FOREBODY VORTEX CONTROL ON HIGH PERFORMANCE AIRCRAFT USING PWM-CONTROLLED PLASMA ACTUATORS

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Abstract

The active flow control technology to manipulate forebody vortices on a slender tangent ogive nose body is being developed. The plasma actuators are being used to exploit the bi-stable nature of the asymmetric forebody vortex wake for lateral/directional control in low-speed and high-angle-of attack regimes. The experiments have confirmed that the plasma actuator can be used to displace the vortex on the forebody model by the Coanda effect. The results of the force and moment measurement indicate that this displacement could successfully generate significant change in their side force, which could be utilized to extend maneuvering flight envelop for future fighter designs.

1 Introduction

The nose portion of the fuselage on many modern fighter aircraft consists of a long slender pointed forebody. As the angle of attack of the aircraft is increased, the flow around the forebody separates, as shown in Fig. 1. The forebody vortices are initially symmetric but become asymmetric at some critical angle of attack.

When the vortices are symmetric, they influence the normal force and pitching moment contribution of the fuselage to the airplane aerodynamics. When the vortices become asymmetric, a side force and yawing moment are created, as illustrated in Fig. 2. Because of the reduction of directional stability in this regime, the yawing moment created by the asymmetric vortices can cause the airplane to yaw rapidly to the right or left. The direction of motion depends upon the orientation of the asymmetric vortices. The rapid yaw divergence is commonly called “nose slice” and may lead to a spin departure. Factors that contribute to the yaw divergence are loss of directional stability, asymmetric yawing moments and adverse yaw.

In the regime that the forebody vortices form asymmetric configuration, the directional stability and control of a fighter aircraft diminishes, primarily due to the influence of the fuselage wake on the vertical tail surface. As the angle of attack is increased, more and more of the vertical tail is immersed in the separated flow field coming off the fuselage. This flow field reduces the effectiveness of the vertical tail as well as the rudder. The ailerons also begin to lose their effectiveness due to stall over the outboard wing panels. The loss of directional stability can lead to a yaw divergence and entry

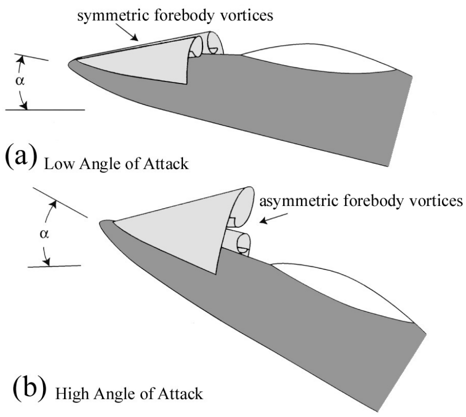


Fig. 1. Forebody flow separation[1].

into a spin[1]. These flow features suggest the possibility of directional control only using forebody vortices for the high angle of attack flight. Malcolm[2] illustrates the loss of aerodynamic control from the rudder versus the potential control power that could be achieved from forebody flow control.

In the past several decades a great deal of research has been devoted to develop ways of exploiting the bi-stable nature of the asymmetric wake to increase aircraft control capability at large angles of attack. In a review article by Malcolm[2], some of the earlier flow control concepts was introduced. The concepts included movable strakes, blowing surface jets, blowing and suction slots, suction through surface holes and miniaturized tip strakes. Many of these concepts have been successful in the laboratory and a few have even been successfully tested on experimental flight vehicles. However, active flow technology has not as yet been incorporated on a production aircraft. This is most likely do reliability and other practical design issues. Clearly there is a need for a practical flow control concept that can be implemented on slender high performance fighters, such a scheme would allow an extension of the maneuvering flight envelop for future fighter designs.

1.1 Concept of forebody flow control using plasma actuators

At Tottori University, in collaboration with the Center for Flow Physic and Control at the University of Notre Dame, research study is underway to investigate the manipulation of forebody vortices on a slender tangent ogive nose body through active flow control technology. In this research SDBD plasma actuators, which is actively being developed at the University of Notre Dame[3-6], are being used to exploit the bi-stable nature of the asymmetric forebody vortex wake for lateral control.

