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Technical Notes

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Wind-Tunnel Study of Gurney Flaps Applied to Micro Aerial Vehicle Wing

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Nomenclature

b = model wing span, m
C_D = drag coefficient
C_L = lift coefficient
C_m = pitching moment coefficient respect to the quarter chord

Introduction

SMALL uninhabited air vehicles and micro air vehicles (MAV) are small, inexpensive platforms, flying by remote pilot or autonomously. Maximum linear dimensions are in the range of 400 and 150 mm, respectively [1]. One of the various challenges associated with designing small flying vehicles is the precipitous reduction in aerodynamic efficiency as the Reynolds number drops below 100,000 [2], the upper flight regime for a typical MAV. Experimental results at Reynolds numbers between 50,000 and 100,000 demonstrate the modest achievable values of maximum lift-to-drag ratio [1,3]. The use of a simple Gurney flap on the vehicle's wing is a promising simple technique to enhance the aerodynamic characteristics, thus improving the vehicle's flying qualities. A Gurney flap is a very small flat plate located normal to the trailing edge on the pressure side of an airfoil.

This Engineering Note provides experimental evidence that by using a Gurney flap on a MAV wing, one sees a beneficial effect on lift, a reduction in drag in certain conditions, and an increase in maximum lift-to-drag ratio compared with the clean airfoil. Experimental and numerical studies [4–12] demonstrated an increase of lift with the Gurney flap due to the effective augment in trailing-edge camber [4] and an extension of attached flow on the airfoil upper surface [5] in respect to the clean wing. However, benefits in terms of drag are not always present, and scatter in results are postulated to be dependent on the airfoil trailing-edge angle and flap size. Variations in drag and lift-to-drag ratio outcomes are evident from computational studies [6] and experimental results on single and multi-element airfoils, showing a slight increase of drag [7] or an increase in the lift-to-drag ratio [8].

Myose et al. [9,10] performed experiments on three-dimensional wings. The result demonstrated an increase in the maximum lift coefficient and a little drag penalty compared with the baseline configuration. On three-dimensional wings, a slight improvement in performance is observed when the Gurney flap is located inboard rather then outboard. Laser Doppler anemometry [11] suggests a twin-vortex structure downstream of the flap, consisting of a von Karman vortex street of alternately shed vortices increasing the trailing-edge suction of the airfoil. Giguere et al. [12] propose the boundary-layer (BL) thickness at the trailing edge on the pressure side of the baseline airfoil as an indicative, rather than definitive, scaling factor for the size of the optimum flap for best lift-to-drag performance.

No results are available for very thin reflex airfoils. Although it can be assumed that a Gurney flap would have a beneficial effect on lift, the results on drag and lift-to-drag ratio are sparse and exhibit a relatively high uncertainty. With a very thin airfoil at low Reynolds number, dedicated wind tunnel tests are considered critical for the evaluation of Gurney flaps used for MAV application. Two flaps were tested in the wind tunnel with the same height but different span-wise lengths.

Experimental Method

Two Gurney flaps were tested with spanwise lengths of 50 and 75% of b and a height of 2.8% of mean aerodynamic chord (MAC). The wind tunnel model consisted of a wing, Fig. 1, fabricated with two plies of bidirectional carbon fiber and elliptical leading-edge planform shape. The wing is used on a tailless pocket-MAV compact surveillance platform [1] prototype.

The wing area measures 0.0376 m^2; the standard mean chord (m) (SMC) and mean aerodynamic chord (m) are 0.0997 and 0.1073 m; the wingspan is 0.377 m, giving a wing's aspect ratio of 3.78. The airfoil has a mildly reflexed, very thin section with a thickness of 0.90 mm and a camber of 6% at 25% MAC. The wind-tunnel tests consisted of angle-of-attack (AOA) sweeps at 73,300 and 95,200 Reynolds numbers with three configurations: clean, small (50%b), and large (75%b) flap. All tests were performed in an open-circuit, closed-test-section, low-turbulence wind tunnel with a 0.9 by 0.9-m cross-test section. The aerodynamic forces and moments were acquired through a six-component sting balance with a typical resolution of 0.030 N [1]. The uncertainties analysis and the estimate of the propagation error were based on standard uncertainties analysis methods using a second power relation as the square root of the sum of the squares [13]. A basic strategy based on randomization of the independent variables was applied to guard the results from systematic errors; the tests were all run in a short period of time; therefore, blocking was not strictly required. Future experiments will include repetitions for a better understanding of the random variance in the data.

