Pulsed-Discharge Flow Control over a Conical Forebody

Borui Zheng∗, Chao Gao†, Yibin Li‡, Feng Liu§, and Shijun Luo¶
Northwestern Polytechnical University, Xi’an 710072, China
University of California, Irvine, CA 92697-3975

Duty cycle modulation of the alternating blowing from two opposite facing plasma actuators on the leeward surface near the apex of a cone of semi-apex angle 10º to control the mean lateral force and moment and the flow control mechanism are presented. The pressure distributions over the cone forebody are measured by steady and unsteady pressure-transducers. The experiments are performed in a 3.0 m × 1.6 m open-circuit wind tunnel at wind speed of 20 m/s, 45º angle of attack and Reynolds number of $2 \times 10^5$ based on the cone base diameter. The measurements of pressure distributions indicate that the bi-stable vortex pattern appears to be shifted in opposite direction when the port or starboard actuator is activated while the other is kept off during the test. The flow control effectiveness is analyzed at various free-stream velocities, angles of attack and pulse frequencies. It is shown that the reduced pulse-repetition frequency based on the local diameter at the plasma actuator equal to one yields the highest effectiveness among the cases considered.

Nomenclature

$C_n =$ yawing moment coefficient about cone base, yawing moment/$q_\infty SD$

$\Delta C_n = C_n$ (pulse port on, starboard on or duty cycle) - $C_n$ (plasma off)

$C_p =$ pressure coefficient

$C_Y =$ overall side-force coefficient, overall side force/$q_\infty S$

$\Delta C_Y = C_Y$ (pulse port on, starboard on or duty cycle) - $C_Y$ (plasma off)

$C_{Yd} =$ ensemble-averaged local side-force coefficient, local side force/$q_\infty d$

$\Delta C_{Yd} = C_{Yd}$ (pulse port on, starboard on or duty cycle) - $C_{Yd}$ (plasma off)

$D =$ base diameter of circular cone forebody

$d =$ local diameter of circular cone forebody

$F =$ carrier frequency of a.c. voltage source

$f =$ frequency of duty cycle

$f_p =$ frequency of periodic pulse

$L =$ length of circular cone forebody

$q_\infty =$ free-stream dynamic pressure

$Re =$ free-stream Reynolds number based on D

$T =$ period of duty cycle

$T_p =$ period of periodic pulse

$U_\infty =$ free-stream velocity

$V_{p-p} =$ peak-to-peak voltage of a.c. voltage source

$W =$ input power of a.c. voltage source

∗ Graduate Student, Department of Fluid Mechanics.
† Professor and Vice Director, National Key Laboratory of Sceince and Technology on Aerodynamic Design and Research.
‡ Professor, College of Aeronautical Engineering Department.
§ Professor, Department of Mechanical and Aerospace Engineering, Associate Fellow AIAA.
¶ Researcher, Department of Mechanical and Aerospace Engineering.
\[ \alpha = \text{angle of attack} \]
\[ \theta = \text{circumferential angle measured from bottom meridian line, positive when clockwise} \]
\[ \tau = \text{fraction of time when starboard actuator is on over a duty cycle period} \]
\[ \tau_p = \text{fraction of time when port or starboard actuator is on over a periodic pulse period} \]
\[ \Omega = \text{reduced angular frequency of periodic pulse, } 2\pi f_p d/U_\infty \]

I. Introduction

Proportional lateral control on slender forebodies at high angles of attack is highly needed in aerodynamic design of aircrafts. The fact that the separation vortices over pointed forebodies generate large air loads 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.\textsuperscript{1-3}

Recently, Liu et al.\textsuperscript{4} reported the 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 and the freestream velocity used in the experiment is 5 m/s. Advancing into higher freestream velocity is of interest to the subsonic aerodynamic researchers.

As shown by Patel et al.\textsuperscript{5} and others, the periodic pulsed discharge yields greater impact on the flow separation than the steady discharge. Zheng et al.\textsuperscript{6} studied periodic-pulse-induced flow over a cone model using a two-dimensional particle image velocimetry (PIV) in the absence of external flow at one atmospheric pressure. It confirmed that the main mechanism of the periodic pulse actuation in momentum transfer is the formation of strong discrete vortices, rather than the gas acceleration. In the present paper, we conduct the wind tunnel study aiming at a higher freestream velocity. In the following sections, the experimental setup is described. The steady and unsteady pressure measurements are studied. The experimental results of the periodic pulse and duty cycle actuations are then presented. Finally conclusions are drawn.

