Sensors and Actuators A 276 (2018) 284–295

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Effects of capacitance on a plasma synthetic jet actuator with a conical cavity

Mengxiao Tang, Yun Wu*, Hongyu Wang, Di Jin, Shanguang Guo, Tian Gan

Science and Technology on Plasma Dynamics Laboratory, The Air Force Engineering University, Xi'an, 710038, China

ARTICLE INFO

Article history:
Received 29 November 2017
Received in revised form 2 April 2018
Accepted 23 April 2018
Available online 24 April 2018

Keywords:
Plasma actuator
Synthetic jet
Discharge capacitance
Typical structure

ABSTRACT

Plasma Synthetic Jet Actuator (PSJA), which incorporates no mechanical parts, zero mass flux capability, adjustable operating frequency and momentum throughput, has drawn increasing attention on high speed flow control. Experiments were conducted on a PSJA with a conical cavity at same energy input, the energy supplied to the PSJA mainly comes from a charged capacitor in a high voltage. The effect of different capacitances on the control authority of the actuator in quiescent condition, as well as its essential characteristics, are investigated. In the experiments, qualitative and quantitative measurements including electrical characteristics, high-speed schlieren, phase locked particle image velocimetry, and dynamic pressure, were fulfilled. Comparative analysis was carried out to study the jet flow difference caused by discharge duration, which depends on the capacitance(1 μF, 2 μF, 4.7 μF and 10 μF), and the energy supplied to the actuator is assumed to be constant. Results show that the discharge duration extends as capacitance increases, so the air inside the cavity is heated more homogeneously. However, smaller capacitance leads to shorter discharge time, but a more vigorous jet flow with stronger blast wave and higher accelerated zone. Accordingly performance fade of the actuator was found as the capacitance increases. Furthermore, two typical morphological features, including the initial intermittent accelerated zones (blast jet) and the heated jet body (hot jet), are adopted to form a conceptual model, by which the nature of the jet was characterized.

1. Introduction

The application of a reasonable and reliable flow control technique contributes to the improvement of the aircraft performance. In terms of a high-speed flight, it still holds some challenging problems in resolving the most common physical phenomenon. The shock wave/boundary layer interaction(SWBLI), typically results in severe viscous drag, shock drag, and even a region of separated flow [1]. Concerning this issue, a few flow control techniques have been developed, which can be classified into negative and active methods [2]. The active flow control, with a wide and promising application prospect, have attained considerable attention because they can provide the optimum performance by improving the aerodynamic configuration in real time in flight [3].

Plasma-based active flow control technique is a promising active method. Except for its drawbacks such as high voltage generators, wiring, electromagnetic emissions, electrodes duration, low efficiency and so on, it still has prominent technological superiority in application because of its broadband characteristic, fast response and ease of manufacture, which enjoy tremendous potentials to increase the aircraft performance. The commonly used plasma aerodynamic actuation is mainly based on joule heating or body force, which includes direct arc discharge actuation, dielectrics barrier discharge actuator(DBDA), localized arc filament plasma actuator(LAFPA)and plasma synthetic jet actuator(PSJA) [4–7]. Among them, DBDA is usually used to manipulate low-speed flow with its weak-induced velocity. LAFPA, with the strong joule heating effect, shows potential in high-speed flow control by modifying aerodynamic configuration [8]. With regard to the PSJA, it provides more powerful excitation to the flow field by concentrating large amount of thermal energy in a confined cavity. The periodically heated gas in the cavity is then erupted at a high speed, which is characterized by low density due to joule heating. The actuator has shown its potential in high-speed flow manipulation based on the thermal and momentum effect, such as flow topology modifications of SWBLI, suppression of supersonic separation [9–11].

* Corresponding author.
E-mail address: 13871704983@163.com (Y. Wu).

https://doi.org/10.1016/j.sna.2018.04.038

However, the control effect of the PSJA is not as satisfying as expected in flow control application due to its short duration, low energy conversion efficiency and small affected area [12–14]. In order to achieve better control authority of the PSJA, systematic researches have been carried out by Zong and Zhang et al. [15–17]. Their studies indicated that the performance of the PSJA is principally determined by the configuration design of the actuator, the type of power supply and the design of discharge circuit. Wang et al. [18] revealed that the jet flow with high momentum can be produced with a three-electrode design in the cavity, in which a sufficient long arc is formed. Zhang et al. put forward the multi-channel discharge circuit to extend the spatial scale of the affected region [19]. It is also found that different types of power supplies lead to different discharge form, the resulting amount energy deposition and discharge timescale are also different. The comparison of the actuator's properties using inductive and capacitive discharge has been reported respectively [20]. With regard to the capacitive discharge, there is no doubt that the discharge capacitance is a dominant part as a direct energy source. Experiments have shown that the leading edge velocity of the jet flow, the timescale of jet evolution and the jet thrust all increase with the increase of capacitance. Tough the heating efficiency drops [21], more energy can be deposited in the actuator. Since the improvement on the performance is clearly aroused by a larger quantity of energy input. It is worthwhile studying how the control authority of the PSJA changes with different capacitances if the energy input is kept the same, which is what's been done in this paper.

