AIAA JOURNAL
Vol. 48, No. 11, November 2010

Technical Notes

Combined Plasma and Gurney Flap Flow Control at Low Flight Reynolds Numbers

Chan Yong Schuele*
Technical University of Berlin, 10623 Berlin, Germany
and
David Greenblatt†
Technion—Israel Institute of Technology, 32000 Haifa, Israel

DOI: 10.2514/1.J050502

Nomenclature

$CXXGYY$ = specification for camber c ($XX\%$) and h/c ($YY\%$)
C_l = airfoil lift coefficient, $l/q_\infty c$
C_d = airfoil drag coefficient, $d/q_\infty c$
c = chord length
$\langle c_\mu \rangle$ = oscillatory momentum coefficient
F^+ = dimensionless unsteady modulation frequency, $f_m c/U_\infty$
f = plasma actuation frequency
f_m = plasma modulation frequency
h = Gurney flap height normal to surface
q_∞ = dynamic pressure
Re = Reynolds number, $U_\infty c/\nu$
U_∞ = freestream velocity
α = angle of attack
δ = boundary-layer thickness
ε = aerodynamic efficiency, C_l/C_d

Subscripts

max = maximum value
0 = baseline value

I. Introduction

THE generation of high lift at very low flight Reynolds numbers is a difficult task, because the boundary layer does not undergo transition and hence separates when subjected to relatively mild adverse pressure gradients. As vehicle size and speed requirements decrease substantially, corresponding to $Re < 20,000$, it is widely recognized that conventional low Reynolds number aerodynamics ($Re > 200,000$) is of little use, and biologically inspired platforms are often proposed. An alternative is to consider flow control that is tailored for low Reynolds numbers on conventional geometries. This paper presents such an approach, in which a combination of active and passive flow control was assessed by employing dielectric barrier discharge (DBD) plasma actuators at airfoil leading edges and employing Gurney flaps at the trailing edges. The Reynolds number range of 3000 to 20,000 was considered. Active control was a logical choice for leading-edge separation control, because passive tripping is not possible at $Re < 20,000$. DBD actuators were selected mainly because they are particularly effective at low Reynolds numbers. Moreover, they are light, robust, and can be operated in an energy efficient manner (milliwatts/centimeter) when pulsed at the low duty cycles typically required for separation control [1].

Gurney flaps are widely used (e.g., [2–5]) and were chosen for the trailing edges because they always increase lift and can also increase the maximum aerodynamic efficiency $\varepsilon_{\max} \equiv (C_l/C_d)_{\max}$ when they are small enough: typically, $h/c < 0.5\%$. Giguère et al. [2] considered a variety of experimental investigations and concluded that the optimum Gurney flap height (namely, the one that results in the largest ε) scales with the pressure surface boundary-layer thickness at the trailing edge. Considering that $\delta \sim Re^{\frac{1}{2}}$, it can easily be seen that a reduction in Reynolds numbers from, say, 350,000 (approximate critical Reynolds numbers on a flat plate) to 20,000 and 3000, requires factor-of-4 and factor-of-11 increases in optimum Gurney flap height. Hence, based on this scaling, unusually large optimum Gurney flap heights can be expected at low Reynolds numbers: namely, 10 to 20% of chord. Bechert et al. [5] developed a semi-empirical model to describe the effect of Gurney flaps at conventional low Reynolds numbers: typically, $500,000 \le Re \le 1 \times 10^6$. The model incorporated the dual effect of increasing drag as $C_d \sim h/c$ and increasing maximum lift as $(C_{l,\max} - C_{l0,\max})/C_{l0,\max} \sim (h/c)^{\frac{1}{2}}$. The model shows that as the baseline maximum aerodynamic efficiency $\varepsilon_{\max,0}$ decreases, e.g., as a result of a decrease in Reynolds number ($C_d \sim 1/Re^{\frac{1}{2}}$), increasingly larger Gurney flaps produce a net increase in $\varepsilon_{\max}$. According to the model, with $\varepsilon_{\max,0} = 20$, a Gurney flap of approximately 5% produces an increase in $\varepsilon_{\max}$. Hence, consistent with the arguments presented above, for very low flight number such as those tested here ($3000 \le Re \le 20,000$), unusually large Gurney flaps can be expected to produce significant increases in lift and still increase $\varepsilon_{\max}$.

