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Experimental Studies on the Drag Reduction and Lift Enhancement of a Delta Wing

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An experimental wind-tunnel investigation is undertaken to determine the effects of riblets and Gurney flaps on a 40-deg delta wing at a chord Reynolds number of 2.5 × 10^5. The results show that riblets reduce the drag of the delta wing over a range of angle of attack; the V-shaped riblet with $h = s = 0.2$ mm has the most significant effect at an angle of attack of 6 deg. A drag reduction of 40% is obtained, and the corresponding lift-to-drag ratio is also a maximum with an increase of about 61% over the clean wing. On the other hand, in comparison with the baseline clean configuration, all Gurney flaps increase the lift coefficient. The best performance is obtained for the 1% chord Gurney flap, which yields a maximum lift-to-drag ratio at a 6-deg angle of attack; this provides an increase of 17.3% compared with the clean wing configuration. However, no favorable effects are found when the riblets and the Gurney flaps are used together.

Nomenclature

C	=	root chord length of the delta wing, mm
C_D	=	drag coefficient
C_L	=	lift coefficient
Gi	=	Gurney flap height of $i\%C$, where i is 1, 2, 3, 5
h	=	height of riblets, mm
L/D	=	lift-to-drag ratio
M	=	Mach number
Re	=	Reynolds number based on root chord length
s	=	span between peaks of riblets, mm
x	=	chordwise direction
y	=	normal direction
α	=	angle of attack, deg
$\triangle$	=	increment

Introduction

RECENT research has shown that appropriately designed riblet surfaces can reduce skin friction. Walsh[1] of NASA Langley Research Center conducted experiments to examine turbulent drag reduction of riblet surfaces on a flat plate. He tested several types of riblet surfaces, and the experiments revealed that the optimum design of the riblet surfaces is a symmetrical V-shaped one. Drag reduction was found when the nondimensional height h^+ is less than 25 and nondimensional space s^+ is less than 30. A maximum 8% drag reduction was obtained when $h^+ = s^+ = 15$.

Coustols[2] studied the drag characteristic on an LC100D airfoil at angles of attack of 0∼6 deg. In his experiment, only the surface region $x/C = 0.2$∼0.95 was covered with riblets, and a drag reduction of 2.7% was obtained from wake measurements at $x/C = 1.5$ while the angle of attack is less than 3 deg. Sundaram et al.[3] conducted experiments on a NACA0012 airfoil with the riblets in region $x/C = 0.12$∼0.96 and showed that a 16% drag reduction was obtained while angle of attack was less than 6 deg.

In the transonic flow condition, McLean et al.[4] conducted an experiment on a T-33 wing that was covered with 3M Company riblet film on some regions of the upper side, and a drag reduction of 6% was obtained at $M = 0.45$∼0.7. Coustols and Schmitt[5] found a friction drag reduction of 7∼8% on a CAST7 wing at $M = 0.65$∼0.76. Viswanath and Mukund[6] also found a drag reduction of 6∼12% when testing an ADA-S1 airfoil, which was covered with riblet film on the upper and lower sides at the region $x/C > 0.15$, at an angle of attack −0.5∼1 deg.

Another way to increase the airfoil lift is to use a Gurney flap. The Gurney flap is a short flat plate attached to the trailing edge perpendicular to the chordline on the pressure side of the airfoil. Numerous tests on Gurney flaps have been conducted because of its marked effect on improving the performance of airfoils. The first Gurney flap experiment was conducted by Liebeck[7] on a Newman airfoil. He found that the addition of a 1.25%C Gurney flap increased the lift and reduced the drag for high lift coefficients and that, to maximize the benefits of this device, its height should be kept between 1%C and 2%C. Neuhart and Pendergraft[8] conducted a water tunnel study of Gurney flaps. Different Gurney flap configurations on a NACA0012 symmetrical airfoil were tested at a Reynolds number of 8.5×10^3. Their tests revealed that the most beneficial Gurney flap height was 4.2%C. This Gurney flap had the most favorable effects on the upper surface flow separation at an angle of attack up to 3.5 deg. Neuhart and Pendergraft[8] also suggested that the increase in lift is most likely due to the effective increase in trailing-edge closure angle at high lift coefficients.