Results and Discussion

The experimental results are presented in the form of C_L versus angle of attack, C_L versus C_D, quarter-chord C_m and (C_L/C_D) ratio versus C_L. Figure 2a shows the increase of lift coefficient of the wing with small (50%b) and large (75%b) Gurney flaps in respect to the clean wing, at a freestream Reynolds number of 95,200 based on the MAC. The same figure suggests a slight increase of the lift curve slope for the wing with flap; however, the intrinsic errors in measurements in both lift coefficient and the AOA increase the uncertainty in a differential rate such as the lift slope. The figure also

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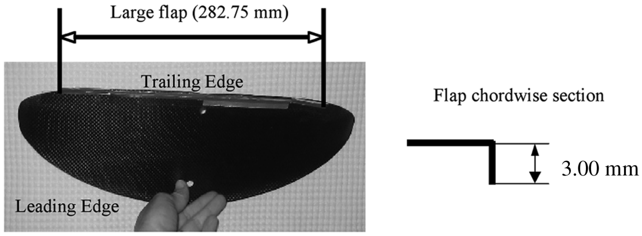


a) b)

Fig. 1 a) MAV wind-tunnel wing model with Gurney flap applied at the trailing edge; b) flap section.

displays the decrease of the stall angle and the angle for zero lift for the wings with flaps. Figure 2b depicts the C_L versus C_D for the above conditions and configurations. There is a noticeable decrease in drag above a certain value of C_L. The tests were planned to explore a specific high-lift MAV design; therefore, the lower limit for the AOA during the tests was limited to 2 deg.

The decrease in drag at medium-high lift, which was observed in previous works [4,5,9,10], is attributed to the beneficial effects of the Gurney flap on the separation bubble extension. The presence and extent of drag decrease also suggests dependence on a combination of AOA and airfoil trailing-edge angle, with the large angle being beneficial. The propagation of uncertainty in the variables for the lift and drag coefficients yields the estimate of their uncertainty with 95% confidence reported as bars in Fig. 2 for the small flap case. Similar bar values apply to all results and are not plotted for clarity.

Figure 3 illustrates potential Reynolds number effects on C_L and C_D at two velocities with clean and small flap (50%b). Interestingly enough, the clean wing shows no Reynolds number dependency on drag whereas the flapped wing exhibits no drag decrease (and no penalties) for Reynolds number of 73,300, rather a drag decrease for higher Reynolds number (95,200). It is relevant to remark that the drag's decrease is observed when comparing for the same lift coefficient instead of the same AOA. The presence of the Gurney flap is benign to the laminar separation location; therefore, it is plausible that the bubble wake momentum deficit reduction, caused by the Gurney flap, is velocity and AOA dependent.

Figure 4 illustrates the effects of the flaps on the C_L/C_D ratio versus C_L. As expected, there is an increase from a certain value of the lift coefficient; such increase is proportional to the flap length. No reliable experimental data on the trailing-edge BL thickness for a similar under-cambered thin airfoil three-dimensional wing are available; therefore, it is not possible to verify the proposed BL thickness scale factor for maximum lift-to-drag ratio. It is useful to emphasize that the drag decrease and lift-to-drag ratio enhancement are evinced at given lift conditions rather than angle of attack. The drag at given AOA for the flapped wing is typically higher compared with the baseline clean wing.

Figure 5 demonstrates that the quarter-chord nose-down pitching moment for the wings with the flap is incremented, substantiating the theory that the Gurney flap increases the effective camber. The pitching moment increase is proportional to the flap span-wise extension. The airfoil and wing design were selected purely from

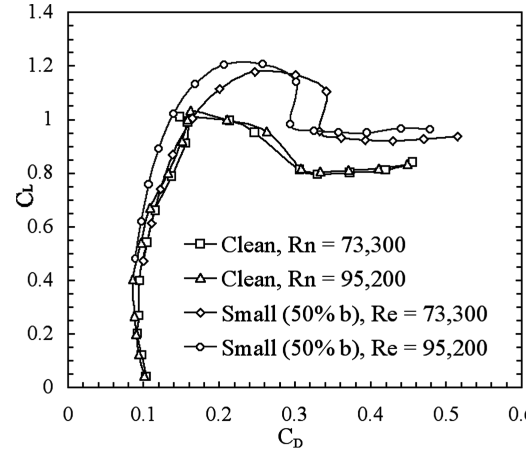


Fig. 3 Drag coefficient for clean wing and with small Gurney flap.

