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Pulsed Plasma Actuators for Separation Flow Control

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ABSTRACT

An experimental investigation of separation control using steady and pulsed plasma actuators was carried out on an Eppler E338 airfoil at typical micro air vehicle Reynolds numbers (20,000≤Re≤140,000). Pulsing was achieved by modulating the high frequency plasma excitation voltage. The actuators were calibrated directly using a laser doppler anemometer, with and without free-stream velocity, and this allowed the quantification of both steady and unsteady momentum introduced into the flow. At conventional low Reynolds numbers (Re>100,000) asymmetric single phase plasma actuators can have a detrimental effect on airfoil performance due to the introduction of low momentum fluid into the boundary layer. The effect of actuation, particularly at $F^+\approx 1$, became more effective with decreasing Reynolds number resulting in significant improvements in $C_{l,max}$. This was attributed to the increasing momentum coefficient, which increased as a consequence of the decreasing free-stream velocities. Particularly low duty cycles of 3% were sufficient for effective separation control, corresponding to power inputs on the order of 500 milliwatts per meter actuator length.

INTRODUCTION

Achieving sustained flight of micro air vehicles (MAVs) brings significant challenges to due their small dimensions (*b*≤15cm, *M*=90g) and low flight speeds, resulting in very low flight Reynolds numbers [1]. A typical MAV mission includes low-speed loiter at around 30km/h, where $C_{l,\max}$ must exceed unity at *Re*<100,000 [4]. However, airfoil performance deteriorates significantly in this Reynolds number range and passive tripping of the boundary layer is not possible for *Re*<50,000 [3]. The particular difficulties of low *Re* flight have spawned unconventional approaches inspired by bird and insect flight. For example, boundary layer control via leading-edge two-dimensional perturbations was investigated for *Re*=50,000 and 30,000 [6]. This bionic method generates traveling quasi-two-dimensional vortices over a stationary airfoil, bringing high-momentum fluid to the surface, thereby delaying separation and improving performance without the complexity associated with wing movement or flapping. Perturbations at F^+=1 resulted in the restoration of conventional low-Reynolds-number lift and aerodynamic efficiency, while excitation-induced lift oscillations were small and hysteresis associated with stall was eliminated. However, with decreasing *Re*, larger perturbations (expresses as C_μ) were required to generate useful lift. At MAV scales, actuator size, effectiveness and efficiency are key factors in determining the applicability. Plasma-based actuators have recently demonstrated application to separation control [7], [8], [9], [11], [12], [13]. The first separation flow control on airfoils at typical MAV Reynolds numbers (13,000<*Re*<140,000) were demonstrated by plasma actuation using high voltage (10–20 kV) charged corona discharge wires in 1999 [7], [8]. Göksel demonstrated significant improvement to an Eppler E338 airfoil performance [e.g. $C_{l,\max}$ $(l/d)_{\max}$], particularly for 10,000<*Re*<70,000 [7].

For a given power input (in this case ~8.5Watts) $C_{l,\max}$ was shown to increase with decreasing Reynolds number up to 3.2 at *Re*=10,000. The reason for this is that the relative power (or presumed momentum) input by the actuators increased with decreasing *Re*. In certain circumstances, however, separation control by periodic excitation (e.g. via two-dimensional jets) requires up to two orders of magnitude less C_μ than steady blowing in order to achieve similar performance benefits (e.g. ΔC_l). With this as motivation, the present investigation was undertaken to examine the possibility of controlling separation by means plasma actuators in a pulsed mode at typical MAV Reynolds numbers. A pulsed plasma jet, generated using the single phase actuation technique near the leading edge of the airfoil was utilized for this purpose [9], [12], [13]. Momentum added to a flow by means of pulsed actuation introduces both time-mean and unsteady components of momentum ($C_\mu, \langle C_\mu \rangle$) and these were directly quantified in the present investigation.