Our research program is focusing on a control concept that would use SDBD plasma actuators on the port and starboard of the nose to rapidly switch the forebody vortices back and forth between the two stable states. Fig. 3 is a sketch that illustrates the proposed concept. By varying the duty-cycle parameter between stable states a time average load can be created. The magnitude of side force and yawing moment should be proportional to the duty cycle parameter τ/T, where τ is the time that the flow is in one stable state during the period, T, of one cycle of the actuators. Using small jets located near the nose of slender forebody model, Lee[7] has shown that the side force varies linearly with the duty cycle. In this research, the feasibility of the concept of forebody vortex control using plasma actuator is tested and the

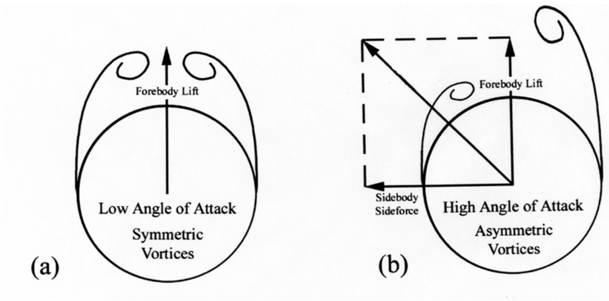


Fig. 2. Cross-sectional flow patterns on a slender forebody.

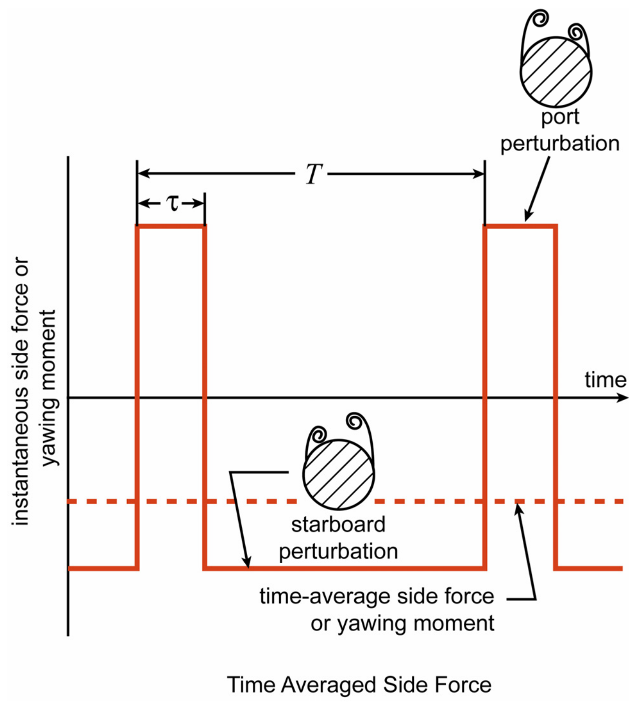


Fig. 3. Time-average side force created by varying the duty cycle parameter.

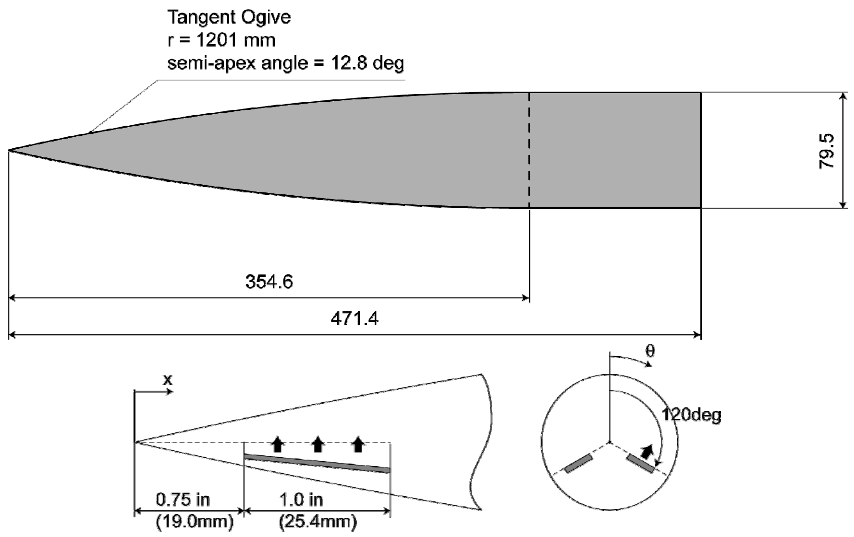


Fig. 4. Forebody model.

above mentioned pulse-width-modulation method to attain linear directional characteristics in high angle of attach regime is developed.

