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The study of flow separation control by a nanosecond pulse discharge actuator

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A B S T R A C T

The basic dynamic characteristic of a nanosecond (NS) pulse discharge actuator in still air is investigated, which introduces viscid and inviscid effects to the flow, namely, heated air and pressure waves, respectively. The efficacy of a dielectric barrier discharge plasma actuator driven by a nanosecond pulse for active flow separation control is investigated experimentally on a NASA SC(2)-0712 aerofoil at $Re = 0.5 \times 10^6$ (25 m/s). The pressure distribution on the aerofoil surface is measured, and the result indicates that the separation is well controlled at a high angle of attack. The PIV test result shows that the forcing frequency selectively affects the flow over the aerofoil, and a higher forcing frequency has a better influence on the leading edge shear layer. Schlieren imaging experiments at $Re = 0.1 \times 10^6$ (5 m/s) show that the main disturbance factor for the nanosecond pulse plasma actuator is the heating effect, which changes the local temperature and density and induces several vortex structures. The vortex structures entrain the outer high-momentum fluid into the shear layer, thereby strengthening the mixing of the shear layer with the main flow and delaying separation or even reattaching a separated flow. The research reveals the major disturbance factor introduced by NS discharge applied to flow separation control. Furthermore, the spatiotemporal disturbance process induced by the pulse discharge is investigated.

1. Introduction

Flow separation commonly occurs in aviation, aerospace, and fluid mechanical operations, often resulting in losses of lift, pressure recovery losses, and drag increases. It is therefore important to determine how to alter the location of the separation or even completely avoid it. Most flow control problems, such as vortexes, separation, wakes and jet flow, are related to the shear layer. Usually, those phenomena are so-called convective instability, in which the flow is vulnerable to outside disturbances caused by pressure, density, temperature or velocity changes. It is therefore feasible to obtain flow separation control by manipulation of the shear layer reattachment using external perturbance [1]. Wu et al. [2] and Greenblatt and Wygnanski [3] also indicated that the excitation of the separated shear layer is an important factor affecting flow control.

To avoid separation and improve the aerodynamic performance, many investigations of flow control techniques have been conducted, such as zero-net mass-flux (ZNMF) or synthetic jet actuators, vibrating ribbons, vibrating flaps, and electromagnetic, magneto-hydrodynamic and plasma actuators [4].

Because the DBD (dielectric barrier discharge) plasma actuator has no moving mechanical parts, a low weight and size, and can provide control over a wide range of frequencies, it has outstanding potential. The DBD plasma actuator has been used in many flow control areas, such as transition delay [5], unmanned aerial vehicle separation control [6], vortex shedding control [7], and micro air vehicle flow control [8,9]). Corke et al. [10], Wang [11], and Benard and Moreau [12] provided thorough reviews of AC surface DBD actuators applied to airflow control. Benard and Moreau [12] reported that single DBDs can produce a mean force and electric wind velocity up to 1 mN/W and 7 m/s, respectively. With multi-DBD designs, the velocity could reach up to 11 m/s and the force up to 350 mN/m.

The DBD plasma actuator is driven by a nanosecond pulse voltage discharge, which results in a high energy release in a short time. Compared to alternating current voltage discharge, the thermal effect is a dominant factor for flow control [13,14]. Roupassov et al. demonstrated the effect of flow separation control over a very wide velocity (Ma = 0.05–0.85) range, Rethmel [15] and Little [16] demonstrated the capability of nanosecond pulse DBD actuators to control flow separation with a flow Reynolds number up to 1×10^6 (62 m/s).

The main mechanism of the ns-DBD actuator is confirmed to be different from that of the alternating current DBD actuator. Some

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reports have shown that there is a rapid temperature rise in the proximity of the plasma filament during the pulse discharge, and it is generally agreed that the main mechanism of the pulsed nanosecond DBD plasma actuator is Joule heating [14,16–20]. They believe that the ns-DBD plasma actuator generates a pressure wave due to thermal effects, which is a factor in the control authority. The pressure wave interferes with the separated flow and causes it to be attached.

In addition to the pressure wave, the induced velocity and vortex are also possible factors that could affect the flow. Roupassov et al. [14] reported that the emerging pressure wave, together with the secondary vortex flows, disturbs the separate flow. Rethmel et al. [15] reported that nanosecond pulse DBD actuators can extend the stall angle by functioning as an active trip. At the post stall angle, the discharge generates coherent spanwise vortices that transfer momentum from the freestream to the separated region, thus controlling the separation flow. Zheng et al. [21] reported that the behavior of the pressure wave is dominated by the input voltage amplitude, and the discharge introduces a highly transient and localized disturbance to the quiescent air. However, they believe that the vortex induced by the wave passage is relatively weak, and they postulate that such weak vortexes have no significant effects on the external flow. The mechanism of NS-DBD for flow control could be classified as large-scale vortex, flow transition, or other categories. Popov et al. [22] successful predicted the phenomenology of disturbances in the laminar boundary layer produced by NS-DBD plasma actuators. They also believe that the primary effect of the NS-DBD actuator is the excitation of the *T–S* waves. Leonov et al. [23] reported that there are two different types of perturbation generated by the nanosecond pulse surface DBD discharge, pressure wave and thermal perturbations. The thermal perturbations of the boundary layer on a sub-millisecond time scale (i.e., not pressure waves) play a significant role in the boundary layer transition and separation control.

