Optimal DBD Duty-Cycle for Conical Forebody Side-Force Proportional Control

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An optimization of the single-dielectric-barrier-discharge plasma actuators with duty-cycle manipulation presented by Feng Liu, et al. in AIAA Journal, Vol. 46, No.11, 2008 for proportional control of lateral force over a slender circular conical forebody at high angles of attack is studied. A novel design and placement of the pair of plasma actuators near the cone apex are found such that the flow induced by port actuation is more anti-symmetric to that induced by starboard actuation with respect to the forebody symmetric plane. The duty-cycle frequency is determined experimentally to provide more linear proportional side force variation with respect to duty ratio of the port and starboard actuations. The flow mechanisms of various plasma actuations are analyzed with measured results of time-averaged pressure tapings and time-accurate PIV over a typical forebody station. The experiments are performed in a smoke wind tunnel of 0.5m×0.6m at angle of attack of 45 deg and 5m/s wind speed with Reynolds number 40,000 based on the cone base diameter. The test frequency of the duty cycle ranges from 1 Hz to 100 Hz.

Nomenclature

- $C_p = $ pressure coefficient
- $C_{Yd} = $ time-averaged local side-force coefficient, local side force/$q_\infty d$
- $C_{Nd} = $ time-averaged local normal-force coefficient, local normal force/$q_\infty d$
- $D = $ base diameter of circular cone forebody
- $d = $ local diameter of circular cone forebody
- $F = $ wave-frequency of AC voltage source
- $f^+ = $ reduced frequency of actuator duty cycle (Strouhal number), $2\pi f D/U_\infty$
- $f = $ plasma duty-cycle actuation frequency
- $L = $ length of circular cone forebody
- $q_\infty = $ free-stream dynamic pressure
- $Re = $ free-stream Reynolds number based on $D$, $U_\infty D/\nu$
- $S = $ base area of circular cone forebody
- $T = $ period of duty cycle
- $t = $ time of duty cycle
- $U_\infty = $ free-stream velocity
- $V_{p-p} = $ peak-to-peak voltage of a.c. voltage source
- $x, y, z = $ body coordinates, $x$ toward base, $y$ toward starboard, right-hand system

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Both computational and experimental research show that the vortices are very sensitive to small perturbations near the apex of a forebody. 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 and Williams. Most of these methods are based on steady methods in the sense that the control actuation is through a static or steady excitation.

The separation vortices exhibit a bi-stable mode of asymmetry, in which the vortices assume one of two mirror-imaged asymmetric configurations at high angles of attack. Such bi-stable behavior makes continuous proportional control difficult to achieve with a conventional steady type of actuation. Bernhardt and Williams used unsteady blowing near the forebody apex of an ogive-cylinder model and demonstrated the possibility of switching the flow from one of its asymmetric bi-stable modes to the other at 45° and 558° of angle of attack. The proportional control has not achieved 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. 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 used a miniature swinging strake mounted at the apex of their ogive cylinder model. They discovered that the flow would respond continuously to the mean angle settings if the frequency and amplitude of the oscillation of the strake are tuned appropriately. 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.

Plasma active flow control has received growing attention in recent years because of the advantages of not having mechanical parts, zero reaction time, higher frequency bandwidths and relatively low energy consumption. What is most important, the plasma actuators can be arranged conveniently on the parts surface of the vehicle. Many researchers choose the single dielectric barrier discharge (SDBD) as the plasma actuation type. 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 successfully demonstrated their use in the control of separation over stationary and oscillating airfoils. Huang et al. also used them to control separation over turbine blades. A review is provided by Corke and Post. Takashi Matsuno et al. used a pair of plasma actuators which located at the ±120° from the leeward meridian near the nose of a tangent ogive nose/cylindrical model to manipulate the forebody vortices. The experiments have confirmed that the plasma actuator can be used to displace the vortex on the forebody model by the Coanda effect.

It has been shown in the literature that the introduction of periodic disturbances near the separation location can prevent or delay the onset of separation. M. P. Patel et al. shown that by using unsteady excitations, plasma actuators are highly effective in controlling flow separation and delaying wing stall and the actuator power requirements can be significantly reduced. They predicted a optimized reduced frequency for airfoil \( f = f L_{sep}/U_\infty = 1 \), where \( f \) is the unsteady actuator forcing frequency, \( L_{sep} \) is the streamwise extent of flow separation which in case of a full leading-edge separation is the airfoil chord length, \( c \), and \( U_\infty \) is the freestream velocity. Many researchers found this criterion played a role for plasma flow control on different test models (as listed in table 1).