2 Experimental Setup

The wind tunnel experiments have been conducted in the subsonic open-return wind tunnel in the Hessert Laboratory at the University of Notre Dame and the low speed wind tunnel at Tottori University. The wind tunnel at Notre Dame has a closed test section of 0.61 x 0.61m in cross section and 1.8m in length. The wind tunnel at Tottori University has an open test section of 1.0 x 0.7m in cross section and about 2.0m in length.

The forebody model selected for this study is shown in Fig. 4. It was designed so that it could be mounted to a five component internal balance. The nose portion of the model includes two 1 inch plasma actuators located at the +120 degrees from the leeward meridian. In Fig. 5 one can see the model with the actuators and a close-up view of the actuators when they are on. The blue glow of the ionized air created by the actuator is clearly visible.

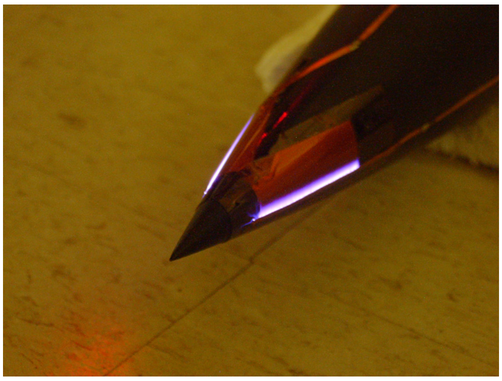


Fig. 5. Glow from the ionized air created by the plasma actuators.

Figure 6 shows a schematic of the power supply used to generate the plasma. A reference waveform of a high-voltage AC input is generated by a function generator and amplified by a solid state high power amplifier, which increases the input power up to 100 W with the amplitude of 70Vpp. Via high voltage transformer the AC input attains the amplitude up to 20kV with a frequency of 5-15kHz. The voltage and current of the AC input was monitored by an oscilloscope, with the reference waveform from the function generators or an output of a force balance.

In this experiment we controlled the duty cycle of the actuation period between the port

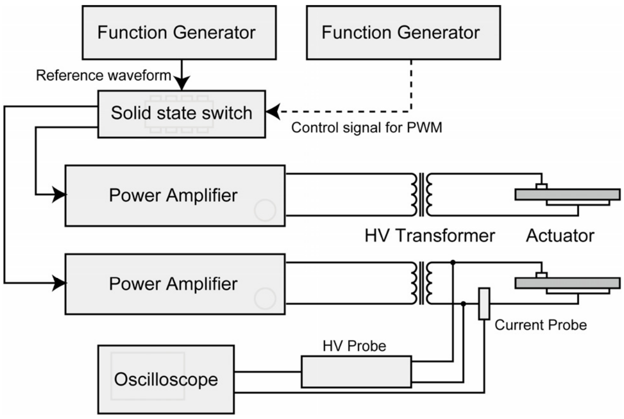


Fig. 6. Schematic of the power supply for plasma actuator.

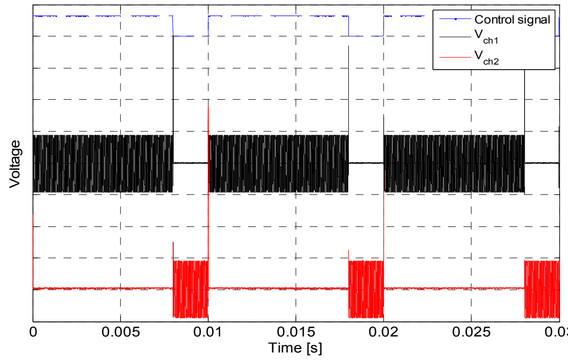


Fig. 7. Input voltage of a PWM actuation, τ/T =0.8.

