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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 differet sections. The test result shows we can use port single-pulsed discharge to achieve the linear proportional contol 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	=	yawing moment coefficient about cone base, yawing moment/q_∞SD
C_p	=	pressure coefficient
C_{Nd}	=	overall side-force coefficient, overall side force/q_∞S
C_{Yd}	=	ensemble-averaged local side-force coefficient, local side force/q_∞d
c_{Yd}	=	phase-locked averaged local side-force coefficient
D	=	base diameter of circular cone forebody
d	=	local diameter of circular cone forebody
F	=	frequency of a.c. voltage source
f	=	frequency of duty cycle
L	=	length of circular cone forebody
q_∞	=	free-stream dynamic pressure
Re	=	free-stream Reynolds number based on D
S	=	base area of circular cone forebody
T	=	period of duty cycle
t	=	time of duty cycle
U_∞	=	free-stream velocity
V_{p-p}	=	peak-to-peak voltage of a.c. voltage source
w	=	input power of a.c. voltage source
x, y, z	=	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.[4-6] 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 addtion, The cone tip of length 150 mm is made of plastic for plasma-actuator accommondation.

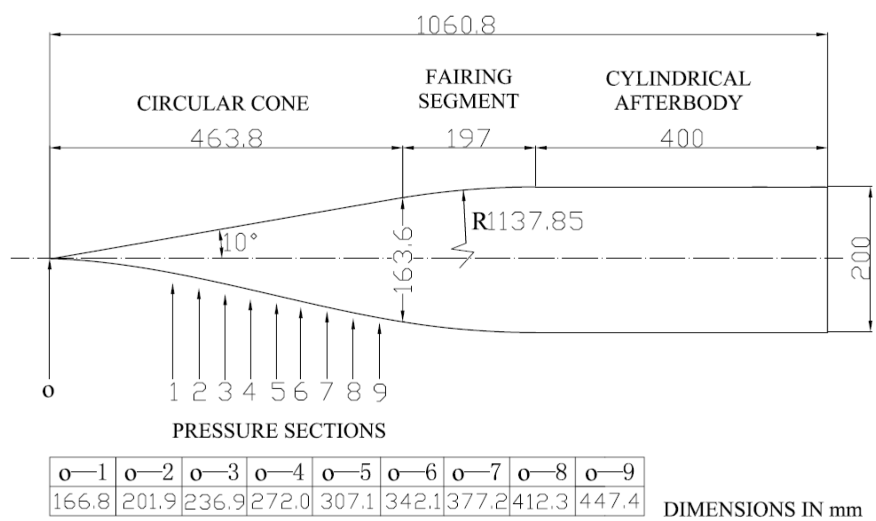
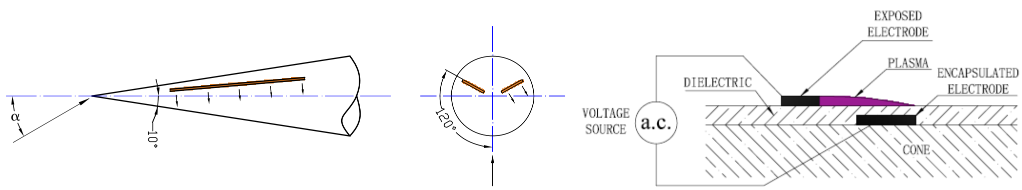


Fig 1. Test model

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 θ 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.



a) arrangement b) SDBD

Fig.2 Sketches of the plasma actuators

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 α = 35° . The free-stream velocity U_∞ = 5 m/s. The Reynolds number based on the cone base diameter is 5×10^4.

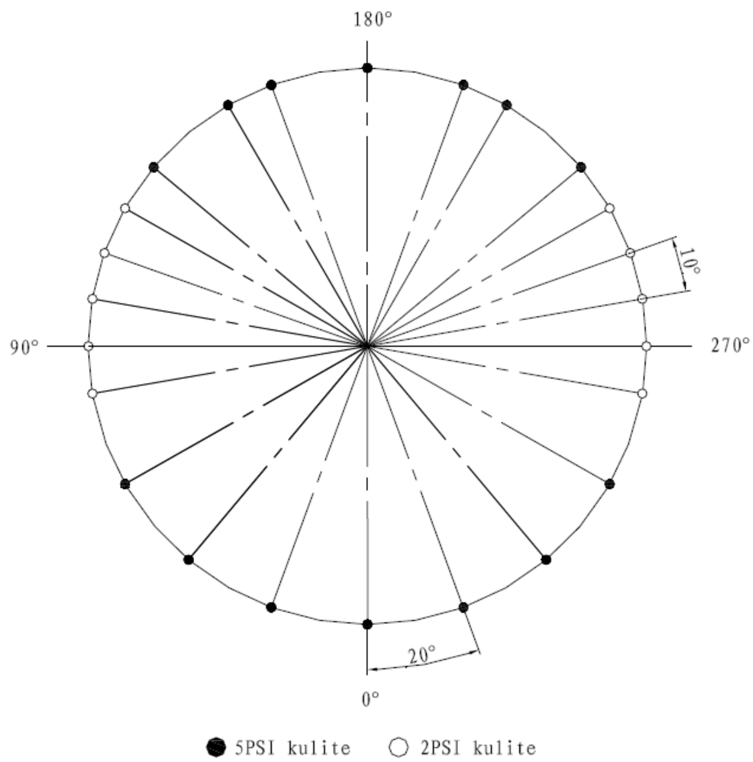


Fig 3 The distribution of unsteady pressure tappings

The 288 time-averaged pressure tappings are arranged in rings of 36, every 10° around the circumference of the cone, at all sections except Section 8. The time-averaged pressure tappings are Models 9816 by the PSI Company, which sample at frequency of 100 Hz. The Consecutive sampling time of steady pressure tappings is 15 seconds. In addition, 24 unsteady pressure tappings are mounted around the circumference of Section 8 as shown in Fig. 3. The unsteady pressure tappings are ten Model XCS−093-2D and fourteen XCS−093-5D by the Kulite Semiconductor Products Inc. with sampling frequency of 5000 Hz. Input pressure range is 2psi and 5psi, respectively. The perpendicular acceleration sensitivity % FS/g are both 1.5×10^{-3}. The Consecutive sampling time of unsteady pressure tappings is 30 seconds.