II. Experimental Setup

The model and the plasma actuators are the same as Ref. 4 except the pressure instrumentations. Each of the two actuators on the cone model is separately driven by a multi-channel plasma generator made by Y.B. Li, an author of the present paper. The waveform of the a.c. source is sine wave. The peak-to-peak voltage and carrier frequency are set at \( V_{p-p} \approx 12.2-14.2 \text{ kV} \) and \( F \approx 30 \text{ kHz} \), respectively. The pulse frequency can be set by the controlling software attached to the power supply. Three pulse frequencies are selected during the experiment, which are \( f_p = 50 \text{ Hz}, 100 \text{ Hz} \) and \( 500 \text{ Hz} \), while the frequency of duty cycle actuation is set as \( f = 500 \text{ Hz} \). Tab. 1 gives the input power of the plasma pulse discharge, and the input power of duty cycle is always 364 W. Fig. 1 shows the signals of periodic pulse and duty cycle actuation.

<table>
<thead>
<tr>
<th>Duty Ratio (( \tau_p ))</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (V)</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Current (A)</td>
<td>1.4</td>
<td>1.6</td>
<td>2.0</td>
<td>2.3</td>
<td>2.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Input Power (W)</td>
<td>224</td>
<td>256</td>
<td>320</td>
<td>368</td>
<td>400</td>
<td>432</td>
</tr>
</tbody>
</table>

The tests are conducted in an open-circuit low-speed wind tunnel at Northwestern Polytechnical University. The test section has a 3.0 m x 1.6 m cross section. The model is rigidly mounted on a support from the port side of the model aft-cylinder as shown in Fig. 2. The support is fixed onto the turning plate of angle of attack imbedded in the bottom wall of the wind-tunnel test-section. The model support is not symmetric with respect to the incidence plane of the model and, thus, would have an asymmetric interference on the flow around the cone forebody. The cone-cylinder model is tested at \( \alpha = 45^\circ, 50^\circ \) and \( 55^\circ \), \( U_\infty = 15, 20 \) and 25 m/s. The Reynolds number based on the cone base diameter is about \( 1.5 \times 10^5 \sim 2.5 \times 10^5 \). Local side force, overall side force and yawing moment acting on a station of the cone forebody are calculated from the measured pressures. The local side-force coefficient \( C_{Yd} \) is normalized with the local diameter of the cone and is positive when pointing to the starboard side of the cone. The

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yawing moment coefficient $C_n$ is normalized with the base diameter of the cone and is positive when yawing to the starboard side of the cone. The model is carefully cleaned prior to each run.

Figure 1. Periodic pulsed actuation signals (a) and duty cycle actuation signals (b)
Surface pressure measurements are chosen for the model-load instrumentation to maximize the information provided about the complex flow and allow rigid mounting of the model required for the high-angle-of-attack tests. The 288 time-averaged pressure transducers are arranged in rings of 36, every 10° around the circumference of the cone and at Stations 1 to 7 and Station 9. The time-averaged pressure transducers are Models 9816 by the PSI Company, which samples at frequency of 100 Hz. In addition to the time-averaged transducers, 24 unsteady pressure transducers are mounted around the circumference of Station 8 as shown in Fig. 3. The unsteady pressure transducers are Model XCQ−093 by the Kulite Semiconductor Products Inc. with sampling frequency of 5000 Hz. The input pressure range is 0.35 BAR and perpendicular acceleration sensitivity % FS/g is $1.5 \times 10^{-3}$. Consecutive 10 seconds samplings of both steady and unsteady pressure transducers are recorded for analysis. In the present paper, the flow control effectiveness is studied on the steady pressure distributions only.
III. Base Measurements

A. Plasma-off flow at zero angle of attack

In order to check the accuracy of the model setup in the wind tunnel, a test is run at zero angle of attack and with plasma off. Fig. 4 presents the ensemble-averaged pressure distributions over the circumference of Stations 1–7 and Station 9 at $\alpha = 0^\circ$, $U_\infty = 20$ m/s. Aside from some slight irregularities, the measured pressure distributions indicate essentially an axisymmetric flow around the cone. In the present study, the model support is not symmetric to the incidence plane and the plasma actuators are made by hands 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 may be the cause for the mentioned irregularities of the pressure distributions. Nevertheless, the disturbances were tolerably small.

