AIAA JOURNAL
Vol. 46, No. 11, November 2008

Technical Notes

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Flow Control over a Conical Forebody Using Duty-Cycled Plasma Actuators

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DOI: 10.2514/1.39435

I. Introduction

INITIALLY symmetric separation vortices over slender wings and bodies become asymmetric as the angle of attack is increased beyond a certain value, causing large lateral aerodynamic loads. In addition, conventional aerodynamic control surfaces become ineffective in such situations because of vortex wakes generated by the forebody. Much theoretical, computational, and experimental work has been spent on the understanding, prediction, and control of the onset of vortex asymmetry [1–9]. It has been found both computationally and experimentally that the vortices are very sensitive to small perturbations near the apex of a forebody [3,5,9]. Although methods have been developed to delay the onset of asymmetric vortex shedding, the fact that the separation vortices generate large airloads and are very sensitive to small perturbations offers an exceptional opportunity for manipulating them with little energy input to achieve active lateral control of the vehicle in place of conventional control surfaces. Methods toward such a goal, by using various deployable mechanical devices and suction and blowing mechanisms, have been studied and reviewed by Malcolm [10,11] and Williams [12]. Most of these methods are based on steady methods in the sense that the control actuation is through a static or steady excitation.

There has been strong experimental and computational evidence [3,9,13] that the separation vortices exhibit a bistable mode of asymmetry at high angles of attack, in which the vortices assume one of two mirror-imaged asymmetric configurations. Such bistable behavior makes continuous proportional control difficult to achieve with a conventional steady type of actuation. Bernhardt and Williams [14] used unsteady blowing near the forebody apex and demonstrated the possibility of switching the flow from one of its asymmetric bistable modes to the other for one angle of attack, but was short of achieving proportional control for conditions in which the bistable modes dominated, because the blowing was done either on the port or starboard side only. Realizing that the flow may respond continuously to dynamic alternating excitations, Hanff et al. [15] alternated blowing from two forward facing nozzles near the apex of their test model to deliberately switch the vortices between their two bistable configurations with given duty cycles and at fast enough frequencies. Ming and Gu [16], however, used a miniature swinging strake mounted at the apex of their ogive cylinder model. A steady-type control would set the angle of the strake at a fixed input value and expect the flow to respond continuously to different input angles. Tests, however, showed otherwise because of the bistable nature of the vortex configurations. Ming and Gu then oscillated the strake around preset mean angles. They discovered that, if the frequency and amplitude of the oscillation are tuned appropriately, the flow would respond continuously to the mean angle settings. By using such ingenious unsteady dynamic controls, both groups succeeded in demonstrating the feasibility of proportional control on the side forces over slender ogive forebodies.

In recent years, flow control with electromagnetic energy addition has received growing attention because of the advantages of not having mechanical parts, while at the same time having broader frequency bandwidths. One such development is the use of single dielectric barrier discharge (SDBD) plasma actuators. The effect of the SDBD actuator is to impart momentum to the flow, much like flow suction or blowing but without the mass injection. Post and Corke [17,18] successfully demonstrated their use in the control of separation over stationary and oscillating airfoils. Huang et al. [19,20] also used them to control separation over turbine blades. A review is provided by Corke and Post [21].

In this work, we replace the blowing nozzles in the method of Hanff et al. [15] by a pair of SDBD plasma actuators. We report 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 SDBD plasma actuators near the cone apex combined with a duty-cycle technique. This work proves the feasibility of using low-power plasma actuators to not only avoid the unpredictable onset of asymmetric aerodynamic loads but also provide the highly needed lateral control of slender forebodies at high angles of attack.

II. Experimental Setup

Because the nose of any pointed forebody is locally conical in shape, the flow may be regarded as locally equivalent to that about a tangent cone. For this reason, an experimental model of a circular cone with a 10 deg semi-apex angle faired to a cylindrical afterbody is tested.

The model consists of two separate pieces. The frontal portion of the cone is made of plastic and has a length of 150 mm. The rest of the model is made of metal. The total length of the cone is 463.8 mm with a base diameter of 163.6 mm. Two long strips of SDBD plasma actuators are installed on the plastic frontal cone near the apex, as shown in Fig. 1a. The frontal piece of the cone is interchangeable so that cones with different designs of the plasma actuators can be tested. Care is taken in manufacturing and mounting of the frontal

Received 28 June 2008; accepted for publication 11 August 2008.

