could be inferred that much benefit would be achieved when a Gurney flap and an apex flap were used on a delta wing simultaneously. In this paper, the work was performed to provide some insight into the flow control.

Experiment

The force/moment measurement was conducted in the three-dimensional open-circuit wind tunnel in Beijing University of

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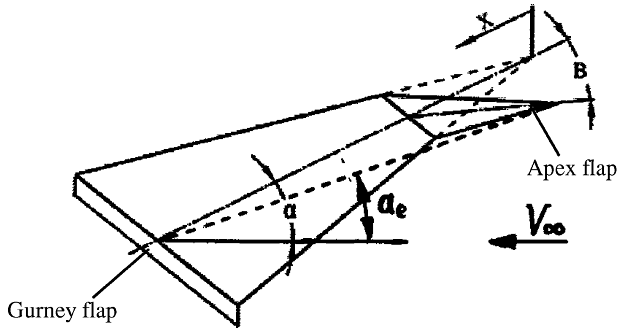


Fig. 1 Schematic diagram of experimental model.

Aeronautics and Astronautics, which has a 1.02×0.76 m ellipse-shaped test cross section 2 m long and the turbulence intensity of the coming flow is less than 0.3% at the wind speed of 20 m/s. The experiment was undertaken at a freestream velocity of 20 m/s, which yields a root-chord Reynolds number of 3.16×10^5.

The basic clean wing used in the experiment is a 5-mm-thick delta wing with a swept-back angle of 70 deg and Cr is 250 mm. The leading edge of the delta wing is beveled windward at 45 deg. The drooping angle of the apex flap can be changed around the axis located at 40% Cr, as shown in Fig. 1. And it can be set to within 0.5 deg. A six-component stain balance was used to measure the force/moment of the delta wing. The full scales for lift, drag, and pitching moment are 5 kg, 1 kg, and 0.3 kg · m, respectively. The accuracy of the balance is estimated at 0.13% of full scale for lift and 0.28% for drag and 0.31% for pitching moment. An aluminous cone jointed the model to the balance. The model was pitched through prescribed angle of attack ranging from 20 to 50 deg. The model angle of attack can be set to within 0.05 deg. Angle of attack is represented as α_e, which is the angle from the line connecting the leading edge to the trailing edge and the freestream, as shown in Fig. 1.

Gurney flaps are made of 2-mm-thick PVC plate. Seven nondimensional Gurney flap heights normalized by Cr—0, 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0%—are selected and referred to as G0, G1, G2, G3, G4, G5, and G6, respectively, in the text and figures.

In this paper, subscript A-G represents the configuration of the delta wing with both the apex flap and a Gurney flap, and nonsubscript represents the clean wing without Gurney flaps and the apex flap.

Results and Discussion

Force/moment measurement was conducted to investigate the longitudinal aerodynamics of the delta wing at a series of the drooping angle from 0 to 30 deg with variable Gurney flaps from G0 to G6.

Both the apex flap and Gurney flaps enhance lift coefficient of the delta wing. Experimental results indicate that a large portion of lift enhancement is obtained at lower angles of attack ($\alpha < 25$ deg) with a Gurney flap; however, at high angles of attack ($\alpha_e > 25$ deg) the apex flap is more efficient, as shown in Figs. 2a and 2b. This difference results from the different flow characteristics affected by Gurney flaps and apex flaps. For the case of Gurney flaps attached to the trailing edge, the Kutta condition near the trailing edge is changed[4]; the flow attached on the wing surfaces is different from that no Gurney flap. Thus at lower angles of attack Gurney flaps obtain gains. For the case of the delta wing with the apex flap, the camber of the wing increases because of the drooping apex flap; consequently, effective angle of attack becomes less than the wing absolute angle of attack α, and LEV are affected much and VBD are postponed. Therefore, when angles of attack are greater than the angle at which LEV occurs on the wing, the effects of the apex flap are notable. The distinction between α_e and α resulting from the drooping apex flap is far over that from a Gurney flap in magnitude. In this experiment, corresponding to the maximum nondimensional Gurney flap height of 3%, this maximum difference is 1.72 deg. Comparatively, when the drooping angle is 16 deg the corresponding difference is 5.85 deg. To show the difference, the lift coefficient of the delta wing vs effective angle of attack α_e as well as α is presented in this paper. Here α_e only considered the effect of the apex flap, and the slight effect of Gurney flap on α_e is neglected.