![Figure 4. $U_\infty = 20$ m/s, $\alpha = 0^\circ$, $C_p$ vs. $\theta$, plasma off](image)

B. Convergence of ensemble averaged pressures with sampling time

![Figure 5. Comparison of pressures ensemble-averaged over 1s - 10s for periodic pulse and duty cycle actuation, $U_\infty = 20$ m/s, $\alpha = 45^\circ$, Station 8](image)
Figures 5 presents the convergence of the ensemble-averaged pressure distribution over Station 8 at $U_\infty = 20\text{m/s}$, $\alpha = 45^\circ$ for (a) starboard periodic pulse actuation with $F = 30\text{ kHz}$, $f_p = 50\text{ Hz}$, $\tau_p = 50\%$, $V_{p-p} = 12.7-14.2\text{ kV}$ and (b) duty cycle actuation with $F = 30\text{ kHz}$, $f = 500\text{ Hz}$, $\tau = 50\%$, $V_{p-p} = 12.2\text{ kV}$, respectively. The pressure distributions around the circumference of Stations 1-9 where the PSI-9816 and Kulite transducers are mounted with sampling frequency of 100 Hz and 5000 Hz, respectively. The comparisons reveal that there are no differences in the averaged pressures for the sampling time greater than 1 second. The same is true for plasma-off and port-on (not shown here for brevity). We will present the 10 seconds averaged data in the subsequent sections. It is seen that the suction peaks of pressure distributions seem well captured by the 24 unsteady pressure transducers on Station 8.

C. Effects of the a.c. carrier frequency on induced velocity

In order to analyze the effects of the a.c. carrier frequency on induced velocity, a series of PIV experiments have been done in the absence of external flow.

<table>
<thead>
<tr>
<th>Carrier Frequency (kHz)</th>
<th>Current (A)</th>
<th>Input Power (W)</th>
<th>Maximum Velocity (m/s)</th>
<th>Position of Maximum Velocity (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.3</td>
<td>36</td>
<td>1.97</td>
<td>(8.30, 0.44)</td>
</tr>
<tr>
<td>15</td>
<td>0.5</td>
<td>60</td>
<td>2.234</td>
<td>(8.87, 0.44)</td>
</tr>
<tr>
<td>20</td>
<td>0.65</td>
<td>78</td>
<td>2.218</td>
<td>(8.87, 0.44)</td>
</tr>
<tr>
<td>25</td>
<td>0.8</td>
<td>96</td>
<td>2.292</td>
<td>(11.50, 0.44)</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>120</td>
<td>2.245</td>
<td>(9.78, 0.44)</td>
</tr>
<tr>
<td>35</td>
<td>1.25</td>
<td>150</td>
<td>2.413</td>
<td>(9.25, 0.44)</td>
</tr>
<tr>
<td>40</td>
<td>1.5</td>
<td>180</td>
<td>2.885</td>
<td>(10.74, 0.44)</td>
</tr>
<tr>
<td>45</td>
<td>1.6</td>
<td>192</td>
<td>2.292</td>
<td>(10.91, 0.44)</td>
</tr>
<tr>
<td>50</td>
<td>1.7</td>
<td>204</td>
<td>2.396</td>
<td>(10.53, 0.44)</td>
</tr>
</tbody>
</table>

The plasma actuator consists of two copper electrodes each of 0.03 mm in thickness and 15 mm in length. The width of the exposed and encapsulated electrode is 1 mm and 2 mm, respectively. The two electrodes are separated by a gap of 1.5 mm. The dielectric insulator layer is made from several Kapton tape layers. The thickness of each layer is 0.04 mm. Plasma actuators are working at the state of continuous discharge, and the peak-to-peak voltage is set at $V_{p-p} = 13\text{ kV}$. The PIV system layout is the same as Ref. 6. The repeat rate of the laser double-pulse is set at 15Hz, and consecutive 15 seconds of sampling are performed for each case. PIV data are taken at the mid-span location of the actuator, the downstream upper edge of the exposed electrode actuator is set as the origin of the...
coordinates and the actuator generates a jet flow towards the positive x-direction. The maximum induced velocity occurs at approximately 10 mm away from the actuator on the downstream.