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_∞ = 5 m/s in the present study. The corresponding Reynolds numbers based on the cone base diameter are 5×10^4. Fig. 4 presents the pressure distributions at plasma off, U_∞ = 5 m/s and α = 0°. 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.

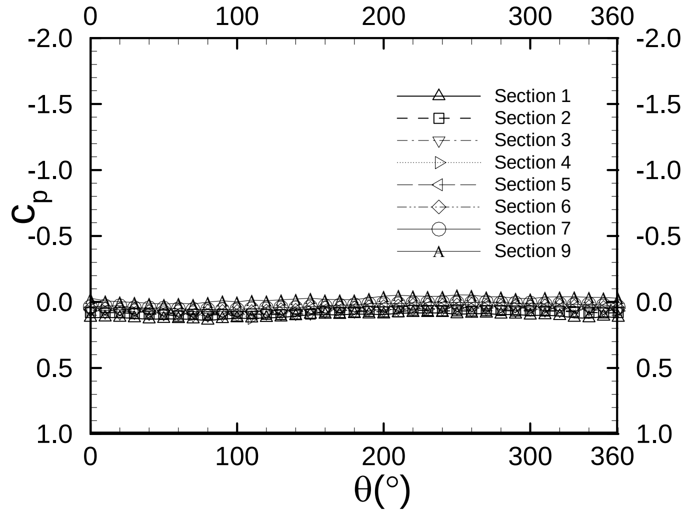


Fig 4. Pressure distributions over various sections for plasma off at α = 0° and U∞ =5 m/s

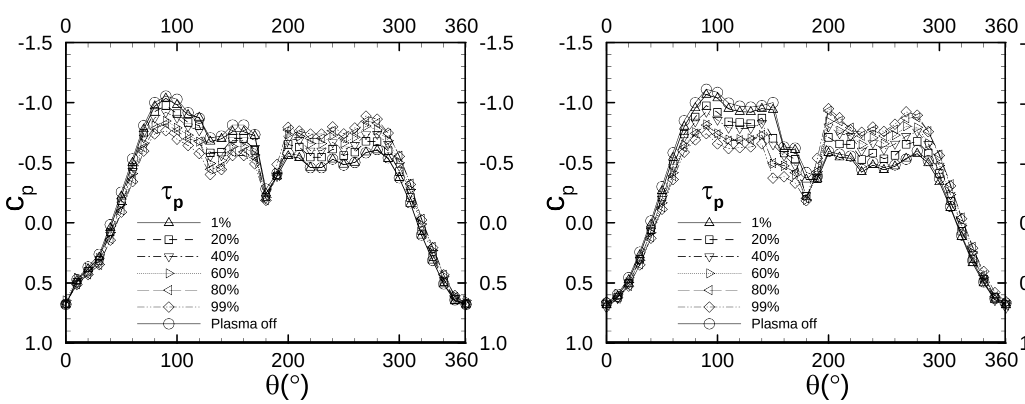
B. Steady measurement results

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 kV and $F \approx$ 11.8 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 1. Input power versus periodic-pulse duty ratio

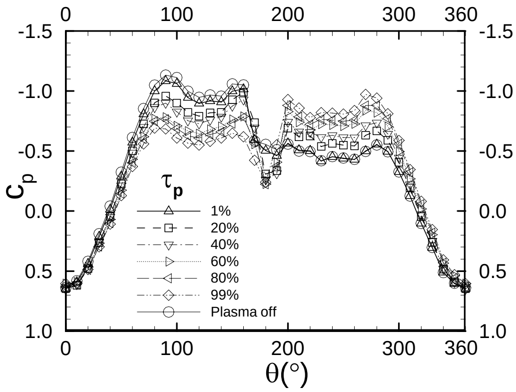
Duty cycle (τ)	0.01	0.2	0.4	0.6	0.8	0.99
Input voltage （V）	18	18	18	18	18	18
Input current （A）	0	0.15	0.33	0.57	0.74	0.82
Input power （W）	0	2.70	5.94	10.26	13.32	14.76

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 cnotrol of asymmetrical vortices can be also achieved by single-pulsed discharge with different duty cycle ratios.