II. Experimental Setup

The experiments were conducted in an open-section wind tunnel at flow speeds between 1 and 6 m/s, corresponding to chord Reynolds numbers between 3000 and 20,000. The airfoils used had 50 mm chord lengths and 150 mm span lengths. They were constructed from 2-mm-thick surface-polished plates with rectangular trailing edges and circular 1-mm-radius leading edges. A previous investigation [6] concluded that the specific trailing-edge design does not affect performance meaningfully at very low Reynolds numbers. One airfoil was flat, with no surface curvature, and the other was curved to the shape of a circular arc of 8% camber. To ensure two-dimensionality, Plexiglas® endplates were attached to the wingtips. Active flow control was achieved using DBD actuators mounted at the airfoil leading edges. All actuators were of identical design: namely, upper (exposed) and lower (encapsulated) electrodes (both 70 μm thick) separated by three layers of 50-μm-thick Kapton® tape; full details of their construction and calibration can be found in [1]. Gurney flaps of $h/c = 10$ and 20% were attached to the trailing edges for selected cases, as shown for the flat-plate inset in Fig. 1a. Airfoil lift and drag measurements were made using a strain-gauge-based bending-beam balance that is fully described in Greenblatt et al. [1].

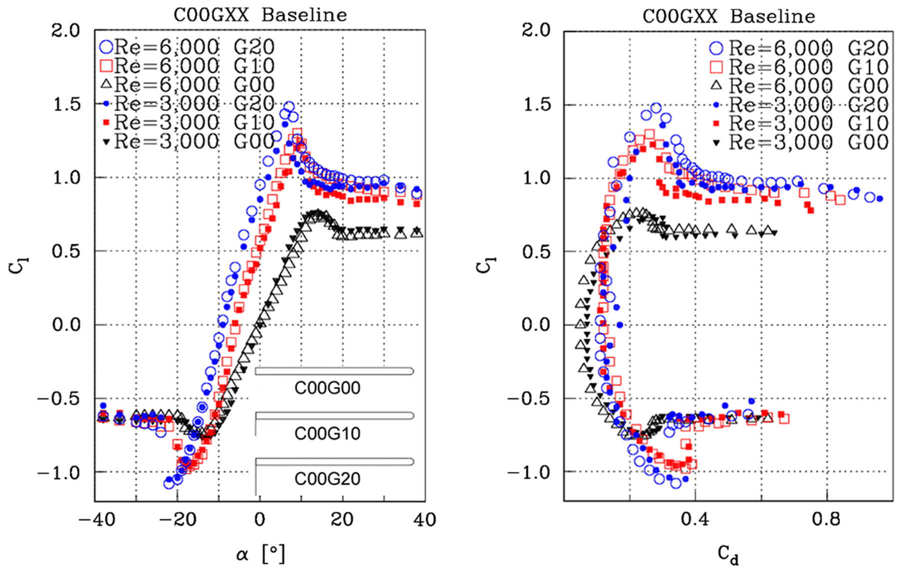
III. Results

A. Passive Flow Control: Large Gurney Flaps

Initial aerodynamic load data were acquired to assess the effect of the Gurney flaps alone; data for $Re = 3000$ and 6000 in the range

Received 11 February 2010; revision received 22 July 2010; accepted for publication 25 July 2010.

*Currently Graduate Student, Hessert Laboratory for Aerospace Research, University of Notre Dame, Notre Dame, IN 46556.
†Senior Lecturer, Faculty of Mechanical Engineering, Technion City. Senior Member AIAA.



a) b)

Fig. 1 Application of Gurney flaps on the flat-plate airfoil: a) lift coefficient versus angle of attack and b) lift coefficient versus drag coefficient ($Re = 3000$ and 6000).

$-40° \leq \alpha \leq 40°$ are presented in Figs. 1a and 1b. The specific configuration presented is indicated by the abbreviation $CXXGYY$, where CXX denotes the camber as a percentage of the chord length and GYY denotes the Gurney flap height as a percentage of the chord length. Figure 1a indicates that the application of large Gurney flaps has three main effects on lift:

1) $C_{l,\max}$ is increased significantly (62 and 82% at $Re = 3000$ and 71 and 95% at $Re = 6000$ for $C00G10$ and $C00G20$, respectively), with steeper stall at lower angles of attack.