Recently, Liu et al. 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. The main objective of the following research is to find the optimized reduced frequency to get a rigid linear proportional control of lateral forces on the cone forebody.

In this paper an investigation on flow control of slender conical forebody by using SDBD plasma actuator is performed. A parametric study on proportional lateral force control is conducted for a wide range of reduced frequency values. A pressure measurements technique and a 2D PIV technique are used in presented test. After an

\[ \alpha = \text{angle of attack} \]
\[ \theta = \text{meridian angle measured clockwise from windward generator at positive } \alpha \text{ and looking upstream} \]
\[ \tau = \text{fraction of time when starboard actuator is on over a duty-cycle period} \]
\[ \omega_c = \text{axial vorticity in } x \text{ direction} \]
\[ \psi = \text{phase angle of duty cycle, } 2\pi n/13, n = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12. \]
introduction of the study on a slender conical forebody, a description of the experimental setup is given which is followed by a discussion on the results. Finally some conclusions are presented.

Table 1. Brief Introductions of Some Forebody Vortex Control Experiments

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Model/Characteristic</th>
<th>Flow control technique</th>
<th>Reynolds number</th>
<th>Optimized reduced frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seifert A. et al\textsuperscript{17}.</td>
<td>Airfoil/flap chord</td>
<td>Unsteady blowing</td>
<td>$1.0 \times 10^5$-$1.0 \times 10^6$</td>
<td>$f_{c_{flap}}/U_\infty &lt;1.0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1.0-3.0$</td>
</tr>
<tr>
<td>Corke, T. et al\textsuperscript{16}.</td>
<td>Airfoil/chord</td>
<td>Plasma actuation</td>
<td>$0.2 \times 10^6$-$0.3 \times 10^6$</td>
<td>$f_{c}/U_\infty \approx 1.0$</td>
</tr>
<tr>
<td>P. F. Zhang al\textsuperscript{19}.</td>
<td>Delta wing/chord</td>
<td>Plasma actuation</td>
<td>$2.8 \times 10^5$</td>
<td>$f_{c}/U_\infty \approx 1.0$</td>
</tr>
<tr>
<td>D. Greenblatt et al\textsuperscript{20}.</td>
<td>Delta wing +Gurney flaps/ chord of flaps</td>
<td>Plasma actuation</td>
<td>$2.0 \times 10^4$-$7.5 \times 10^4$</td>
<td>$f_{c}/U_\infty \approx 1.0$</td>
</tr>
<tr>
<td>F. O. Thomas at al\textsuperscript{21}.</td>
<td>Circular cylinder/Cylinder diameter</td>
<td>Plasma actuation</td>
<td>$3.3 \times 10^5$</td>
<td>$fD/U_\infty =1.0$</td>
</tr>
</tbody>
</table>

II. Experimental Setup

A. Smoke Wind-Tunnel

The flow-control experiments are performed in a height $\times$ width $\times$ length $=0.5m \times 0.6m \times 0.6m$ 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 $U_\infty = 5$ m/s with a Reynolds number 40,000 based on the cone base diameter.

In the smoke wind tunnel sketch, the item 6 smoke generator is used to generate discrete smoke lines in the test section inside item 8 plenum chamber. For PIV test, uniformly distributed smoke particles are required in the test section. A smoke generator is set in front of item 1 inlet. A concentration of smoke beam passes through item 1-7 and becomes well-distributed in the test section.

![Wind tunnel sketch](image)

Figure 1. Wind tunnel sketch
B. Forebody Model Configuration

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.

![CIRCULAR CONE FAIRING SEGMENT](image)

**Figure 2. The model and static pressure tappings arrangements sketch**

The time-averaged pressure tappings are arranged in 10° increments around the azimuth of the cone at station x/L=0.5 (figure 1). These pressure taps around the circumference of the measured station is used to detect changes in the configuration of the vortices. The model is carefully cleaned prior to each run of the wind tunnel.

C. Design Concept of Single Dielectric Barrier Discharge Plasma Actuator

Different designs and placements of the plasma actuators were studied in reference 15 and 23. Based on these investigation the present design and placement is proposed, one pair of long strips of SDBD plasma-actuators are placed symmetrically on the plastic frontal cone near the apex as shown in Fig. 3a). 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 covered electrode from the exposed electrode as shown in Fig. 3b). 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.