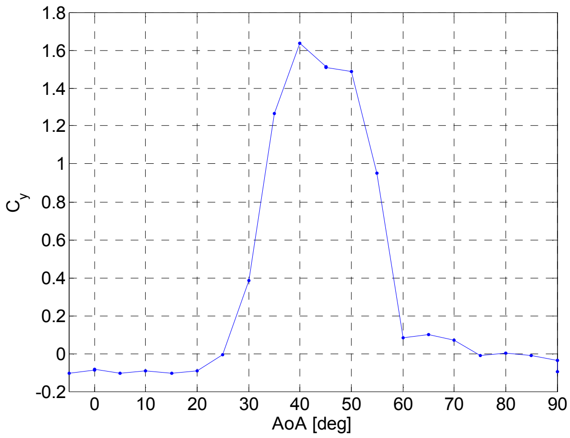


Fig. 8. Side force coefficient vs. angle of attack for the current forebody model.

and starboard actuators. Fig. 7 is an example of this input waveform for port and starboard pulse-width-modulation (PWM) actuation, with the duty cycle of 0.8. In this paper the duty cycle is defined as Fig. 3 shows, that is the period of the port actuation is represented as τ.

In addition to the experiments for the forebody model, the two-dimensional circular cylinder model (60mm diameter) was employed for this research. That model was mainly used for the flow visualization to examine the unsteady response of the motion of the wake vortices during PWM actuation.

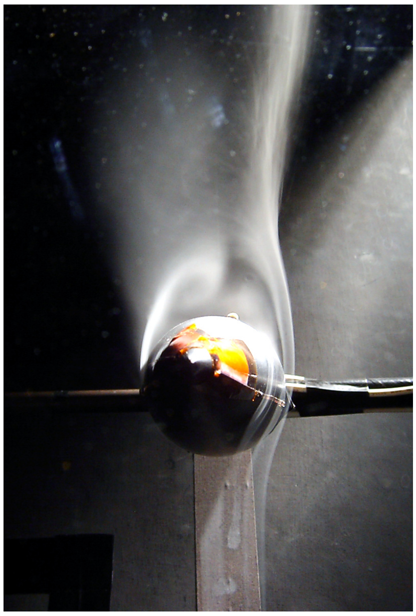
3. Discussion of experimental data

The flow visualization experiments and force and moment measurements have been carried out for an evaluation of the effectiveness of the plasma actuators for forebody vortices.

By the characteristics of side force about angle of attack, shown in Fig. 8, it is clear that the forebody vortices on the model was set asymmetrically between α=25~60deg. Fig. 9 shows the flow visualization of the forebody vortices with and without actuation of the plasma actuator at the angle of attack is 64 deg. In this case the actuator was actuated on the port side of the model (right hand side in these photographs). The smoke pattern clearly shows a difference in the location of the vortices when the actuators are off or on. At these conditions, the vortex on the actuator side reattached when the actuator was on, thereby creating a negative side force similar to that described in Fig. 2(b).

The influence of the input voltage to the actuator on the side force coefficient is shown in Fig. 10. The measurement was carried out under the condition that the AoA is equal to 45deg and the freestream velocity of 9.22m/s (Re = 0.5×10^5). AC frequency for generating plasma was set to 11 kHz at this experiment. The input voltage is peak-to-peak value of the voltage charged to the actuator. In this figure it is observed that by port actuation the side force coefficient Cy goes negative. As in the flow visualization, negative side force indicates that the port vortex is placed closer to the model surface, which agrees with the expected

a) Plasma Actuator off



b) Plasma Actuator on

Fig. 9. Flow visualization of the forebody vortices.

mechanism by the Coanda effect. This observation also agrees with the results of the experiment on the small jets by Lee[8].

The responses of the aerodynamic loads to the unsteady actuation primarily depend on the response of the vortex motion to the actuation. Fig. 11 is an example of the flow visualization of the wake vortex of the circular cylinder model during the unsteady actuation. In this case their response to the plasma actuation was significantly rapid compared to the characteristic time of natural wake vortex. This suggests that the modulation frequency of the plasma actuation could be independent from the natural frequency in the PWM actuation.