The effects of Gurney flaps on lift coefficient of the highly swept-back delta wing are similar to those of the delta wing with 40-deg swept-back angle.[9,10] All Gurney flaps used in the experiment increase the lift coefficient of the delta wing. The lift increase is more significant before stalling than after stalling. Corresponding to each drooping angle tested, there is a most effective height of Gurney flaps; here for the drooping angle of 4 deg, the optimum height is 2.5%, greater than the results of others.[5] Experiment results also show that Gurney flaps increase the maximum lift coefficient of the delta wing with a slight decrease of stalling angle. All of these could be seen in Fig. 3, which gives the results at the drooping angle of 4 deg.

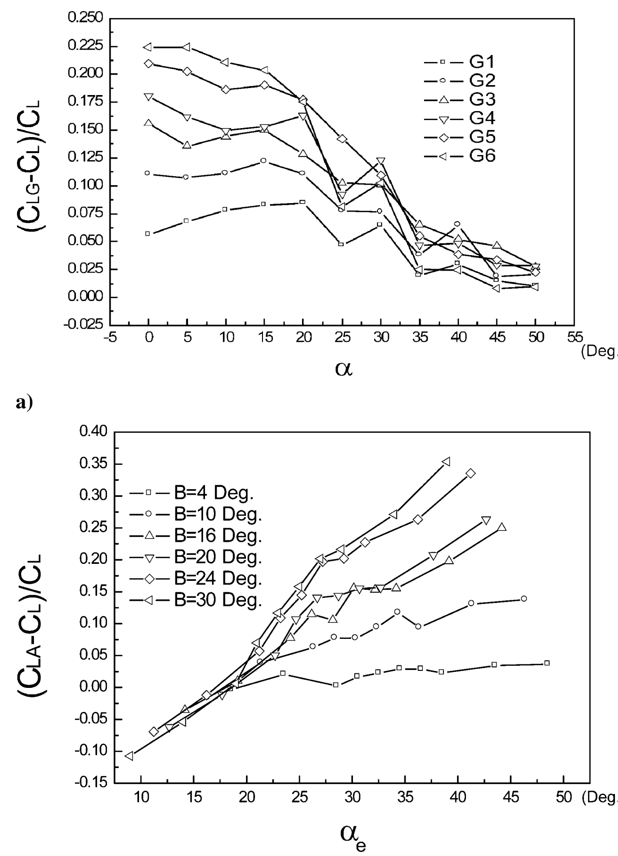


Fig. 2 Relative increment of lift coefficient vs angle of attack: a) Gurney flap and b) apex flap.

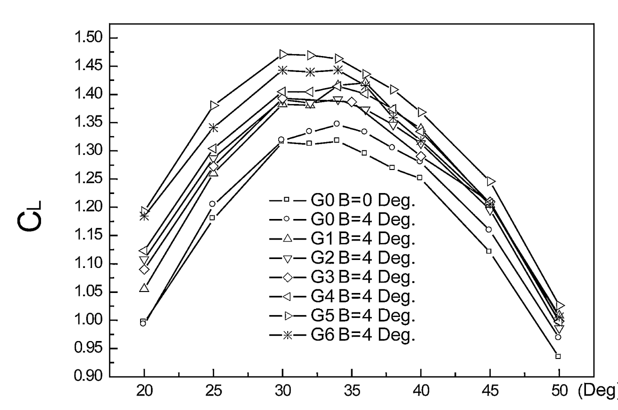


Fig. 3 Lift coefficient vs angle of attack.