Storms and Jang[9] measured aerodynamic loads and pressure distributions on a NACA4412 airfoil. They found that the Gurney flap generated an additional nose-down pitching moment in comparison with the clean airfoil. A computational study by Jang et al.[10] further suggested that the Gurney flap works by affecting the Kutta condition on the airfoil. The downward turning of the flow relieves the adverse pressure gradient near the trailing edge and, thus, increases the suction over the upper surface. Myose et al.[11] measured aerodynamic loads, airfoil pressure distribution, wake, and boundary-layer profiles for a NACA0011 airfoil with Gurney flaps. They found that the wake behind the airfoil was shifted downward as suggested by the earlier flow visualization studies. Giguere et al.[12] suggested that the increase in lift with the Gurney flap was obtained with very little penalty in drag because the Gurney flap resides within the airfoil's boundary layer. Based on their results on LA203A and Gottingen 797 airfoils, as well as a review of past studies, they found that the optimum Gurney flap height scales with the boundary-layer thickness.

As indicated by the mentioned surveys, there have been a number of studies on the effect of riblets and Gurney flaps. However, these studies were almost limited to one- or two-element airfoils, and seldom have the studies been conducted on delta wings. The purpose of this investigation is to examine the effect of

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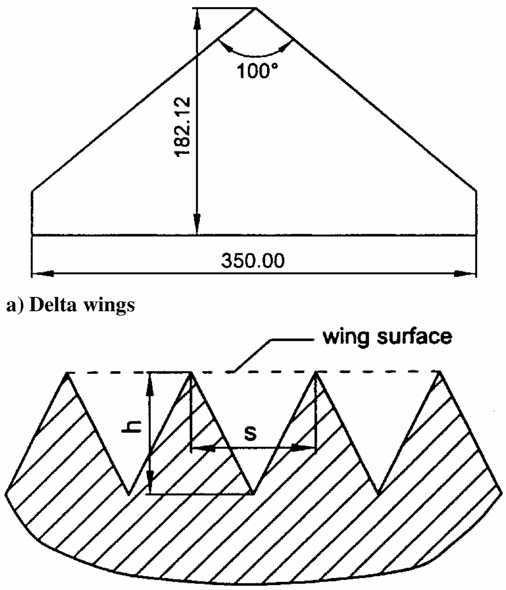


a) Delta wings

b) Riblets

Fig. 1 Geometry of the delta wings and riblets.

riblets and Gurney flaps on a plain delta wing at different angles of attack.

Experimental Setup

The experiment was conducted in the D1 wind tunnel of Beijing University of Aeronautics and Astronautics. The three-dimensional open wind tunnel has a 1.02×0.76 m ellipse-shaped test section with a length of 2 m and turbulence in the incoming flow of less than 0.3%. The 40-deg delta wing is made of aluminum alloy, as shown in Fig. 1a. The wing is 3 mm thick and has a root chord of 182.12 mm. The leading and side edges are beveled at 60 deg.

Three types of wings were tested in this investigation, W1, W2, and W3. The W1 wing was the basic smooth delta wing without riblets. The W2 and W3 wings had the same geometry as the W1 wing, but riblets were made on the upper and lower surfaces. The riblet surface, which had the same projected area as the smooth surface, was constructed with symmetric grooves of triangular cross section, $h = s = 0.2$ mm for W2 wing, and $h = s = 0.4$ mm for W3 wing (Fig. 1b).

The Gurney flaps were made of 0.6-mm-thick mild steel that spanned the whole trailing edge of the wings, and they were tested by attaching them to the trailing edge, perpendicular to the lower surface of the wings. Four plain Gurney flaps of $1\%C$, $2\%C$, $3\%C$, and $5\%C$ were selected and are referred to as G1, G2, G3, and G5, respectively.

