Influence of burst-modulated frequency on sawtooth DBD plasma actuator for flow separation control

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The dielectric barrier discharge (DBD) plasma actuator has been demonstrated to be an effective electro-hydrodynamics (EHD) device for flow separation control [1-3]. DBD plasma actuators are typically operated at high frequency (kHz ~ MHz) "steady" mode. It has been found that plasma actuator under burst mode actuation has excellent control efficiency due to the vortex interaction between the unsteady forcing and the separated flow, which has strong influence on the reattached shear layer [4]. Recently, three-dimensional plasma actuators have been studied with a view to increase the aerodynamic performance [5]. There are numerous characterization studies on three-dimensional plasma actuators, but its application for flow separation control is rather scarce. Therefore, the present experimental study aims to investigate the influence of non-dimensional burst frequency F^+ ($= f_b c/U_\infty$, where f_b, c and U_∞ are the burst frequency, the airfoil chord length and the freestream velocity, respectively) on the sawtooth plasma actuator (one kind of three-dimensional plasma actuator [6]) for flow separation control and lift enhancement.

Experiments were conducted in a closed-loop wind tunnel with (0.8m × 1.0m × 5.0 m). The Reynolds number is 7.7×10^4. The turbulence intensity was less than 0.4%. Two identical-sized smooth false walls with rounded leading-edge were installed near the test section inlet to ensure two-dimensional flow around the NACA 0015 airfoil model (Fig. 1a). The c and span length of the airfoil model were 200 and 300 mm, respectively. The airfoil was fabricated into two parts; the first part is the main airfoil body (Fig. 1b), whereas the second part is the airfoil hood (Fig. 1c). The sawtooth electrodes of the actuator are arranged with opposite saw-teeth pointing at each other (Fig. 1d). Therefore, the gap width between the exposed and the encapsulated grounded electrodes varies periodically in the spanwise direction. Load cell and PIV technology were used for the investigation of lift enhancement and flow control mechanisms under unsteady plasma actuation.

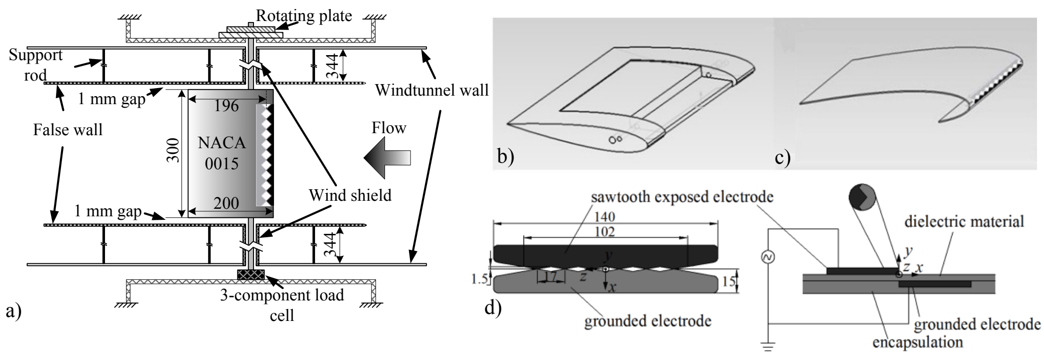

Figure 1: a) wind tunnel setup for the force measurement, b) main airfoil body, c) airfoil hood, and sawtooth DBD plasma actuator.

At a fixed post-stalled angle-of-attack $\alpha = 16°$ and at an applied voltage V_a of 15 kV, the burst-modulated actuation with F^+ ranging from 0.6 – 1.0 and DC between 2% and 10%, is found to be more effective at increasing the lift coefficient C_L than the steady-mode actuation. Under the optimum $F^+ = 0.6$ and DC = 5%, the actuation on the airfoil leading-edge leads to a delay in stall α by 3° and an increase in maximum lift coefficient C_{Lmax} by 27.5% (cf. no control case, Fig. 2a). Due to the sawtooth-shaped electrodes, two flow mechanisms are proposed based on the flow fields acquired by PIV as shown in Fig 2b-f; at the tip of the sawtooth (P-P plane), the periodic disturbances resulted from the burst-modulated plasma actuator lead to the turbulent entrainment into the shear layer that triggers the transition to turbulence, thus allowing postponed separation. At the trough region, the three-dimensional periodic disturbances resulted from the non-uniform plasma density amplify the shear layer instability, therefore forcing a shear-layer reattachment downstream of the actuator, meanwhile generating vortex structures that give rise to lift enhancement.

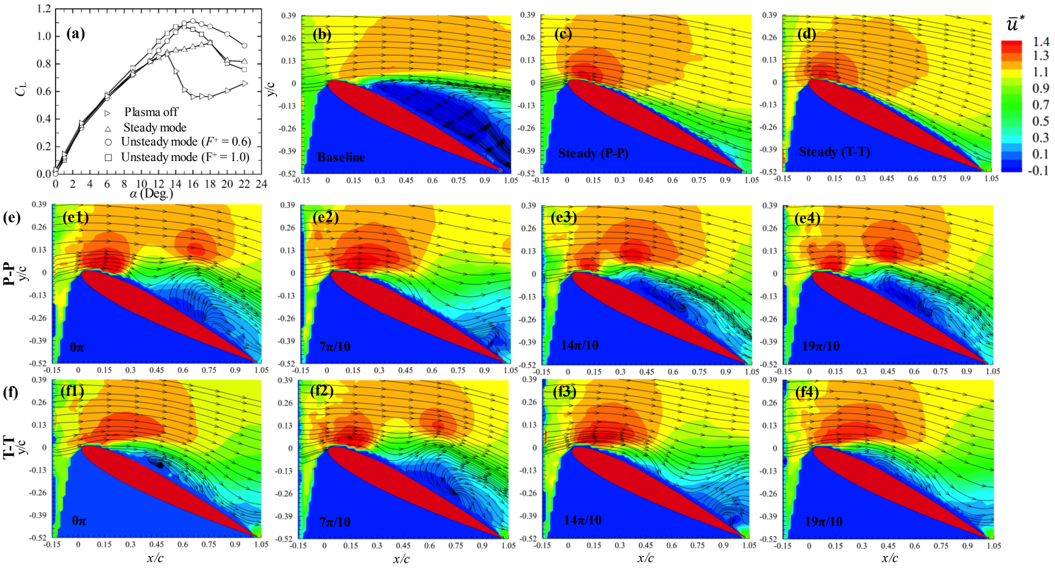

Figure 2: (a) Dependence of C_L on α. The non-dimensional phase-averaged streamwise velocity $\bar{u}^*$ ($= \bar{u}/U_\infty$) with streamlines of airfoil under (b) baseline (no control), (c) and (d) steady actuation and (e) and (f) unsteady control. f = 11 kHz and V_a = 15 kV. F^+ = 0.6 for PIV measurement. P-P and T-T stand for peak-to-peak and trough-to-trough, respectively.

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