Figure 6 illustrates that the maximum induced velocity nearly keep constant when carrier frequency changing from 10 kHz to 50 kHz, and the input power is 36 W at $F = 10$ kHz and 204 W at $F = 50$ kHz. The frequency of 30 kHz will be chosen in following sections based on the consideration of the best flow control effectiveness and the least input power.

IV. Periodic Pulse Actuations

A. Different freestream velocities.

The pressure distributions in Fig. 7 show the flow control of plasma is effective at $U_\infty = 15, 20$ and 25 m/s, $\alpha = 45^\circ$. The typical bi-stable mode may be affected by free-stream conditions and slight geometric imperfections of the cone near the apex. By taking advantage of the sensitivity of the flow near the apex of the cone, we can control the vortex configuration and thus the side force and moment by activating one of the installed plasma actuators. The starboard-on results are almost overlapped with those of the plasma-off, as shown in Fig. 7 (a). This is because the asymmetric perturbations produced by the port-side plasma actuator merely reassure the preexisting plasma-off asymmetry of the flow.

![Figure 7](image-url)

(a) $U_\infty = 15$ m/s
(b) $U_\infty = 20$ m/s
(c) $U_\infty = 25$ m/s

Figure 7. $C_p$ vs. $\theta$, $\alpha = 45^\circ$, $f_p = 50$ Hz, $\tau_p = 70\%$, $V_{p-p} = 12.7$ kV, $F = 30$ kHz, Station 1
Figure 7(b) illustrates that when the port plasma actuator is activated, the pressure distributions exhibit stronger suction on the starboard side and weaker suction on the port side, indicating that the starboard-side vortex moves closer to the cone while the port vortex moves farther away from the cone. It leads to the change of positions of the two vortices. The location of the boundary layer separation point can be inferred as the end point of the pressure recovery as demonstrated by Hall et al.7 The plasma blowing edge is located at $\theta = \pm 120^\circ$. The plasma blows in the circumferential and downward direction tangent to cross section surface of the cone. The plasma jet tends to stay attached to the circular circumference due to Coanda effects. In comparison with plasma-off, when plasma is port-on, the port-side boundary-layer separation point moves downward from $\theta = 120^\circ$ to $\theta = 110^\circ$ while the starboard-side boundary-layer separation point moves upward from $\theta = -120^\circ$ to $\theta = -110^\circ$.

Although the differences between the pressure distributions of the three modes are small at $U_\infty = 25$ m/s as shown in Fig. 7(c), significant effects of the plasma on flow control is still observed. It is noted that the changes produced by port-on and starboard-on are opposite in direction but not equal in magnitude. Among other factors, the asymmetric model support and the imperfections of the model, particularly those due to the installment of the plasma actuators mentioned earlier, are believed to prevent the results from exact bi-stable. It is known that the flow asymmetry depends on the body roll angle or the micro surface imperfections of the model for plasma-off.8

Table 3 compares local side force coefficient calculated from the pressure distributions of plasma-off, port-on and starboard-on modes. The $\Delta C_{Yd}$ is the deviation of the local side force coefficient under actuator port on or starboard on from plasma off. The deviation at $U_\infty = 20$ m/s is larger than other cases, which agrees with the changes of suction peaks shown in Fig. 7. It indicates the flow control effectiveness is dramatic at $U_\infty = 20$ m/s, which may be the result of coupling of plasma actuator electrical parameters and free-stream velocity. From the pressure distributions, we may infer that the port plasma actuator induces a momentum input in the direction opposite to the freestream flow direction, which pushes the boundary layer separation line towards the upstream direction and thus sends the port vortex with its feeding shear-layer away from the cone surface. The shift of boundary-layer separation locations causes the local side force to change immediately. The detailed mechanisms of unsteady actuation will be studied in our future research.