![Arrangement](image)

**a) Arrangement**

![Single Dielectric Barrier Discharge](image)

**b) Single Dielectric Barrier Discharge**

**Figure 3. Sketches of the plasma actuators.**
The right edge of the exposed electrode shown in Fig. 3b is aligned with the cone at the azimuth angle $\theta = \pm 90^\circ$ which are near the separation lines, where $\theta$ is measured from the windward meridian of the cone and 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. Fig. 4 shows the sketch of the unwrapped plasma actuators before glued around the model tip surface.

The actuators are each connected to a high voltage ac source (model CTP-2000K by Nanjing Suman Co.) that provides about 14 kV peak-to-peak voltage sinusoidal excitation to the electrodes 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 is activated alternately with a specified duty cycle, $\tau$, 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 $1 - \tau$ (as Fig. 5 presented). 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 range from 1Hz to 100Hz in order to study the influence of reduced frequency on the separation flow control over the cone forbody, which is also the limitation of the digital pulse wave generator.

D. PIV Facility

In addition to pressure measurements, two-dimensional PIV was performed, the laser sheet coincides with the cross section of pressure measured station o-1 in order to make a comparison of the results gotten from the two different measurement techniques. The PIV measurement plane was normal to the axis of the model as shown in Fig. 6. 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. Data were processed in 32×32 pixel interrogation areas with 50% overlap. The laser produces double pulses with a time interval of 30 μs which is a short duration and, thus, the measured crossflow velocity can be considered as time accurate. The laser sheet is located close to the pressure-measurement station but perpendicular to the forebody surface at θ =180° in order to minimize the light-reflection effects.

![Figure 6. PIV layout in wind tunnel](image)

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.

For plasma off/on operation mode, the repeat rate of the laser double-pulse is set at 10 Hz and consecutive 10 seconds of sampling are performed for each case. For duty cycle control mode, PIV sampling rate is 13Hz and the sample duration is also 10 seconds.

E. Pressure Measurements

Only ensemble-time-averaged pressures are measured. They are measured at one cross section of the conical forebody, since the pressure distribution over the forebody at angle of attack of 45° is approximately conical except in the immediate neighborhood of the body apex24. 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 50 Hz. The local side forces are calculated from the measured pressures. The sectional side-force coefficient $C_{yd}$ is normalized with the local diameter $d$ and is positive when pointing to the starboard side of the cone.

III. Experimental Results and discussion
A. Plasma Off, Port On and Starboard On

The time-averaged PIV images are presented in figure 7 for plasma off, plasma port-on and plasma starboard-on, respectively. The cross velocity vectors are superposed on the contours of the axial vorticity $\omega_x$ which is calculated from the measured velocity. For all cases, $\omega_x$ is positive when the corticity is clockwise and negative when counter-clockwise. The side force coefficient $C_{Yd}$, normal force coefficient $C_{Nd}$ and separation position $\theta_p$ & $\theta_s$ on port & starboard of the measure station are presented in table 2.

The pressure distributions and the vortex flow patterns induced by port actuation and starboard actuation are anti-symmetric with respect to the incidence plane of the forebody. The actuation raises the flow velocity, decreases the pressure, delays the boundary-layer separation, and moves in the separated shear layer and vortex on the actuating side relative to the other side, and the resulting local side forces for the two actuations are opposite in sign, and nearly equal in amplitude at the given angle of attack, $C_{Ydp} = -0.76$ and $C_{Yds} = +0.84$. Note that there are inevitable small imperfections in the model due to hand making as before. The normal force coefficient is nearly constant.
Figure 7  Pressure distribution and PIV over the forebody station under steady actuations.