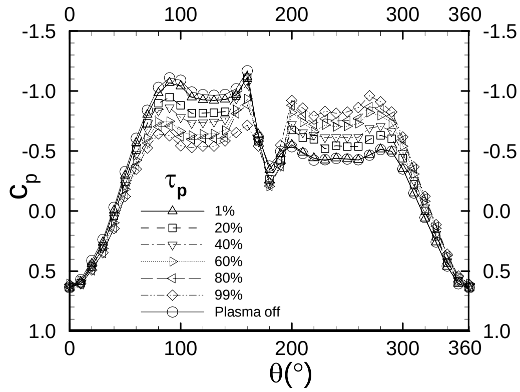


a) Section 1

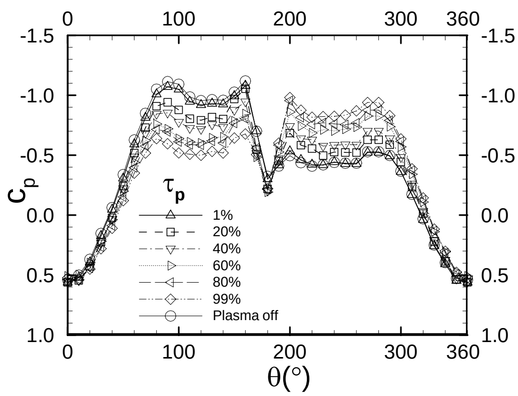
b) Section 3



c) Section 5



d) Section 7



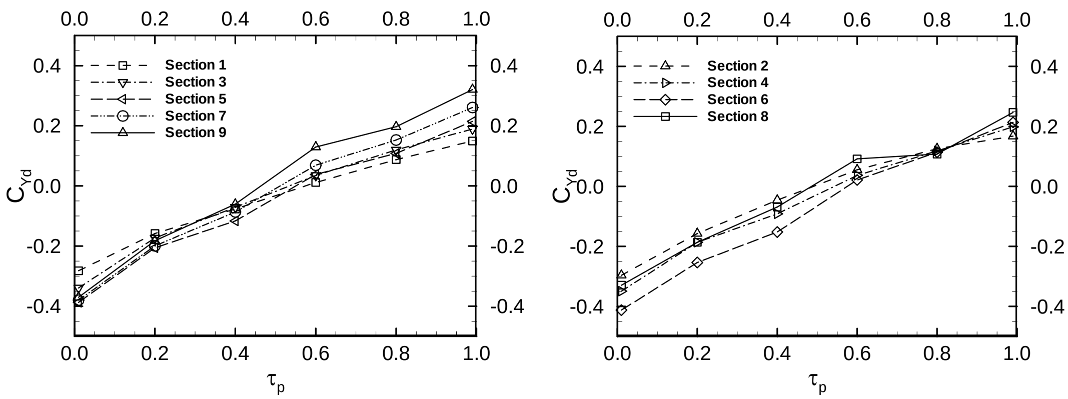
e) Section 9

Fig. 5 Circumference pressure distribution variations with different duty cycle ratios in odd sections

The results of τ_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 τ_p=0.6 are almost symmetric, and the local side force C_{Yd} is nearly 0. The pressure distributions for τ_p=0.01 and τ_p=0.99 switch in the bistable mode. But, it is not strictly anti-symmetric. The port side suction peak of τ_p=0.01 is stronger than the starboard side suction peak of τ_p=0.99.

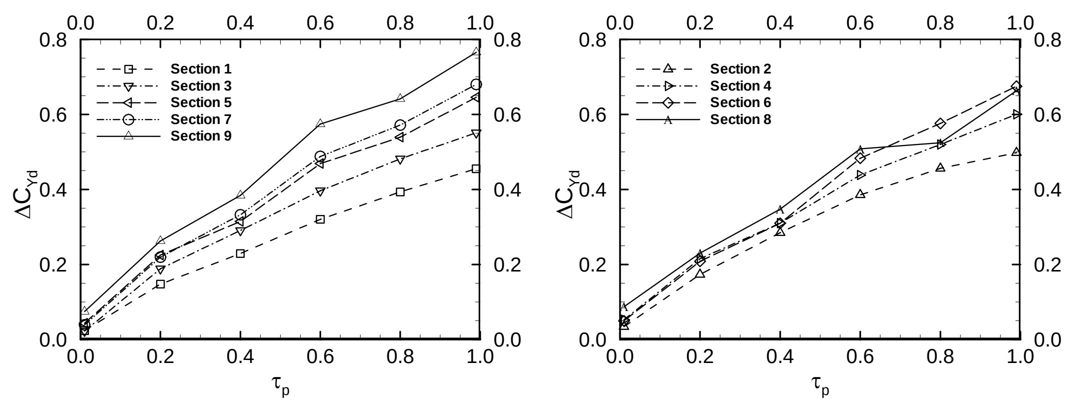
Figure 6 presents the local side force as τ_p is increased from 0.01 to 0.99 for odd sections and even sections. Figure 7 compares the increment of local side force as τ_p is increased from 0.01 to 0.99 for odd sections and even sections. The increment of local side force ΔC_{Yd} is the local side force 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 ΔC_{Yd} show good linearity, and the more close to the head of cone , the better the linearity is.

The overall side force coefficient C_Y 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 dirrerent 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_Y at the duty cycle ratio, τ_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=50Hz higher than previous studies[4-6] f=10Hz. The other reason is the improved design of the actuators.



a) odd sections b) even sections

Fig. 6 Local side force coefficient variations with different duty cycle ratios



a) odd sections b) even sections

Fig. 7 The increment of local side force coefficient variations with different duty cycle ratios

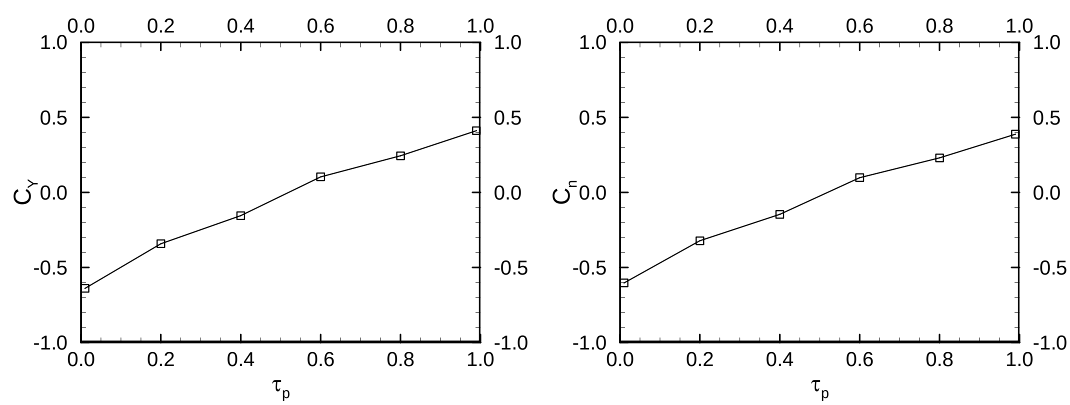


Fig. 8 The variations of overall side force and yawing moment coefficients on cone with different duty cycle ratios

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.