Different from a Gurney flap adopted alone, a Gurney flap together with the apex flap enhances lift coefficient of the delta wing at experimental angles of attack from 20 to 50 deg without the penalty of stalling angle of attack. As shown in Fig. 4a, the angle of stall is almost the same as that of the clean wing because of the decrease of stalling angle with the Gurney flap and the increase of stalling angle with the apex flap. The application of both flaps has the advantage over single Gurney flap or single apex flap.

The effects of the apex flap on drag coefficient of the delta wing are very different from that of Gurney flaps. As shown in Fig. 4b, the apex flap reduces drag coefficient at some angles of attack, but the Gurney flap increases drag coefficient at all experimental angles of attack, and the higher the Gurney flap the more the drag coefficient increases.[14] The application of Gurney flaps in company with the apex flap on the delta wing also increases drag coefficiental though the magnitude is smaller than that with Gurney flaps alone. Figure 4c indicates that the Gurney flap increases lift with much penalty of drag. The apex flap used with the Gurney flap mitigates this disadvantage.

As shown in Fig. 5, all Gurney flaps used in the experiment decrease lift-to-drag ratio at a certain drooping angle tested, and the higher the Gurney flap the more the reduction of lift-to-drag ratio. This is inconsistent with that in Ref. 9. Figure 5 also shows that maximum lift-to-drag ratio can be obtained when the apex flap angle is approach to the wing angle of attack α no matter what the height of the Gurney flap is. Some heights of Gurney flap increase lift-to-drag ratio at moderate-to-high lift coefficient, as shown in Fig. 6a. Significant lift increase provided by Gurney flaps at lower angles of attack with comparatively smaller drag might be responsible for the improvement of lift-to-drag ratio.

Different from the effect of Gurney flaps on lift-to-drag ratio, the apex flap increases lift-to-drag ratio over the range of lift coefficient

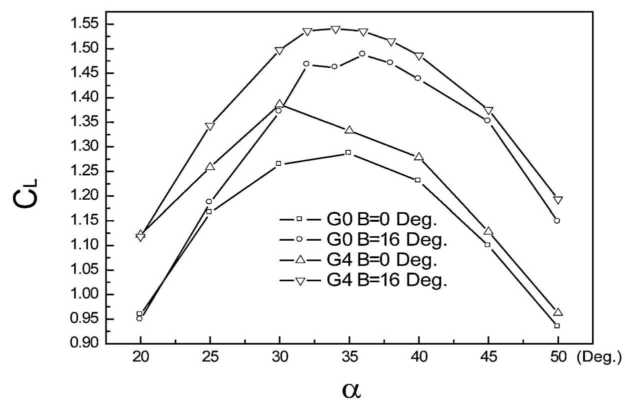


Fig. 4a Lift coefficient vs angle of attack.

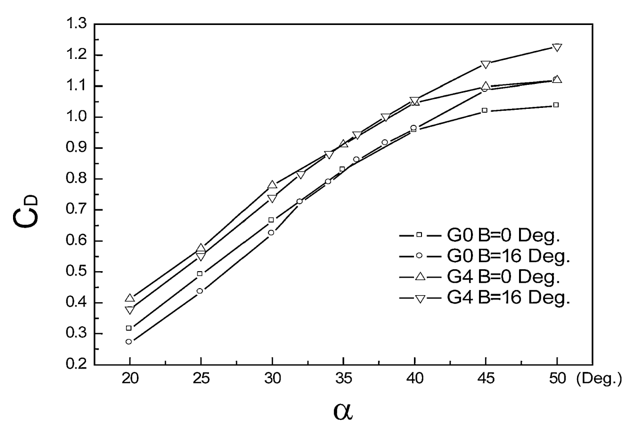


Fig. 4b Drag coefficient vs angle of attack.

