Sensors and Actuators A 235 (2015) 71–79

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Influence of the discharge location on the performance of a three-electrode plasma synthetic jet actuator

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ARTICLE INFO

Article history:
Received 24 June 2015
Received in revised form 3 September 2015
Accepted 10 September 2015
Available online 8 October 2015

Keywords:
Plasma actuator
Synthetic jet
Discharge location
Pulsed discharge

ABSTRACT

Plasma synthetic jet actuator (PSJA) is a novel device for high speed flow control. This paper reports both the schlieren measurement and the CFD simulation results of the discharge location's influence on the performance of a three-electrode PSJA. The schlieren images qualitatively show that discharge location has a significant influence on the PSJA performance. The CFD simulation results quantitatively indicate how the discharge location affects the energy distribution and evolution. When the discharge is near the orifice, the gas near the orifice is heated firstly, and the expelled gas takes away more energy at the initial jet stage. On the contrary, when the discharge is far from the orifice, the expelled gas temperature is lower at the initial jet stage, and the expelled gas takes the energy away much slower. The results demonstrate that, as discharge location closer from the orifice, the jet velocity at the actuator exit increases faster and also decreases faster, showing a strong pulsing characteristic. With farther discharge location from the orifice, the jet exit velocity increases slower, but can keep a relative high value for a longer time, which means a longer duty cycle. Farther discharge location from the orifice also leads to the increase of both the jet momentum and the expelled mass per pulse.

1. Introduction

Since the Johns Hopkins University Applied Physics Laboratory (JHU/APL) put forward a novel flow control actuator named plasma synthetic jet actuator (PSJA) or SparkJet actuator in 2003 [1], more and more investigations have been performed on this promising technology [2–5]. The research team in JHU has conducted a systematic study on the PSJA characteristics using Particle Image Velocimetry, schlieren system, dynamical pressure sensor and CFD method. The results indicate that the actuator geometry, discharge energy and the discharge frequency have significant effects on the actuator performance [6–13].

In the development stage, the PSJA consists of two electrodes, a chamber and an orifice [14,15]. Limited by the discharge energy, the actuator chamber was designed to be very small to produce jet efficiently. As a result, the expelled mass per pulse is also very small. To improve the expelled mass per pulse, Haack et al. optimized the actuator design using three electrodes instead of two electrodes [16]. Under the new design, the energy for gas heating provided by a capacitor can be increased to the order of Joule. But with increasing discharge energy, if the volume of actuator remains unchanged, the temperature would reach up to the material heat-resistant limit. Thus, to overcome this limitation as well as to increase the expelled mass per pulse, a larger chamber volume were used. In the early research on three-electrode PSJA, the research point is mainly focused on the influence of discharge energy. Wang et al. has shown the jet velocity increases for an increase in capacitance [17]. Using image processing technology, Zhong et al. analyzed the energy's influence in detail, and found that there were three patterns of flow field evolution [18]. In this paper, from a different perspective, the influence of discharge location was concentrated on.

Generally, the heating region is decided by discharge region directly. Belinger et al. found that the heating region and discharge region are approximately the same [19]. Based on this conclusion, the influence of the discharge location on the PSJA performance is an important issue. Quint et al. found that the PSJA performance evolution in the first working cycle is strongly influenced by the discharge location, even when the actuator height is only 4 mm [20]. Therefore, with increasing discharge energy and chamber height, the discharge location must have a more significant effect on the PSJA performance. And in the steady working condition, how the

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http://dx.doi.org/10.1016/j.sna.2015.09.019
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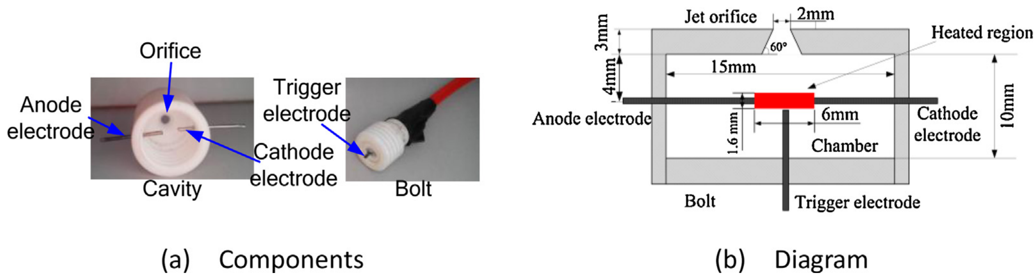

Fig. 1. The three-electrode PSJA.

discharge location affects the PSJA performance makes more sense. These research points are necessary to be investigated for more effective flow control.

In this paper, the influence of discharge location on the performance of a three-electrode PSJA is investigated using both the schlieren measurement and the CFD simulation. The schlieren measurement is used to investigate the influence qualitatively and validate the simulation, while the CFD simulation is used to reveal the detailed actuator performance with different discharge locations. The temperature in the chamber, the expelled jet mass, the actuator exit mean density, the actuator exit mean velocity, and the jet momentum are adopted to describe the actuator performance. Different from previous investigations, this paper mainly focuses on the actuator performance in steady working condition rather than in the first working cycle, which has greater practical significance.