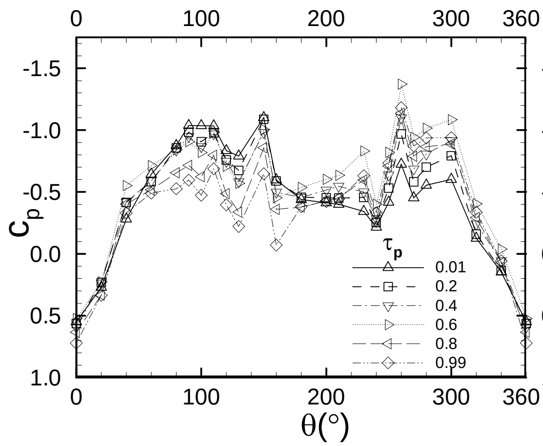
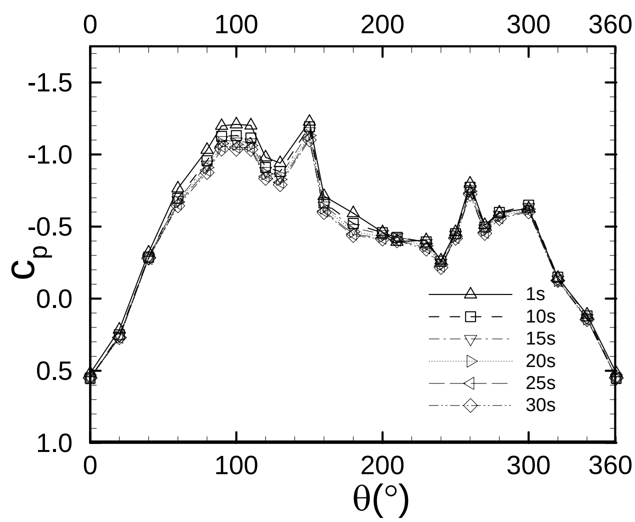
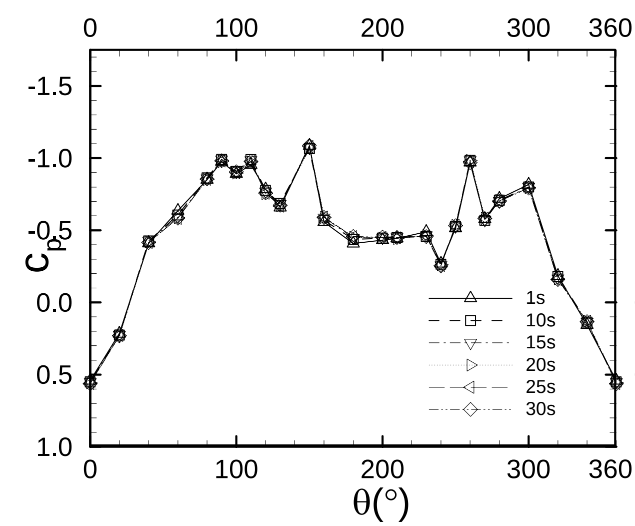


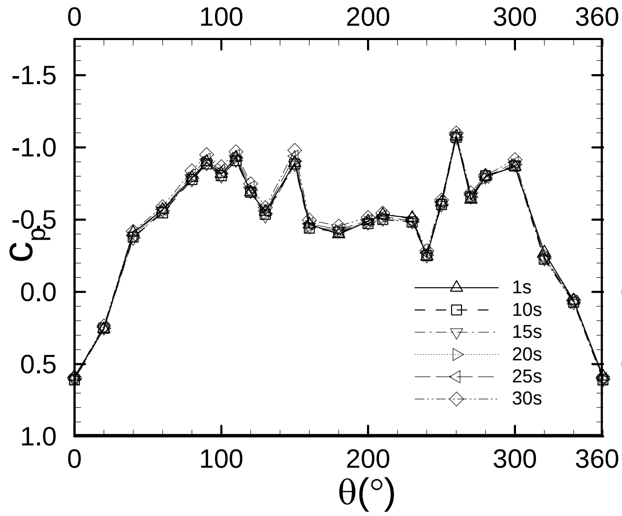
Fig. 9 Ensemble-averaged pressure distributions with different duty cycle ratios at Section 8