Currently, the performance of PSJA is mainly evaluated with discharge efficiency and jet flow affected scale. Results show that the ratio of the jet mechanical energy to the electrical energy is rather low in order of 0.1%, while the maximum value is 0.22% [22]. But the establishment of the multichannel discharge circuit [19] enormously improves the performance of PSJA. The discharge efficiency is greatly raised and the affected area is 6 times as large as a conventional PSJA. Additionally, typical structures such as blast wave, vortex ring and low-density jet body have been found in the experiments [23]. Especially, with different geometrical parameters, the structural changes were captured by schlieren imaging [24]. With the increase of the distance between the two electrodes ranging from 0.5 mm to 3 mm, the flow field is first characterized only by the appearance of several blast waves and then by a distinct jet body together with vortex rings. And the PIV results also identified the jet flow evolution [23] can be affected by the orifice shape. Different orifice shapes result in different shapes of the starting vortex ring. Compared with the round orifice, the slot orifice's vortex ring becomes warped due to the expansion and shows a lower propagation velocity. However, even though the jet structures were clearly captured and depicted, less attention was focused on the relationship between such structures and the performance of the actuator. We assume that an certain correlation can be built between the control authority of PSJA and the typical jet structures. Different structures may play different roles in flow manipulation. Therefore, the function of each flow structures needs to be discussed.

In the experiments, we proposed an actuator with a conical cavity. The cavity configuration contributes to accelerate its inner air, and besides, flow loss can be reduced. Various discharge capacitance C (1 μF, 2 μF, 4.7 μF, 10 μF) are used. In order to ensure a constant amount of energy deposition in the actuator, the energy supplied to the capacitor is controlled by adjusting power voltage. The effect of different capacitances on the performance of the PSJA, as well as diverse typical jet structures, were investigated. Firstly, the electrical characterization with different capacitances is studied by a voltage probe and a current probe. Then the high-speed schlieren imaging was used to capture the subtle structures of the jet flow, the morphology evolution of which can be clearly described. Finally the particle image velocimetry (PIV) was conducted on the jet flow to study the velocity and vorticity field quantitatively, and dynamic pressure were measured to evaluate its impact effect.

2. Experimental setup

2.1. Actuator and power supply

As shown in Fig. 1, the plasma synthetic jet actuator(PSJA) consists of a Teflon cavity and two tungsten electrodes which respectively served as an anode and a cathode. The cavity has a confined volume of 302 mm^3 with a height of 18 mm. Different from any other cylinder-shaped configurations, the actuator's cavity is designed as a convergent conical one without an upper wall which can prevent energy loss from obstruction. On the top side of the cavity, a cylindrical orifice with a diameter of 2.2 mm and a depth of 2 mm is drilled as the jet exit. The electrodes are equipped axisymmetrically into the cavity, with a 6 mm space. The distance between the tip of the electrodes and the bottom of the cavity is 8 mm.

The power supply system is composed of a high-voltage pulsed power(HVPP) and a direct current power(DCP), which is developed by Zong who has integrated the trigger electrode and anode into a single one from the original three-electrode type [24]. Two diodes are supplied in the discharge circuit to prevent the reversing current. The HVPP is responsible for air disruption between the electrodes. The DCP supplies energy to the actuator by charging the capacitor continuously. Once the HVPP is triggered, the discharge channel is initiated across the anode and cathode, and the energy stored in the capacitor is released abruptly, which makes the air in the cavity heated and expanded. In the experiment, a waveform generator is used to trigger the HVPP with a TTL signal whose pulse width is 10 μs. Four high-voltage capacitors with its respective capacitance C of 1 μF, 2 μF, 4.7 μF and 10 μF are installed in the circuit. On the right side of the schematic, the localized arc filament plasma actuator with the same electrode spacing(6 mm) as the electrode gap of PSJA is shown. In order to give an insight into the effect of capacitance on the discharge in the cavity, the arc morphology and its resulting heating volume evolution are firstly discussed through the localized arc discharge.

2.2. Measurements

2.2.1. Electrical measurements

For the electrical measurements, a high voltage probe(P6015A) that is connected to the anode was used to measure the capacitor's voltage (U_{DC}). The arc current (I_C) was measured by a current probe(TCP0030A) that is connected to the cathode. The measured data is recorded by an oscilloscope with a sampling rate of 100 MHz. The total energy E_c stored in the capacitor was computed in Eq. (1). The arc energy E_0 was obtained by multiplying the arc voltage $V(t)$ with the arc current $I(t)$ and integrating the product over the arc transit duration (t_p).

$$E_c = 1/2CU_{DC}^2 \tag{1}$$

$$E_0 = \int_0^{t_p} V(t)I(t)dt \tag{2}$$

2.2.2. Schlieren imaging system

As shown in Fig. 2, the high-speed schlieren imaging system is used to study the arc luminance characteristics, as well as capture the schlieren images of the jet flow topology. Meanwhile, the evolution of the heating volume without a cavity is also revealed in the experiment. The schlieren system includes major components of a continuous Xenon lamp which serves as light source, two concave mirrors with a 3 m focus length and a high speed CCD camera.