PIV Study of Conical Forebody Flow Control Using Plasma Actuators

Jianlei Wang¹, Huaxing Li², Xianshi Meng³,
(1. National Key Laboratory of Science and Technology on Aerodynamic Design and Research, Northwestern Polytechnical University, Xi’an 710072, China)

Feng Liu⁴, Shijun Luo⁵
(2. The Department of Mechanical and Aerospace Engineering, University of California, CA 92697-3975, America)

Duty cycle modulation of the alternate blowing from two opposite facing plasma actuators on the leeward surface near the apex of a cone having semi-apex angle of 10° to control the mean lateral force, moment and the flow control mechanisms are presented. The pressure distributions over the cone forebody are measured using steady pressure-tappings. The flowfields are visualized by a two-dimensional particle image velocimetry (PIV). The experiments are performed at 5m/s wind speed with Reynolds number 40,000 based on the cone base diameter. The opposite bi-stable vortex patterns appear when the port or starboard actuator is activated while the other is kept off during the test. The phase-locked (locked to the plasma duty cycle) averaged vortex cores controlled by the duty-cycled plasma actuation are periodic and vary around the position of the ensemble averaged vortex cores.

Nomenclature

\[ C_p = \text{pressure coefficient} \]
\[ C_{vd} = \text{time-averaged local side-force coefficient, local side force}/q_{\infty}d \]
\[ D = \text{base diameter of circular cone forebody} \]
\[ d = \text{local diameter of circular cone forebody} \]
\[ F = \text{frequency of AC voltage source} \]
\[ f = \text{frequency of duty cycle} \]
\[ L = \text{length of circular cone forebody} \]
\[ q_{\infty} = \text{free-stream dynamic pressure} \]
\[ Re = \text{free-stream Reynolds number based on D, } U_{\infty}D/\nu \]
\[ S = \text{base area of circular cone forebody} \]
\[ T = \text{period of duty cycle} \]

¹ PHD Student, Department of Fluid Mechanics.
² Professor, Department of Fluid Mechanics.
³ Post Doctor, Department of Fluid Mechanics.
⁴ Professor, Department of Mechanical and Aerospace Engineering. Associate Fellow AIAA.
⁵ Researcher, Department of Mechanical and Aerospace Engineering.
\( t \) = time of duty cycle
\( U_\infty \) = free-stream velocity
\( V_{p-p} \) = amplitude of oscillation
\( x, y, z \) = body coordinates, \( x \) toward base, \( y \) toward starboard, right-hand system
\( \alpha \) = angle of attack
\( \theta \) = meridian angle measured from windward generator, positive when clockwise
\( \tau \) = fraction of time when starboard actuator is on over a duty-cycle period
\( \psi \) = phase angle of duty cycle
\( \Omega \) = reduced angular frequency of duty-cycle, \( 2\pi f_D/U_\infty \)

I. Introduction

Proportional lateral control on slender forebodies at high angles of attack is highly needed in aerodynamic design of air vehicles. The fact that the separation vortices over pointed forebodies generate large airload 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 vehicle in place of conventional control surfaces. It has been found experimentally that unsteady dynamic control techniques are needed to achieve this goal.\(^1\)\(^-\)\(^3\)

Recently, Liu et al.\(^4\) 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.

Various methods have been used to study vortex flowfield over bodies. Hall\(^5\) found the location of boundary layer separation observed by Keener’s oil flow\(^6\) coincides well with the end of the pressure recovery in Lamont’s pressure data\(^7\) for 3.5 ogive nose tested under nearly same conditions. The primary flow features can be inferred from pressure data with orifices every 10° around the circumference of the body. Bernhardt and Williams\(^1\) used smoke-strobe light to show the side views of forebody vortices and smoke-laser sheet to present an axial view of the forebody wake in proportional control of asymmetric forebody vortices. 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\(^8\) used ensemble averaged and phase-locked averaged particle image velocity and vorticity field to reveal detailed flow mechanisms for cylinder flow control under steady and unsteady plasma actuations.

