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PLASMA FLOW CONTROL OVER FOREBODY AT HIGH ANGLES OF ATTACK

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Forward blowing from a pair of plasma actuators on the leeward surface and near the apex is used to switch the asymmetric vortex pair over a cone of semi-apex angle 10° at high angles of attack. Wind tunnel pressure measurements show that by appropriate design of the actuators and appropriate choice of the AC voltage and frequency, side forces and yawing moments of opposite signs can be obtained at a given angle of attack by activating one of the plasma actuators. Further work is suggested.

Keywords: Flow dynamics; plasma; flow control; high angle of attack; asymmetric vortex; single-dielectric barrier discharge (SDBD).

1. Introduction

Symmetric separation vortices over slender bodies may become asymmetric as the angle of attack is increased beyond a certain value, causing asymmetric forces even at symmetric flight conditions. One of the first observations of vortex asymmetry onset was reported in 1951 by Allen and Perkins.[1] Interest in the phenomenon has been intensified since the late 1970s as concepts for highly maneuverable aircraft have been developed. These high-performance aircraft are expected to operate routinely at high angles of attack at which vortex asymmetry is known to occur.

High-angle-of-attack flow control is applied at the region close to the apex of the forebody. Compared with wings, control on cone is required over a much smaller area and thus physical requirements such as size and weight could be much smaller. Excellent reviews of this activity can be found in papers by Malcolm[2,3] and Williams.[4]

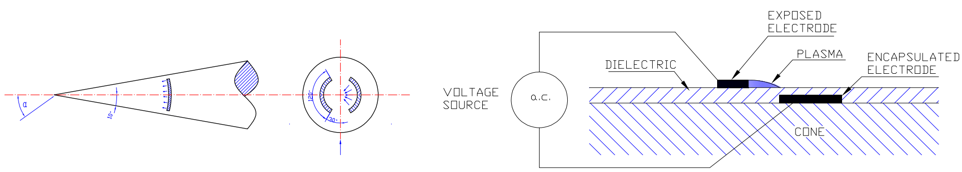
Hanff *et al.*[5] used the duty cycle modulation of the alternating flow blowing from two forward facing nozzles to control the mean lateral aerodynamic forces and moments over slender bodies. Compared with the flow blowing, flow control with electromagnetic energy addition receives significant attention since it is fully electronic with no mechanical devices so that it can have fast response for feedback control. It is highly desirable to replace the blowing nozzles in the method of Hanff *et al.*[5] with a pair of plasma actuators of single dielectric barrier discharge (SDBD).[6] The present paper is aimed at the study of a plasma flow control over a pointed slender forebody of revolution. In the following sections, the experimental setup is described and the experimental results are then presented and discussed. Finally conclusions are drawn.

2. Experimental Setup

The tests are conducted in an open-circuit low-speed wind tunnel. The test section has a 3.0 m × 1.6 m cross section. The experimental model is a circular cone of 10° semi-apex angle faired to a cylindrical after body. The cone tip is made of plastic for plasma-actuator accommodation and the rest of the model is made of metal.

The SDBD plasma actuators are designed small and compact so that they can be placed as close to the cone apex as possible and without mutual interference as shown in Fig. 1(a). The plasma actuator consists of two asymmetric copper electrodes and a thin Kapton dielectric film wraps around the cone surface and separates the encapsulated electrode from the exposed electrode as shown in Fig. 1(b). The effect of the SDBD actuator is to impart momentum to the flow in the direction from the top exposed electrode toward the encapsulated electrode,[6] in a way similar to employing suction or blowing along the cone surface but without the mass injection.

A pair of the SDBD actuators is mounted on the cone surface symmetrically. The side edges of the port-side electrodes are located at the meridian angle θ = 30° and 120°, where θ is measured from the windward meridian of the cone and the clockwise direction is set positive when looking upstream. The leading edge of the exposed electrode is located at 25 mm from the cone apex. The encapsulated electrode is located below the exposed electrode so that the effect of the plasma is to induce a flow tangential to the cone surface and in the opposite direction of the oncoming flow when the cone is at a positive angle of attack (see arrows in Fig. 1(a)). The plasma-actuator arrangement is intended to affect the position of the tip vortex near the apex of the forebody.



(a) Arrangement (b) SDBD

Fig.1. Sketches of the plasma actuators.