### Table 3. Flow control effectiveness at different free-stream velocities

<table>
<thead>
<tr>
<th>$U_\infty$</th>
<th>15 m/s</th>
<th>20 m/s</th>
<th>25 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{Yd}$</td>
<td>$\Delta C_{Yd}$</td>
<td>$C_{Yd}$</td>
<td>$\Delta C_{Yd}$</td>
</tr>
<tr>
<td>plasma off</td>
<td>-0.894</td>
<td>0</td>
<td>-0.712</td>
</tr>
<tr>
<td>Port on</td>
<td>-0.552</td>
<td>0.342</td>
<td>0.538</td>
</tr>
<tr>
<td>Starboard on</td>
<td>-0.994</td>
<td>-0.100</td>
<td>-0.427</td>
</tr>
</tbody>
</table>

B. Different pulse repetition frequencies

Patel et al.7 reported that plasma actuators are highly effective in controlling flow separation and delaying wing stall using unsteady excitations that are scaled with the natural vortex-shedding frequency. The introduction of unsteady disturbances near the separation location can cause the generation of large coherent vortex structures that could prevent or delay the onset of separation. These structures are thought to bring high-momentum fluid to the surface, enabling the flow to withstand the adverse pressure gradient without separating. Defined a reduced frequency, $\Omega \approx 2\pi f_p d/U_\infty$, where $f_p$ is the unsteady forcing frequency. $d$ is characteristic length, $U_\infty$ is the free-stream velocity. Results from unsteady frequency sensitivity tests conducted on 2-D airfoil section shapes since then, support the optimum conditions at $\Omega \approx 1$.

In order to verify that $\Omega \approx 1$ is the optimum pulse discharge frequency for cone too, we test the flow control effectiveness under $f_p = 50$Hz, 100Hz and 500Hz, corresponding to $\Omega \approx 2\pi f_p d/U_\infty \approx 0.1, 0.2$ and 1. Because the plasma actuators are installed at the circular cone forebody, where the flow control effective is the most significant, so we take $d$ as the local diameter at the middle of actuator. Three duty cycle period conditions have been presented, which are $\tau_p = 50\%$, 70\% and 90\%, the pressure distributions and local side force coefficient are compared to analyze the effectiveness at different pulse discharge frequencies.
Figure 8. $C_p$ vs. $\theta$, $U_\infty = 20$ m/s, $\alpha = 45^\circ$, $V_{pp} = 14.2$ kV, $f = 30$ kHz, Station 1

(a) $\tau_p = 50\%$, Port on  
(b) $\tau_p = 50\%$, Starboard on  
(c) $\tau_p = 70\%$, Port on  
(d) $\tau_p = 70\%$, Starboard on  
(e) $\tau_p = 90\%$, Port on  
(f) $\tau_p = 90\%$, Starboard on
Figure 8 compares the ensemble-averaged pressure distributions at Station 1 under different pulse frequencies. It is seen that the suction peaks on the starboard side induced by port on at \( f_p = 500 \text{ Hz} \) is very distinct from other pulse frequencies, while the suction peak of starboard on at \( f_p = 500 \text{ Hz} \) is almost the same as other frequencies. The asymmetry effect may be caused by model imperfection. The reduced frequency \( \Omega \approx 1 \) seems more effective than other frequencies at flow control by plasma actuators. This point is consistent with Ref. 5, except that their model is an airfoil. Thus if we raise the pulse frequency, the effective wind speed of flow control might be increased higher.

Table 4 compares the local side force coefficient calculated from the measured pressures. It is seen that \( \Delta C_{Yd} \) of \( f_p = 500 \text{ Hz} \) is almost the absolutely largest among all the cases. The local side force produced by plasma actuators at \( f_p = 500 \text{ Hz} \) is the biggest. To be strict, it should make more comparisons at different pulse frequencies, but we just take \( \Omega \approx 1 \) as the optimum frequency in the present paper.