In this work, we investigate the flow mechanisms under the plasma actuations of Ref.\(^4\). Three modes of operations of the actuators are considered. The plasma-off mode corresponds to the case when neither of the two actuators is activated. The port-on or starboard-on mode refers to the conditions when either the port or starboard actuator is activated while the other is kept off during the test, respectively. The third mode is the duty-cycled plasma actuation in which the two actuators on the cone is activated alternately with a specified duty cycle. For the first two modes, the flow can be considered as steady. For the mode of plasma duty cycle the flow is unsteady. For steady flow only ensemble averages are studied. For unsteady flow, in addition to ensemble averages, the phase-locked to duty cycle averages are examined. We employed steady and unsteady pressure tappings and particle image velocimetry (PIV) technique to study the flows over the cone forebody.\(^4\) In the following sections, the experimental setup is described. The experimental results on the flows of plasma-off,
port-on, starboard-on and the plasma duty cycle are presented and discussed. Finally conclusions are drawn.

II. Experimental Setup

The flow-control experiments are performed in a 0.5m×0.6m×0.6m direct-circuit open test section wind tunnel at Northwestern Polytechnical University. The cone-cylinder model is tested at $\alpha = 45^\circ$. The free stream velocity is $U_\infty = 5m/s$ with a Reynolds number 40,000 based on the cone base diameter.

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, a combination of a circular cone with a 10 deg semi-apex angle and a fairing segment is tested. The whole model is made of plastic. The total length of the cone is 331.3 mm with a base diameter of 116.9 mm.

![Figure 1. The model and pressure tappings arrangements sketch](image1)

The time-averaged pressure tappings are arranged in 10° increments around the azimuth of the cone at one station at a distance 167.5mm from the tip of the cone (figure 1). These pressure taps around the circumference of the measured station are used to detect changes in the configuration of the vortices. The model of pressure taps is 9816 by the PSI Company with an accuracy of up to ±0.05% FS, which are read at frequency of 100 Hz. The local side forces are calculated from the measured pressures. The sectional side-force coefficient $C_{y_d}$ is normalized with the local diameter $d$ and is positive when pointing to the starboard side of the cone. The model is carefully cleaned prior to each run of the wind tunnel.

In addition to pressure measurements, two-dimensional PIV was performed, the laser sheet coincides with the cross section of pressure measured station in order to make a comparison of the results obtained by the two different measurement technique. The PIV measurement plane was normal to the axis of the model. Measurements were made with one Nd:YAG 200-mJ lasers. A CCD camera of
1200×1600 pixel is used to record the cross-flow image which has height and width 112 mm × 84 mm. The repeat rate of the laser double-pulse is set at 13 Hz and consecutive 10 seconds of sampling are performed for each case. The camera is located upstream of the laser plane in the incidence plane of the model (Fig. 2). The flow seeds are smoke particles of approximately 1 μm in diameter commonly used in cinema industry, mixed with atmosphere air and sucked into the test section of the open-circuit wind tunnel through the entrance.

A pair of long strips of SDBD plasma-actuators is placed symmetrically on the plastic frontal cone near the apex as shown in Fig. 3(a). The plasma actuator consists of two pieces of copper electrodes. A thin Kapton dielectric film wraps around the cone surface and separates the covered electrode from the exposed electrode as shown in Fig. 3(b). The length of the electrodes is 100 mm along the cone meridian with the leading edge located at 15 mm from the cone apex. The width of the exposed and covered electrode is 2 mm and 10 mm, respectively. There is no gap or overlap between the exposed and covered electrode.

The actuators are each connected to a high voltage ac source respectively. The ac sources provide about 14 kV peak-to-peak voltage sinusoidal excitation at a frequency of 9 kHz.

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. 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−τ. The duty cycles are achieved by modulating the carrier AC voltage sources by a digital pulse wave generator. The duty cycle frequency is set in 35Hz.