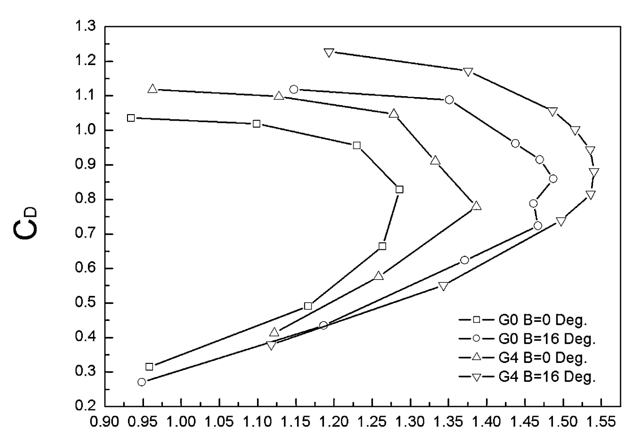


Fig. 4c Drag coefficient vs lift coefficient.

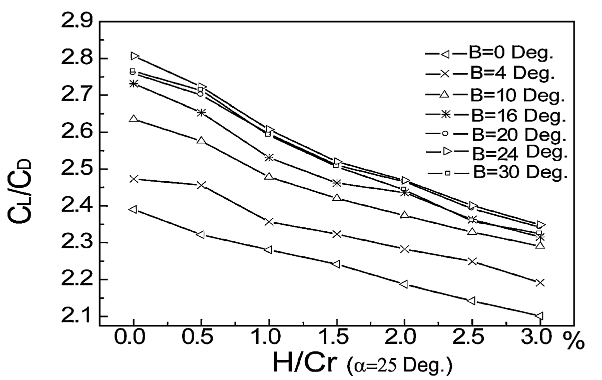
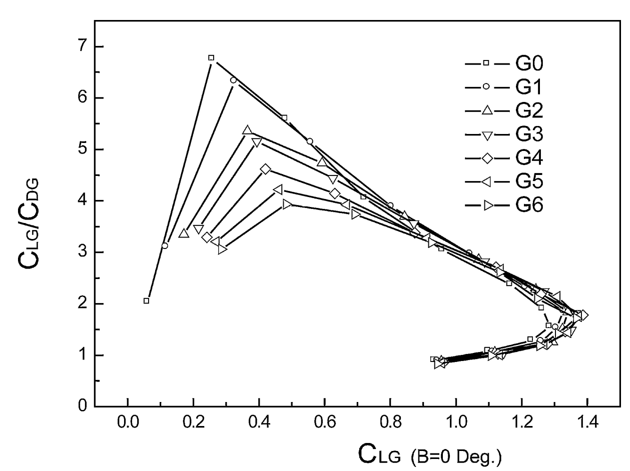
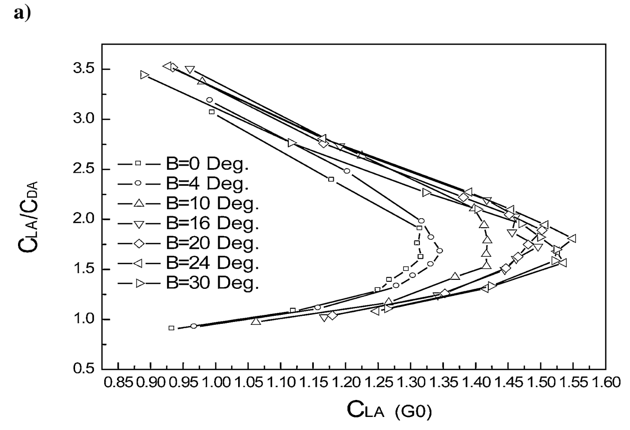


Fig. 5 Lift-to-drag ratio vs height of Gurney flap.



a)



b)

Fig. 6 Lift-to-drag ratio vs lift coefficient: a) Gurney flap and b) apex flap.

before stalling, as shown in Fig. 6b. Corresponding to the effects of Gurney flaps and the apex flap on lift coefficient and drag coefficient, the increase of lift-to-drag ratio provided by a Gurney flap plus the apex flap outweighs that provided by the single apex flap. The latter is also more than that obtained with a Gurney flap alone. Those can be seen from Fig. 7, which gives the variation of lift-to-drag vs angle of attack at the drooping angle of 16 deg with the Gurney flap, G4. Figure 8 shows the relative increment of lift-to-drag ratio, where the maximum increment with the Gurney flap alone is 53%, and corresponding amplitude with the apex flap is 79% and 88% for the combination of the Gurney flap and the apex flap. These data reveal that the application of the Gurney flap and the apex flap improves the longitudinal aerodynamics of the delta wing significantly.