EXPERIMENTAL SETUP

Experiments were performed on an Eppler E338 airfoil (*c*=17.8cm, *b*=50cm) mounted between circular endplates downstream of the exit of a 600mm and a 1200mm diameter low speed open jet wind tunnel. Lift and drag were measured using a two component balance.

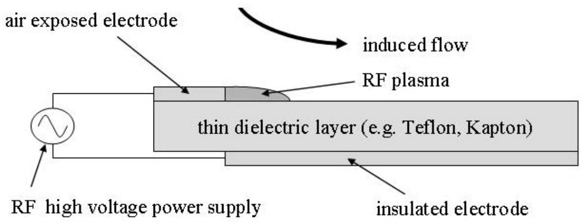

***Figure 1**. Schematic of the plasma actuator used for the present experiments.*

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This airfoil was previously used for flow control experiments with high voltage (10–20kV) charged corona discharge wires, and a full description of the setup can be found in [7], [11], [13]. The plasma actuator consisted of two thin metal electrodes separated by a dielectric layer which formed part of the airfoil surface (see fig. 1) [9], [10], [11].

The momentum in the jet was quantified by performing LDV profile measurements, at 3mm, 12mm and 25 mm downstream of the actuator. For the purpose of pulsed (or unsteady) actuation, the wave modulation method was employed where the kHz carrier wave is modulated by a square-wave that correspond to low frequencies appropriate for separation control [9], [12], [13], [14]. This introduces mean (u_J) and unsteady ($\tilde{u}_J$ and $\tilde{v}_J$) velocity components and thus the jet momentum is made up of time-mean and oscillatory component quantified by

$$J_{\text{tot}} = J + \langle J \rangle = \int_0^\infty \rho (u_J^2 - u^2) dy + \int_0^\infty \rho (\tilde{u}_J^2 + \tilde{v}_J^2) dy \qquad (1)$$

where the first term represents the steady contribution, the second term represents the oscillatory contribution and u is the time-mean velocity profile without plasma actuation. Consequently, the total momentum coefficient is defined as

$$C_{\mu,\text{tot}} = C_\mu + \langle C_\mu \rangle \qquad (2)$$

and also expressed as ($C_\mu , \langle C_\mu \rangle$). For all data acquired here, the actuator was excited with a signal of intermittent bursts of 4.0 kHz that were modulated in the range of 2.5 to 100 Hz. The duty cycle was varied from 1% to 100% at constant voltage.

DISCUSSION OF RESULTS

Fig. 2 shows actuator calibration data for $U_\infty = 0$, where duty cycle was gradually increased from 1% to 100%. It was noted that a duty cycle threshold between 2% and 4% is reached where there is a significant increase in near-wall unsteady momentum. Peak unsteady momentum is reached at a duty cycle of approximately 10%. Further increases in duty cycle result in decreases to both steady and unsteady near wall momentum. At 100% duty cycle a near-steady wall jet is formed with relatively large mean near wall momentum. Additional actuator calibrations, described in section 2, where performed with various free-stream velocities ($U_\infty \neq 0$).

The airfoil data is presented below in terms of deceasing Reynolds number, starting at typical low *Re*~140,000 (conventional low *Re*) and reducing to ~20,000 (approximate lower MAV limit). Fig. 3 shows C_l versus α for *Re*=140,000. We note that plasma control at 100% duty cycle has a *detrimental* effect and reduces $C_{l,\max}$. This is because a relatively slow speed *steady jet* is being generated by the plasma actuator that is much less than the free-stream velocity with $C_\mu \approx 0.1\%$ (see section 2). Hence, the low momentum fluid introduced near the wall, in fact, promotes separation. This may appear counterintuitive, but a similar effect was noted when using conventional steady slot blowing with $U_J / U_\infty < 1$ [2].