2) Negative $C_{l,\max}$ at negative angles of attack also increases at correspondingly larger angles of attack.

3) The lift slope changes due to the application of the flaps.

Increases in maximum lift are always observed when deploying Gurney flaps, but here the changes are much more significant, due to the relatively large flaps. Even though surface pressures were not measured here, it is assumed that the flaps have the dual effect of increasing the lower-surface pressure and decreasing the upper-surface pressure (e.g., Jeffrey et al. [3]). Indeed, these data are fully consistent with the $(h/c)^{\frac{1}{2}}$ model proposed by Bechert et al. [5], where the difference between the prediction and the present data at each Reynolds number never exceeds 3.5%.

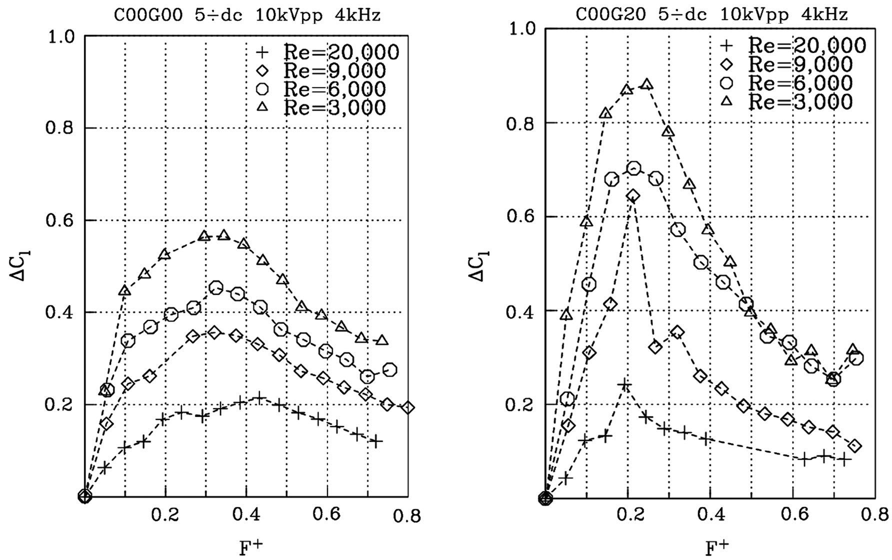
A particularly unusual observation is the increase in negative $C_{l,\max}$. The reason for this is that at negative angles of attack, flow separated from the leading edge and reattached to the flap, generating

Table 1 Summary of aerodynamic data corresponding to maximum ε for passive flow control

Re	$\varepsilon_{\max}$	$C_l^{3/2}/C_d$	C_l	α
$C00G00$				
3,000	3.72	2.6	0.35	6
6,000	5.39	3.8	0.44	6
9,000	6.74	4.6	0.3	4
20,000	6.75	4.9	0.39	6
$C00G10$				
3,000	6.08	6.03	0.81	4
6,000	6.23	6.39	1.03	5
9,000	7.32	7.16	0.9	4
20,000	8.04	7.82	0.83	3
$C00G20$				
3,000	5.25	5.69	1.18	4
6,000	6.45	8.81	1.11	2
9,000	7.23	7.61	1.11	2
20,000	7.53	8.73	1.34	2
$C08G00$				
3,000	3.39	2.83	0.51	5
6,000	3.67	3.23	0.56	6
9,000	4.24	3.9	0.55	5
20,000	5.02	4.96	0.91	8
$C08G10$				
3,000	4.12	3.86	0.68	4
6,000	4.88	4.74	0.81	1
9,000	5.91	6.17	0.87	3
20,000	6.86	8.3	1.46	8
$C08G20$				
3,000	3.82	3.48	0.8	0
6,000	5.32	4.59	0.31	0
9,000	4.87	5.15	0.83	0
20,000	7.11	6.7	0.65	-4

Table 2 Summary of aerodynamic data corresponding to maximum C_l for passive flow control