It is noticed that the variation of lift-to-drag ratio depends on the drooping angle of the apex flap, Gurney flap height, and angle of attack. Experimental results indicate that the apex flap increases lift-to-drag ratio at all experimental drooping angles with all Gurney flaps tested. The maximum increase is obtained when the drooping angle approximately equals the angle of attack, as shown in Fig. 9. That is to say, lift-to-drag ratio reaches maximum when the apex flap is nearly parallel to the coming flow. It could be accounted for that the apex flap contributed no pressure drag.

For the delta wing with a Gurney flaps, the apex flap, or a Gurney flap plus the apex flap, the nose-down pitching moment is increased, as shown in Fig. 10. A little difference for the case of Gurney flap is that pitching-moment coefficient shifts upward slightly when the angle of attack is near to the stalling angle, that is, the static allowance has seldom affected by these flaps.

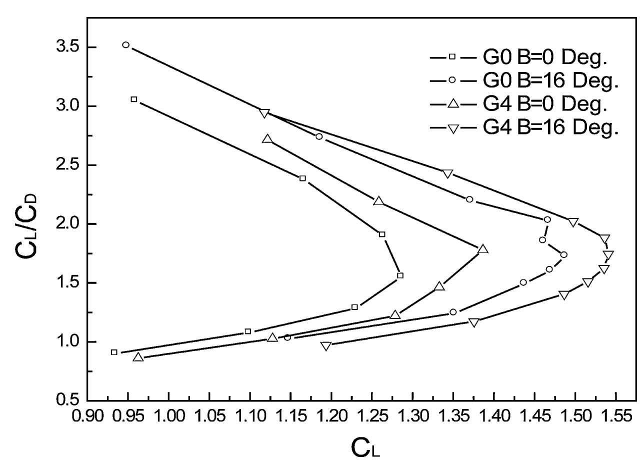


Fig. 7 Lift-to-drag ratio vs lift coefficient.

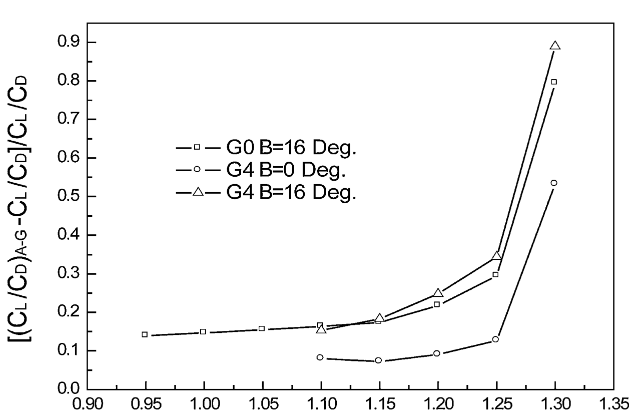


Fig. 8 Relative increment of lift-to-drag ratio vs lift coefficient.

