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FULL LENGTH ARTICLE

Turbulent boundary layer separation control using plasma actuator at Reynolds number 2,000,000

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Abstract An experimental investigation was conducted to evaluate the effect of symmetrical plasma actuators on turbulent boundary layer separation control at high Reynolds number. Compared with the traditional control method of plasma actuator, the whole test model was made of aluminum and acted as a covered electrode of the symmetrical plasma actuator. The experimental study of plasma actuators' effect on surrounding air, a canonical zero-pressure gradient turbulent boundary, was carried out using particle image velocimetry (PIV) and laser Doppler velocimetry (LDV) in the 0.75 m × 0.75 m low speed wind tunnel to reveal the symmetrical plasma actuator characterization in an external flow. A half model of wing-body configuration was experimentally investigated in the ∅ 3.2 m low speed wind tunnel with a six-component strain gauge balance and PIV. The results show that the turbulent boundary layer separation of wing can be obviously suppressed and the maximum lift coefficient is improved at high Reynolds number with the symmetrical plasma actuator. It turns out that the maximum lift coefficient increased by approximately 8.98% and the stall angle of attack was delayed by approximately 2° at Reynolds number 2×10^6. The effective mechanism for the turbulent separation control by the symmetrical plasma actuators is to induce the vortex near the wing surface which could create the relatively large-scale disturbance and promote momentum mixing between low speed flow and main flow regions.

1. Introduction

Currently, active flow control (AFC) technology is a popular method that can improve the aircraft aerodynamics performance without added drag and also liberate designers from the restriction of traditional aerodynamic design.

Dielectric barrier discharge (DBD) plasma flow control method has been extensively proved to be a promising AFC technology[1] in the field of separation control for wing,[2,3] lift

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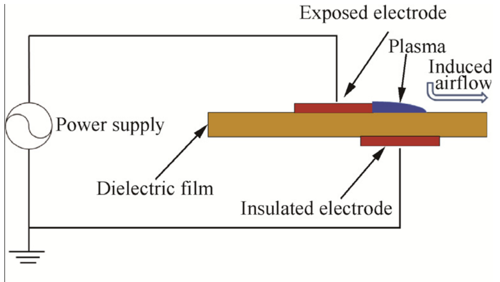
enhancement[4,5] and separation flow control for airfoil,[6] boundary layer control,[7–10] separation control for low-pressure turbine blades,[11] control of bluff body,[12–14] control of compressor cascade,[15,16] control of broadband noise,[17] and control of jet diffusers.[18] Compared with the traditional AFC technology, the benefits of plasma actuator are obvious, such as simple structure without moving parts and rapid response. Remarkable reviews on plasma flow control technology have been published lately.[19–21]

Separation control of wing using plasma actuators at low-middle Reynolds number was investigated by numerous researchers with experimental and computational methods.[22–32] By numerical simulation method, Asada and Fujii made an investigation on the laminar separation control by a plasma actuator around NACA 0015 at Reynolds number 63,000 recently.[33] They indicated that the plasma actuation can promote the transition to turbulence at the laminar separation shear layer more effectively and then the turbulent mixing led to early reattachment of the separated flow. The effect of the location and operating conditions of the plasma actuator was widely studied by Sato et al.[34] It was found that the most effective location is just upstream of the natural separation point. The deep stall flow control was investigated by Aono et al. at Reynolds number 260,000.[35] They carried out an optimization study of the burst frequency of the plasma actuator and proved the applicability of the plasma actuator for control of the laminar separated flow at middle Reynolds number. It was suggested that the optimum burst frequency becomes higher than that at low Reynolds number. From these investigations, the promotion of the turbulent transition at the shear-layer is the key for effective laminar-separation control with the plasma actuator at low-middle Reynolds number.[35]

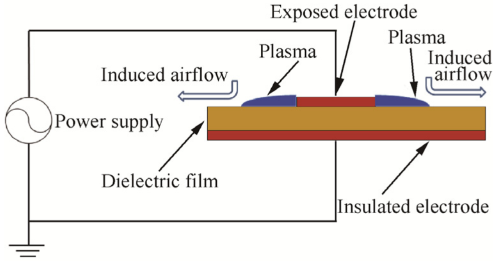
However, some researchers could question the applications of the plasma actuator. Because the Reynolds number of real airplane is usually over 10^6 that could be beyond the plasma authority from the literature. In order to meet the requests of engineering application, the plasma authority must be improved at higher Reynolds number. In this high Reynolds number zone, flow is often separated in turbulence but not in laminar. Therefore, the separation characteristics are different from the laminar separation. It is not clear whether the same tactic for the laminar separation control at low-middle Reynolds number could be suitable for the turbulence separation control.

The purpose of this investigation was to study the turbulent boundary layer separation control over a wing-body configuration using a symmetrical plasma actuator at Reynolds number 2×10^6. The integral control effect of the symmetrical plasma actuator is described by the force measurements and particle image velocimetry (PIV) results. Moreover, this paper highlights how the induced airflow by the plasma actuator interacts with the boundary layer with laser Doppler velocimetry (LDV) technology and smoke visualization, and discusses the controlling mechanism of the plasma actuator.

2. DBD plasma actuator



(a) Typical DBD plasma actuator



(b) Symmetrical DBD plasma actuator

Fig. 1 Electrodes configuration of DBD plasma actuators.

Classical DBD plasma actuator comprises an upper electrode and a lower electrode that are separated by insulating material. One of the electrodes is exposed to the ambient air and the other is completely encapsulated by dielectric material (Fig. 1(a)). When a high voltage power supply is applied to the two electrodes, ionized air (plasma) at the edge of the exposed electrode is produced. The plasma covers the region projected by the covered electrode. As a result of the electric field gradient, the plasma produces a body force[36–38] that acts on the surrounding air and induces the airflow in the direction from the upper electrode towards the lower electrode.[39,40] The process of ionizing the air at this configuration is referred to as DBD. Fig. 2(a) presents the plasma discharge image for the ordinary plasma actuator. It can be seen that a single bluish line in the darkness is close to the edge of the exposed electrode.

Compared with the typical one, this work used the testing model made of metal and copper foil tape as a lower electrode and an upper electrode respectively (Fig. 1(b)). Therefore, there are two bright lines on both sides of the exposed electrode for symmetrical actuator (Fig. 2(b)). These discharge photographs are consistent with DBD theory as mentioned above that the glow usually occurs at the edge of exposed electrode and spreads to the projected area of covered electrode. Since the lower electrode covers the whole upper electrode, the symmetrical actuator could produce the double bluish lines. The induced velocity field of the plasma actuator at the test arrangement will be discussed in more details later in this paper.

3. Plasma actuator characterization

3.1. Experimental setup

(1) Wind tunnel

The experiments were carried out in an open-circuit low speed wind tunnel with a test section 1.05 m × 0.75 m × 0.75 m at China Aerodynamics Research and Development Center (CARDC), which is capable of generating a maximum wind speed of 55 m/s with the turbulence

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