A six-component sting balance was used for lift and drag measurements. The model was pitched through prescribed angle of attacks ranging from 0 to 26 deg. The experiments were conducted at a freestream velocity of 20 m/s, which yields a Reynolds number, based on the wing's centerline root chord, of 2.5×10^5.

The accuracy of the balance is estimated at 0.13% for lift and 0.28% for drag measurements, and the model angle of attack can be set to within 0.05 deg.

Results and Discussion

Drag-Reduction of Riblets Surface

The change of drag coefficient C_D and lift coefficient C_L with angle of attack is shown in Figs. 2a and 2b. It is seen that, over the range of attack angle tested, the drag coefficients of W2 and W3 are both decreased compared with W1 wing. On the W2 wing, a 40% reduction of the drag coefficient is obtained at 6-deg attack angle, and on the W3 wing, a 22% reduction of coefficient is obtained at 2-deg attack angle, as shown in Fig. 2c. The lift coefficient of W2 is almost the same as the W1 wing over the range of angle of attack, whereas the W3 wing has a slight decrease in lift coefficient near the poststall angle. Figure 2d shows the lift-to-drag ratio vs angle of attack. The maximum lift-to-drag ratio of 16.4% is obtained on the W2 wing at 6-deg angle of attack, and the increment is 61% compared with the W1 wing. Figure 2e indicates that for a given lift coefficient, the W2 wing can almost always present a higher lift-to-drag ratio than the W1 wing.

In comparison with two-dimensional airfoils, the riblet surfaces on the W2 wing are even more effective in improving the lift-to-drag ratio on the delta wing, which shows a 61% increase in lift-to-drag ratio as well as a 40% reduction of drag. However, the corresponding angle of maximum lift-to-drag ratio, 6 deg, is far lower than the poststall angle, 20 deg. Furthermore, the experiment shows that the two types of riblets can still reduce the drag coefficient up to 2.5% even after poststall angle.