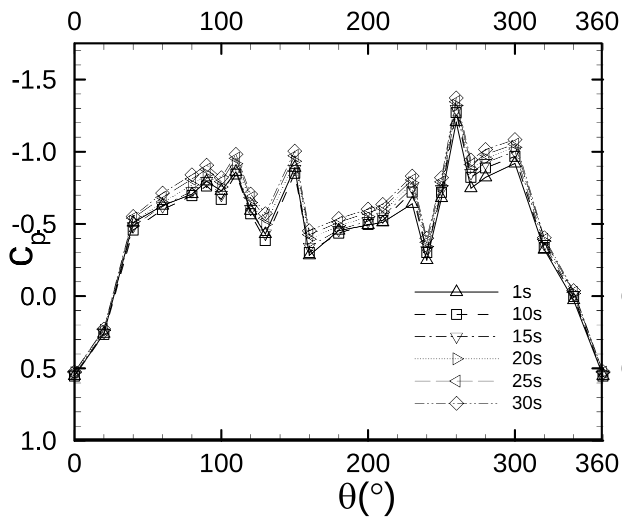
a) τ_p=0.01



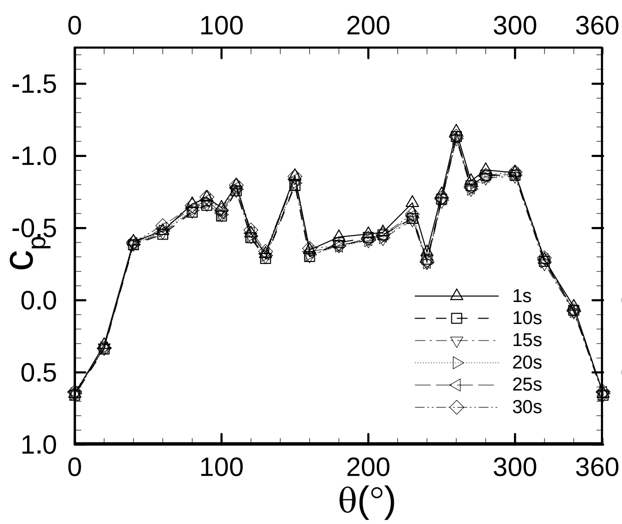
b) τ_p=0.2



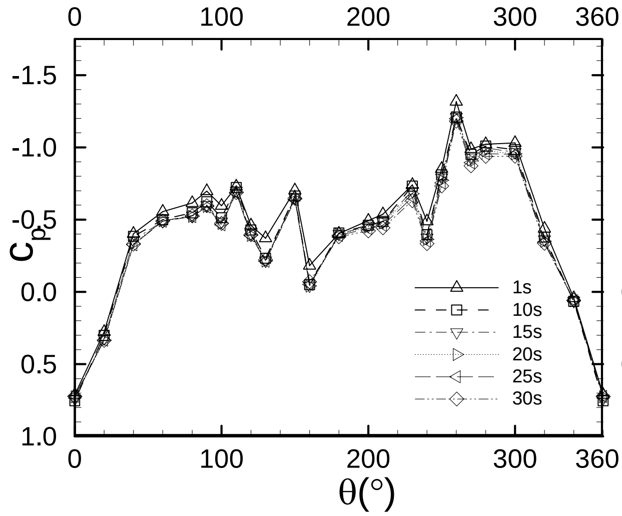
c) τ_p=0.4



d) τ_p=0.6

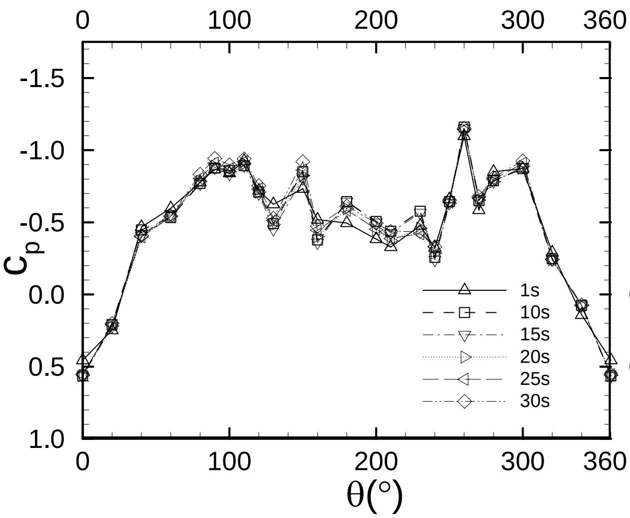


e) τ_p=0.8

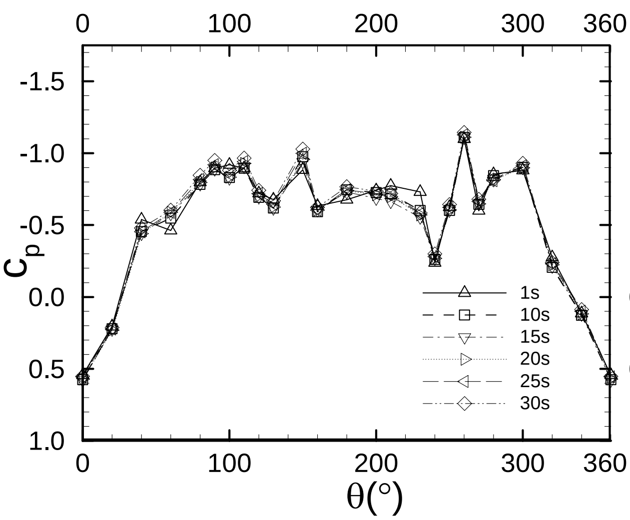


f) τ_p=0.99

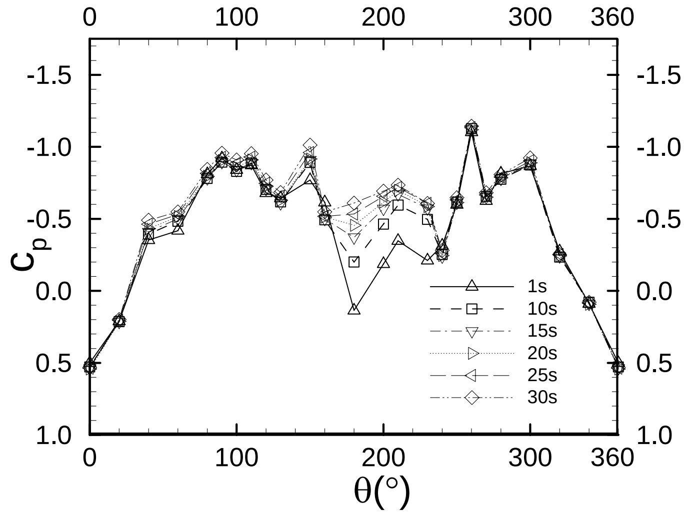
Fig 10. Pressures ensemble-averaged over 1 s, 10s, 15 s, 20s, 25s and 30 s for different τ_p at Section 8