The right edge of the exposed electrode shown in Fig. 3(b) is aligned with the cone at the azimuth angle θ = ±120° which are near the separation lines, where θ is measured from the windward meridian of the cone and the positive is clockwise when looking upstream (Fig. 3a). The direction of the induced flow produced by actuators is downstream. The design idea for the position and the induced flow direction is intended to affect the boundary-layer separation positions via a plasma-induced Coanda effect. The actuators are hand-made and attached directly to the cone surface with no allowance.
III. Experimental Results and discussion

A. Flow of Plasma-Off, Port-on and Starboard-On, Ensemble-Averaged Results

The flows for plasma-off, port-on and starboard-on are all steady flows. Ensemble-averaged pressures and flow filed measured from steady tappings and PIV separately are considered in this section.

Figure 4 compares the ensemble-averaged pressure distributions for plasma-off, port-on and starboard-on at $\alpha=45^\circ$, $U_{\infty}=5\text{m/s}$ The pressure distributions for plasma-off and starboard-on coincidentally coincide. They are nearly anti-symmetric to that for port-on with respect to the line $\theta=180^\circ$. It is noted that in the tests of Ref. 4 the present model for plasma-off experienced a side force closed to that for port-on. In fact, the force asymmetry for a slender body of revolution at high angle of attack depends on the small asymmetric disturbances in the flow, including the micro surface imperfections on the tip on the body.

Figure 5 shows the PIV results correspond to the pressure distributions modes. When plasma is off, as shown in Fig. 5(a) the port-side shear layer is curved around the body circumference and rolled into a vortex core located close to the body surface and near the incidence plane, and the starboard-side shear layer is outboard and rolled into a vortex core located away from the body. The pressure suction peak on the port side is higher than that on the starboard side, and the local side force is negative. The same is true for port-on and starboard-on as shown in Fig. 5 (b) and (c).

B. Flow of Plasma Duty Cycle, Ensemble-Averaged Results

The plasma duty cycle frequency is $f=35\text{Hz}$. The period of the duty cycle is $T=1/35\text{s}$. For $\tau=0.2$, the time proportion for port and starboard plasma actuation in the period is 20% and 80%, respectively. Figure 6 and 7 present the variations of ensemble averaged pressure distribution local side force coefficient $C_{vl}$ versus $\tau$, respectively at $\alpha=45^\circ$, $U_{\infty}=5\text{m/s}$. It is seen that the variation of $C_{vl}$ with $\tau$ is almost linear. Figure 8 presents the ensemble-averaged cross-flow velocity vectors and axial vorticity contours of plasma duty cycle control. The PIV results correspond to the pressure distributions and local side force results. When $\tau=0.1$ the starboard side vortex core located close to the body surface and the port side vortex core located away from the body. The pressure suction peak on the starboard side is higher than that on the port side. With the $\tau$ increasing the starboard side vortex core is removed from the body surface gradually while the port side vortex core become loose to the body surface.
suction peak on the starboard side moves to the port side gradually with the $\tau$ increasing as shown in Figure. 7.

Figure 5. Comparison of ensemble-averaged PIV results for plasma-off, port-on and starboard-on, $\alpha=45^\circ$, $U_\infty=5$ m/s.

Figure 6. Variations of ensemble-averaged Pressures distribution at $\alpha=45^\circ$. 
Figure 7. Variations of ensemble-averaged local side force produced, \( \alpha=45^\circ \), \( U_\infty=5 \text{ m/s} \).

a) \( \tau=01\% \)  
b) \( \tau=20\% \)  
c) \( \tau=40\% \)  
d) \( \tau=50\% \)  
e) \( \tau=60\% \)  
f) \( \tau=80\% \)  
g) \( \tau=99\% \)  

Figure 8. Ensemble-averaged cross-flow velocity vectors and axial vorticity contours of plasma duty cycle control, \( \alpha=45^\circ \), \( U_\infty=5 \text{ m/s} \).
C. Flow of Plasma Duty Cycle, Phase-Locked-Averaged Results

Phase-locked-averaged method is a kind of method to measure a periodic variation flow filed. When we survey a periodic variation flow filed with equipment which could not adjusted to synchronous with the variation of the flow filed.

