Flow Control over Conical Forebody with Port Pulsed Plasma Actuator

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A study using plasma port single-pulsed discharge is performed on the flow control of asymmetrical vortices over slender conical forebody. The different circumferential steady and unsteady pressure distributions are measured in the wind tunnel test. At the same time, the local side force, the increment of local side force and the overall side force and moment are calculated with the circumferential pressure distributions of different sections. The test result shows we can use port single-pulsed discharge to achieve the linear proportional control of asymmetrical force and moment over slender conical forebody and have good linearity. Both ensemble averaged and phase-locked averaged pressure distributions at Section 8 have reached convergence. Compared with the phase-locked averaged pressure distributions of different phase angle at Section 8, the response of flow field is hysteresis of the pulsed modulating frequency.

Nomenclature

\[ C_n = \text{yawing moment coefficient about cone base, yawing moment/q}_\text{SD} \]
\[ C_p = \text{pressure coefficient} \]
\[ C_{Nd} = \text{overall side-force coefficient, overall side force/q}_\text{S} \]
\[ C_{yd} = \text{ensemble-averaged local side-force coefficient, local side force/q}_\text{d} \]
\[ c_{yd} = \text{phase-locked averaged local side-force coefficient} \]
\[ D = \text{base diameter of circular cone forebody} \]
\[ d = \text{local diameter of circular cone forebody} \]
\[ F = \text{frequency of a.c. voltage source} \]
\[ f = \text{frequency of duty cycle} \]
\[ L = \text{length of circular cone forebody} \]
\[ q_\text{w} = \text{free-stream dynamic pressure} \]
\[ Re = \text{free-stream Reynolds number based on D} \]
\[ S = \text{base area of circular cone forebody} \]
\[ T = \text{period of duty cycle} \]
\[ t = \text{time of duty cycle} \]
\[ U_\text{w} = \text{free-stream velocity} \]
\[ V_{p-p} = \text{peak-to-peak voltage of a.c. voltage source} \]
\[ w = \text{input power of a.c. voltage source} \]
\[ x, y, z = \text{body coordinates, x toward base, y toward starboard, right-hand system} \]

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I. Introduction

The head of air vehicles which are advanced maneuverability is usually slender conical forebody. At high angle of attack, a pair of separated vortices will appear over slender forebody. The large side force and moment will be generated when the separated vortices is asymmetrical.\(^1\)\(^2\) This large airloads are uncertain and affected the performance of air vehicles largely. However, the separation vortices over pointed forebodies are very sensitive to small perturbations near the body apex.\(^3\) So, It 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 is probable and necessary to achieve active lateral control of asymmetrical vortices over slender conical forebody. Recently, Liu, Meng et al.\(^4\)\(^5\) 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. This test based on the former studies also achieves proportional control of lateral forces and moments over a slender conical forebody using single-pulsed discharge with different duty cycle ratios.

II. Experimental Setup

The test model consists three pieces and is a circular cone of 10° semi-apex angle faired to a cylindrical afterbody as showed in Fig 1. The total length of the circular cone is 463.8mm with a base diameter of 163.6 mm. There are nine sections used to measure pressure. The unsteady pressure is measured on section 8 and others is steady pressure measurement section. In addition, The cone tip of length 150 mm is made of plastic for plasma-actuator accommodation.

![Fig 1. Test model](image-url)

Two long strips of SDBD plasma-actuators are installed symmetrically on the plastic frontal cone near the apex as shown in Fig. 2(a). 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. 2(b). The right edge of the exposed electrode shown in Fig. 2(b) is aligned with the cone at the azimuth angle \(\theta = \pm 120°\), where \(\theta\) is measured from the windward meridian of the cone and positive is clockwise when looking upstream (Fig. 2(a)). 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 mm 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 tests are conducted in an open-circuit low-speed wind tunnel at Northwestern Polytechnical University. The test section has a 3.0m × 1.6m cross section. The cone-cylinder model is tested at $\alpha = 35^\circ$. The free-stream velocity $U_\infty = 5$ m/s. The Reynolds number based on the cone base diameter is $5 \times 10^4$.

### III. Experimental Results and Discussions

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

In order 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. The free stream velocity is set at $U_\infty = 5$ m/s in the present study. The corresponding Reynolds numbers based on the cone base diameter are $5 \times 10^4$. Fig. 4 presents the pressure distributions at plasma off, $U_\infty = 5$ m/s and $\alpha = 0^\circ$. Aside from some slight irregularities, the measured pressure distributions indicate essentially an axisymmetric flow around the cone. In the present study, the hand-made plasma actuators and no...
allowance for the attachment could have been the cause for the mentioned irregularities of the pressure distributions. Nevertheless, the disturbances were tolerably small.