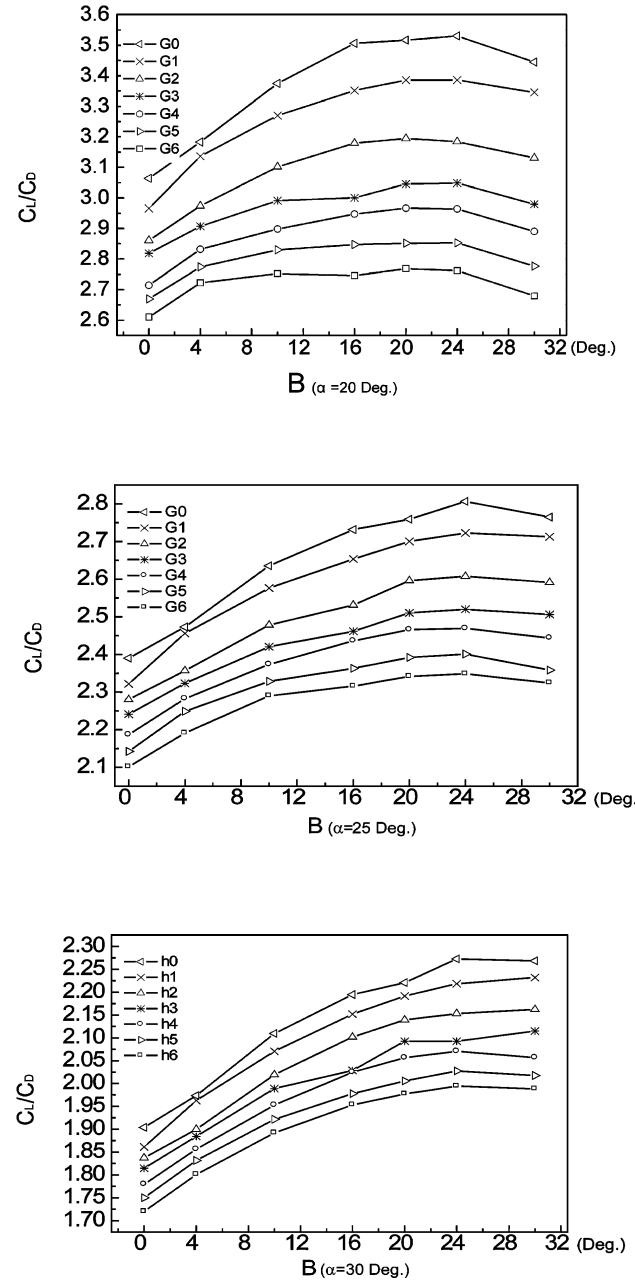


Fig. 9 Lift-to-drag ratio vs angle of apex flap.

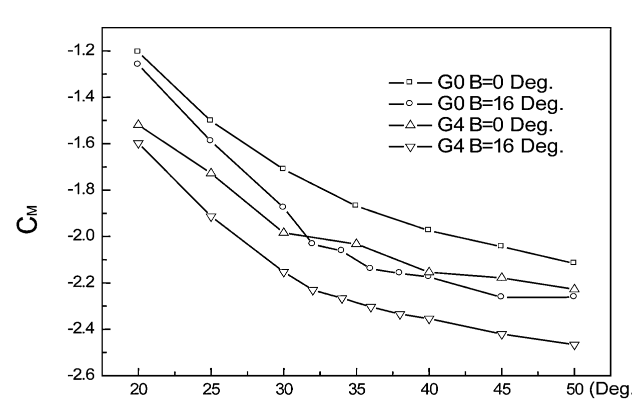


Fig. 10 Pitching moment vs drooping angle of attack: a) vs angle of attack and b) vs effective angle of attack.

Conclusions

The wind-tunnel experiment was conducted to investigate the effects of Gurney flaps and the apex flap of 40% Cr long on the longitudinal aerodynamics of the highly swept-back delta wing, some conclusions have been obtained as follows:

1) The significant increase of lift coefficient is provided by Gurney flap with the penalty of drag before stalling, whereas for the apex flap the drag reduction can be obtained at some angles of attack.

2) The increase of lift-to-drag ratio is obtained with some Gurney flap heights at moderate-to-high lift coefficient, and the lift-to-drag ratio is increased over the tested range of lift coefficients before stalling for the apex flap.

3) The application of a Gurney flap in company with the apex flap has the advantages over the Gurney flap or the apex flap alone.

4) The status that the apex flap is nearly parallel to the coming flow is the optimum design to increase lift-drag-drag ratio.

5) Static allowance decreases with the increase of angle of attack, but Gurney flaps and the apex flap have little effect on static allowance.

6) A Gurney flap plus the apex flap is an effective method to enhance highly swept-back delta-wing aerodynamics. For a given apex flap, proper Gurney flap height will provide a favorable flight performance with the apex flap drooping angle near to the angle of attack.

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