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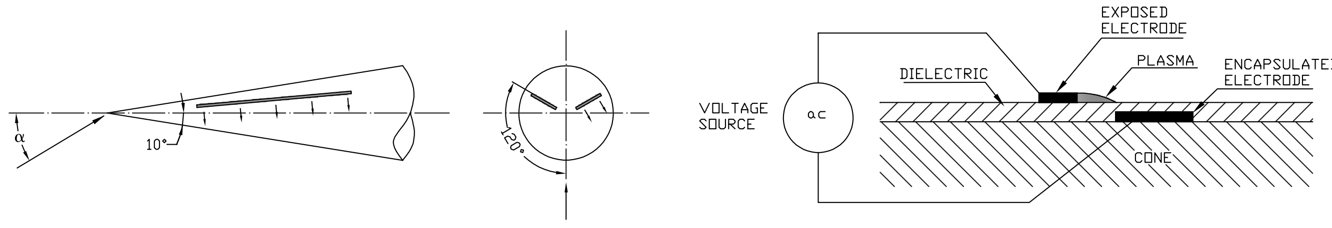


a) Arrangement **b) SDBD**

Fig. 1 Sketches of the plasma actuators.

cone to the rear portion of the model to make sure they are well aligned.

Relatively small SDBD plasma actuators are made so that they can be placed as close to the cone apex as possible. The plasma actuator consists of two asymmetric copper electrodes, each of 0.03 mm thickness. A thin Kapton dielectric film wraps around the cone surface and separates the encapsulated electrode from the exposed electrode, as shown in Fig. 1b. The length of the electrodes is 20 mm along the cone meridian with the leading edge located at 9 mm from the cone apex. The width of the exposed and encapsulated electrode is 1 and 2 mm, respectively. The two electrodes are separated by a gap of 1.5 mm, where the plasma is created and emits a blue glow in darkness. 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 [21], in a way similar to employing suction or blowing along the cone surface but without the mass injection. For our particular actuators, the gap between the electrodes was optimized for maximum induced airflow based on experiments conducted in still air outside the wind tunnel.

A pair of the SDBD actuators are mounted on the cone surface symmetrically. Three different designs of the actuators and mounting schemes have been tested. The one shown in Fig. 1 is found to be the most effective. In this scheme, the right edge of the exposed electrode shown in Fig. 1b is aligned with the cone at the azimuth angle $\theta = \pm 120$ deg, where θ is measured from the windward meridian of the cone and positive is clockwise when looking upstream (Fig. 1a). 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). The plasma actuator arrangement is intended to affect the boundary-layer separation position from the downstream side of the separation line.

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 plasma-on mode refers to the conditions when either the port or starboard actuator is activated while the other is kept off during the test. These are called the port-on and starboard-on modes, respectively. Each of the two actuators on the cone model is separately driven by an ac voltage source (model CTP-2000K by Nanjing Suman Co.). The waveform of the ac source is a 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. The measured power consumption is approximately 19.3 W. The third mode employs a duty-cycle technique in which the two actuators on the cone are activated alternately with a specified duty cycle τ, defined as the fraction of time when the starboard actuator is on over a duty-cycle period. The fraction of time that the port actuator is on is then $1 - \tau$. The duty cycles are achieved by modulating the carrier ac voltage sources by a digital pulse wave generator at a frequency of 10 Hz. The nondimensional duty-cycle frequency based on the cone base diameter is about two.

The tests are conducted in an open-circuit, low-speed wind tunnel at the Aerodynamic Design and Research National Laboratory, Northwestern Polytechnical University. The test section has a 3.0×1.6 m cross section. The model is rigidly mounted on the support in the test section, as shown in Fig. 2. The model is carefully cleaned before each run of the wind tunnel.

Fig. 2 Model in the wind tunnel.

Surface pressure measurements are instrumented at seven axial stations uniformly distributed from $x/L = 0.340$ to 0.813 on the cone forebody. At each of the seven axial stations, 36 pressure taps are uniformly distributed with an interval of 10 deg azimuthal angle around the circumference of the cone. Static pressures are read from PSI 9816 and 8400 transducers at 64 and 127 times per second, respectively. The computer system was set up to output 1 and 5 s averages. A comparison of the measurements reveal that there are no differences in the 1 and 5 s average pressures in our experiments. We will present the 5 s average data next. Among the total 252 pressure taps, fewer than 10 were found to give abnormal pressure readings, which were removed and replaced by linearly interpolated values from neighboring normal readings in the data processing phase.

III. Experimental Results and Discussions

The freestream velocity is set at $U_\infty = 5$ m/s in the present study. The corresponding Reynolds number based on the cone base diameter is 5×10^4. Side forces and the yawing moments acting on the cone forebody are calculated from the measured pressures and normalized by the area and diameter of the cone base. The side-force coefficient C_Y is positive when pointing to the starboard side of the cone. The yawing-moment coefficient C_n is taken about the cone base and positive when yawing starboard.