![Graph showing pressure distributions over various sections for plasma off at \( \alpha = 0^\circ \) and \( U_\infty = 5 \text{ m/s} \)]

**B. Steady measurement results**

In this test, the state of plasma-actuators is port single-pulsed discharge. So, the starboard actuators is always off. The peak-to-peak voltage and frequency loading on the actuators are set at \( V_{p-p} \approx 14.5 \text{ kV} \) and \( F \approx 11.8 \text{ kHz} \), respectively. The pulsed modulating frequency is 50Hz. Table 1 shows variations of input power with different duty cycle ratios. With the increased duty cycle ratios, input power is raised gradually.

<table>
<thead>
<tr>
<th>Duty cycle (( \tau ))</th>
<th>0.01</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>0.99</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage (V)</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Input current (A)</td>
<td>0</td>
<td>0.15</td>
<td>0.33</td>
<td>0.57</td>
<td>0.74</td>
<td>0.82</td>
</tr>
<tr>
<td>Input power (W)</td>
<td>0</td>
<td>2.70</td>
<td>5.94</td>
<td>10.26</td>
<td>13.32</td>
<td>14.76</td>
</tr>
</tbody>
</table>

Table 1. Input power versus periodic-pulse duty ratio

Figure 5 compares the pressure distributions for different duty cycle ratios at odd Sections. The stronger suction peaks change continuously from port side to starboard side with variations of duty cycle ratios. This results show that the flow control of asymmetrical vortices can be also achieved by single-pulsed discharge with different duty cycle ratios.
Fig. 5 Circumference pressure distribution variations with different duty cycle ratios in odd sections

The results of \( \tau_p = 0.01 \) showed in Fig 5 almost overlap with the results of plasma off. This is because the work time of actuators is so short in a period that few power can input in the flow. So, the influence to the flow is miniscule. It can be proved in Table 1. The pressure distributions for \( \tau_p = 0.6 \) are almost symmetric, and the local side force \( C_{yd} \) is nearly 0. The pressure distributions for \( \tau_p = 0.01 \) and \( \tau_p = 0.99 \) switch in the bistable mode. But, it is not strictly anti-symmetric. The port side suction peak of \( \tau_p = 0.01 \) is stronger than the starboard side suction peak of \( \tau_p = 0.99 \).

Figure 6 presents the local side force as \( \tau_p \) is increased from 0.01 to 0.99 for odd sections and even sections. Figure 7 compares the increment of local side force as \( \tau_p \) is increased from 0.01 to 0.99 for odd sections and even sections. The increment of local side force \( \Delta C_{yd} \) is the local side force of different duty-cycle ratios minus the local side force of plasma off. It can be seen in Fig 6 and Fig 7 that the variation of \( C_{yd} \) and \( \Delta C_{yd} \) show good linearity, and the more close to the head of cone, the better the linearity is.

The overall side force coefficient \( C_f \) and yawing moment coefficient \( C_n \) with different duty cycle ratios are calculated as shown in Fig 8. The curve is almost linear for variations of duty-cycle ratios. The result illustrates that we can use single-pulsed discharge with different duty-cycle ratios to achieve linear proportional control of asymmetrical force and moment over slender conical forebody. And it clearly demonstrates the ability of achieving any intermediate values of the forces and moments between the two opposite bistable conditions by continuously varying the value of duty-cycle ratios. If the side force, \( C_f \) at the duty cycle ratio, \( \tau_p = 0 \) (plasma off) happens to be positive (not negative), the port actuator has to be replaced by the starboard actuator and a linear variation of the side force and yawing moment versus duty cycle ratio can be also achieved. Compared with the results of Ref. 4-6, the linearity of this test is improved largely. The most important reason is that the pulsed modulating frequency of this test is \( f = 50 \text{Hz} \) higher than previous studies \( f = 10 \text{Hz} \). The other reason is the improved design of the actuators.
C. Unsteady measurement results

Flow under plasma single-pulsed discharge control is naturally unsteady. On Section 8 the pressures are measured by Kulite transducers. The Kulite pressure-transducer measurement with sampling frequency of 5000Hz can detect small fluctuations in pressure. Figure 9 presents the ensemble-averaged pressure of 30s with different duty-cycle ratios at Section 8. The stronger suction peaks change continuously from port side to starboard side with variations of duty cycle ratios. This result is in accord with the steady measurement result.

Figure 10 compares the ensemble-averaged pressure distributions at Section 8 obtained with sampling times of 1s, 10s, 15s, 20s, 25s and 30s at various duty cycles ratios. The ensemble averaged pressure is convergence when the sampling time is lower than 30s. Thus, the ensemble-averaged pressure may approach a limit, and the flow under
the plasma duty-cycled control could be considered steady when the averaging time is 30s in this test. Therefore, typical aircraft under the plasma duty-cycled control would respond the steady, ensemble-averaged loads rather than unsteady, instantaneous loads.

