학술논문 유체공학 부문

2차원 평판날개에서의 Tripwire가 공력에 미치는 영향

Aerodynamics of a 2-D Flat-plate Airfoil with Tripwire

제 두 호* 이 종 우*
Du-ho Je Jongwoo Lee

ABSTRACT

In this paper, we experimentally investigated the effects of attached cylindrical tripwires on the aerodynamic performance. The research was carried out with a simple two-dimensional (2-D) rectangular airfoil fabricated from thin flat-plate aluminium, with elliptical leading and trailing edges. Tripwires of varying widths and thicknesses, and attack angles of -5°~20° were used to investigate the aerodynamic characteristics (e.g. lift and drag forces) of the airfoil. We found that attaching the tripwires to the lower surface of the airfoil enhanced the lift force and increased the lift-to-drag ratio for low attack angles. However, attaching the tripwires to the upper surface tended to have the opposite effects. Moreover, we found that attaching the tripwires to the trailing edge had similar effects as a Gurney flap. The aerodynamic characteristics of the flat-plate airfoil with tripwires can be used to develop passive control devices for aircraft wings in order to increase their aerodynamic performance when gliding at low attack angles.

Keywords : Flat-plate Airfoil, Tripwire, Lift, Drag, Lift-to-drag Ratio, Gurney Flap

1. Introduction

MAVs (Micro Air Vehicles), which introduced a fascinating area to aerospace engineering through their recent development, are used in many fields such as military technology, medical services, and chemical research. Since their small size makes them undetectable by surveillance equipment, they are particularly used for military missions such as reconnaissance and surveillance of enemy camps. These applications of MAVs have prompted engineers to develop more efficient shapes; hence, we conducted experiments with a 2-D rectangular flat-plate airfoil with cylindrical tripwires at low Reynolds numbers.

According to previous studies, MAVs fly at low Reynolds numbers in the region from 2×10^4 to 2×10^5 (Pelletier and Mueller, 2000[1]). However, very little data are available on the aerodynamic characteristics of their flat-plate airfoil at Reynolds number within this range. Besides, previous researches on flat-plate airfoils only investigated their aerodynamic performance from a

† 2013년 4월 15일 접수~2013년 7월 26일 게재승인
* 육군사관학교 무기기계공학과(Dep. Weapons and Mechanical Engineering, Korea Military Academy)
책임저자 : 제두호(duhoje@gmail.com)

geometric perspective. They include the experimental and numerical investigation of their efficiency using various thicknesses, shapes of the leading and trailing edges, and geometric shapes (e.g. rectangular or delta airfoils). Pelletier and Mueller(2000)[1] performed experiments on flat-plate airfoils with a thickness-to-chord length of 1.93 % at Reynolds number from 6×10^4 to 1.4×10^5, and also on cambered flat-plate airfoils. Selig *et al*. (1989)[2] also presented their findings on the aerodynamic characteristics of a flat-plate airfoil with a thickness-to-chord length ratio of 2 %. Moreover, Null and Shkarayev (2005)[3] investigated the effect of a very thin camber on the aerodynamic characteristics of MAV wings of different shapes, and found that a cambered wing with a 5 % circular arc produced the greatest lift force and highest lift-to-drag ratio. However, although these researches investigated the effect of the geometry of the wing on the aerodynamic performance, they did not conduct experiments to develop a passive control device for enhancing the aerodynamic force.

Hence, in the present study, we experimentally investigate the effects of attached cylindrical tripwires on the aerodynamic performance of rectangular flat-plate airfoils by directly measuring the aerodynamic forces in a wind tunnel.

2. Materials and Method

2.1 Flat-plate airfoil model

For our investigation, we fabricated a flat-plate aluminium airfoil model with a thickness to chord length ratio (*t/c*) of 2 %. The airfoil had 5-to-1 elliptical leading and trailing edges and a simple rectangular shape. The chord length (*c*) and wing span (*s*) were respectively 100 mm and 248 mm. The value of the thickness-to-chord length ratio and the elliptical leading and trailing edges were chosen in order to facilitate comparison with previous studies. The thickness-to-chord length ratio of 2 % was sufficient to mimic the wings of several birds, which glide at low Reynolds numbers (Pelletier and Mueller, 2000[1]).

