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Control of Unsteady Plasma Flows over Conical Forebody

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Abstract An experimental study of the active control of vortices over slender forebodies is performed on a 20° circular-cone-cylinder model using a pair of Single-Dielectric-Barrier-Discharge (SDBD) plasma actuators combined with duty-cycle technique. The tests are carried out in a low-turbulence 3.0 m×1.6 m low-speed wind tunnel at an angle of attack of 45°. The Reynolds number based on the cone base diameter is 50 000. The results consist of measurements of circumferential pressure distributions over eight stations along the cone forebody, including one station using unsteady pressure tappings, under three different modes of controls: plasma-off, plasma port-on or starboard-on, and plasma duty-cycle actuation. The cross-sectional side forces over the cone are calculated from the measured pressures. The ensemble and phase-locked averaged loads at various duty cycles are investigated. The test results indicate that the variation of the phase-locked-averaged side force in a period of the duty cycle is a smooth-wave curve rather than the square-wave curve. The linearity of the controlled lateral forces and moments with respect to the duty cycle is improved over previous studies because of the improved design of the actuators.

Key words: slender body, asymmetric vortices, high angle of attack aerodynamics, plasma, active flow control, slender body

INTRODUCTION

The separation vortices over pointed forebodies generate large airloads and are very sensitive to small perturbations near the body apex offers an exceptional opportunity for manipulating them with little energy input to achieve active lateral control of the verhicle in place of conventional control surfaces. It has been found experimentally that unsteady dynamic control techniques are needed to achieve this goal [1-3].

Liu et al. [4,5] and Meng et al. [6] reported wind-tunnel experiments that demonstrate nearly linear proportional control of lateral forces and moments over a slender conical forebody at high angles of attack by employing a novel design of a pair of single dielectric barrier discharge (SDBD) plasma actuators near the cone apex combined with a duty cycle technique.

Lamont [7] used miniature pressure tappings for measuring unsteady pressures in addition to the time-averaged pressure tappings to demonstrate that his experimental setup had produced the hoped-for absence of serious flow unsteadiness. Thomas, Kozlov and Corke [8] studied ensemble averaged and phase-locked averaged particle image velocimetry of the flow over a cylinder controlled by plasma duty cycles. Flow under plasma duty-cycle actuation is naturally unsteady. The reduced angular frequency of duty cycle is of the order of 1. On the other end, the reduced angular frequency range of typical aircraft aerodynamic maneuvers is of the order of 0.01 based on the spectrum of unsteady flow phenomena over delta wings given by Menke et al., [9] which is much smaller than that of the plasma duty-cycle. Thus, typical aircraft could not respond the instantaneous (unsteady) loads under plasma duty-cycle actuations but just respond the time-averaged (steady) loads. This observation agrees with the predictions of Hanff et al. [3] Therefore, the ensemble-averaged pressures are useful in aircraft-maneuver design, and the phase-locked averaged pressures are required for flow-mechanism study.

To study the mechanisms of plasma flow control, Takashi Matsuno et al. [10] used the flow visualization experiments and force and moment measurements technique, Wang et al. [11] studied by using 2D particle image velocimetry technique. The unsteady pressures in the plasma duty cycles are investigated here in detail.

EXPERIMENTAL SETUP

A circular cone with a 108 semi-apex angle faired to a cylinder afterbody is test. The total length of the cone segment is $L = 463$ mm with a base diameter of 163.6 mm. The frontal portion of the cone is made of plastic and has a length of 150 mm. Ten unsteady pressure tappings are mounted around the circumference at $x/L = 0.89$. Seven tappings are distributed every 308 from $\theta = 908$ to 2 708 and the rest three at $\theta = 08$ and ± 508 as Figure 1. They are measured with sampling frequency of 500 Hz. Consecutive 15 s samplings of all tappings are recorded for analyses. Two long strips of SDBD plasma-actuators are installed symmetrically on the plastic frontal cone near the apex Figure 2. The duty cycles are achieved by modulating the carrier a.c. voltage sources by a digital pulse wave generator at a frequency of 10 Hz.

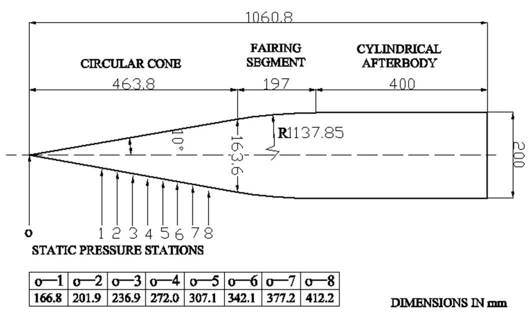


Figure 1: Sketches of the model

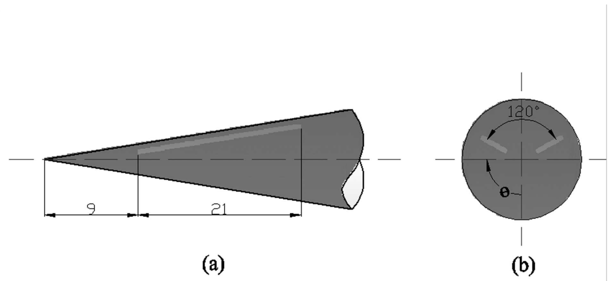
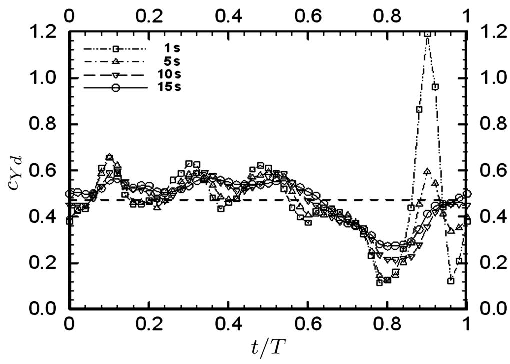