Fig. 9 Ensemble-averaged pressure distributions with different duty cycle ratios at Section 8
\[ \theta^\circ \]

Graphs showing \( C_{pD} \) versus \( \theta^\circ \) for different values of \( \tau_p \):

- **c) \( \tau_p = 0.4 \)**
- **d) \( \tau_p = 0.6 \)**
- **e) \( \tau_p = 0.8 \)**
Fig 10. Pressures ensemble-averaged over 1 s, 10 s, 15 s, 20 s, 25 s and 30 s for different $\tau_p$ at Section 8

f) $\tau_p=0.99$

a) $\Psi = 0^\circ$

b) $\Psi = 72^\circ$
Fig. 11 Convergence of phase-locked-averaged pressure distribution with different times ($\tau_p=0.4$)
Fig 12. Phase-locked-averaged pressures compared with ensemble-averaged pressures for different \( \tau_p \).
In this test, the sampling frequency of the Kulite pressure-transducer is 5000Hz with consecutive sampling time 30s, and the pulsed modulating frequency is 50Hz. Thus, there are 100 phase angles in one pulsed modulating period. Every phase angles has 1500 sampling data in 30s. Figure 11 presents phase-locked-averaged pressure distributions with sampling times of 1s, 10s, 15s, 20s, 25s and 30s at five evenly distributed phase angles $\Psi = 0^\circ, 72^\circ, 144^\circ, 216^\circ,$ and $288^\circ$ for $\tau_p=0.4$. Each of phase angle is convergent when the sampling time is 30s except the azimuth angles $\theta=160^\circ$ to $240^\circ$ at $\Psi=144^\circ$. This is because the location of the region of azimuth angles $\theta=160^\circ$ to $240^\circ$ is in the middle of two separated vortices and more sensitive to small perturbations. This phenomenon shows the unsteady characteristics of this experiment with single-pulsed discharge. Overall, the convergence of phase-locked-averaged pressure distributions is well in this test.

Figure 12 presents the phase-locked-averaged pressure distributions at five evenly distributed phase angles $\Psi = 0^\circ, 72^\circ, 144^\circ, 216^\circ,$ and $288^\circ$, compared with the ensemble-averaged pressure distributions at Section 8. The phase-locked-averaged pressure distribution almost coincides with the ensemble averaged pressure distribution at each $\tau_p$ except the region of azimuth angles $\theta=160^\circ$ to $240^\circ$ at $\tau_p=0.01$ and $\tau_p=0.4$. The pressure distributions haven’t changed with the duty-cycle actuations. In one pulsed period, the working time of plasma actuator is $\tau_p$ and the off time is $1-\tau_p$. So, if the response of flow is instantaneous for the plasma actuator, the pressure distributions should be different and the stronger suction peaks should be changed when the plasma actuator is off. Compared with Figure 12, there is no obvious difference between the ensemble-averaged and phase-locked-averaged pressure distributions. And the result is different from the Ref. 5-6. It is shown that the response of flow is hysteresis of the pulsed modulating frequency.
c) \( \tau_p = 0.4 \)

d) \( \tau_p = 0.6 \)

e) \( \tau_p = 0.8 \)
Fig 13. Phase-locked-averaged local side force compared with ensemble-averaged local side force for different $\tau_p$ at Section 8

Figures 13 shows convergence of the phase-locked averaged local side force coefficient $c_{Yd}$ with sampling time from 1s to 30s at duty cycle $\tau_p = 0.01, 0.2, 0.4, 0.6, 0.8, 0.99$. The time of $t/T = 0$ is set, by estimation, at the beginning of the plasma actuation. The corresponding ensemble averaged local side force coefficient $C_{Yd}$ is shown by dotted line in the figures. The value of the ensemble-averaged local side force $C_{Yd}$ is, in fact, the average of the phase-locked $c_{Yd}$ over a period of the duty cycle. Large fluctuations are observed at small averaging times, because at a given phase angle of the duty cycle there are only 50 samples per second (from the pressure transducer) to be averaged. However, by comparing the results of various averaging times, those of the 30s are approaching a limit, which is given by ensemble averaged local side force coefficient. The variation of the phase-locked averaged side force with time, $c_{Yd}(t)$ for a given duty cycle is a small smooth-wave curve. But, the variation don’t follow the plasma duty cycle actuation. There is no big variations with different phase angle when the status is changed in a period of duty cycle actuation. The results are different from the Ref. 5-6. Thus, it also proves that the response of flow is hysteresis of the pulsed modulating frequency.

IV. Conclusion

The results show that we can use single-pulsed discharge with different duty-cycle ratios to achieve linear proportional control of asymmetrical force and moment over slender conical forebody. The linearity of the controlled lateral forces and moments with respect to the duty cycle is improved over previous studies because of the higher pulsed modulating frequency and improved design of the actuators.

Under pulsed modulating frequency 50Hz, both ensemble averaged and phase-locked averaged pressure distributions at Section 8 have reached convergence. The phase-locked averaged pressure distributions and local side force show that the response of flow is hysteresis of the pulsed modulating frequency.

Acknowledgments

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References