Therefore, the mechanism of nanosecond plasma discharge for flow separation control is still worth studying. As multiple disturbance factors exist in nanosecond plasma discharge, such as the pressure wave induced by discharge heating, vortex induced by the pressure wave, and vortex induced by the discharge heating effect (namely, density or temperature change), the major factor, or combination of two or three, that disturbs the flow needs to be clarified. The present paper evaluates the aerodynamic effects of a nanosecond pulse plasma actuator on a separation foil and deeply studies the interaction between the plasma and separated shear layer in the spatial and temporal dimensions. The aim of this work is to discover the physical process of separation control and distinguish the major disturbance factor that impacts the separated flow.

2. Experimental facilities and techniques

2.1. Wind tunnel facility and aerofoil model

The experiment is conducted in a low-speed wind tunnel at the Nanjing University of Aeronautics and Astronautics. The dimension of the test section (height × width) is 1 m × 1.5 m, and the air flow in the tunnel is varied continuously from 5 to 30 m/s, with the freestream turbulence intensity at 0.08%.

A NASA SC(2)-0712 aerofoil model with a chord length of $C = 300$ mm and a span of 500 mm is used. The model is made from acrylonitrile butadiene styrene plastic. 49 static pressure taps are located close to the test section centreline (Fig. 1). To limit the three-dimensional flow effects at the wing tips of the rectangular wing, two circular Plexiglas plates of 500 mm diameter are attached.

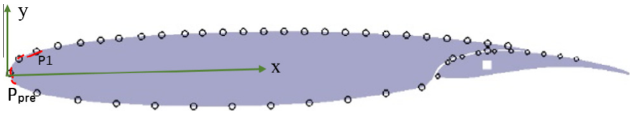

Fig. 1. Side view of the NASA SC(2)-0712 aerofoil model (dark circles represent pressure taps on the test section, and red lines represent plasma actuators at different positions). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. DBD plasma actuator

The plasma actuator is composed of two copper tape electrodes separated by a Kapton tape dielectric arranged in an asymmetric manner (Fig. 2). The covered ground electrode is 10 mm wide, the exposed high voltage electrode is 5 mm wide, and the distance between the electrodes is set to 1 mm. Both electrodes have a thickness of 0.08 mm, the dielectric barrier is composed of 3 layers of Kapton tape, and the total thickness of the dielectric barrier is 0.18 mm. Hence, the total thickness of the DBD actuator is 0.34 mm.

In this research, the actuators are excited by a pulsed nanosecond voltage provided by a nanosecond pulse generator, NPG-15/2000(N), which can be operated by external triggering through an optical-fibre connector. This provides an adjustable discharge frequency and an adjustable number of pulses. The pulse provided by the pulsed generator has a 4 ns pulse rise time and a 20 ns pulse width. The max pulse energy is 30 mJ, and the peak-to-peak voltage $V_{pp} = 13–18$ kV at a matched 75 Ω load. Simultaneous measurements of voltage and current for NS-DBD plasma are shown in Fig. 3. In this research, the lengths of the actuators are 450 mm, the peak-to-peak voltage $V_{pp} = 15.3$ kV, and the pulse current is 40 A.

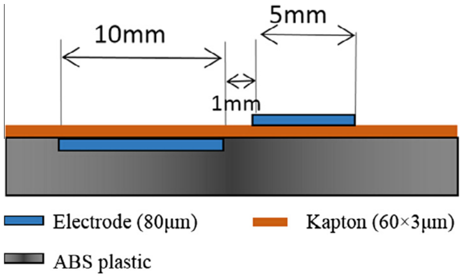

Fig. 2. Scheme of DBD plasma actuator.

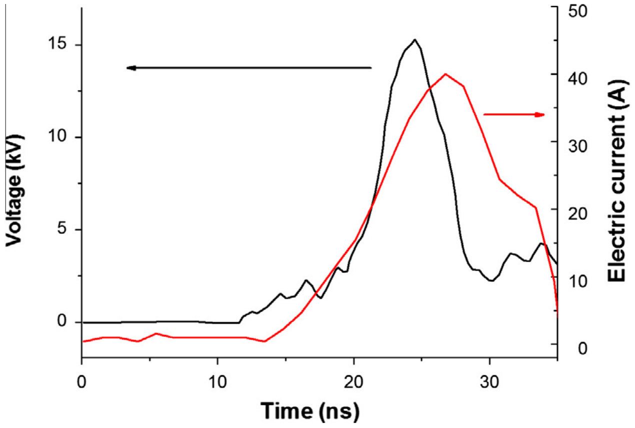

Fig. 3. Sample voltage and current of one pulse discharge.