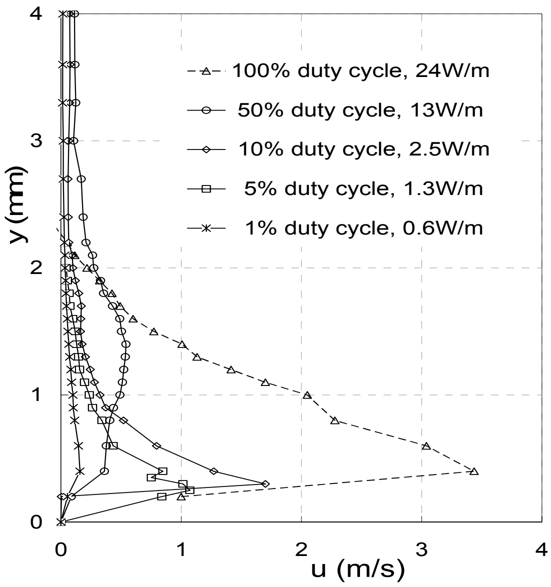

Figure 2a. *Mean velocity 3mm downstream of the actuator for different duty cycles at U_∞=0.*

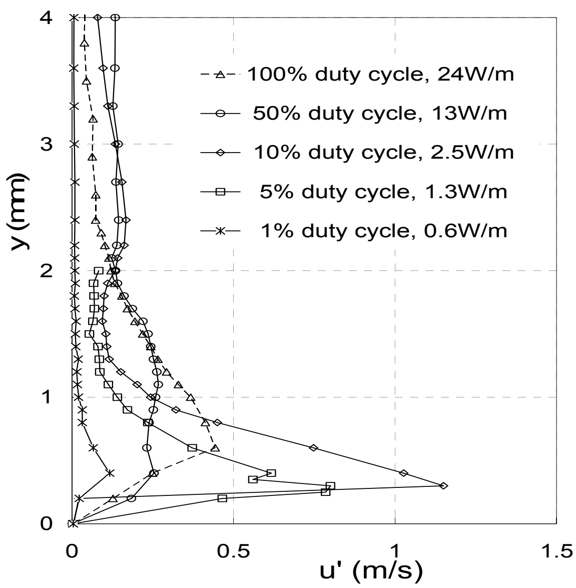

Figure 2b. *Fluctuating velocity 3mm downstream of the actuator for different duty cycles at U_∞=0.*

All other duty cycles considered (≤50%, corresponding to F^+=1) have a net positive post-stall effect with relatively low $\langle C_\mu \rangle < 0.1\%$. Changes to post-stall lift and small changes to $C_{l,\max}$ at conventional low Reynolds numbers have been observed by others (e.g. [9], [13]). Interestingly, data is marginally superior when the duty cycle is reduced from 50% to 10%. This might have been expected when considering the data in fig. 2b, which shows that the 10% duty cycle actuation produced greater unsteady near-wall momentum. Moreover, this result is even more significant when we account for the fact that duty cycle percentage correlates linearly with power consumption.

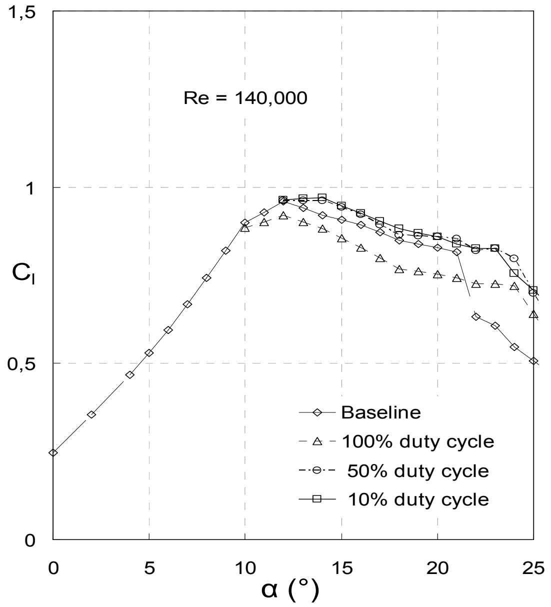

Figure 3. *Example of the effect of plasma actuation at F^+=1 on airfoil performance at conventional low Reynolds numbers.*