Lift-Enhancement with Gurney Flaps

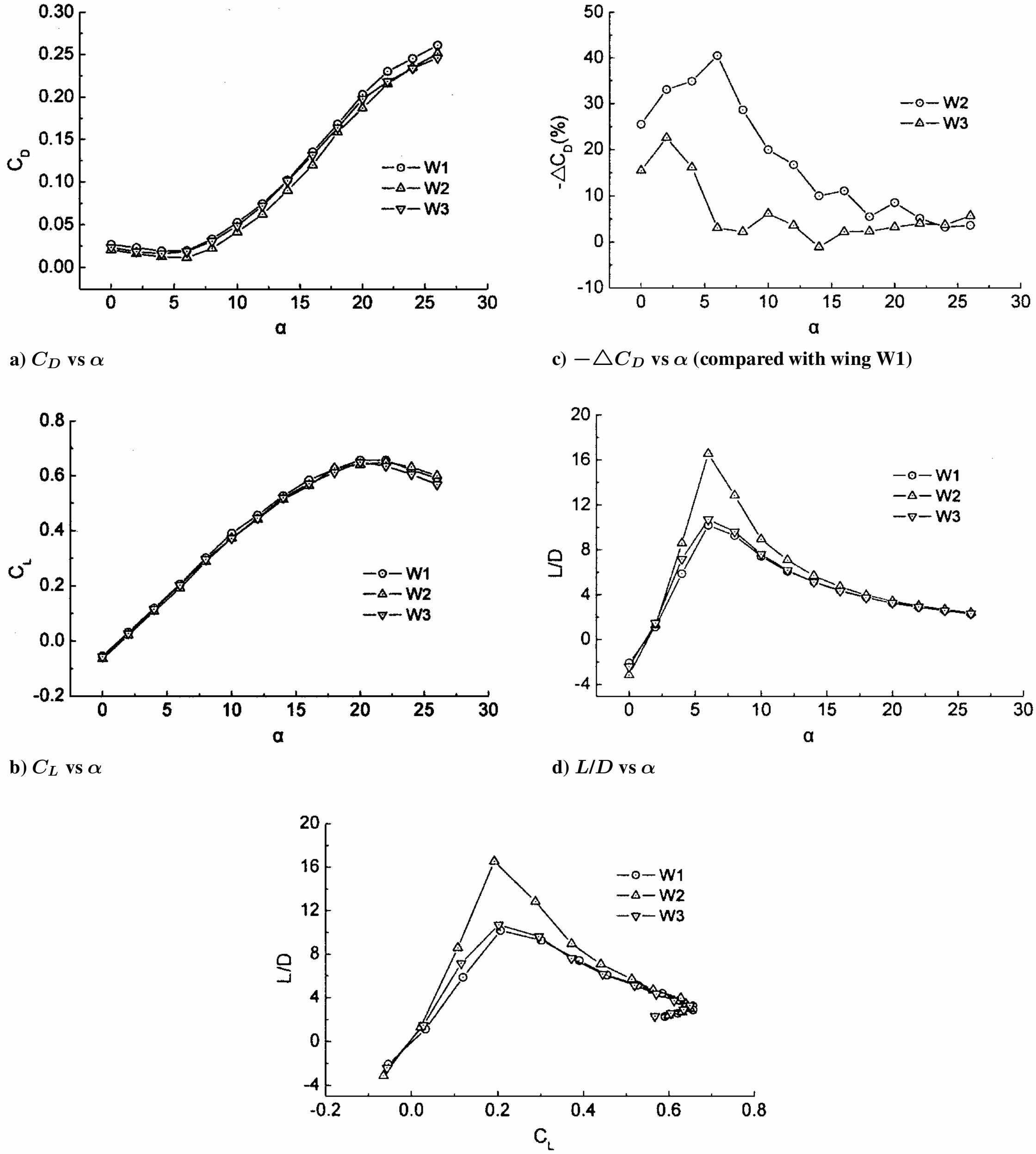
Figure 3 shows the lift and drag coefficient results of the wing with Gurney flaps. The effect of the Gurney flap is to increase the maximum lift coefficient substantially, as shown in Fig. 3a. The increase is most significant with a large Gurney flap and less pronounced with a small Gurney flap. The lift curves are shifted upward and slightly to the left with the increase of Gurney flap height. The slopes of the curves also generally appear unchanged. Consequently, the stall angle is slightly decreased when a larger Gurney flap is utilized. These results suggest that the Gurney flap serves to increase the effective camber of the wing. Compared with the clean wing, the maximum lift coefficient is increased by 15.7, 25.7, 25.7, and 32.8% for the G1, G2, G3, and G5 Gurney flaps, respectively. However, the increase in lift obtained with the Gurney flap comes at the price of increased drag, as shown in Fig. 3b.

Figure 3c shows the characteristics of lift to drag with angle of attack. When compared with the clean wing, all of the flaps provide a higher lift-to-drag ratio in 0~3 deg angle of attack range. The G1 Gurney flap has the maximum lift-to-drag ratio at 6-deg angle of attack, which is an increase of 17.3%. When the angle of attack is increased above 8 deg, all of the Gurney flaps no longer provide higher lift-to-drag ratio than the clean wing.

It is well known that the lift force that an aircraft must produce to remain aloft corresponds to a required lift coefficient and not a required angle of attack. Thus, the comparison between the clean wing and wing with Gurney flaps at the same lift coefficient is significant, as presented in Fig. 3d. For lift coefficient above 0.25, the G1 Gurney flap has a comparable or better efficiency than the clean wing. Furthermore, when the coefficient is above 0.5, all four Gurney flaps provide higher lift-to-drag ratio than the clean wing. These results, thus, indicate that Gurney flaps should be used at moderate-to-high lift conditions, such as takeoff and landing, and should not be used at low lift conditions, such as cruise. To utilize the Gurney flap efficiently, it is suggested that the Gurney flap be closed at cruise.