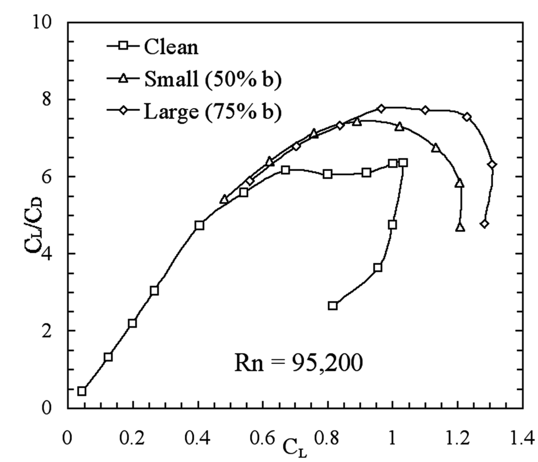
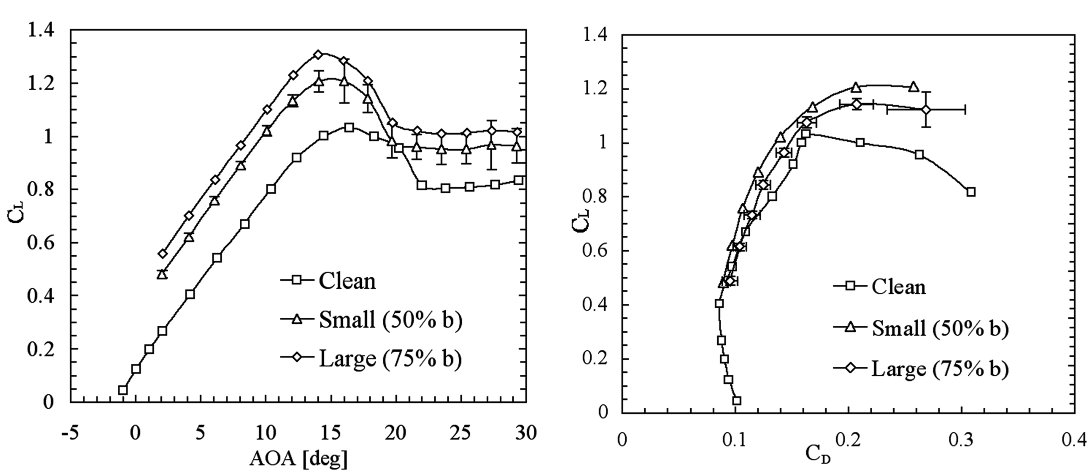


Fig. 4 Lift-to-drag ratio for clean wing and with Gurney flaps.



a) b)

Fig. 2 a) Lift and b) drag coefficients for clean wing and with 2.8% MAC Gurney flaps.

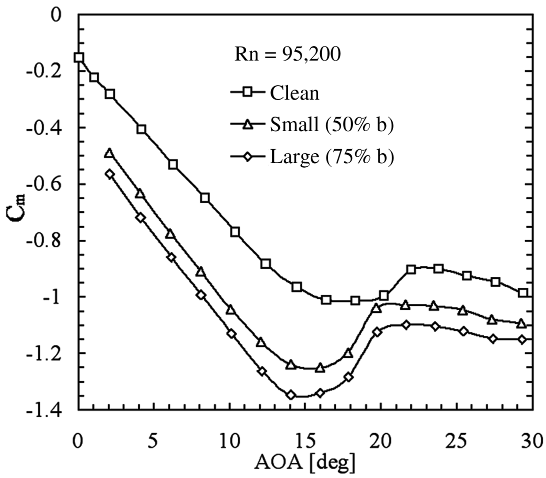


Fig. 5 Quarter-chord pitching moment coefficient for clean wing and with Gurney flaps.

flight test trials, and the mild reflex shape does not noticeably affect the pitch-down moment of the basic nonreflex cambered airfoil.

Conclusions

The results provided in this Note confirm the effectiveness of Gurney flaps applied to a micro aerial vehicle's thin-airfoil wing at low Reynolds numbers. With flaps, the maximum lift coefficient increases by 26.5% in comparison with clean wings. The lift curve slope slightly increases, whereas the stall angle and the angle for zero lift decrease. The drag results on the flapped wing demonstrate different characteristics at two Reynolds numbers. No significant change in drag and a drag reduction (above a medium value of the lift coefficient) are observed at lower and higher Reynolds number, respectively, suggesting the Gurney flap exerts a benign influence on the laminar separation location. It is plausible that the bubble wake momentum deficit reduction, caused by the flap of given geometry, is velocity and angle-of-attack dependent. The maximum lift-to-drag ratio increases by 22.4%, and the quarter-chord nose-down pitching moment is intensified. The augmented values of lift and pitching moment substantiate the theory of Gurney flaps' increasing the effective camber on airfoils.

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