Re	$C_{l,\max}$	ε	$C_l^{3/2}/C_d$	α
$C00G00$				
3,000	0.74	2.74	2.36	14
6,000	0.76	3.43	3.98	13
9,000	0.73	4.77	4.05	11
20,000	0.7	4.94	4.1	11
$C00G10$				
3,000	1.2	4.53	5.04	9
6,000	1.3	4.93	5.6	9
9,000	1.34	5.65	6.5	9
20,000	1.33	5.91	6.8	9
$C00G20$				
3,000	1.26	4.47	5.2	6
6,000	1.48	5.27	6.4	7
9,000	1.5	4.99	6.1	7
20,000	1.55	5.27	6.56	7
$C08G00$				
3,000	0.9	2.39	2	18
6,000	1.01	2.52	2.5	15
9,000	1.01	3.56	3.6	12
20,000	1.16	4.08	4.4	13
$C08G10$				
3,000	1.32	3.37	2.9	10
6,000	1.34	3.67	4.18	9
9,000	1.47	4.63	5.6	11
20,000	1.64	5.86	7.5	13
$C08G20$				
3,000	1.23	3.01	3.35	8
6,000	1.33	3.32	3.83	9
9,000	1.57	3.91	4.9	9
20,000	1.89	3.46	4.76	12



a) b)

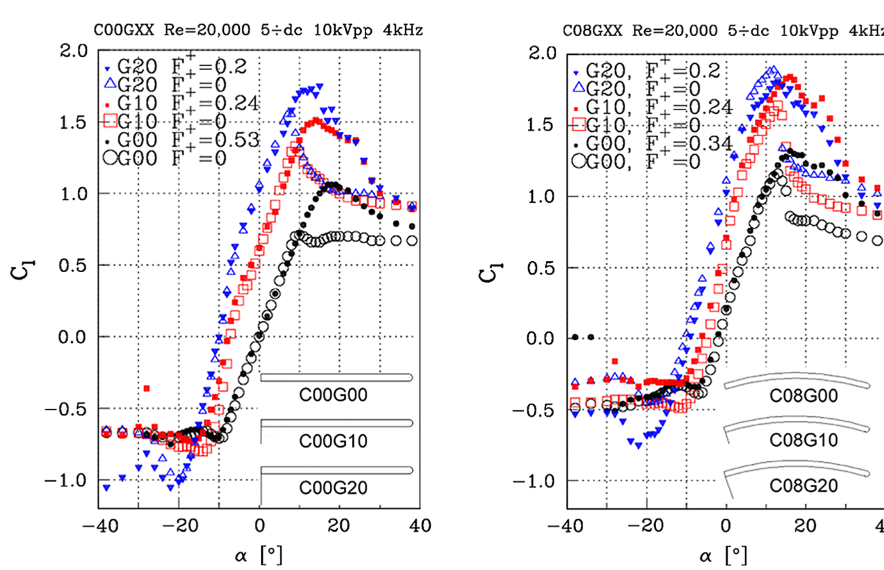
Fig. 2 Frequency scan for optimum unsteady pulsed excitation frequency at $\alpha = 24°$, 10 kVpp sinusoidal voltage, 5% duty cycle, and $f = 4$ kHz: a) flat plate and b) flat plate plus 20% Gurney flap.

a bubble or "trapped vortex" on the airfoil. When viewed inverted, the large Gurney flap resembles a Hurley flap [7] that was originally designed with the express purpose of trapping a vortex and producing high lift. However, it should be noted that Hurley's configuration required active blowing in order to trap the vortex and maintain attached flow on the flap. In contrast, the "bubble-trapping" mechanism observed here occurs naturally at these low Reynolds numbers. In certain instances, leading-edge perturbations (see the next section) shortened the bubble and eliminated the lift-producing effect. The observed increase of the lift slope noted above is consistent with conventional low Reynolds number investigations that report significant differences in the upper pressure distribution with increasing angle of attack (e.g., Jeffrey et al. [3]).

Figure 1b illustrates the projected, but nevertheless, counterintuitive result that large Gurney flaps in fact increase ε_{max} (consider a line drawn from the zero tangent to the data). However, it appears that the optimum is closer to $h/c = 10\%$. This is consistent with both the boundary-layer scaling of Giguère et al. [2] and the model of Bechert et al. [5] noted in Sec. I. Thus, even though the flaps significantly increase drag, the proportionate increase in lift is larger, and this produces the larger ε_{max}. It is worth noting that three-dimensional modification to the flaps such as serrated edges or holes, which reduce vortex-shedding strength, have the effect of further reducing drag (see Meyer et al. [4]), although this was not attempted here. A summary of data for both airfoils, with and without Gurney flaps, appears in Tables 1 and 2.