A. Base Plasma-Off Flow at Zero Angle of Attack

To check the symmetry of the cone and model alignment in the wind tunnel, a test is run at zero angle of attack and with plasma off. Aside from some slight irregularities, the measured pressure distributions (not shown here for brevity) indicate essentially an axisymmetric flow around the cone. In the present study, the plasma actuators are made by hand and then attached to the cone tip surface with glue. The dielectric film wraps around the entire circumference. No allowance is made on the cone surface for the attachment, which could have been the cause for the mentioned irregularities of the pressure distributions. Nevertheless, the disturbances were tolerably small.

B. Comparison of Plasma-Off and Plasma-On Results

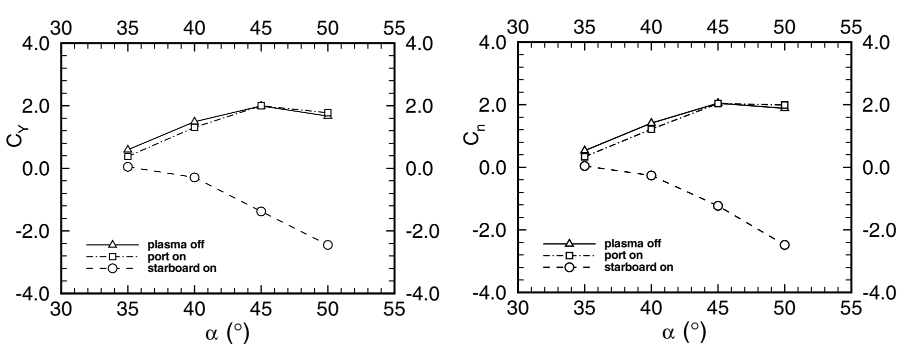
Experiments were performed for the plasma-off, starboard-on, and port-on modes. Figure 3 compares the measured side force and yawing moment in the angle-of-attack range $\alpha = 35$–50 deg. As the angle of attack is increased, the plasma-off asymmetric forces and moments increase, signifying increased asymmetry of the separation vortices with increasing angle of attack. In this case, the starboard vortex is closer to the cone surface than the port-side vortex. The surface pressure distributions shown in Fig. 4 for $\alpha = 45$ deg confirm the stronger suction on the starboard side than that on the port side of the cone by the separation vortices.

In a typical bistable mode, the asymmetry may be either toward the starboard side or the port side, affected by slight imperfections of the cone near the apex and also freestream conditions. In our experiment, the imperfections of the model with the plasma actuators, and possibly conditions of the wind tunnel, have forced an asymmetry resulting in positive side forces and moments. By taking advantage of the sensitivity of the flow on the conditions near the apex of the cone, however, we can control the vortex configuration and thus the side force and moment by activating one of the installed plasma actuators. The port-on results shown in Figs. 3 and 4 almost overlap with those of the plasma-off results. This is because the asymmetric perturbations produced by the port-side plasma actuator merely reassure the preexisting plasma-off asymmetry of the flow. Activating the starboard plasma actuator, however, produces a desired switch of the asymmetry. Both forces and moments change signs. The asymmetric surface pressure distributions, shown in Fig. 4 for the case of 45 deg angle of attack, switch sides. The starboard-on pressure distributions show stronger suction on the port side of the cone, indicating that the port-side vortex has moved closer to the cone while the starboard vortex moved farther from the cone. The starboard plasma actuator induces a momentum input in the direction opposite to the oncoming flow direction, which pushes the boundary-layer separation line to move in the upstream direction and thus sends the starboard vortex with its feeding shear-layer away from the cone surface. This causes a switch of positions of the two vortices from one of their bistable asymmetric modes to the other, resulting in the switch of the suction peaks over the body, as shown in Fig. 4. This flow control mechanism is evident in the present study from the pressure measurements. In the preceding analysis, use is made of the work by Hall [22], who established a relation between the vortex flow and the surface pressure distribution on slender bodies by comparing flow visualization and surface pressure measurements in the literature. Future research is planned to conduct measurement of the velocity field by laser particle image velocimetry to reveal the detailed flowfield and provide benchmark data for computational fluid dynamics (CFD) models for the plasma actuators.

The starboard-on and the port-on forces and moments shown in Fig. 3 are opposite in sign but not exactly equal in amplitude at a given angle of attack. Among other factors, the imperfections of the model, particularly those due to the installment of the plasma actuators mentioned earlier, are believed to have prevented the results from following the presumed exact bistable behavior. Nevertheless, our pressure and force data clearly demonstrate the effectiveness of the plasma actuators in controlling bistable vortex flow patterns.

