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Manipulation of ramp-induced shock wave/boundary layer interaction using a transverse plasma jet array

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ABSTRACT

The unsteadiness of ramp-induced shock wave/boundary layer interaction under the disturbance of an array of plasma jets was experimentally investigated using high-speed Schlieren imaging. The plasma jet was created by arc discharge in a confined small cavity, with a volume of 50 mm^3. The boundary layer thickness at the position where the upstream array of the actuators locates is $\delta = 2.11$ mm. Two jet orifices with a diameter of $D = 1$ mm, 2 mm ($\delta/D = 2.11$, 1.05) are designed. The multichannel discharge circuit was used to extend the spanwise disturbance region of the jets. The size of separation zone was reduced when interacting with the plasma jet plume. Meawhile, an upstream motion of the separation shock and reattachment shock is observed during the recompression process caused by the obstruction and accumulation of the jets.

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1. Introduction

The unsteadiness of shock wave/boundary layer interaction (SWBLI) induces significant pressure oscillations that can accelerate the fatigue of aircraft materials. Flow control techniques are promising to alleviate those unstable oscillations. The destructive separation shock generated by SWBLI oscillates in a relatively low frequency range covering wide spatial and temporal scales. The source of such oscillation receives overwhelming attention. Various perspectives have been proposed, mainly focusing on the "superstructures" in the upstream boundary layer and the large-scale coherent structures in the separation zone (Clemens and Narayanaswamy, 2014).

To suppress the unsteadiness and the separation pertaining to SWBLI, various strategies including passive and active control methods have been proposed, with an objective of either directly manipulating the separation shock or reducing the separation zone (Frank et al., 2012; Russell et al., 2016). Passive methods generally rely on the mixing effect of streamwise vortices produced upstream the interaction; Verma et al. (2012, 2013) employed micro mechanical vortex generators and steady micro-jets to reduce separation and shock strength, aiming at alleviating the unsteadiness. Subsequently, extensive parametric studies were performed by other researchers to optimize the performance of these devices (Binbin and Qingjun, 2015). The active category pivots around plasma aerodynamic actuation actuators including continuous ones such as direct-current arc/glow discharge and magnetically driven surface discharges (MHD), and pulsed ones such as dielectric barrier discharge (DBD), localized arc filament plasma actuators (LAFPAs), and pulsed plasma synthetic jet actuators (PPSJA) (Gnani n et al., 2016). Their effectiveness on both the shock and separation zone originates either from heat disturbance in the shock or by triggering flow instability in the upstream shear layer of the separated flow.

PPSJA is of particularly interest to supersonic flow control community due to its flexible manipulation and wide frequency band. The frequency of the separation shock has been demonstrated to be linked to the pulsation frequencies of the jets (Narayanaswamy et al., 2012). Several PPSJA studies have assessed its potential for flow manipulation. Zong et al. (2016) carried out a deal of optimization work to improve the actuator performance. Zhang et al. (2017) proposed a novel multichannel discharge technique to extent the actuation effect to a wide spatial range. Their measurements revealed that the discharge efficiency can be improved significantly. Although laboratory studies demonstrate the potential of PPSJA in high-speed flow manipulation, the usable operation frequency has been identified as a limiting factor towards industrial applications. As the exciting frequency increases, the deposited energy per pulse is reduced, resulting in significantly weakened jet intensity. For this reason, Wang et al. (2017) hypothesized that the disturbance effect could be enhanced if the jets interacts with a normal shock. Based on this hypothesis, the effect of a high-frequency counter-flow plasma jets actuator on a ramp-induced SWBLI was investigated. By a numerical simulation, they

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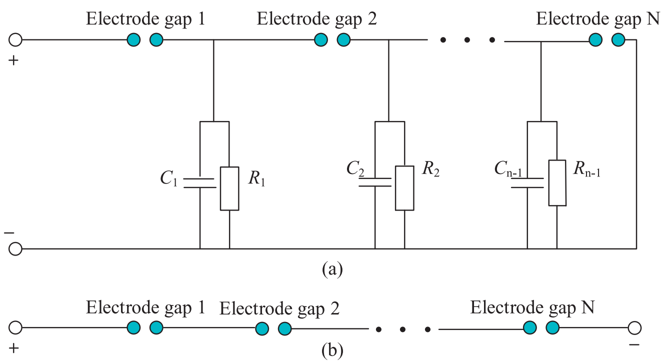

Fig. 1. The nultichannel discharge circuits.

attributed the enhancement to the baroclinic effect from the interaction between the jets and the normal shock.