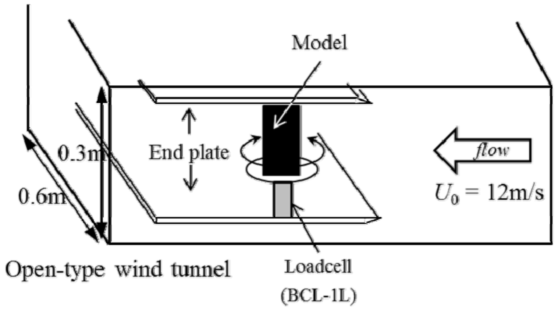


Fig. 1. Schematic diagram for force measurement in the wind tunnel

2.2 Wind tunnel

Our test was conducted in an open-circuit blowing-type wind tunnel. Fig. 1 is a schematic diagram of the flat-plate airfoil model in the wind tunnel. Here, x, y, and z denote the streamwise, vertical, and spanwise directions, respectively, and the origin is located at the center of gravity. The test section was made of acryl and measured 3 m × 0.3 m × 0.6 m in the streamwise, vertical, and spanwise directions, respectively. The maximum wind speed at the test section was 30 m/s, and the uniformity of the mean streamwise velocity and background turbulence intensity were both within 0.5 % at u_∞ = 12 m/s.

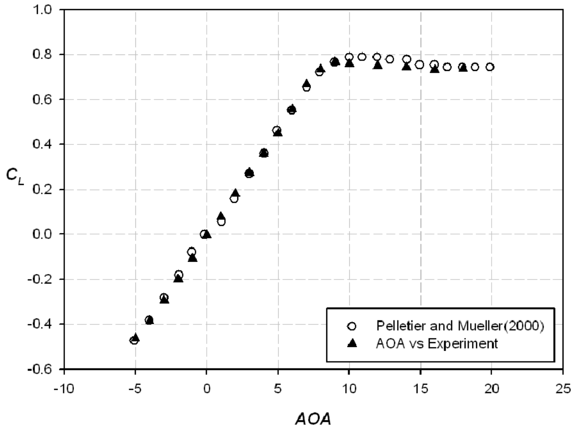
The end plates were at a distance of 20 mm from each wall of the test section. The gaps between the flat-plate airfoil and the end plates were adjusted to approximately 1 mm. According to the theory suggested by Barlow *et al*. (2006)[4], the gap should be less than 0.5 % of the wing span. Moreover, Mueller and Burns (1982)[5] showed that a gap of 0.1～1.4 mm was usually accepatable and did not affect the results. For a 248 mm span, the maximum gap allowable is 1.24 mm, which was larger than the gaps used in the present study. All the results were corrected for solid and wake blockage using the techniques developed by Barlow *et al*. (2006)[4] and Selig and McGranahan (2003)[6]. A streamlined body was used to cover the strut to minimize the interference of the support.

2.3 Force Measurement

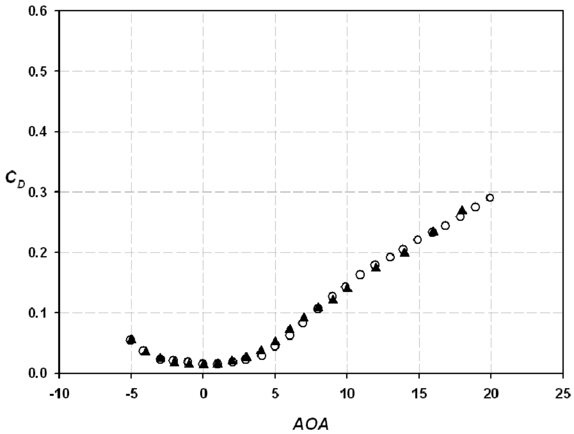
To measure the aerodynamic forces, we used a 1-axis loadcell (BCL 1L, CAS Co.,). Drag and lift forces were measured by varying the attack angle (α) between -5° and 10° in increments of 1°, and from 10° to 18° in increments of 2°. We used the different increments because the flat-plate airfoil model mimicked the wings of birds, which exhibit better gliding performance at low attack angles. Hence, we were interested in the aerodynamic forces at low attack angles before stalling. The signals from the loadcell were amplified by a signal conditioning amplifier (2310B, Vishay Micro-Measurements) and digitized by an A/D converter (PXI-6259, National Instrument Co., Austin, TX, USA). When they became steady, they were sampled for 30 s at a rate of 10 kHz to obtain a fully converged mean value. The force was measured for free-stream velocities (u_∞) of 12 m/s, the corresponding chord Reynolds number (Re_c) of which was 0.8×10^5, where c is the chord length of the flat-plate airfoil. This chord Reynolds number corresponds to real MAVs and small UAVs (Unmanned Aerial Vehicles) (Mueller and DeLaurier, 2003[7]).