Riblets Surface Plus Gurney Flaps

Figure 4 shows the lift-to-drag ratio with angle of attack for delta wings with riblets surface and Gurney flaps in comparison with the wing with riblet surfaces and the plate wing without riblets. From Fig. 4a, it is seen that lift-to-drag ratio of the wing with riblets and Gurney flaps is apparently decreased in comparison with the W2 riblets surface wing, as well as in comparison with the clean wing. Figure 4b shows the same characteristics. From the analysis presented, we have observed that both the W2 riblets surface and the G1 Gurney flap are effective in improving the lift-to-drag ratio of the delta wing when they are used separately. When they are used together, however, the effect of improving lift-to-drag ratio is adverse. Thus it is revealed that these two methods of improving lift-to-drag ratio are somehow uncompatible. Figure 5 shows the lift-to-drag characteristics of W1 and W2 wings with and without G1 Gurney flap. It clearly shows that when these two methods are



a) C_D vs α

b) C_L vs α

c) $-\triangle C_D$ vs α (compared with wing W1)

d) L/D vs α

e) L/D vs C_L

Fig. 2 Aerodynamic characteristics of the wings with riblets.

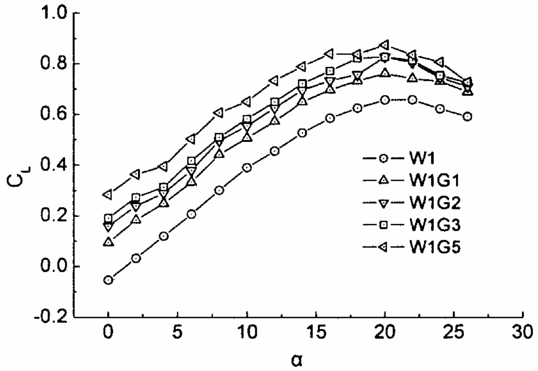
used together, the aerodynamic characteristics of the delta wing are worsened.

Physical Mechanism Analysis

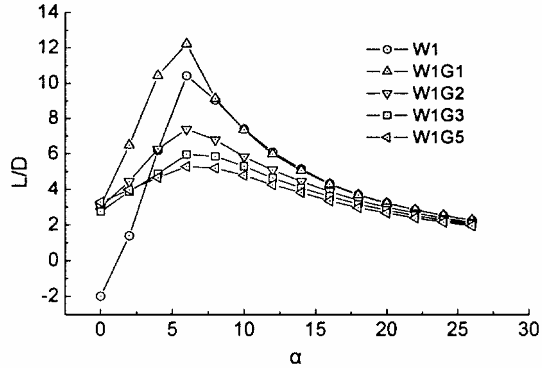
Research on the physical mechanism of drag reduction using riblets and lift enhancement using Gurney flaps has been paid a great deal of attention in the past two decades. With regard to drag-reduction using riblets, Bacher and Smith[13] hypothesized a flowfield over a riblet surface as shown in Fig. 6. A pair of counter-rotating streamwise vortices interacted with the cross-stream secondary vortices yielded by the riblet peaks, and the secondary vortices weakened the streamwise vortices, which left low-speed flow at the bottom of the riblets. Therefore, the friction drag (and, thus, the total drag) was reduced. Choi[14] pointed out that the riblets limited the spanwise flow of the streamwise vortices and, thus, weakened the bursting on the surface, and the total friction drag of the surface was greatly reduced.

Previous research[7–12] on lift enhancement using Gurney flap indicated that the Gurney flap increased the effective camber of airfoil (of the wing), thus increasing the overall circulation (and consequently the lift).