If the period of the flow filed is $\lambda_1$, and the period of the collection device is $\lambda_2$. And we make the time stamp which the collection device lunched first time as 0. Then the time stamp when the collection device lunched n times is $n \lambda_2$. For the period flow filed this time stamp is at the phase angle $n \lambda_2 \%\lambda_1 \times \frac{2\pi}{\lambda_1}$.

For this test the phase-locked-averaged vortex core positions are investigated to reveal the plasma-duty-cycled flow mechanisms over the conical forebody at high angles of attack. The PIV sampling has a rate of 13Hz($\lambda_2$) and is taken consecutively for 10s in the tests. The frequency of duty cycle is 35Hz($\lambda_1$). In one period of the plasma duty cycle there are 13 readings evenly distributed at phase-angle increment of $2\pi/13$. At a given phase angle there are 10 samples to be averaged in 10 seconds.

At a given $\tau$ the vortex cores keep swaying in a restricted range around a center where the ensemble average vortex core is. The ranges which the vortex cores sway in become larger while the $\tau$ is close to 0.5 and smaller while the $\tau$ is close to 1 or 0. Figure 9 presents the vortex center trajectory of port side vortex. The circle depicts the location of the ensemble average vortex core. Figure 10 presents the PIV results of the flow filed at $\tau=0.5$, vortex core sway can be read in the figure.
Figure 9. Vortex Center Trajectory, $\alpha=45^\circ$, $U_\infty=5\text{m/s}$, port side vortex.

- a) $\psi=0$
- b) $\psi=2\pi/13$
- c) $\psi=4\pi/13$
- d) $\psi=6\pi/13$
- e) $\psi=8\pi/13$
- f) $\psi=10\pi/13$
- g) $\tau=60\%$
- h) $\tau=70\%$
- i) $\tau=80\%$
- j) $\tau=90\%$
- k) $\tau=99\%$
A novel design and placement of a pair of plasma actuators on the forebody tip combined with the duty cycle technique provide proportional lateral control of a slender conical forebody at 45° angles of attack and low speed has been demonstrated. The flow mechanisms are studied by steady pressure tappings and a two-dimensional particle image velocimetry with phase-locked-averaged method.

Cross flow velocity-vectors and vorticity-contours over the forebody clearly reveal that a wash flow toward port/starboard over the forebody lee surface appears when port-/starboard-actuator is activated, respectively. The wash flow direction is correlated to the shift of the boundary-layer separation point. When the actuator on one side is activated, the separation point on the unactivated side shifts downstream, which, on the unactivated side, causes the vortex core to move closing-in, raises the suction peak, and, thus, produces a side force pointing to the unactivated side.

**IV. Conclusions**

Figure 10. Phase Locked Averaged PIV, α=45° U∞=5 m/s τ=0.5.
Under duty cycle of frequency 35Hz, it is found that the ensemble-averaged local side force measured in the experiments varies linearly with the ratio of duty cycle ratio. It is expected that the ensemble-averaged overall side force and yawing moment vary linearly with duty cycle ratio based on that the fact that the pressure distribution over the conical forebody is conical as shown in the Reference11.

For the phase-locked averaged flow filed obtained by PIV, it is found for the first time, that the vortex core’s position of the phase-locked-averaged vibrates around the position where the ensemble-averaged vortex core is located. The range with which the vortex core vibrates in is becomes larger when the $\tau$ is close to 0.5 and become smaller while the $\tau$ closes to 0 or 1.

Acknowledgments

The present work is supported by the Doctorate Foundation of Northwestern Polytechnical University (CX201001) and the Specialized Research Fund for the Doctoral Program of Higher Education (20096102120001). The authors would like to express their gratitude to Bin Tian, Shuai Zhao in Northwestern Polytechnical University for their valuable technical guidance and support in the wind-tunnel tests.

References

5Hall, R.M., “Influence of Reynolds number on forebody side forces for 3.5-diameter tangent-ogive bodies,” AIAA-87-2274, Jun. 1987