Three modes of operations of the actuators are defined. The plasma-off mode corresponds to the case when neither of the two actuators is activated. The port-on mode refers to the conditions when the port actuator is activated while the starboard actuator is kept off during the test. The starboard-on mode is the conditions when the starboard actuator is activated while the port actuator is kept off. The waveform of the A.C. source is sine wave. The peak-to-peak voltage and frequency are set at $V_{p-p} \approx$ 14 kV and F $\approx$ 8.9 kHz, respectively. Surface pressure measurements are chosen for the model instrumentation to maximize the information provided about the complex flow. There are 252 pressure orifices in total on the cone forebody surface which are uniformly arranged in cross-sectional from x/L = 0.340 to 0.813 on each cross section 36 orifices are evenly distributed circumferentially with a meridian angle difference of 10°.

3. Experimental Results and Discussions

Experiments were performed for the plasma-off, starboard-on, and port-on modes. In a typical bi-stable mode, the asymmetry may be towards either the starboard side or the port side, affected by slight imperfections of the cone near the apex and also free-stream conditions.[8] Taking advantage of the sensitivity of the flow to the conditions near the apex of the cone, however, we can control the vortex configuration and thus the pressure distribution asymmetry by activating one of the installed plasma actuators.

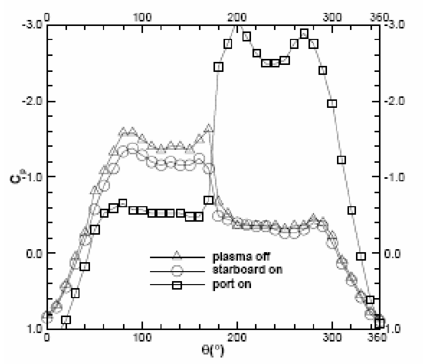


Fig. 2. Comparison of pressure distributions for the plasma off and on at α = 40, U_∞ = 5 m/s.

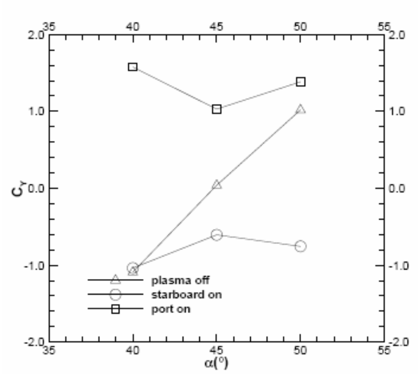


Fig. 3. Overall side force.

The plasma-off pressure distributions in Fig. 2 show a stronger suction on the port side than that on the starboard side of the cone, indicating that the port-side vortex is located closer to the cone than the starboard-side vortex.[9] The starboard-on distributions in Fig. 2 almost overlap with those of plasma-off. This is because the asymmetric perturbations produced by the starboard-side plasma actuator merely reassure the pre-existing plasma-off asymmetry of the flow. Activating the port-side plasma actuator, however, produces a desired switch of the asymmetry. The port-on pressure distributions show stronger suction on the starboard side of the cone, indicating that the starboard-side vortex has moved closer to the cone while the port-side vortex moved farther from the cone. The port plasma actuator induces a momentum input in the direction opposite to the oncoming flow direction, which presumably pushes the port-side vortex away from the cone surface and thus, brings the starboard vortex with its feeding shear-layer close by the cone. The starboard-on and the port-on overall side force shown in Fig. 3 are opposite in sign but not exactly equal in amplitude at a given angle of attack. Nevertheless, our pressure and forces data clearly demonstrate the effectiveness of the plasma actuators in controlling bi-stable vortex flow patterns.

4. Conclusion

Opposite lateral forces over a slender conical forebody at high angles of attack have been demonstrated by employing a novel design and placement of a pair of single-dielectric-barrier-discharge (SDBD) plasma actuators near the cone apex. The plasma actuators impart momentum to the flow. When properly located on the cone surface, they manipulate the relative position of the separation vortices over the forebody. It is feasible to achieve any intermediate lateral forces between the two opposite extreme values at high angles of attack by employing the present forward-blowing plasma actuators modulated with a duty-cycle technique. Further investigations should be pursued to study the detailed flow mechanism and to refine and optimize the design of the actuators.

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