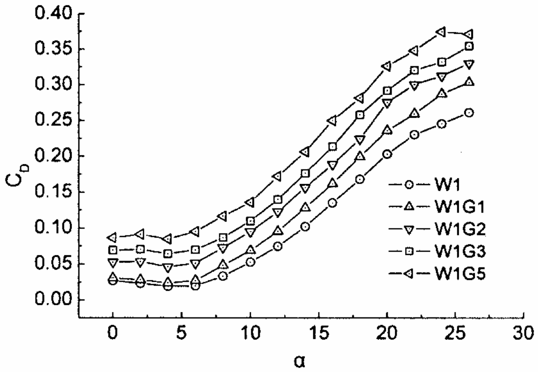
In this experiment, when riblets alone are adopted (Fig. 2), the stream flows mainly along the riblets, and the vortices generated by the riblets affect each other, leaving low-speed flow at the bottom of the riblets; therefore, the friction drag is greatly reduced and, thus, the total drag. When the Gurney flap alone is used (Fig. 3), the flow immediately aft of the Gurney flaps turns significantly downward with two vortices of opposite rotation formed behind the Gurney flap; an upstream separation bubble is formed in front of the Gurney flap. This decreases the wake momentum deficit and, furthermore, decreases the total drag of the wing. On the other hand, the effective camber and total circulation of the wing are both increased, and the lift is increased correspondingly. Because of the Gurney flap at the trailing edge of the smooth wing W1, the stream will flow spanwise, but because the wing has no riblets, there is little drag generated by this spanwise flow. When the riblets and the Gurney flap are used together, the spanwise flow of the stream (Fig. 7), however, results in greater friction drag. Also, the streamlines no longer flow along the riblets only; therefore, the skin drag reduction due to riblets



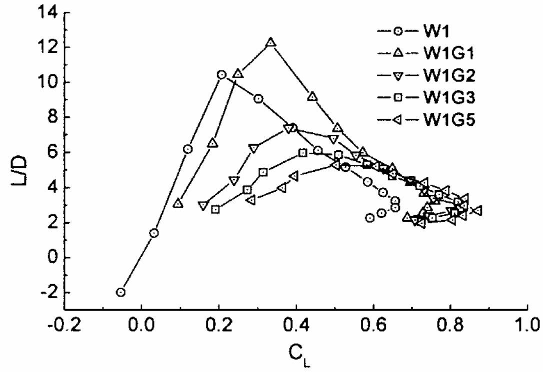
a) C_L vs α



c) L/D vs α

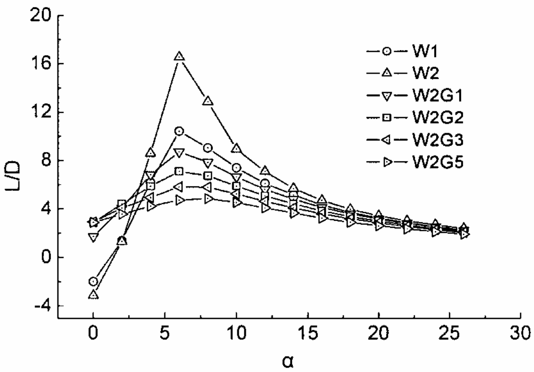


b) C_D vs α

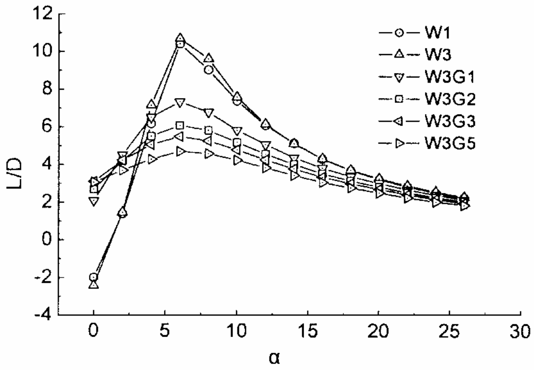


d) L/D vs C_L

Fig. 3 Aerodynamics characteristics of the wing with Gurney flaps.