B. Active Flow Control: Optimum Modulation Frequencies

A single spanwise-oriented leading-edge DBD plasma actuator was used for active control on each airfoil configuration. To estimate the optimum unsteady modulation frequency, the angle of attack was fixed in the poststall regime at $\alpha = 24°$, and the pulsed excitation frequency was increased from 0 to physical frequencies corresponding to approximately $F^+ = 0.8$ for each Reynolds number. In a previous study [1], it was ascertained that pulsed frequencies at $F^+ > 1$ produced successively smaller lift increases, and hence the range was limited to $F^+ < 1$ here. In all cases, the



a) b)

Fig. 3 Application of the leading-edge plasma actuator at near optimum excitation frequencies together with 10 and 20% Gurney flaps at $Re = 20,000$: a) flat-plate airfoil and b) 8% cambered airfoil.

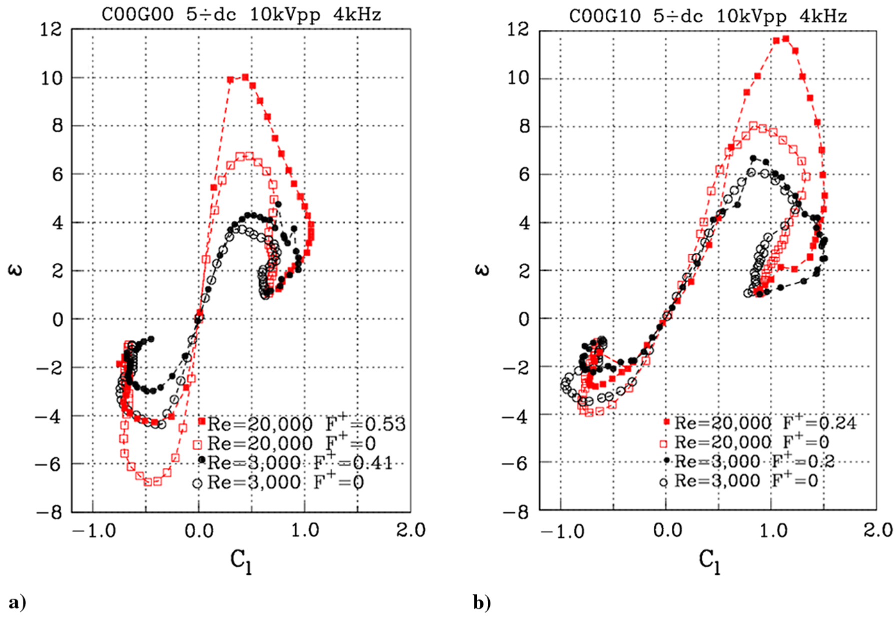


Fig. 4 Comparison of aerodynamic efficiency versus C_l at $Re = 3000$ and 20,000, with applied plasma actuator and Gurney flap on the flat-plate airfoil.

duty cycle, plasma actuation frequency, and voltage were kept constant at 5%, 4 kHz, and 10 kVpp (kilovolts peak to peak). In Fig. 2 two typical curves of lift coefficient versus excitation frequency are shown; Figs. 2a and 2b show data for the flat plate without a flap and with the 20% Gurney flap, respectively. Without the flap, the lift coefficient at all Reynolds numbers responds in a gradual manner to forcing, attaining a gentle peak in the range of $0.35 < F^+ < 0.5$. The relative change of the lift coefficient decreases with increasing Reynolds number, due to the reduction in momentum coefficient; the perturbation momentum depends on the modulation frequency [1] as well as the freestream dynamic pressure. For example, at $F^+ \approx 0.3$ the unsteady momentum coefficient $\langle c_\mu \rangle$ reduces from 0.76 to 0.001% as Reynolds number increases from 3000 to 20,000.

Active control on the airfoil with the Gurney flap is qualitatively and quantitatively different from that without the flap, and these differences manifest in three ways. First, there is a sharp peak in the lift enhancement; second, this occurs at $F^+ \approx 0.2$, irrespective of Reynolds number; and third, the maximum changes in lift are substantially larger for most Reynolds numbers. These observations are difficult to explain, because they imply that the Gurney flap fundamentally affects the manner in which the vortices are generated and advected over the airfoil surface. As noted above, Gurney flaps affect the upper pressure distribution [3]; however, it is not evident why they produce such a dramatic differences to active control effectiveness.

