VISUALIZATION AND CONTROL OF FORE-BODY VORTICES

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ABSTRACT

A preliminary experimental study was conducted to assess the feasibility of using active flow control to manipulate the bi-stable nature of the asymmetric fore-body vortices on a slender ogive nose body. Single-Dielectric Barrier Discharge (SDBD) plasma actuators were used to switch the asymmetric wake pattern from one stable state to the other. By varying the time parameter between the two stable states in a given cycle a time average side force and yawing moment were created on the body that could be used for controlling high performance aircraft at large angles of attack where aerodynamic controls become ineffective. Flow visualization was an integral part of this study and was used to help in properly locating the actuators on the body surface and to visualize how the wake reacted to the actuators. Both surface oil flow visualization and off surface smoke flow visualization techniques were used to study the effectiveness of manipulating the fore-body vortices.

INTRODUCTION

The flight boundaries of modern aircraft have been extended to meet the increased requirements for greater maneuverability. The demand for greater maneuverability requires flight through large angles of attack where the separated flow field is dominated by vortical structures. The flow field around a slender fore-body configuration such as the forward portion of a modern fighter aircraft can be characterized by four separate flow regimes [1]. Figure 1 is a sketch of the flow field around a body of revolution at various angles of attack. As the figure illustrates, the wake is composed of two symmetric vortices in the moderate angle of attack range. As the angle of attack is increased, the starting position of the vortices moves toward the nose. Increasing the angle of attack to the range of 20-50 degrees, the vortex pattern is typically asymmetrical but steady. Also it should be noted that the appearance of more than two body vortices is possible on long slender bodies. Further increases in angle of attack to the 50-70 degree range, results in an unsteady asymmetric pattern that when viewed in the cross flow plane resembles the classic von Karman vortex street. Finally in the range of 70-90 degrees the wake is essentially turbulent. The ranges shown in Figure 1...
are qualitative in nature and therefore should not be construed as absolute criteria for transition from one regime to another. The transition actually depends upon several factors. They are the cross-flow Mach number, cross-flow Reynolds number, nose shape, and nose fineness ratio [2-7].

![Figure 1. Vortex patterns on a fore-body shape as a function of angle of attack.](image)

The flight regime for which there is the most practical interest for modern fighter aircraft is the region where the fore-body wake is dominated by either steady symmetric or asymmetric vortices. The occurrence of vortex asymmetry in the flow gives rise to large side force and yawing moment on the body for a symmetric flight condition (no sideslip). The interaction of the asymmetric wake with aft tail surfaces can also produce large induced rolling moments. Chambers, Anglin, and Bowman [8] and Coe, Chambers and Letko [9], studied the influence of a long slender nose on a phenomenon called nose slide and the spin characteristics of high performance fighter aircraft. Figure 2 is an illustration of the symmetric and asymmetric fore-body wake on a long slender nose fighter. The normal force and side force created by the fore-body vortices on a modern fighter aircraft are initially symmetric but become asymmetric at some critical angle of attack as shown in Figure 2. When the vortices are symmetric, they influence the normal force and pitching moment contribution of the fuselage, however when the wake is asymmetric a side force and yawing moment are also created. Figure 3 shows the fore-body vortices in the cross flow plane. An interesting feature of the asymmetric fore-body vortices is that they are steady and have a bi-stable mode. In the asymmetric state one vortex is near the fore-body surface while the other is farther away from the surface which is the flow mechanism that creates the side force and yawing moment on the body. The opposite orientation of the vortex pattern is also stable.

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. The directional stability and control of a fighter aircraft diminishes with increasing angle of attack. This is due primarily 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 into a spin [8, 9].

![Symmetric Forebody Vortices](image1)

**(a)** Low Angle of Attack

![Asymmetric Forebody Vortices](image2)

**(b)** High Angle of Attack

**Figure 2.** Fore-body flow separation [8].

In Figure 4, Malcomb [10] illustrates the loss of aerodynamic control from the rudder versus the potential control power that could be achieved from fore-body flow control. In several review articles by Malcolm [10, 11], he reviews some of the earlier flow control concepts. The concepts included movable strakes, blowing surface jets, blowing and suction slots, suction through surface holes and miniaturized tip strakes [12-25].

![Bi-stable Configuration](image3)

**Figure 3.** Bi-stable states of the asymmetric vortex pattern.
Figure 4. Typical loss of yaw control power with increasing angle of attack and potential benefits fore-body vortex control.

More recently research using micro blowing schemes like synthetic jets has received considerable attention. 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.