3. Results and Discussion

The lift coefficient (C_L) and drag coefficient (C_D) are defined as $C_L = L/(0.5\rho u_\infty^2 A)$ and $C_D = D/(0.5\rho u_\infty^2 A)$, where ρ is the density of air; A is the planform area of the wing model; and L and D are the lift and drag forces, respectively. Fig. 2 shows the variations of C_L and C_D with the attack angle α for the two-dimensional rectangular flat-plate airfoil, which are also compared with those of Pelletier and Mueller (2000)[1]. The uncertainty of results is within 98 % (C_L) and 95 % (C_D). As shown in Fig. 2, the results of the present experiment are in good agreement with those of Pelletier and Mueller (2000)[1]. The lift coefficient varies linearly with the attack angle between -5° and 8°. However, after stalling, it decreases suddenly and then approximately plateaus. In contrast, the variation of the drag coefficient shows no abrupt change in the post-stall region. These stall characteristics are classified as thin-airfoil stall. According to McCullough and Gault (1951)[8], for an airfoil with a sharp leading edge, thin-airfoil stall is said to occur when there is no abrupt decrease in the lift coefficient and no abrupt increase in the drag coefficient at low Reynolds numbers.



(a)



(b)

Fig. 2. Variations of the lift and drag coefficients with the attack angle (α) at Re_c = 80,000 : (a) C_L; (b) C_D

Table 1 lists the parameters of the cylindrical tripwires, namely, their thicknesses and the spacing between adjacent wires. The tripwires were attached to the upper and lower surfaces of the airfoil using various combinations of the variables.

Table 1. Parameters for trip-wire(s) thickness(*k/c*) and spacing between the adjacent wires(*w/c*)

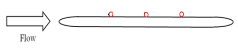
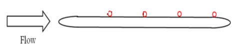
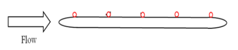
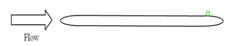
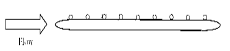
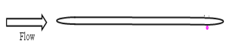
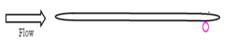
	k/c	*w/c*	Schematic diagram
Case1	0.011	0.22	
Case2	0.011	0.22	
Case3	0.011	0.22	
Case4	0.011	-	
Case5	0.011	0.11	
Case6	0.005	-	
Case7	0.02	-	

Fig. 3 also shows the variations of the lift and drag coefficients and the lift-to-drag ratio with the attack angle for *Cases 1 ~ 5* when the tripwires attached on the lower surface of airfoil. As can be seen in Fig. 3(a), when the tripwires were attached to the lower surface, the lift coefficient increased with the attack angle for all cases, except *Case 1*. *Case 4* particularly shows good performance of the lift force for all attack angles.

Moreover, as the density of the tripwires increased, the lift coefficient converged to the base of the airfoil. Furthermore, the slope of the lift-curve of the tripwires attached to the lower surface is nearly constant.

In *Case 4*, the tripwire on the trailing edge seemed to have the same effect as a Gurney flap on an airfoil. Going by previous studies, the lift coefficient increases without changing the slope of the lift curve when a Gurney flap is installed at the trailing edge of the airfoil (Storms and Jang, 1994[9]; Troolin *et al*., 2006[10]; Liu and Montefort, 2007[11]; Wang *et al*., 2008[12]; Li *et al.*, 2009[13]). The drag coefficient in Fig. 3(b) shows an abrupt increase when the attack angle exceeds 8°, which is when stalling occurs. With the tripwires, the differences between the drag coefficients are significant for high angles of attack. On the other hand, the drag coefficient of *Case 4* is similar to that of the base airfoil for an attack angle of -5 ~ 0°. In Fig. 3(c), the lift-to-drag ratios of *Case 4* are higher than those of the