### Table 4. Flow control effectiveness under different periodic pulse frequencies

<table>
<thead>
<tr>
<th>( f_p )</th>
<th>( 50 \text{ Hz} )</th>
<th>( 100 \text{ Hz} )</th>
<th>( 500 \text{ Hz} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Omega )</td>
<td>0.104</td>
<td>0.207</td>
<td>1.04</td>
</tr>
<tr>
<td>plasma off</td>
<td>( C_{Yd} )</td>
<td>( \Delta C_{Yd} )</td>
<td>( C_{Yd} )</td>
</tr>
<tr>
<td>Port on</td>
<td>-0.085</td>
<td>0</td>
<td>0.004</td>
</tr>
<tr>
<td>Starboard on</td>
<td>-0.238</td>
<td>0.322</td>
<td>-0.249</td>
</tr>
</tbody>
</table>

**C. Different angles of attack.**

Figure 9 shows that the flow control is effective at \( \alpha = 45^\circ \) and \( 50^\circ \), but has no effect at \( 55^\circ \). From Tab. 5, we can also notice that \( \Delta C_{Yd} \) become smaller as \( \alpha \) increasing, and \( \Delta C_{Yd} \) nearly equals to zero at \( 55^\circ \). The reason may be that the separation area becomes larger and the boundary layer line moves to the upstream direction when raising the angle of attack. The momentum induced by plasma actuators can not stand up to the increasing adverse pressure gradient, then the position of the separation line of the boundary layer remains unchanged, and the two vortices hold still.
Table 5: Flow control effectiveness at different angles of attack
(U∞ = 20 m/s, fp = 500 Hz, τp = 80%, Vp-p = 14.2 kV, F = 30 kHz, Station 1)

<table>
<thead>
<tr>
<th>α</th>
<th>C_{yd}</th>
<th>ΔC_{yd}</th>
<th>C_{yd}</th>
<th>ΔC_{yd}</th>
<th>C_{yd}</th>
<th>ΔC_{yd}</th>
</tr>
</thead>
<tbody>
<tr>
<td>plasma off</td>
<td>0.150</td>
<td>0</td>
<td>0.963</td>
<td>0</td>
<td>-0.148</td>
<td>0</td>
</tr>
<tr>
<td>Port on</td>
<td>0.757</td>
<td>0.606</td>
<td>1.051</td>
<td>0.089</td>
<td>-0.116</td>
<td>0.032</td>
</tr>
<tr>
<td>Starboard on</td>
<td>-0.270</td>
<td>-0.420</td>
<td>0.486</td>
<td>-0.476</td>
<td>-0.130</td>
<td>0.018</td>
</tr>
</tbody>
</table>

V. Duty Cycle Actuations

We employ the plasma actuators by switching on and off the starboard or port plasma actuator with duty cycle at f = 500Hz, Ω ≈ 1. The τ = 0 and τ = 1 cases correspond to the steady port-on and starboard-on, respectively, which produces 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 τ = 0 to τ = 1.
A. Pressure distributions of duty cycle

Figure 10. $C_p$ vs. $\theta$, $U_\infty = 20$ m/s, $\alpha = 45^\circ$, $f = 500$ Hz, $V_{pp} = 12.2$ kV, $F = 30$ kHz, Station 1

Figure 10(a) presents the ensemble-averaged pressure distributions $C_p$ vs. $\theta$ of $\tau = 0$-$50\%$, Station 1, at $U_\infty = 20$ m/s, $\alpha = 45^\circ$. It is seen that the suction peaks of $\tau = 0$ and $10\%$ are the same. And the suction peak on the starboard side is descending as $\tau$ changes from 0 to 50%. Fig. 10 (b) shows the suction peak on the port side is rising except $\tau = 100\%$. We can see that the port side suction peak rises, while the starboard side suction peak descends as $\tau$ change from 60% to 100%. The unsteady excitation is the same as or even more effective than the steady actuation in certain cases in Fig. 10, this might be caused by the effect of flow hysteresis, namely, the change of flow can not catch up with the alteration of the electrical characteristics, this trait can be used to save the power input.

B. Local side-force distributions of duty cycle

From Fig. 11, it can be seen qualitatively that $\tau = 10\%$ almost coincides with $\tau = 0$, and $C_{Yd}$ along axial direction under $\tau = 90\%$ is even smaller than $\tau = 1$. From Tab. 6, it can be found quantitatively that $\Delta C_{Yd}$ of $\tau = 10\%$ is slightly smaller than $\tau = 0$, while $\Delta C_{Yd}$ of $\tau = 90\%$ is larger than $\tau = 1$. This may result from the model imperfection or the installation of the plasma actuators.