At the Center for Flow Physics and Control (FlowPAC) at the University of Notre Dame a preliminary research study has been conducted to investigate the manipulation of forebody vortices on a slender tangent ogive nose body through active flow control technology. In this research plasma actuators are being used to exploit the bi-stable nature of the asymmetric forebody vortex wake for lateral control. Dr. Thomas C. Corke of the University of Notre Dame has pioneered the development of Single-Dielectric Barrier Discharge (SDBD) plasma actuators for controlling flow separation, lift enhancement and drag reduction [26-28]. The SDBD plasma actuator consists of two electrodes as shown in Figure 5. The thin electrodes are typically made of copper foil tape. One electrode is exposed to the air while the other is encapsulated in a dielectric material. When the a.c. voltage reaches a high enough amplitude, the flow over the encapsulated electrode begins to ionize. Corke and his colleagues [29-30] have shown that the ionized air and the electric field of the electrodes create a body force that acts on the air flowing over the actuator. The body force can be tailored by the arrangement and orientation of the electrodes.
SDBD plasma actuators have a number of distinct advantages over other active flow control devices. These include that (1) they are fully electronic with no mechanical parts and therefore are able to withstand high force loading, (2) they can be laminated onto wing or body surfaces and therefore they do not require slots or cavities, and (3) they have a broad frequency bandwidth so that they can have fast response for feedback control.

EXPERIMENTAL PROGRAM

The Center for Flow Physics and Control at the University of Notre Dame is currently investigating the manipulation of fore-body vortices on a slender tangent ogive nose body through active flow control technology. In this research program plasma flow actuators are being used to exploit the bi-stable nature of the asymmetric fore-body vortex wake for lateral control. Visualization of the fore-body vortices has been an integral part of our research effort.

The model selected for the Notre Dame study was a tangent ogive nose/cylindrical model as shown in Figure 6. The model 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.
b) The nose portion of the model showing the axial and circumferential position of the plasma actuators.

Figure 6. Model tested at Notre Dame (all dimensions in millimeters).

A close-up photograph of the nose portion of the model is shown in Figure 7. The plasma actuators are on and the blue glow of the ionized air created by the actuator is clearly visible in the picture.

In this preliminary study the plasma actuators were found to be very effective in switching the asymmetric fore-body vortices from one bi-stable state to the other. The actuators were operated only in a steady manner. In Figure 8 when both actuators are turned off, the model experiences a side force coefficient due to the asymmetry of the vortex pattern. As the voltage of the starboard actuator is increased (port actuator is off) the side force coefficient increases up to a maximum then remains essentially constant for further increases in the input voltage. With the starboard actuator off, increasing the voltage to the port actuator decrease and ultimately a change in sign of the side force coefficient. Again further increases in the input voltage result in constant negative side force coefficient.

Figure 7. Nose portion of the model showing the glow from ionized air create by the plasma actuator (no wind case).
Figure 8. Change in $C_y$ versus voltage to the plasma actuator.

In our study flow visualization played an important role in selecting the location of the plasma actuators and assessing their affect on the fore-body vortices. Surface visualization using an oil flow technique to visualize the surface skin friction lines was used to help in selecting the appropriate location for placement of the plasma actuators. Figure 9 shows the skin friction lines using the oil flow technique. A sketch of the skin friction lines is also included in this figure.
Figure 9. Oil flow visualization of the surface skin friction lines.

Off surface flow visualization was used to assess the effectiveness of the actuators to manipulate the fore-body vortices between the two stable flow states. Both still and video images were obtained. The video images clearly showed that the vortices could be rapidly moved between the bi-stable states. Figure 10 is a laser sheet photograph showing the asymmetric fore-body pattern in the cross flow plane.

Figure 10. Laser light sheet technique used the illuminate the smoke entrained into the fore-body vortices.
In summary this preliminary study showed the feasibility of using flow control to control the side force and yawing moment on a slender fore-body nose shape. By exploiting the bi-stable nature of the asymmetric vortex pattern a potential control moment can be developed that would be very useful for maneuvering high performance aircraft. While this initial study focused on steady actuation of the plasma actuators to switch in the pattern the real benefit of using these actuators is in the unsteady mode. By varying the time between the two stable states a time average side force and yawing moment can be created as illustrated in Figure 11 [31]. The magnitude and direction of the force can be controlled by the difference in time between the stable states.

![Figure 11. Time-Average Side Force created by varying the duty cycle parameter τ [31].](image)

REFERENCES


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