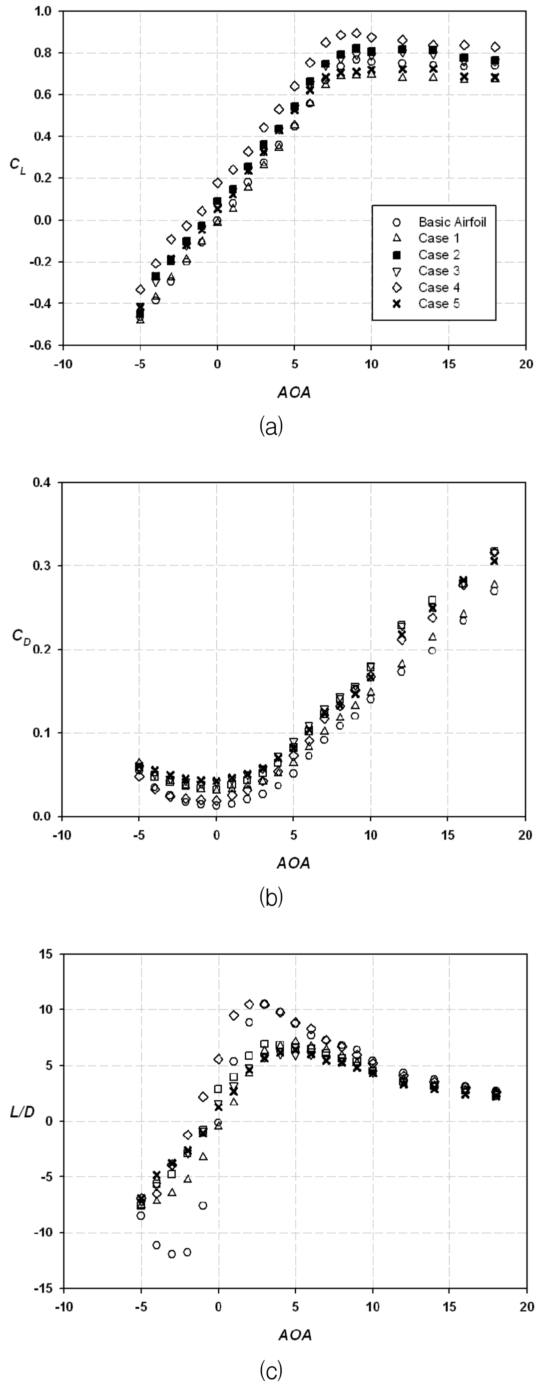
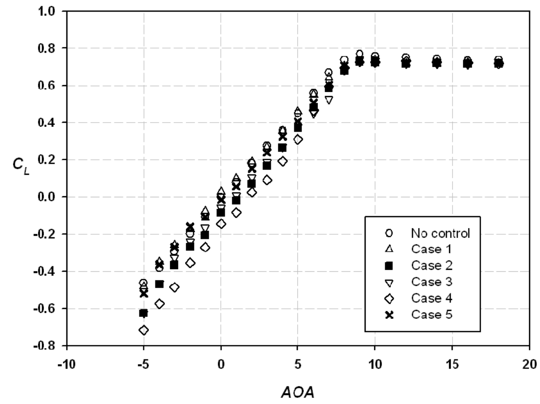
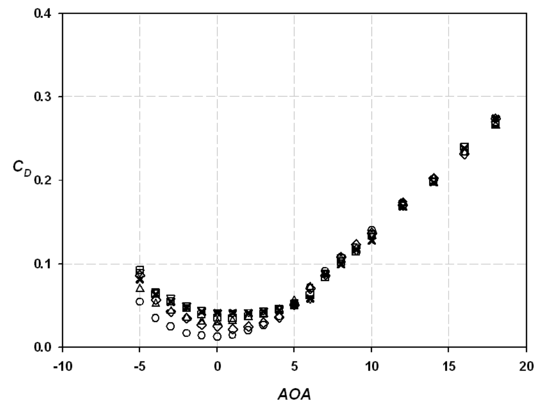


