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Investigation on 3D flow field induced by a plasma actuator with serrated electrode

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Abstract This paper presents an experimental investigation on flow field induced by a dielectric barrier discharge (DBD) plasma actuator with serrated electrodes in still air to further improve its flow control effectiveness. For comparison, the actuator with widely used linear electrodes was also studied. Experiments were carried out using 2D particle image velocimetry. Particular attention was given to the flow topology, discharge phenomenon, and vortex formation mechanism. Results showed that a 2D wall jet was induced by the linear actuators, whereas the plasma actuators with serrated electrode introduced a series of streamwise vorticities, which might benefit flow control (e.g., enhancing the momentum transport in the separated boundary flow). In addition, the mechanism of 3D flow topology induced by the serrated DBD actuator was analyzed in detail.

Keywords Plasma actuator · Serrated electrode · Vortex dynamics · Particle image velocimetry

1 Introduction

Plasma actuators based on the dielectric barrier discharge (DBD), well known as one of the active flow control devices, has been studied for many years [1]. Under a high voltage ($\sim$kV) and high-frequency AC ($\sim$kHz), a region of weakly ionized air (plasma) is created, resulting in a space–time-dependent electro hydrodynamic (EHD) force vector field that acts on ambient (non-ionized and neutrally charged) air, similar to a zero-net-mass-flux jet.

Over the past two decades, much progress has been made to deploy the plasma actuator for flow control, ranging from separation delay on airfoils to the fundamental phenomenology associated with surface discharge itself and basic induced flow in still air by experimental and numerical methods. Corke et al. [1] and Moreau [2] have provided in-depth reviews on the physics and application of Surface-DBD plasma actuators.

Although plasma actuators function in the laboratory, they do not work well in practical flow control applications because of their low output capability. Thus, numerous studies have been conducted to improve actuator performance by investigating the parametric effects of plasma actuators, such as dielectric material and thickness [3], input voltage waveform signals and driving frequency [4, 5], electrode geometry [6–11], and number of actuators in series (multi-DBD actuator) [12, 13].

Numerous researchers recently deployed alternative electrode configurations to improve the control authority of plasma actuators, as these actuators can induce 3D flow structures, such as plasma synthetic jet and spatially distributed jet, which can postpone/suppress flow separation or excite inherent flow instabilities for effective flow control [14, 15]. Among these methods, previous studies reported that plasma actuators using serrated electrode is a promising method with good development potential. Thomas et al. [16] demonstrated that SDBD plasma actuators using an exposed serrated electrode provide a considerable increase in body force over that produced by the same actuator with a conventional linear electrode, especially at low voltage; plasma ignition occurs earlier with the serrated electrode, but thrust gain is clearly diminished at the

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highest operating voltages. These results were verified by Berendt et al. [17]. Using the mapping result of 3C-LDA, Joussot et al. [18] showed that actuators with serrated electrode can induce vortex pairs in still air. This phenomenon was also observed by Durscher and Roy [6] using serpentine actuators in static environment.

As mentioned above, previous studies have shown a three-dimensional flow topology induced by plasma actuators with serrated electrode or curved one. However, due to the serration, plasma actuator with serrated electrode can increase the longitudinal velocity, which can be beneficial for aerodynamic control applications [18]. While Jossout's mapping results of 3C-LDA have studied basic characteristics of plasma actuators with serrated electrode in still air and shown its good prospect, a well-established flow field induced by a plasma actuator using a serrated electrode is still lacking, and the mechanism by which a complex 3D flow field can be generated needs further investigation. Thus, we conducted the present study using particle image velocimetry (PIV) to investigate the airflow induced by a plasma actuator using a serrated electrode and then constructed a physical model to illustrate its mechanism in still air.

2 Experimental setup

2.1 Design of plasma actuator and electrical instruments

The present plasma actuators consisted of 17 μm-thick conductive copper electrode arrays (with no overlap) separated by a 3 mm-thick Teflon ($\varepsilon_r = 2.17$) dielectric plate using standard Printed Circuit Board manufacturing techniques, enabling precise control of device geometries. The general schematic of the actuators is shown in Fig. 1.

The high voltage electrode was exposed to ambient air, and the ground electrode was insulated with a polyimide tape to eliminate discharge on the bottom of the actuator. According to the previous studies, the tooth size should be chosen appropriately. A small size is beneficial to induce thrust [16, 17] whereas a large one induced a more obvious 3D flow field with vorticity [6, 8]. Considering the parameters used in our previous experiments and the future application of SeDBD in airfoil flow control, typical parameters was chosen (as shown in Table 1). For brevity, subsequent sections of this article will refer to the actuator using serrated electrode as "SeDBD" [18] and the actuator using linear electrode as "LnDBD". To avoid the end effects of finite electrode from influencing velocity measurements, the actuators consisted of more than one waveform.

The measurement equipment consisted of a quasi-sinusoidal AC power supply (custom-made, 500 W, sine wave output, operating at frequencies between 4 and 15 kHz), an oscilloscope (Agilent MSO-X 3054A, 500 MHz, 4 Gsa/s), a high-voltage probe (Tektronix P6015A, 75 MHz, ±40 kV), and a current monitor (Tektronix CT2, range 2A, accuracy 1 mA). During the experiments, the frequencies were fixed at 8 kHz, and the peak-to-peak voltage change was between 20 and 40 kV.

2.2 Flow field measurement

A transparent chamber manufactured from glass was used in the experiment to ensure a static environment and provide optical access. The chamber was enclosed and of sufficient size (600 mm × 600 mm × 1000 mm) to make sure the flow was not affected by any external ambient airflow.

The velocity field induced by the actuators was measured using the LaVision standard PIV system. A charged-coupled device camera with a 2048 pixel × 2048 pixel

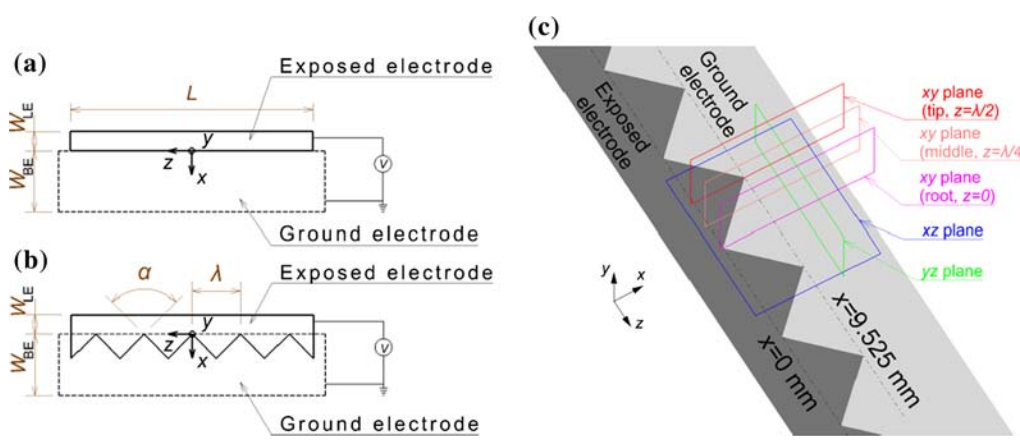

Fig. 1 (Color online) Configuration sketch map of plasma actuators. **a** Plasma actuator with linear electrode; **b** plasma actuator with serrated electrode; **c** field of view of PIV runs, with the coordinates marked