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Aerodynamic performance enhancement of a flying wing using nanosecond pulsed DBD plasma actuator

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Abstract Experimental investigation of aerodynamic control on a 35° swept flying wing by means of nanosecond dielectric barrier discharge (NS-DBD) plasma was carried out at subsonic flow speed of 20–40 m/s, corresponding to Reynolds number of 3.1×10^5–6.2×10^5. In control condition, the plasma actuator was installed symmetrically on the leading edge of the wing. Lift coefficient, drag coefficient, lift-to-drag ratio and pitching moment coefficient were tested with and without control for a range of angles of attack. The tested results indicate that an increase of 14.5% in maximum lift coefficient, a decrease of 34.2% in drag coefficient, an increase of 22.4% in maximum lift-to-drag ratio and an increase of 2° at stall angle of attack could be achieved compared with the baseline case. The effects of pulsed frequency, amplitude and chord Reynolds number were also investigated. And the results revealed that control efficiency demonstrated strong dependence on pulsed frequency. Moreover, the results of pitching moment coefficient indicated that the breakdown of leading edge vortices could be delayed by plasma actuator at low pulsed frequencies.

1. Introduction

Compared with conventional wing configurations, the flying wing shows promising prospect in aerodynamic efficiency and environmental requirements in future, including high lift-to-drag ratio, low drag and excellent stealth character. However, there are also some challenging problems for flying wing,[1–4] including low lift at high angles of attack, low degree of static instability in longitudinal channel and ineffectiveness of the conventional surfaces.

For swept wings, leading edge vortices are dominantly responsible for the lift generation.[5] The vortices at the leading edge can cause low static pressure regions, which will produce suction forces and generate additional lift. At low angles of attack, the vortices remain attached to the leeward surface. As the angle of attack increases, the strength of the vortices increases which will lead to a nonlinear increase in lift coefficient, and the vortex breakdown point moves forward. For

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supercritical angles, complete destruction of the leading edge vortices happens and results in decrease in aerodynamic performance. For flying wings, the flow is much more complex, and experimental investigations have shown that the outer wing begins to stall earlier than the inner wing, which will lead the aerodynamic center to move much forward. And this results in an obvious increase in pitching moment coefficient.

Active flow control techniques have been developed to improve the aerodynamic performance of airfoil and aircraft over the recent years. Among these control techniques, the dielectric barrier discharge (DBD) plasma actuator offers tremendous potential as an active flow-control device due to its no moving parts, a resurface adapting, low power requirement and a fast time response. It has been proved to be an efficient means of aerodynamic control in many cases.[6–9] The dominant mechanism of this kind of DBD actuator has been given by Wang et al.[9] The alternating current dielectric barrier discharge (AC-DBD) plasma actuator can induce wall jet in a steady actuation mode to produce acceleration in boundary layer and produce counter-rotating vortices in an unsteady manner to aid mixture between the boundary layer and the free-stream. The schematic diagram of this kind of DBD plasma actuator is shown in Fig. 1(a). In addition, recent advances in plasma control have demonstrated that nanosecond DBD (NS-DBD) plasma actuator is more effective in aerodynamic control,[10–12] which is based on fundamentally different mechanisms. The discharge happens within few nanoseconds and quickly heats up the air near the discharge, resulting in the rise of pressure and the forming of a shock wave, which is shown in Fig. 1(b).[7]

Plasma actuation has been widely studied to control aerodynamic coefficients of flying wings. Greenblatt et al.[13] investigated the aerodynamic enhancement of a 60° swept flying wing using AC-DBD plasma actuators at speeds below 10 m/s. The results indicate that maximum lift enhancements were observed at pulsed reduced frequency $F^+ = 1$ when plasma actuator was placed near the wing apex. Patel et al.[14] considered the use of distributed AC-DBD plasma actuators at the leading and trailing edges of a 1303 unmanned aerial vehicle (UAV) at flow speed $U_\infty = 15$ m/s. The test shows that plasma actuators could provide the lift of flight control at high angles of attack. Budovsky et al.[15] investigated the flow control on a delta-wing using AC-DBD plasma actuators at low speed. The result shows that plasma actuation could influence the vortex breakdown position. And enhancement in aerodynamic performance was observed when plasma actuator was placed near the leading edge.

In the present tests, subsonic wind tunnel tests are performed using a model of 35° swept flying wing with NS-DBD plasma actuator, which is installed symmetrically on the wing leading edge. Balance measurements were obtained for the lift and drag coefficients, lift to drag ratio and pitching moment coefficient in the range of angles of attack α = 4–30°. Using these experimental methods, the effect of plasma actuator for controlling the aerodynamic coefficients was investigated for flow speed equal to 20, 30 and 40 m/s. The effects of actuator amplitude and frequency and Reynolds number were also investigated to estimate the control efficiency and scaling effect. Moreover, the changes in pitching moment coefficient with and without plasma control were also considered in this paper.

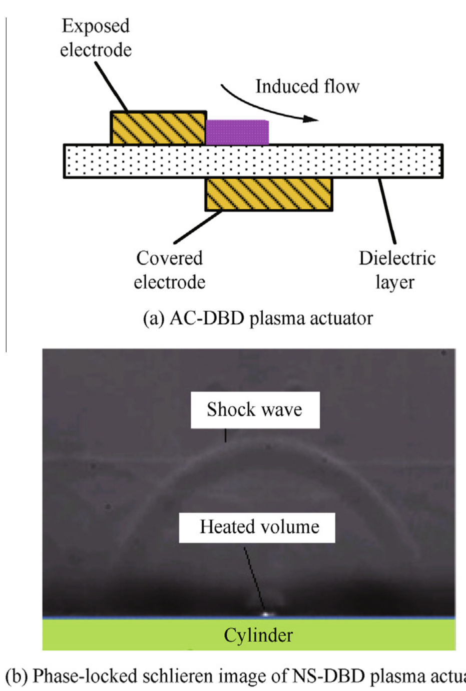

Fig. 1 Schematic diagram of DBD plasma actuator.

2. Experimental setup

2.1. Wind tunnel and model

The experiments were conducted in the FL-5 low-speed wind tunnel at Aerodynamics Research Institute, Aviation Industry Corporation of China. The facility is an open-return wind tunnel with a 1.95 m long test section and a circular cross section of 1.5 m diameter. The maximum air speed in the wind tunnel is 53 m/s, and the turbulence intensity is less than 1%. The photo of the test section of the wind tunnel is shown in Fig. 2(a). The model used here is a typical flying wing with sweep angle of 35° at the leading and trailing edges. It is made from dielectric material and has a 0.953 m wing span length. The model is mounted on the support sting of a six-component force and moment balance. The photo of the model with plasma actuator is shown in Fig. 2(b).

2.2. Plasma actuator

The DBD plasma actuator consists of two electrodes separated by a dielectric layer. The electrodes are made from copper foil tape; one is exposed to the air, and the other is covered by the dielectric material. The dielectric layer is made from three layers of Kapton tapes and has thickness of 0.2 mm in total. A schematic illustration of the actuator has been shown in Fig. 1. In the present experiment, the actuator is placed symmetrically on leeward side near the leading edge of the model. The exposed electrode is 3 mm in width and the covered one is 5 mm in width. They are overlapped by very small amount which can generate uniform plasma along the leading edge. The photo of the actuator installed on the model is shown in Fig. 2(b).