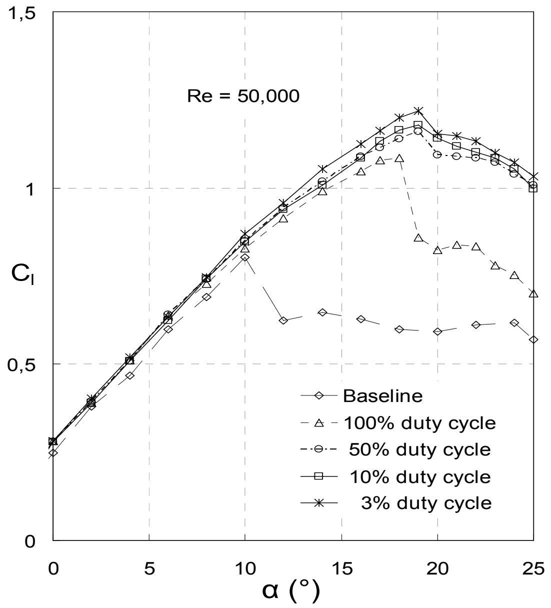

Figure 4. *Effect of plasma actuation at F^+=1.0 on airfoil performance at a typical MAV Reynolds number.*

With Reynolds number reduced to 80,000, the near wall jet velocity is comparable to that in the near wall boundary layer and the detrimental effect on $C_{l,\max}$ disappears (not shown). And at high post-stall angles, when the airfoil is fully stalled, the jet has a positive effect on C_l (not shown).

At *Re*=50,000, shown here for F^+=1.0, the effect of plasma actuation can be far more clearly observed (fig. 4). It is known that at these Reynolds numbers transition is virtually impossible to promote passively [3]. This is reflected in the poor performance of the airfoil with $C_{l,\max} < 0.8$. In this instance, the 100% duty cycle actuation has a net positive effect on $C_{l,\max}$ and this is because it generates a steady wall jet corresponding to C_μ =0.74%. Successive reductions in duty cycle clearly result in improvements in performance, both with respect to the C_l - α linearity as well as $C_{l,\max}$. Note, in addition, that $C_{l,\max}$ is larger than that at the higher Reynolds numbers. It is assumed that this is due to the larger C_μ values which increase as a consequence of the reducing free-stream velocity. This runs counter to the typical baseline trends and has clear potential for reducing loiter speed discussed in the introduction.

Further reductions in Reynolds number to 35,000 and 20,000 showed ever greater effects on control. For example, in the latter case (*Re*=20,000) which is very near the low end of the MAV Reynolds number range, significant effect were observed and hence additional data were acquired in an attempt to optimize control. Employing a 5% duty cycle and placing the airfoil at a post stall angle of attack (α = 18°) a frequency scan was performed for the range $0.25 \le F^+ \le 10.4$ (fig. 5). The optimum is seen to be at $F^+ \approx 1$ and this is consistent with conventional low Reynolds number data [5]. Corke et al. observed that, using plasma actuators, the minimum voltage required to attach a post-stall separated flow was at $F^+ \approx 1$ [9]. Similar effects have also been observed on delta wings using zero mass-flux jets [14]. Further attempts at optimisation considered variation of the duty cycle. It was observed that the optimum lies somewhere between 3% and 8% (not shown). Interestingly, this is the range where the maximum oscillatory momentum is added to the flow.