Table 2. Side force coefficient $C_{Yd}$, normal force coefficient $C_{Nd}$ and separation position $\theta_p$ & $\theta_s$ on port & starboard of the measure station, respectively.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\theta_p$</th>
<th>$\theta_s$</th>
<th>$C_{Yd}$</th>
<th>$C_{Nd}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma off</td>
<td>100°</td>
<td>-110°</td>
<td>0.60</td>
<td>0.82</td>
</tr>
<tr>
<td>Port on ($\tau=0$)</td>
<td>120°</td>
<td>-100°</td>
<td>-0.76</td>
<td>0.87</td>
</tr>
<tr>
<td>Starboard on ($\tau=1$)</td>
<td>100°</td>
<td>-110°</td>
<td>0.84</td>
<td>0.79</td>
</tr>
</tbody>
</table>

B. Optimal Frequency of Duty-Cycle

The duty cycle should be manipulated at a sufficiently low frequency such that the surrounding air can respond significantly to the alternating plasma actuations, and, in the mean time, at a sufficiently high frequency such that the lateral controlled aircraft cannot respond to the resulting instantaneous loads because of its large inertia. However, the aircraft does respond to the ensemble-averaged loads generated by the duty-cycle manipulation. Accordingly, the optimal frequency of duty cycle is searched in the range from 1 Hz to 100Hz.

Figure 8 presents the time averaged pressure distributions for various duty cycle ratio cases with different duty cycle frequency, $\tau = 0.01$−0.99 denote plasma duty cycle ratios.

At measured station, at all reduced frequency values, when port plasma occupied the almost work time ($\tau = 0.01$), the higher suction peak appears on the starboard side of the cone. For various duty cycles ($\tau = 0.01$−0.99), the higher suction peak changes from port side to starboard side. The pressure distributions for 0.01 and 0.99 are likely anti-symmetric, which may happen when the flowfield is bistable, but for other $\tau$ and $1 - \tau$ values, the progress for the higher suction peak changing from port side to starboard side is clearly influenced by reduced frequency. For $f=1$, 5 and 10, this process is smooth, but for $f=35$, 60 and 100, this process become irregular.

Figure 9 presents the ensemble-averaged local side force coefficient $C_{Yd}$ versus $\tau$. It is seen that under the plasma duty-cycle actuation, the ensemble time-averaged local side force varies with the duty ratio almost linearly between the two values produced by the port actuation and starboard actuation when the duty-cycle frequency is equal to 1, 5. and 10 Hz. But, the variation becomes non-linear when the duty-cycle frequency is higher, and the side force may even change sign back and forth as the duty ratio changing from 0 to 0.5 and from 0.5 to 1 due to heavy flow hysteresis.
a) $f = 1 \text{ Hz}$

b) $f = 5 \text{ Hz}$

c) $f = 10 \text{ Hz}$
Figure 8. Comparison of time-averaged pressures for various reduced frequency, 
\( \alpha = 45^\circ \), \( U_\infty = 5\text{m/s} \)

d) \( f = 35 \text{ Hz} \)
e) \( f = 60 \text{ Hz} \)
f) \( f = 100 \text{ Hz} \)
In order to study the mechanisms for linear proportional control of local side force on slender forebody, the ensemble-averaged vortex pattern by PIV technique with typical reduced frequency are analyzed and discussed here. Ensemble-averaged side force coefficient $C_{Yd}$, normal force coefficient $C_{Nd}$, separation position $\theta_p$ & $\theta_s$ on port & starboard of the measure station, respectively, at various duty ratio $\tau$, $f=5$ Hz are presented in table 3. Ensemble-averaged PIV contours of plasma duty cycle control are presented in figure 10.

Both the PIV and pressure distribution show that the ensemble time-averaged local side force varies with the duty ratio continuously between the two values produced by the port actuation and starboard actuation when the duty-cycle frequency is equal to 5 Hz. The ensemble time-averaged flow pattern variation with the duty ratio and frequency matches that of the side force closely.

### Table 3. Ensemble-averaged side force coefficient $C_{Yd}$, separation position $\theta_p$ & $\theta_s$ on port & starboard of the measure station, respectively, at various duty ratio $\tau$, $f=5$ Hz.

<table>
<thead>
<tr>
<th>$\tau$</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_p$</td>
<td>120°</td>
<td>120°</td>
<td>120°</td>
<td>120°</td>
<td>120°</td>
<td>120°</td>
<td>120°</td>
<td>120°</td>
<td>120°</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>-100°</td>
<td>-110°</td>
<td>-110°</td>
<td>-110°</td>
<td>-110°</td>
<td>-110°</td>
<td>-110°</td>
<td>-110°</td>
<td>-110°</td>
</tr>
<tr>
<td>$C_{Yd}$</td>
<td>-0.65</td>
<td>-0.50</td>
<td>-0.32</td>
<td>-0.15</td>
<td>0.01</td>
<td>0.18</td>
<td>0.32</td>
<td>0.49</td>
<td>0.65</td>
</tr>
<tr>
<td>$C_{Nd}$</td>
<td>0.93</td>
<td>0.93</td>
<td>0.91</td>
<td>0.91</td>
<td>0.89</td>
<td>0.89</td>
<td>0.87</td>
<td>0.86</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Figure 9. Time-averaged local side force vs. reduced frequency, $\alpha = 458$, $U_\infty = 5$ m/s.
(a) $\tau = 10\%$