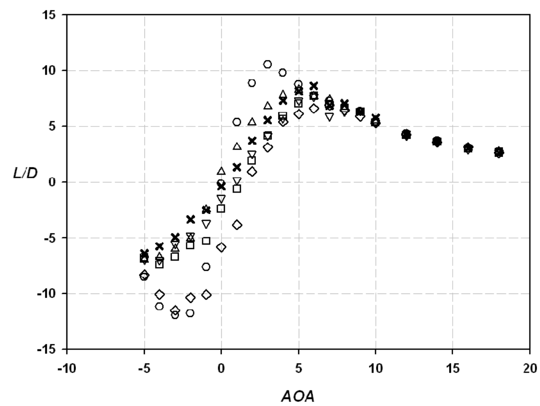
Fig. 3. Variations of the lift and drag coefficients with the attack angle for *Case 1 ~ 5* when the tripwires attached on the lower surface of the airfoil : (a) C_L; (b) C_D; (c) *L/D*



(a)

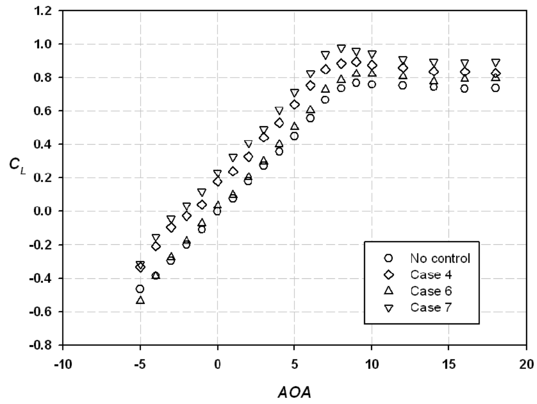


(b)

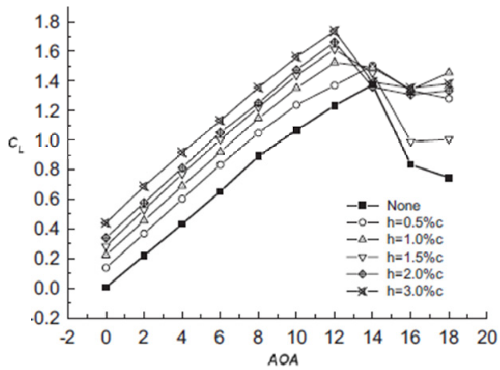


(c)

Fig. 4. Variations of the lift and drag coefficients with the attack angle for *Case 1 ~ 5* when the tripwires attached on the upper surface of the airfoil : (a) C_L; (b) C_D; (c) *L/D*



(a)



(b)

Fig. 5. Variations of the lift coefficients with the attack angle (α) : (a) C_L; (b) C_L with a Gurney flap (Wang *et al.*, 2008[12])

base airfoil for low attack angles below 4°. Moreover, when the attack angle is greater than 4°, the lift-to-drag ratios are comparable to those of the base airfoil owing to the increase in drag force. Therefore, when the tripwire is attached only to the trailing edge, the lift-to-drag ratios increase by up to 20 %. This indicates better gliding performance when the wing is parallel to the ground (i.e. α < 4°).

In Figs. 4(a) and (b), when the tripwires are attached to the upper surface of the airfoil, the tendencies of the lift and drag coefficients are opposite to the foregoing. The lift coefficient decreases for all cases before stalling. Moreover, there is no significant decrease after stalling, owing to the flow separation on the upper surface of the airfoil. Interestingly, in *Case 4*, where the tripwire is attached only to the trailing edge, the effect seems to be the opposite of that of a Gurney flap. The drag coefficient is also nearly the same when the attack angle is over 8°, while all cases show large increase in the drag coefficient for attack angles below 5°. In Fig. 4(c), the tendency of the lift-to-drag ratio is also opposite to that of when the tripwires are attached to the lower surface of the airfoil. The lift-to-drag ratios of *Case 4* are particularly lower than those of the base airfoil owing to the large decrease in the lift force and abrupt increase in the drag force for attack angles below 8°.