C. Application of Combined Active and Passive Flow Control

The optimum control frequencies for each configuration isolated in the previous section were employed to assess the combined effect of passive and active control throughout the entire range of angles of attack. Lift versus angle-of-attack data for $Re = 20,000$ (Fig. 3) show that in every case except the $C08G20$ case, active control increased the maximum lift coefficient and increased the stall angle relative to the passively controlled cases. Hence the effect of combined passive and active control is a cumulative one. The Gurney flap mainly changes the value and nature of the optimum control frequency (cf. Figs. 2a and 2b), but the essential flow control effect is similar to that seen in the absence of the flap. Nevertheless, $\Delta C_{l,\max}$ decreases with increasing flap length and increasing camber. This is commonly observed when leading-edge active flow control is applied in the presence of a simple flap. For 8% camber together with a Gurney flap at $Re = 20,000$, active control slightly decreases $C_{l,\max}$. In this instance, control cannot overcome the strong adverse pressure gradient at the leading edge, although it is pointed out that the momentum coefficient is extremely small: namely, $\langle c_\mu \rangle \sim 0.001\%$ at $Re = 20,000$. Consistent with control at conventional low Reynolds numbers, active control produced very mild poststall lift variations.

With regard to improvements in maximum aerodynamic efficiency $\varepsilon_{\max}$, the effects were strongly Reynolds-number-dependent: Gurney flaps were more effective at low Reynolds numbers, whereas plasma actuation produced superior effects at higher Reynolds numbers. For example, at $Re = 3000$ the 10% Gurney flap produced an increase in $\varepsilon_{\max}$ of 64% (cf. Figs. 4a and 4b), which was comparable to the maximum value of the corresponding baseline configuration at $Re = 20,000$ (see Fig. 4a). In contrast, plasma

Table 3 Summary of aerodynamic data corresponding to maximum ε for active flow control

Re	$\varepsilon_{\max}$	$C_l^{3/2}/C_d$	C_l	α	F^+
$C00G00$					
3,000	4.3	4.1	0.46	9	0.41
6,000	7.04	4.32	0.38	6	0.37
9,000	6.18	5.07	0.4	6	0.48
20,000	10	6.87	0.43	6	0.53
$C00G10$					
3,000	6.68	6.35	0.73	3	0.2
6,000	5.87	5.76	0.82	4	0.21
9,000	9.61	9.99	1.08	7	0.21
20,000	11.7	12.5	1.14	7	0.24
$C00G20$					
3,000	4.93	5.15	1.09	4	0.15
6,000	6.15	6.96	1.12	2	0.22
9,000	7.07	7.5	1.28	4	0.21
20,000	7.24	8.22	1.28	4	0.2
$C08G00$					
3,000	6.4	5.36	0.67	9	0.37
6,000	6.9	6.63	0.64	6	0.43
9,000	9.01	8.75	0.8	8	0.32
20,000	11.8	11.5	0.93	8	0.34
$C08G10$					
3,000	5.18	5.3	0.95	4	0.31
6,000	8.06	7.6	0.9	3	0.22
9,000	6.35	7.1	0.91	3	0.27
20,000	6.6	7.55	0.98	2	0.24
$C08G20$					
3,000	3.79	3.53	0.87	2	——
6,000	5.22	4.8	0.28	0	——
9,000	6.3	4.8	0.12	——	——
20,000	10	6.05	1.03	——	——

Table 4 Summary of aerodynamic data corresponding to maximum C_l for active flow control