(b) $\tau = 20\%$

(c) $\tau = 30\%$
(d) $\tau = 40\%$

(e) $\tau = 50\%$

(f) $\tau = 60\%$
Figure 10  Ensemble-averaged PIV contours of plasma duty cycle control, $f=5$ Hz.
D. Phase-locked-averaged PIV Images, $f = 5$ Hz, $\tau = 50\%$

The temporal characteristics of the flow induced by the duty-cycled plasma actuations are investigated by phase-locked averaged PIV. Consider the case of duty cycle frequency, $f = 5$ Hz. The sampling rate of the used PIV equipment is limited to 15 Hz. As an example, set the PIV sampling rate at 8 Hz. The PIV samples at various duty-cycle phase angle are obtained in Table 4 at $f = 5$ Hz and PIV sampling rate=8 Hz, assuming that the PIV starting sample coincides with the duty-cycle starting period.

In Table 4, the first line gives the order number of the eight consecutive PIV samples measured in one second, and the second and third lines give the duty-cycle period order number and phase angle, respectively, where the PIV samples are located. Since the flow is periodic, the PIV results at all the phase angles listed on the third line, in fact, are good for every period of the duty cycle. It is noted that the phase angles of the third line are spread over the duty-cycle period with a constant phase-angle increment of $2\pi/8$. The PIV number are arranged according to the size of the phase angles in the last line for reading convenience.

**Table 4. Arrangement of PIV samples according to duty-cycle phase angle size, $f = 5$ Hz, PIV sampling rate = 8 Hz.**

<table>
<thead>
<tr>
<th>PIV sampling order number (n)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duty-cycle period number</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>phase angle, $\psi(2n\pi/8)$</td>
<td>0</td>
<td>$2\pi/8$</td>
<td>$4\pi/8$</td>
<td>$6\pi/8$</td>
<td>$\pi$</td>
<td>$10\pi/8$</td>
<td>$12\pi/8$</td>
<td>$14\pi/8$</td>
</tr>
<tr>
<td>Arranged PIV order number</td>
<td>1</td>
<td>6</td>
<td>3</td>
<td>8</td>
<td>5</td>
<td>2</td>
<td>7</td>
<td>4</td>
</tr>
</tbody>
</table>

In the present paper, the PIV sampling rate is taken at a rather large number of 13 Hz for a fine time resolution of the flowfield produced by the duty-cycle plasma actuation. The thirteen PIV images uniformly distributed in a duty-cycle period are determined similarly as shown above in Table X. Fig. X presents the phase-locked averaged PIV images at various duty-cycle phase angles for $f = 5$ Hz, $\tau = 50\%$, sampling rate=13 Hz and sampling duration=10 sec. The 13 consecutive PIV samples are ranged according to the size of the phase angles follows: 8, 3, 11, 6, 1, 9, 4, 12, 7, 2, 10, 5, & 13.

In the present experiments, the duty-cycle actuation and the PIV are operated independently, and, thus, the exact PIV image corresponding to the start of the port actuation is unknown. The starting PIV image is set by judging from the variation of the vortex positions in the PIV images (The original PIV data for various $f$ and $\tau$ are not included in the paper due to space limit and can be obtained from the first author).

The phase-locked time-averaged PIV figure for $f = 5$ Hz, $\tau = 50\%$ are shown in figure 11. We clearly see that the vortex flow pattern of first 5 figures (figure 11a-11f) look like the PIV produced by the port actuation, and the last 6 figures (figure 11h-11m) look like the PIV produced by the starboard actuation. Figure 11g shows the vortex flow pattern when it is switched from port on to starboard on. Such results indicate that the surrounding air responds well to the duty-cycle actuation in the lower duty-cycle frequency cases.
Figure 11  Phase-Locked Averaged PIV Images, \( f = 5 \text{ Hz}, \ \tau = 50\% \).
A. Comparison of Ensemble-averaged Pressures and PIV, $f = 5 \text{ Hz} & 60 \text{ Hz}$, $\tau =30\%$

We noticed that the ensemble time-averaged local side force varies with the duty ratio linearly between the two values produced by the port actuation and starboard actuation when the duty-cycle frequency is equal to 5, but the variation becomes non-linear when the duty-cycle frequency is 60 Hz. For $\tau =30\%$, this difference become biggest.