Fig. 5 shows the effects of the thickness of the tripwire on the lift force on the lower surface of the airfoil when it is attached only to the trailing edge. According to the previous study, a gurney flap can show its effectiveness when the gurney flap located below the boundary layer. In the present study[9], we conjecture the boundary thickness using the Blasius equation since the flow is larminar at the trailing edge. The boundary layer thickness is about 1.7 mm at the trailing edge and the thickness of tripwire is about 1.1 mm (0.011c). So, the tripwire has sufficient condition for a gurney flap. In Fig. 5(a), as the thickness of the wire increases, the lift coefficient also increases. However, the drag force also increases at the same time (not shown here). These aerodynamic characteristics are very similar to those of an airfoil with a Gurney flap, as described earlier. Fig. 5(b) shows the effects of the height of the Gurney flap on the lift force. As the height increases, the lift force also increases and the slope of the lift force is almost constant.

4. Conclusion

In the present study, we investigated the effects of tripwires on the aerodynamic performance of airfoils by directly measuring the lift and drag forces in a wind tunnel at a chord Reynolds number of 80,000. The cylindrical tripwires enhanced the lift force when they were attached to the lower surface of the airfoil, especially when attached only to the trailing edge. The effect was very similar to that of a Gurney flap on an airfoil. Moreover, the lift force increased with increasing thickness of the tripwire. However, when the tripwires were attached to the upper surface of the airfoil, the tendencies of the effects were opposite to the foregoing. We therefore conclude that tripwires can be used to develop a wing control device for MAVs and small UAVs, with better gliding performance obtained at low attack angles.

5. Acknowledgement

This work was supported by the Hwarangdae Research Institute Program funded by the Korea Military Academy.

6. Future work

We plan to perform the same experiment using the PIV (Particle Image Velocimetry) method for Case 4. This is in order to clarify the flow fields of the velocity and vorticity profiles, and compare them with those of a Gurney flap.

References

[1] Pelletier, A. and Mueller, T. J., Low Reynolds Number Aerodynamics of Low-aspect-ratio, Thin/Flat/Cambered-plate Wings, J. Aircraft, Vol. 37, No. 5, 825～832, 2000.

[2] Selig, M. S. and Donovan, J. F., and Fraser, D. B., Airfoils at Low Speeds, Stokely, Virginia Beach, VA, 1989.

[3] Null, W., and Shkarayev, S., Effect of Camber on the Aerodynamics of Adaptive-wing Micro Air Vehicles, J. Aircraft, Vol. 42, No. 6, 1537～1542, 2005.

[4] Barlow, J. B., Rae, W. H. JR. and Pope, A., Low-speed Wind Tunnel Testing, 3rd ed. 288, 353～358, NewYork : Wiley, 1999.

[5] Mueller, T. J. and Burns, T. F., Experimental Studies of the Eppler 61 Airfoil at Low Reynolds Numbers, AIAA paper. 82-0345, 1982.

[6] Selig, M. S. and McGranahan, B. D., Wind Tunnel Aerodynamic Tests of Six Airfoils for Use on Small Wind Turbines, Report. NREL/SR-500-34515, 2003.

[7] Mueller, T. J. and DeLaurier, J. D., Aerodynamic of Small Vehicles, Annu. Rev. 35, 89～111, 2003.

[8] McCullough, G. B. and Gault, D. E., Examples of Three Representative Types of Airfoil-section Stall at Low Speed, NACA TN-2502, 1951.

[9] Storms, B. L. and Jang, C. S., Lift Enhancement of an Airfoil using a Gurney Flap and Vortex Generators, J. Aircraft, Vol. 31, 542～547, 1994.

[10] Troolin, D. R., Longmire, E. K. and Lai, W. T., Time Resolved PIV Analysis of Flow Over a NACA0015 Airfoil with Gurney Flap, Exp. Fluids, 41, 241～254, 2006.

[11] Liu, T. C. and Montefort, J., Thin-airfoil Theoretical Interpretation for Gurney Flap Lift Enhancement, J. Aircraft, Vol. 44, 667～671, 2007.

[12] Wang, J. J., Li, Y. C. and Choi, K. S., Gurney Flap - Lift Enhancement, Mechanisms and Application, Aeronaut J. Vol. 44, 22～47, 2008.

[13] Li, Y. C., Wang, J. J., Tan, G. K. and Zhang, P. F., Effects of Gurney Flaps on the Lift Enhancement of a Cropped Nonslender Delta Wing, Exp. Fluids, 32, 99～105, 2009.