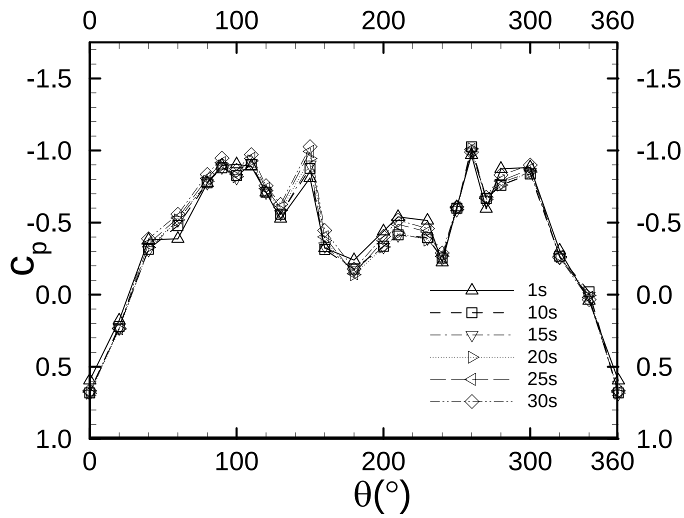
a) Ψ = 0°



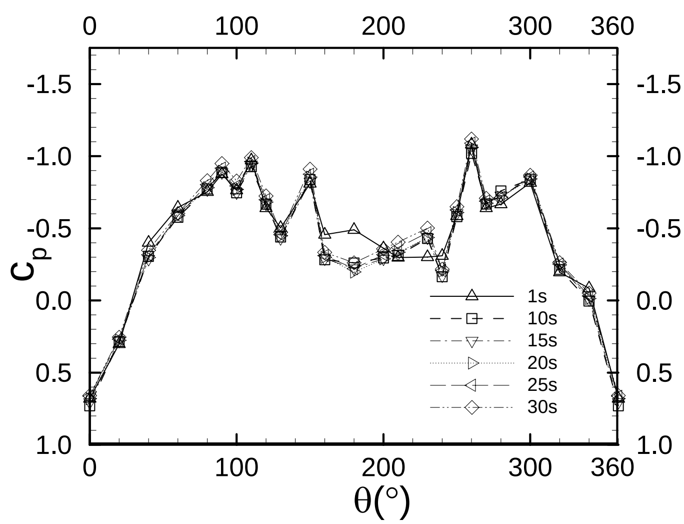
b) Ψ = 72°



c) Ψ = 144°

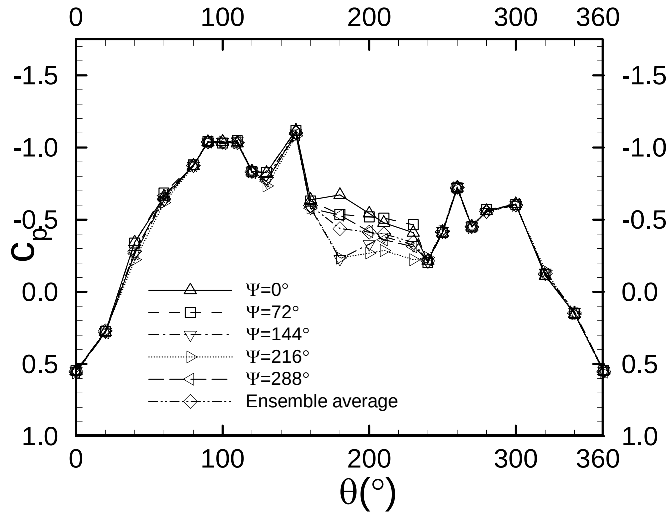


d) Ψ = 216°

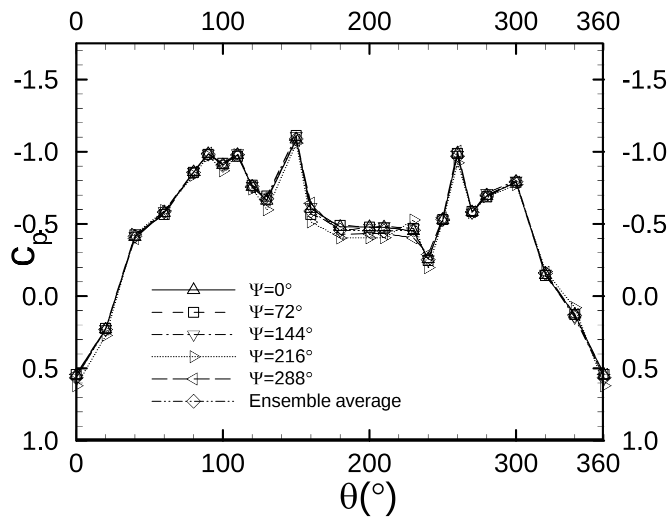


e) Ψ = 288°

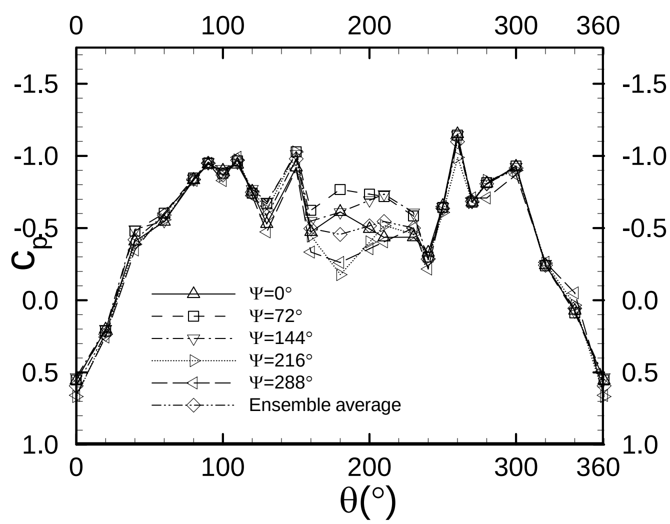
Fig. 11 Convergence of phase-locked-averaged pressure distribution with different times（τ_p=0.4）