Re	$C_{l,\max}$	ε	$C_l^{3/2}/C_d$	α	F^+
$C00G00$					
3,000	0.94	2.03	1.97	22	0.41
6,000	1.05	2.3	2.78	22	0.37
9,000	0.93	2.2	2.28	20	0.48
20,000	1.06	3.64	3.75	17	0.53
$C00G10$					
3,000	1.5	2.48	3.01	20	0.2
6,000	1.52	2.5	3.07	20	0.21
9,000	1.49	3.77	4.61	15	0.21
20,000	1.5	5.13	6.3	14	0.24
$C00G20$					
3,000	1.67	2.23	2.88	20	0.15
6,000	1.82	3.46	3.1	16	0.22
9,000	1.78	3.19	4.25	13	0.21
20,000	1.73	3.47	4.56	14	0.2
$C08G00$					
3,000	1.26	4	2.96	20	0.37
6,000	1.35	3.7	3.72	20	0.43
9,000	1.37	4.12	4.84	20	0.32
20,000	1.32	5.56	5.38	16	0.34
$C08G10$					
3,000	1.64	2.8	4.26	18	0.31
6,000	1.65	3.25	4.53	16	0.22
9,000	1.72	4.01	4.8	17	0.27
20,000	1.84	3.9	5.32	16	0.24
$C08G20$					
3,000	1.23	3.01	3.35	8	——
6,000	1.33	3.32	3.83	9	——
9,000	1.57	3.91	4.9	9	——
20,000	1.89	3.46	4.76	12	——

actuation increased $\varepsilon_{\max}$ by approximately 50%, irrespective of the presence of the Gurney flap. A summary of data for both airfoils, with and without Gurney flaps, appears in Tables 3 and 4.

IV. Conclusions

The overall objective of this work was to apply viable methods of flow control in order to generate high lift at very low flight Reynolds numbers ($3000 < Re < 20,000$) for conventional airfoil configurations (flat plate and 8% cambered plate). Based on the extrapolation of conventional semi-empirical models to the very low flight Reynolds number regime, unusually large Gurney flaps of 10 and 20% significantly increased the maximum lift while still improving airfoil efficiency. These outsized Gurney flaps also increased lift at negative angles of attack by employing an assumed bubble-trapping mechanism. With Gurney flaps removed, leading-edge active flow control via pulsed DBD plasma actuators produced significant lift enhancement by delaying separation to higher angles of attack. Optimum modulation frequencies were in the range of $0.35 < F^+ < 0.5$. In contrast, with the flaps attached, sharper lift peaks were observed at $F^+ \approx 0.2$.

The combination of passive Gurney flaps and active DBD plasma control was cumulative in the sense that the DBD actuator stall-delaying mechanism was also effective on the passively controlled cases. Interestingly, the Gurney flap produced higher improvements in $\varepsilon_{\max}$ for the lower end of the Reynolds range numbers tested whereas the plasma actuators were superior at the higher Reynolds numbers.

References

[1] Greenblatt, D., Göksel, B., Rechenberg, I., Schüle, C., Romann, D., and Paschereit, C., "Dielectric Barrier Discharge Flow Control at Very Low Flight Reynolds Numbers," *AIAA Journal*, Vol. 46, No. 6, 2008, pp. 1528–1541. doi:10.2514/1.33388

[2] Giguère, P., Lemay, J., and Dumas, G., "Gurney Flap Effects and Scaling for Low-Speed Airfoils," AIAA Paper 95-1881, 1995.

[3] Jeffrey, D., Zhang, X., and Hurst, D. W., "Aerodynamics of Gurney Flaps on a Single-Element High-Lift Wing," *Journal of Aircraft*, Vol. 37, No. 2, 2000, pp. 295–301; also AIAA Paper 96-2418, 1996. doi:10.2514/2.2593

[4] Meyer, R., Hage, W., Bechert, D. W., Schatz, M., and Thiele, F., "Drag Reduction on Gurney Flaps by Three-Dimensional Modifications," *Journal of Aircraft*, Vol. 43, No. 1, 2006, pp. 132–140. doi:10.2514/1.14294

[5] Bechert, D. W., Meyer, R., and Hage, W., "Drag Reduction of Airfoils with Miniflaps. Can We Learn from Dragonflies?," AIAA Paper 2000-2315, June 2000.

[6] Mueller, T. J., "Aerodynamic Measurements at Low Reynolds Numbers for Fixed Wing Micro-Air Vehicles," *Development and Operation of UAVs for Military and Civil Applications*, von Karman Inst. for Fluid Dynamics, Rhode-St-Genese, Belgium, Sept. 1999.

[7] Hurley, D. G., *The Use of Boundary Layer Control to Establish Free Stream-Line Flows*, edited by G. V. Lachmann, Pergamon, New York, 1961, pp. 295–341.

E. Gutmark
Associate Editor