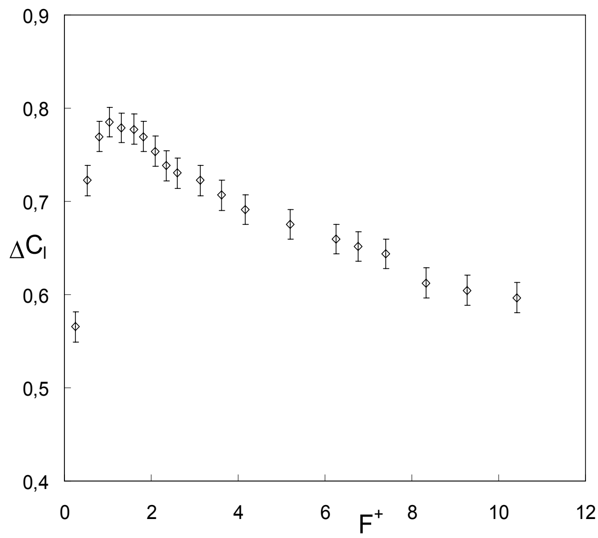

Figure 5. *Effect of reduced frequency on post-stall (α=18° airfoil lift at a low MAV Reynolds number. C_μ*=0.05% and duty cycle = 3%.

Finally, the effect of input voltage on the C_l versus α curves was investigated. It was determined that for V>8kVpp (corresponding to 0.5W/m), the effect on the airfoil performance is clearly significant and $C_{l,\max}$ is larger than at the higher Reynolds numbers (fig. 6a). Note that here the optimum F^+ and duty cycles have been used.

Data was generated for increasing α (filled symbols) and decreasing α (open symbols). Note that below 10kVpp the C_l versus α curve is non linear (c.f. figs. 6a and 6b), but this non linear feature does not show any significant hysteresis trend repeats for decreasing α.

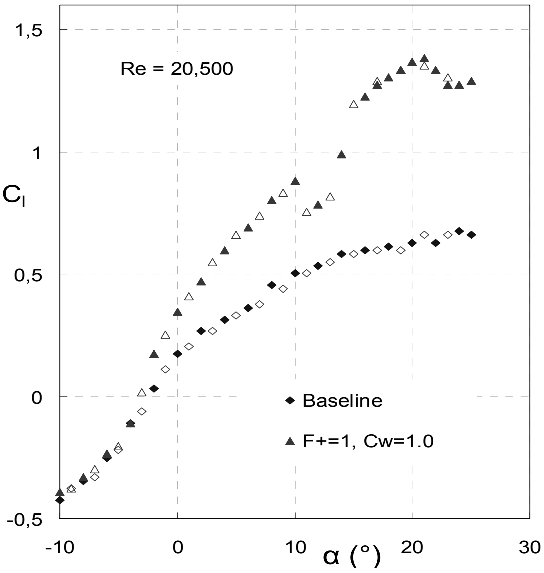

Figure 6a. *Effect of plasma actuation on airfoil performance at a low MAV Reynolds number illustrating non-linear behavior at low C_W. C_μ*=0.04% and duty cycle = 3%.

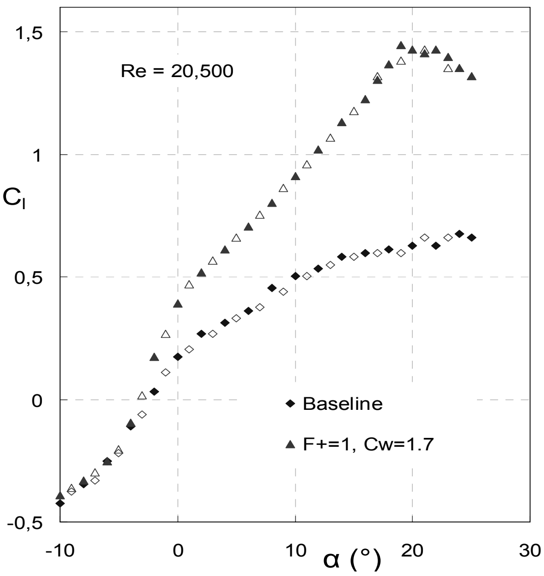

Figure 6b. *Effect of plasma actuation on airfoil performance at a low MAV Reynolds number illustrating the minimum C_W required for linear behavior. C_μ*=0.05% and duty cycle = 3%.

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