So the ensemble time-averaged PIV and pressures presented here to have a comparison. For PIV and pressure distribution for $f = 5 \text{ Hz}$, $\tau =30\%$, the flowfield looks like that of the port on, but the pressure distribution and the local side force coefficient is not same as that of port on. For PIV and pressure distribution for $f = 60 \text{ Hz}$, $\tau =30\%$, it does not looks like that of the port on, the local side force coefficient changes sign back. This indicates that the flowfields are totally different for the same $\tau$ values with different duty-cycle frequencies.

![Figure 12 Comparison of Ensemble-averaged Pressures and PIV, $f = 5 \text{ Hz} & 60 \text{ Hz}$, $\tau =30\%$.](image)

B. Comparison of Phase-Locked-averaged PIV, $f = 5 \text{ Hz} & 60 \text{ Hz}$, $\tau =30\%$

The phase-locked time-averaged PIV for $f =5\text{Hz}$ and $f = 35\text{Hz}$, $\tau=0.3$ are given in Figure 13 and 14. When $f = 5 \text{ Hz}$, the phase-locked time-averaged PIV looks like the PIV produced by either port-on or starboard-on. The two kinds of the phase-locked time-averaged PIV are separated in two groups in every period of the duty-cycle actuation. When $\tau = 0.5$, the number of port-on-like PIV equals to 6 or 7, and the number of starboard-on-like PIV equals the rest of 13. When $\tau = 0.3$, the number of port-on-like PIV equals to 9, and the number of starboard-on-like PIV equals the rest of 13. The ratio of the port-on-like PIV number to the starboard-on-like PIV number is equal to the duty ratio, $\tau$. Thus, the surrounding air responds well to the duty-cycle actuation.
When $f = 60\text{Hz}$ and $\tau = 0.3$, the phase-locked time-averaged PIV does not look like the PIV produced by port-on and starboard-on. The surrounding air does not respond well to the duty-cycle actuation because of heavy hysteretic of the air flow.
Figure 13 Phase-Locked Averaged PIV Images, $f = 5$ Hz, $\tau = 30\%$.

(a) $\psi = 0$

(b) $\psi = 2\pi/13$

(c) $\psi = 4\pi/13$

(d) $\psi = 6\pi/13$
(e) $\psi = \frac{8\pi}{13}$

(f) $\psi = \frac{10\pi}{13}$

(g) $\psi = \frac{12\pi}{13}$

(h) $\psi = \frac{14\pi}{13}$

(i) $\psi = \frac{16\pi}{13}$

(j) $\psi = \frac{18\pi}{13}$
Figure 14 Phase-Locked Averaged PIV Images, $f = 60$ Hz, $\tau = 30\%$.

I. Conclusions

An improved design of the duty-cycled plasma actuations for linear proportional control of lateral forces over a slender circular conical forebody at high angle of attack is demonstrated.

The pair of plasma actuators is placed along the two opposite side rays of the conical forebody near its apex blowing leeward at an angle of attack of 45 deg, freestream velocity of 5 m/s and Reynolds number based on the cone base diameter of 40,000. Duty-cycle frequency of 1, 5, 10, 35, 60 and 100 Hz are tested. The pressure distribution and vortex pattern at just one cross section of the forebody are measured to represent the flow according to the conical property of the flow. The pressure and crossflow-velocity distributions are measured by the time-averaged pressure tappings and a time-accurate PIV, respectively. The local side force is calculated from the pressure distribution. Both ensemble and phase-locked time-averaged PIV are presented, where 13 uniformly distributed phase angles are used to resolve the flow in a duty-cycle period.