2. Experimental investigation

2.1. Experimental setup

The actuator is composed of an anode, a cathode, a trigger electrode, a chamber, and a bolt, as shown in Fig. 1. The chamber has an orifice for expelling gas and two holes for inserting the anode and cathode electrodes. The bolt has a small hole for inserting the trigger electrode. Both the chamber and the bolt are made of ceramic. The anode, the cathode and the trigger electrode are made of tungsten. The distance from the trigger electrode to both the anode and the cathode is 3 mm. The height and the diameter of the chamber are 10 and 15 mm, respectively. The diameter of the jet orifice and the hole for inserting electrodes are 2 and 1.2 mm, respectively. The height of throat is 3 mm. In order to investigate the influence of the discharge location on the PSJA performance, electrodes are placed at 0.2 h, 0.4 h, 0.6 h and 0.8 h, where h is 10 mm, the full height of the chamber. In following sections, case 1, case 2, case 3 and case 4 denote these four different discharge locations, respectively. In Fig. 1(b), the electrodes are placed at 0.2 h. Referred to [19], the heated region is considered to a column region, as shown in Fig. 1(b).

The power supply system is as shown in Fig. 2. A 15 kV nanosecond pulsed power supply (FPG2020NK, FID) is adopted to trigger the discharge spark. A 3 kV DC power supply is adopted to charge a 0.47 μF capacitor. The DC discharge voltage and current are measured with a high voltage probe (P6015A, Tektronix) and a current probe (TCP312, Tektronix), respectively. These two signals are displayed and recorded with an oscilloscope (DPO4140, Tektronix). The discharge frequency in this paper is fixed at 200 Hz.

To visualize the flow, a schlieren system is adopted in this experiment. The light source is a continuous bi-Xenon head lamp. To enhance the light intensity, convex lenses are used to focus the light into a point. A high speed camera (PCO-dimax) is used to capture the images, which is operated on a framing rate of 24215.42 Hz, and an exposure time of 1.28 μs. The image resolution is set as 200 pixels × 400 pixels.

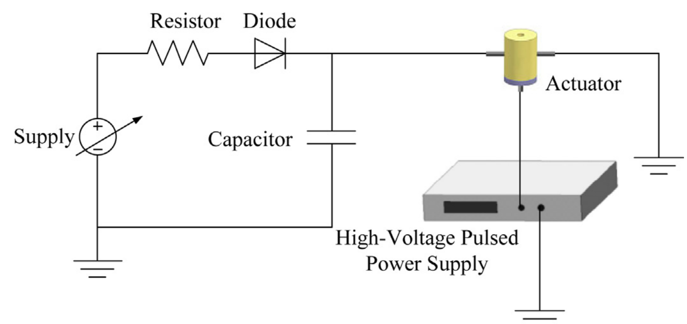

Fig. 2. Power supply system.

2.2. Experimental results

The typical applied voltage and discharge current during a cycle is shown in Fig. 3. The voltage decreases from 3 kV to −2.5 kV in about 2 μs, and recovers to 1 kV in about 4 μs, then falls to 0 kV in about 20 μs. The current increases from 0 A to 286 A in about 1.5 μs, and then falls to 0 A in about 20 μs. Owing to the wire inductance, the voltage and current are not in phase. These characteristics are similar with the experiment done by other group [21]. Since the energy stored in the capacitor is proportional to the square of the voltage, it can be drawn that 88.9% energy is released in the first 4 μs, while the remained energy is released in the last 16 μs, which will be used in CFD simulation as the theoretical basis of adding heat resource.

A single working cycle of the PSJA consists of three stages: energy deposition, jet, and refresh. For the energy deposition stage (stage 1), when the high-voltage pulsed power supply is trigged, the electric discharge channel between the anode and the cathode is initialized. The capacitor energy is released quickly through the electric discharge and the gas in the chamber is heated fast. Once the voltage across the capacitor drops below the sustaining

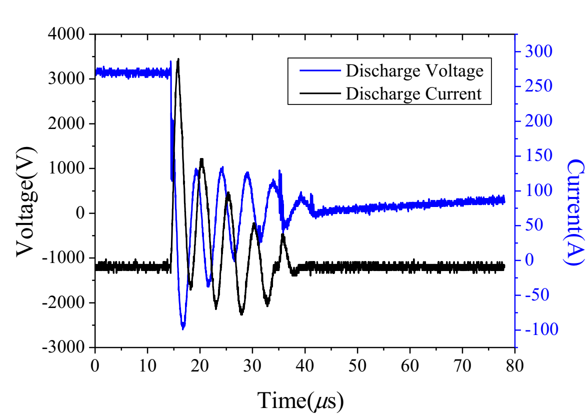

Fig. 3. Voltage and current characteristic of a capacitor discharge.