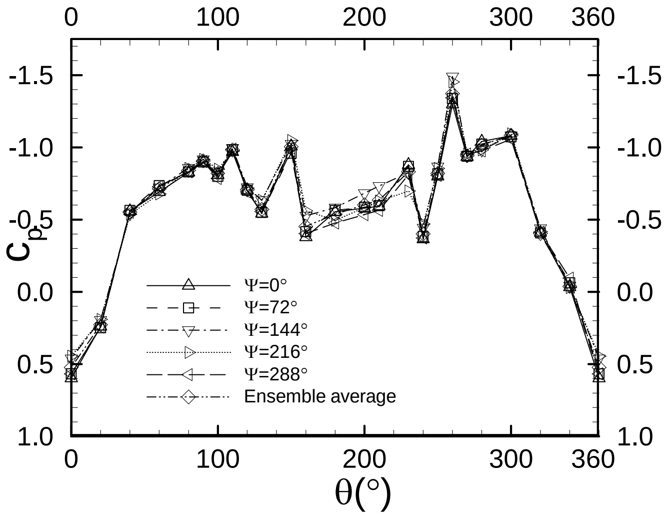
a) τ_p=0.01



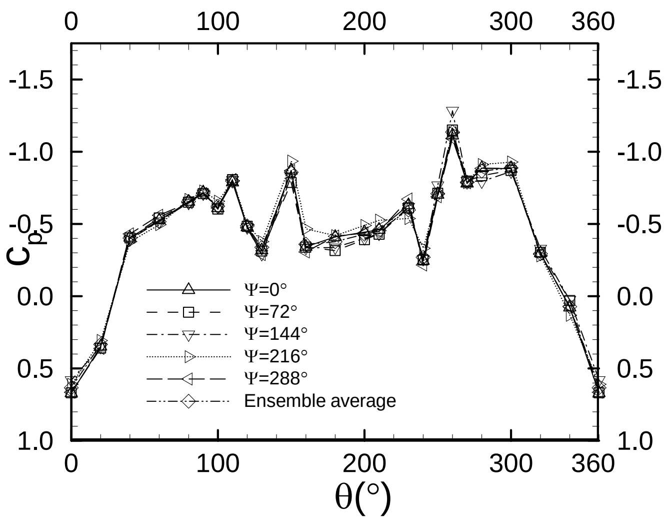
b) τ_p=0.2



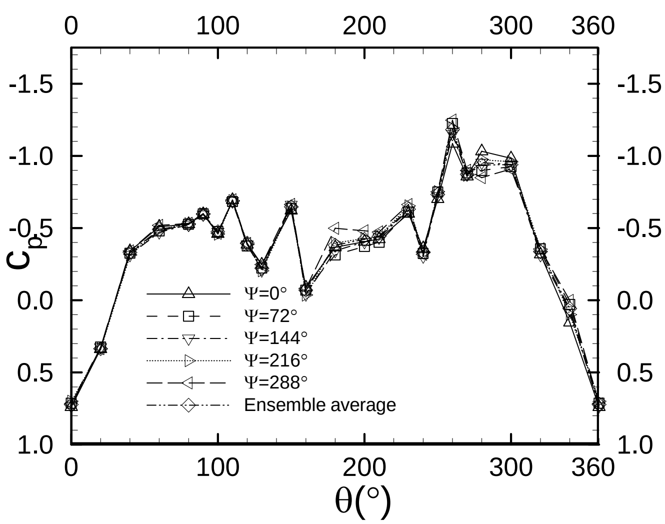
c) τ_p=0.4



d) τ_p=0.6



e) τ_p=0.8

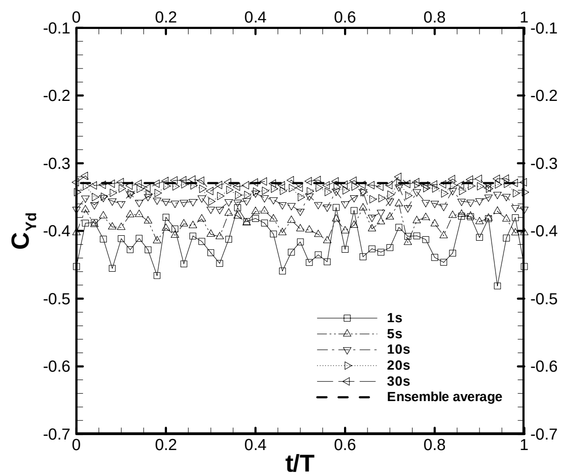


f) τ_p=0.99

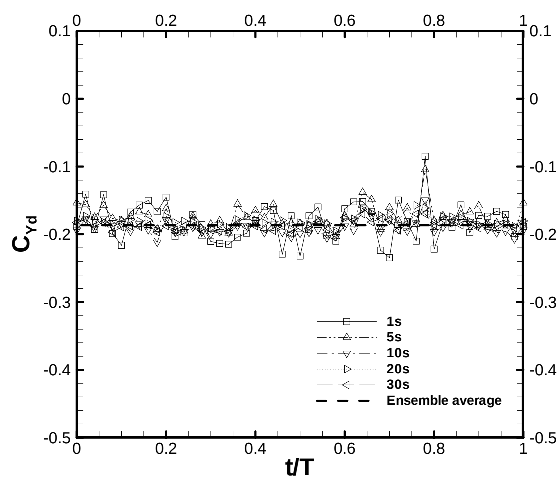
Fig 12. Phase-locked-averaged pressures compared with ensemble-averaged pressures for different τ_p

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 Ψ= 0°, 72°, 144°, 216°, and 288° for τ_p=0.4. Each of phase angle is convergent when the samling time is 30s except the azimuth angles θ=160° to 240° at Ψ=144°. This is because the location of the region of azimuth angles θ=160° to 240° 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.

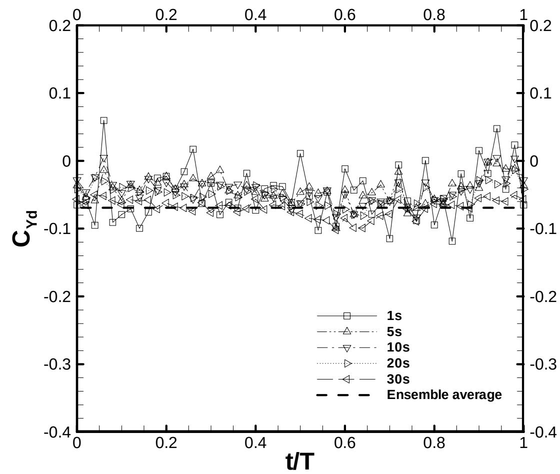
Figure 12 presents the phase-locked-averaged pressure distributions at five evenly distributed phase angles Ψ = 0°, 72°, 144°, 216°, and 288°, compared with the