When either the port or starboard actuator is activated while the other is kept off during the test, the induced flow can be considered steady, since the AC voltage source frequency ($F=9$ kHz) is so high that the surrounding air cannot respond the time-accurate effect. However, the air does respond the time-averaged effects. The pressure distributions and the vortex flow patterns induced by port actuation and starboard actuation are anti-symmetric with respect to the incidence plane of the forebody. The actuation raises the flow velocity, decreases the pressure, delays the boundary-layer separation, and moves in the separated shear layer and vortex on the actuating side relative to the other side, and the resulting local side forces for the two actuations are opposite in sign, and nearly equal in amplitude at the given angle of attack.

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Under the plasma duty-cycle actuation, the ensemble time-averaged local side force varies with the duty ratio almost linearly between the two values produced by the port actuation and starboard actuation when the duty-cycle frequency is higher, and the side force may even change sign back and forth as the duty ratio changing from 0 to 0.5 and from 0.5 to 1 due to heavy flow hysteresis. The ensemble time-averaged flow pattern variation with the duty ratio and frequency matches that of the side force closely. The phase-locked time-averaged PIV shows that the vortex flow pattern is similar to that produced by the port actuation or the other and alternates with the same order and ratio as those of the duty-cycle actuations in the lower frequency cases. This indicates that the surrounding air responds well to the duty-cycle actuation in the lower duty-cycle frequency cases. If the phase-locked averaged side force variation is conjectured to be similar to that of the phase-locked averaged flow pattern, the net local side force during a duty-cycle period could be derived to be a linear function of the duty ratio ($C_{Yd} = C_{Yd,p}(1-\tau) + \tau C_{Yd,s}$, $C_{Yd,s} = C_{Yd,p} - \tau(C_{Yd,p} - C_{Yd,s})$).

In the higher frequency cases, the phase-locked averaged flow patterns are entirely different from those produced by the port actuation and the other, and vary slightly with respect to the phase angle except when the duty ratio is close to 0 or 1. It is noted that the Strouhal number of the duty-cycle actuation based on the conical forebody diameter is of order O(1) in the lower duty-cycle frequency cases, which agrees with the resulting linear proportional control obtained in this paper.

II. Further work

In presented test, the optimized reduced frequency is found with a unique arrangement of the actuators and the rigid linear proportional control is achieved only on pressure measured station of the slender conical forebody, so the further work is needed to find the optimized reduced frequency for linear proportional control of overall lateral forces and moments with different arranged positions and induced flow directions of the plasma actuators.

Appendix

In order to show that the results presented in this paper are convergent, both the ensemble averaged and phase-locked averaged images during different time spans are given here. We can clearly see that the convergent results are gotten with either the steady or unsteady plasma actuation. The instantaneous image is shown to be the same as the corresponding averaged image under the steady actuation, but different from that under the unsteady actuation.

I. Convergence Verification of Averaged PIV Images

1. Port On

(a) $t = 2s$ (b) $t = 5s$
2, Starboard On

(c) $t = 8s$

(d) $t = 10s$

Figure 15 Convergence of PIV versus sampling time, port on.

(c) $t = 8s$

(d) $t = 10s$

Figure 16 Convergence of PIV versus sampling time, starboard on.

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3. Duty Cycle, Ensemble Averaged

![Graphs showing flow field variations with duty cycle and sampling times](image)

(a) $t = 2s$  
(b) $t = 5s$

(c) $t = 8s$  
(d) $t = 10s$

Figure 17  Convergence of PIV versus sampling time, $f=5Hz$, $\tau=50\%$.

4. Duty Cycle, Phase-Locked Averaged

![Graphs showing flow field variations with duty cycle and sampling times](image)

(a) $t = 2s$  
(b) $t = 5s$
II. Instantaneous PIV Images

Two instantaneous PIV images for (a) port on and (b) starboard on are shown in figure 19. They are essentially the same as the ensemble-averaged PIV shown in Subsection III.A. This indicates that the surrounding air cannot respond to the time-accurate variation of the AC vortage source because the source varies at a high frequency, \( F = 9 \) kHz, but the air does respond to the ensemble averaged effect of the AC source.

Another two instantaneous PIV images are shown in figure 20. They are essentially different each other and also different from the ensemble-averaged PIV shown in Subsection III.C and the phase-locked-averaged PIV shown in Subsection III.D.

Such results indicate that when either the port or starboard actuator is activated while the other is kept off during the test, the induced flow can be considered steady, but under the plasma duty-cycle actuation, the induced flow is actually unsteady.
Figure 20 Two instantaneous PIV images for duty cycle, $f = 5$ Hz, $\tau = 50\%$

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