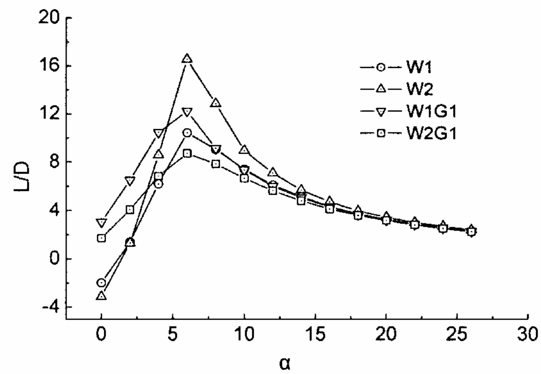


a) L/D vs α (wing W2)

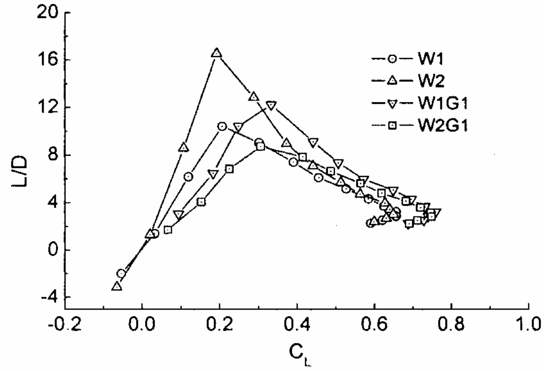


b) L/D vs α (wing W3)

Fig. 4 Aerodynamic characteristics of the wings with riblets and Gurney flaps.



L/D vs α



L/D vs C_L

Fig. 5 Aerodynamic characteristics of W1 and W2 wings with and without G1 Gurney flap.

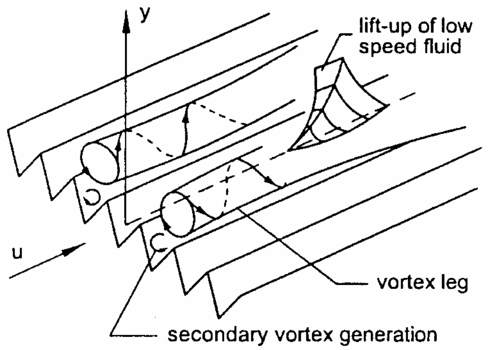


Fig. 6 Schematic of streamwise vortex interaction with riblet surface via viscous effects.[13]

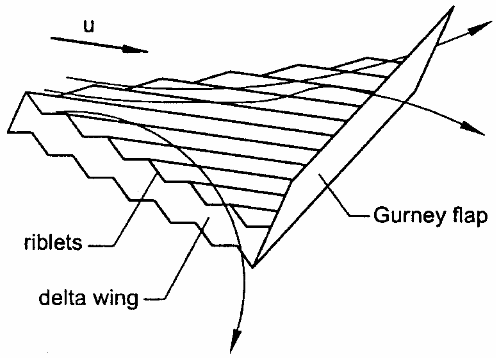


Fig. 7 Hypothesized flow over delta wing with Gurney flap and riblets.

no longer exists. This leads to a drag increase and, thus, a reduction in lift-to-drag ratio of the wing, as indicated in the preceding section.

Conclusions

A 40% drag reduction is obtained on W2 wing at 6-deg angle of attack; the corresponding lift-to-drag ratio is also maximum, with an increase of 61% compared with the clean delta wing;

In comparison with the baseline clean configuration, the Gurney flap improves the maximum lift coefficient, slightly decreases the stall angle, and increases the drag coefficient. The most beneficial Gurney flap height is about $1\%C$, and the maximum increase of lift-to-drag ratio is 17.3% at 6-deg angle of attack;

The Gurney flaps should be employed at moderate-to-high lift coefficient conditions and should not be used at low lift coefficient conditions;

The wing aerodynamic performance was not improved as desired when the riblet surfaces and Gurney flaps are used together.

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