ensemble-averaged pressure distributions at Section 8. The phase-locked-averaged pressure distribution almost coincides with the ensemble averaged pressure distribution at each τ_p except the region of azimuth angles θ=160° to 240° at τ_p=0.01 and τ_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 τ_p and the off time is 1-τ_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.



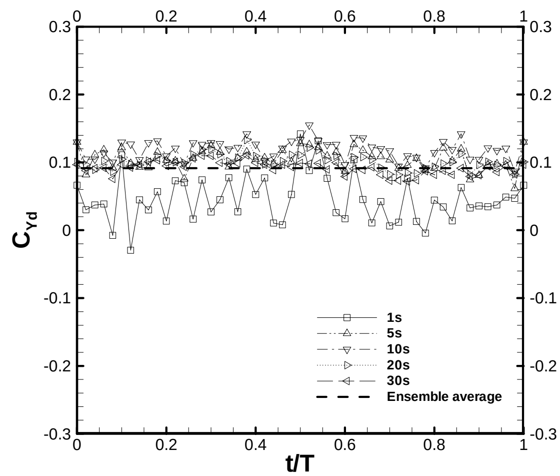
a) τ_p=0.01



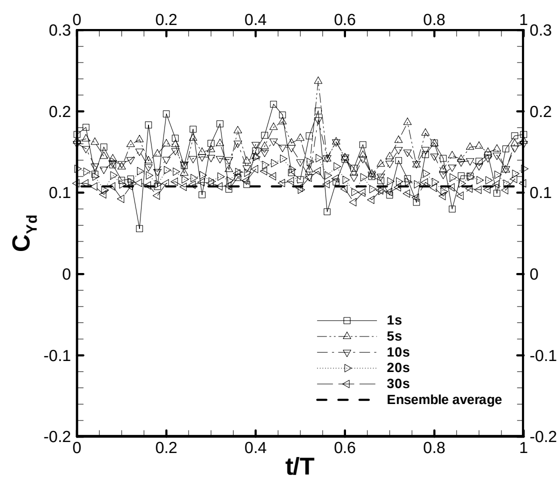
b) τ_p=0.2



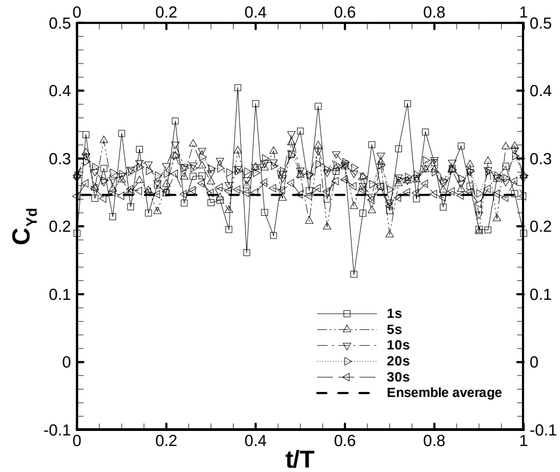
c) τ_p=0.4



d) τ_p=0.6



e) τ_p=0.8



f) τ_p=0.99

Fig 13. Phase-locked-averaged local side force compared with ensemble-averaged local side force for different τ_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 τ_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 transduer) 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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