Figure 11. $C_{Yd}$ vs. $x/L$, $U_\infty = 20$ m/s, $\alpha = 45^\circ$, $f = 500$ Hz, $V_{pp} = 12.2$ kV, $F = 30$ kHz
Table 6. Flow control effectiveness of duty cycle
\( (U_\infty = 20 \text{ m/s}, \alpha = 45^\circ, f = 500 \text{ Hz}, V_{p-p} = 12.2 \text{ kV}, F = 30 \text{ kHz}, \text{Station 1}) \)

<table>
<thead>
<tr>
<th>( \tau )</th>
<th>( C_{Yd} )</th>
<th>( \Delta C_{Yd} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma off</td>
<td>0.930</td>
<td>0</td>
</tr>
<tr>
<td>0%</td>
<td>1.091</td>
<td>0.161</td>
</tr>
<tr>
<td>10%</td>
<td>1.067</td>
<td>0.137</td>
</tr>
<tr>
<td>20%</td>
<td>0.973</td>
<td>0.043</td>
</tr>
<tr>
<td>30%</td>
<td>0.821</td>
<td>-0.108</td>
</tr>
<tr>
<td>40%</td>
<td>0.548</td>
<td>-0.382</td>
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<tr>
<td>50%</td>
<td>0.367</td>
<td>-0.563</td>
</tr>
<tr>
<td>60%</td>
<td>0.235</td>
<td>-0.695</td>
</tr>
<tr>
<td>70%</td>
<td>0.068</td>
<td>-0.862</td>
</tr>
<tr>
<td>80%</td>
<td>-0.120</td>
<td>-1.049</td>
</tr>
<tr>
<td>90%</td>
<td>-0.314</td>
<td>-1.244</td>
</tr>
<tr>
<td>100%</td>
<td>-0.167</td>
<td>-1.097</td>
</tr>
</tbody>
</table>

C. Overall side force and yawing moment of duty cycle

Figure 12 presents the measured side force and yawing moment at \( U_\infty = 20 \text{ m/s}, \alpha = 45^\circ \). Although the measurements do not show strictly linear proportional control, it clearly demonstrates the ability of achieving any intermediate values of the forces and moments between the two opposite bi-stable conditions by continuously varying the value of \( \tau \). 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. It is also seen that the side forces and yawing moments of \( \tau = 10\% \) and \( \tau = 90\% \) are the same as steady actuation or even better. We can take advantage of this trait to save input power. The case of \( \tau = 90\% \) is abnormal, the reason is unclear and will be studied in the future research.

Figure 12. \( C_Y \) & \( C_n \) vs. \( \tau \), \( U_\infty = 20 \text{ m/s}, \alpha = 45^\circ, f = 500 \text{ Hz}, V_{p-p} = 12.2 \text{ kV}, F = 30 \text{ kHz} \)
VI. Conclusions

Nearly linear proportional control of lateral forces and moments over a slender conical forebody at freestream velocity of 20 m/s and angle of attack of 45° have been demonstrated by employing a duty cycle actuation with periodic pulse repetition frequency of 500 Hz from a pair of single-dielectric-barrier-discharge plasma actuators near the cone apex. From the pressure measurements, the following flow features are revealed.

1. Starting from plasma off pressure distribution, the port-on mode raises the starboard suction peak and lowers the port suction peak, while the starboard-on mode raises the port suction peak and lowers the starboard suction peak.

2. When the reduced angular frequency of periodic pulse $2\pi f_d d/U_\infty$ is of the order of 1, the periodic pulse actuation seems to be optimum for cone model. The characteristic length $d$ is taken to be the local diameter of the cone at the center of the plasma actuators, since the plasma discharge direction is circumferential around the forebody.

3. A kick occurs in the lateral force and moment control curves for the duty cycle actuations at duty ratio of 90%. The reason for this is unclear to the authors.

Further investigations should be pursued to study the detail flow mechanism and improve the performance of the actuators.

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References