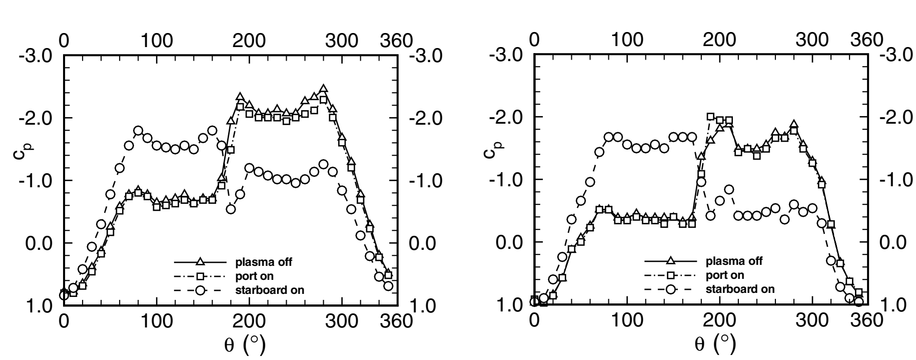
C. Control Through Plasma Duty Cycles

Inspired by the work of Hanff et al. [15] and Ming and Gu [16], we employ the use of plasma actuators by switching on and off the starboard and port plasma actuators with specified duty cycle τ at an appropriate duty-cycle frequency. The $\tau = 0$ and $\tau = 1$ cases correspond to the steady port-on and starboard-on cases, respectively, which produce the two extreme opposite flow conditions discussed in the preceding subsection. It is desired that a linear proportional control of the flow between the two extreme conditions can be achieved by varying the duty cycle from $\tau = 0$ to $\tau = 1$. Figure 5 presents the measured side force and yawing moment as τ is increased from 0 to 100% for four representative angles of



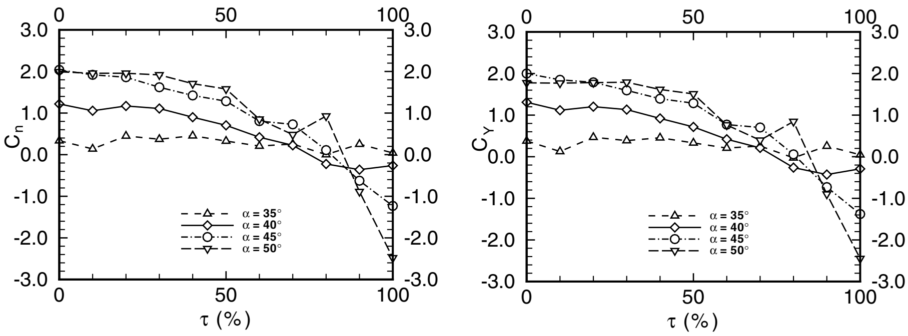
a) Side-force coefficient
b) Yawing-moment coefficient

Fig. 3 Side forces and yawing moments vs angle of attack for plasma-on and -off conditions.



a) Station 1
b) Station 7

Fig. 4 Comparison of pressure distributions for the plasma-off and -on conditions at $\alpha = 45$ deg.



a) Side-force coefficient

b) Yawing-moment coefficient

Fig. 5 Side-force and yawing moment on the cone produced by duty-cycled plasma control.

attack. Although the measurements do not show strictly linear proportional control, they clearly demonstrate the ability of achieving any intermediate values of the forces and moments between the two opposite bistable conditions by continuously varying the value of τ. The deviation from a strict linear proportional control in the presented data may be traced to the imperfections of the model caused by the installation of plasma actuators discussed in the previous subsections.

The vortex flow control mechanism, as discussed in Sec. III.B, coupled with the innovative variable duty-cycle technique is thus shown for the first time to provide complete control on the mean positions of the vortices. This opens up exciting future research opportunities for both computational and experimental efforts to detail the dynamics of the motion of the vortices and optimize the design and placement of the plasma actuators and the input voltage, amplitude, and waveform of the power sources.

IV. Conclusions

Nearly linear proportional control of lateral forces and moments over a slender conical forebody at high angles of attack has been demonstrated by employing a novel design and placement of a pair of single-dielectric-barrier-discharge plasma actuators near the cone apex combined with a duty-cycle technique. The plasma actuators impart momentum to the flow. When properly located on the cone surface, they change the separation location of the flow on the cone and thus manipulate the relative position of the separation vortices over the forebody. By taking advantage of the dynamic response of the vortex patterns to the starboard and port actuators, we are able to achieve any intermediate lateral forces and moments between the two opposite asymmetric configurations of the vortices by alternately switching on the starboard and port actuators with an appropriate duty cycle at an appropriate frequency. This work demonstrates for the first time the feasibility of using plasma actuators to not only avoid the unpredictable onset of asymmetric aerodynamic loads, but also to provide the highly needed lateral control on slender forebodies at high angles of attack. Further investigations should be pursued to study the detailed flow mechanism and to refine and optimize the design of the actuators.

Acknowledgment

The present work is supported by the Foundation for Fundamental Research of the Northwestern Polytechnical University, NPU-FFR-W018101.

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