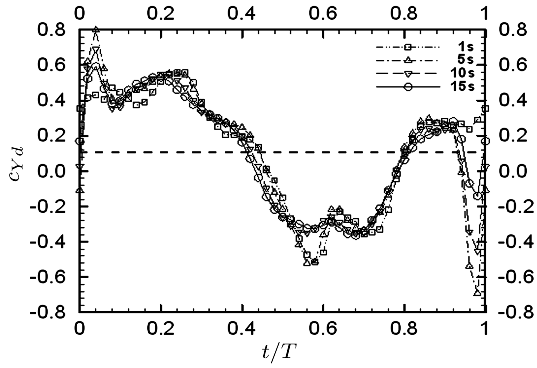
Figure 2: Sketches the plasma actuators

PHASE-LOCKED LOCAL SIDE FORCE AT MEASURED STATION

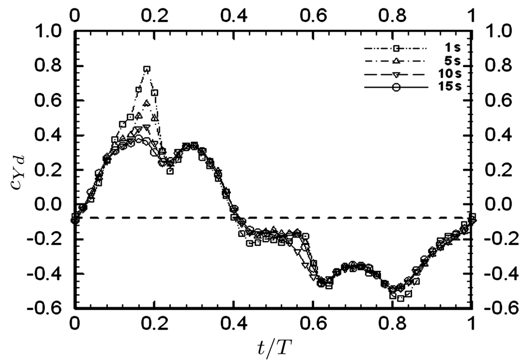
The Kulite sampling has a rate of 500 Hz and is taken consecutively for 15 s in each test. The frequency of duty cycle is 10 Hz. In one period of the duty cycle there are 50 readings evenly distributed at phase-angle increment of 7.28. At a given phase angle there are totally 150 samples to be averaged in the sampling time of 15 s.



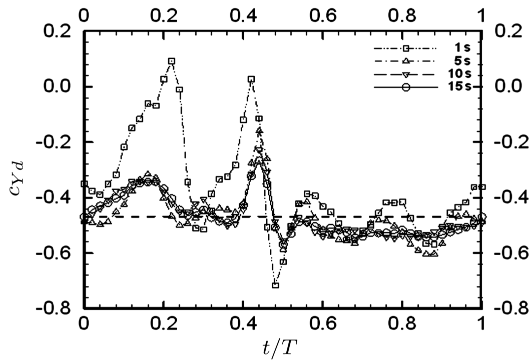
(a) $\tau = 0.2$



(b) $\tau = 0.4$↵



(b) $\tau = 0.6$



(d) $\tau = 0.8$

Figure 3: Local side force phase-locked averaged over 1 s-15 s compared with ensemble-averaged side force (dotted line)

The convergence of the phase-locked averaged local side force coefficient c_{Yd} with sampling time from 1 to 15 s at duty cycle τ = 0.2-0.8 (as Figure 3 shown). It is seen that the curve c_{Yd} versus time t almost converges to a limit at the sampling time of 15 s. The time of t/T = 0 is set, by estimation, at the beginning of the port-side plasma actuation. The corresponding ensemble averaged local side force coefficient c_{Yd} obtained from Figure 5 is shown by dotted line in the figures.

As we see, the variation of the phase-locked averaged side force with time, $c_{Yd}(t)$ for a given duty cycle is a smooth-wave curve. It is not the square-wave curve predicted by Hanff et al. 2 in their Figure 2(a) and also by Nelson et al.[9] Furthermore, the maximum and minimum values of the phase-locked averaged side force $c_{Yd}(t)$ are not the ensemble averaged side forces c_{Yd} of port-on and starboard-on.[2,9] The reason for the deviations is that the plasma duty-cycled flow is inherently unsteady, while the flows under plasma port-on and starbaord-on are practically steady.

It indicates that the smooth-wave curve of $c_{Yd}(t)$ has about five oscillations in a period of the plasma duty cycle at a given duty cycle. The oscillation is weak when the duty cycle closes the two extremes 0.1 and 0.9 and becomes strong when the duty cycle approaches 0.5. As $\tau \approx 0.1$ and 0.9, one of the two opposite plasma actuations is dominant. It is the dominant actuation to determine the flow and small flow oscillations may prevail. When τ approaches 0.5, the two opposite plasma actuations are about of equal duration and a strong cancellation occurs, which may result in the large flow oscillations. This phenomena may be related to the variation of the input power with duty cycle. The input power is maximum at $\tau = 0.1$ and 0.9, minimum at $\tau = 0.5$.

CONCLUSIONS

It is found that the magnitudes of the phase-locked-averaged local side force are much less than those produced by port and starboard actuator alone. Moreover, the variation of the phase-locked-averaged side force with time is smooth rather than abrupt as predicted by some other authors. The reason for the deviations is that the flow under duty cycle is unsteady. The linearity of the controlled lateral forces and moments with respect to the duty cycle is improved over previous studies because of the improved design of the actuators.

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