Figure 12 is the time response of the side force coefficient Cy during the PWM actuation for the forebody model with the angle of attack of 61 deg. The modulation frequency was set at 20Hz at these cases. The duty cycle $\tau/T=0.7$. Obviously the side force responds to the modulated actuation and there is a certain time lag in the response. In this case the typical time lag is 15ms, which is significant compare to the modulation frequency. We also observed that the side force failed to respond to the actuation when the duty cycle came to 0.8 or greater. This

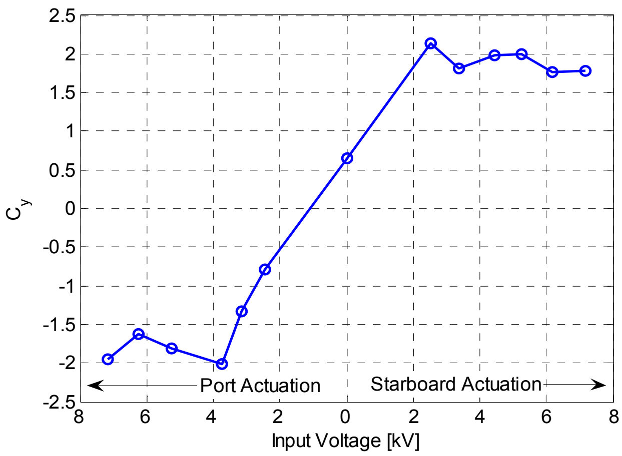
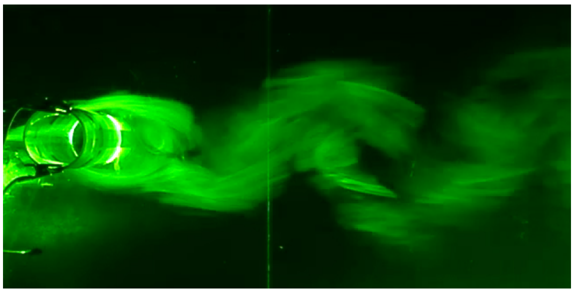
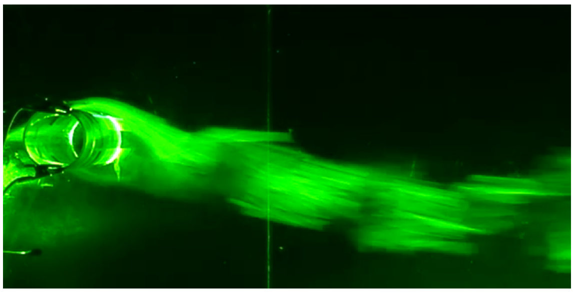


Fig. 10. Change in Cy versus voltage to the plasma actuator.

occurs due to the short period of actuation compared to the large time lag the motion has. This indicates that the performance of PWM actuation for linear aerodynamic control strongly depends on the modulation frequency.



(a) Plasma actuator off ($t=t_0$)



(b) Plasma actuator on ($t=t_0+33.3$ms)

Fig. 11. Flow visualization of the wake vortex with the plasma flow control.

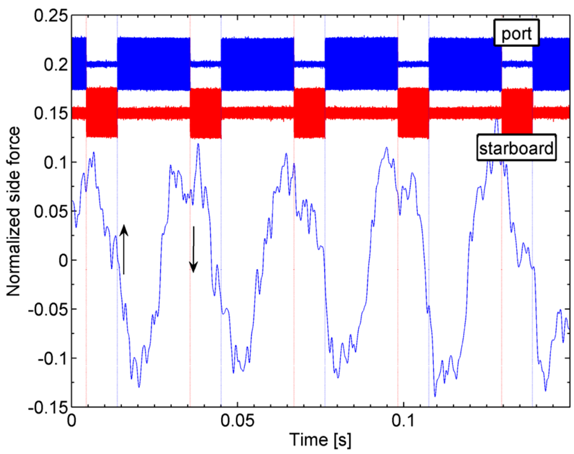


Fig. 12. Cy Response by PWM actuations of the plasma actuators: t/T =0.7.

4. Summary

The active flow control technology to manipulate forebody vortices on a slender tangent ogive nose body is being developed. The plasma actuators are being used to exploit the bi-stable nature of the asymmetric forebody vortex wake for lateral/directional control in low-speed and high angle of attack regimes. The initial experiments have confirmed that the plasma actuator can be used to displace the vortex on the forebody model by the Coanda effect. The results of the force and moment measurement indicate that this displacement could successfully generate significant change in their side force, which could be utilized to extend maneuvering flight envelop for future fighter designs.

In the next phase for this project, the magnitude of the time-averaged side force and yawing moment will be measured as a function of the duty cycle, as well as the unsteady responses of them, and compared to the jet blowing experiments conducted by Lee.

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