In the case of high speed flow, the multichannel discharge technique proposed by Zhang et al. (2017) shows promising application prospect. As shown in Fig. 1(a), the electrical circuit of multichannel discharge scheme operates in a pseudo relay mode. After the ignition of electrode gap 1, the voltage across the electrode gap 2 increases sharply due to the charge of capacitor C_1, leading to the breakdown of electrode gap 2. Ignition of the rest electrode gaps can be realized in a similar 'relay' manner. As a result, this 'relay' discharge circuit extends the overall arc length through increasing the amount of discharge channels. In barometric pressure, 31 discharge gaps can be realized with this circuit (Zhang et al., 2017). In the present experiment, the static pressure of supersonic flow is much lower than ambient value. As an alternative to the circuit shown in Fig. 1(a), multichannel discharge could also be constructed by removing all the auxiliary components (capacitors and resistors) and purely improving the input voltage, as shown in Fig. 1(b). In this case, the breakdown of all the gaps occurs sequentially.

2. Experimental setup

The experiments were conducted in an air-breathing wind tunnel (Mach number: 2). The wind tunnel is supplied with ambient air with stagnation pressure of 96.6kPa± 3% and stagnation temperature of 296 K± 1%. The unit-length Reynolds number in test section based on the free-stream velocity is 1.17×10^7. The outlet diameter R of the nozzle is 300 mm. The wind tunnel has optical windows with 250 mm diameter located on both sides of the test section to diagnose the flow field. The test model, as shown in Fig. 2(a), consisted of a flat plate with a 30°ramp at its rear part. The distance between the flat plate leading edge to the compression corner of the ramp is 176 mm and the span (denoted by W) is 100 mm ($W/R = 1/3$). Three arrays of tiny orifices in a diameter of 1 mm or 2 mm are set as the plasma jet exit, located upstream of the ramp ($\delta/D = 2.11$, 1.05). The actuators were incorporated into the flat plate with five small cylindrical cavities inserted into the holes punched at the bottom of the plate bottom. The actuators are comprised of two cylindrical tungsten electrodes with a diameter of 1 mm and a small cylindrical cavity made of Teflon with inner diameter of 4 mm ± 0. 1 mm and depth of 4 mm ± 0. 1. The space of the electrodes in each pair is 2 mm. The jet exit orifices were spaced at 8 mm apart. Energy is released into the cavity in the form of arc discharge. leading to a dramatic temperature increase inside the cavity. The increase in temperature leads to an increase in cavity pressure, which expels the air out from the exit orifice. In the experiments, five actuators were used and incorporated in a serial circuit, as shown in Fig. 2(b).

A pulsed high voltage power supply (PHVPS) and a DC power supply (DC-PS) are used to feed the actuator (Zong et al., 2016). Capacitive arc discharge was realized using a high voltage non-inductive capacitor charged by the DC-PS, and occurred immediately after the electrodes were broken down by triggering the PHVPS. A time-resolved schlieren system in a typical Z-type configuration with two 300 mm concave mirrors, was designed for wind tunnel flow visualization. A continuous white light Xenon lamp served as the light source. A PHANTOM camera (maximum resolution 1600 × 1200 pixels) was used for image acquisition. A Nikon objective with a variable focal length of 80–300 mm and a lens doubler were mounted. A horizontal knife filter was used to enhance the sensitivity of the system. The sample frequency of the CCD camera was set to 10,000 fps during the experiments. The PHANTOM camera and a DG-535 delay generator were triggered by an oscilloscope when receiving the pressure signal monitored at the rectification section of the wind tunnel. The delay generator further triggered the PHVPS to work. A 0.5 s time delay was set to ensure the flow field was stabilized. Fig. 3 shows a typical structure of the ramp-induced SWBLI induced by a 30°ramp, which consists of separation shock, reattachment shock, main shock, and a separation region. The triple point T is the position where the separation shock and reattachment shock intersect. The streamwise length of the separated zone is determined to be 28.3 mm, based on the intensity RMS of a sequence of schlieren images. Fig. 4 shows the voltage and electrical current of the whole circuit during one pulse period tested at low pressure around 12 kPa in accordance with the experimental conditions in the wind tunnel (with 1000 V DC power). The capacitor was charged to approximately 1000 V, 1200 V, and 1500 V during testing, resulting in total input energy of 403 mJ, 480 mJ, and 716 mJ in a pulse.

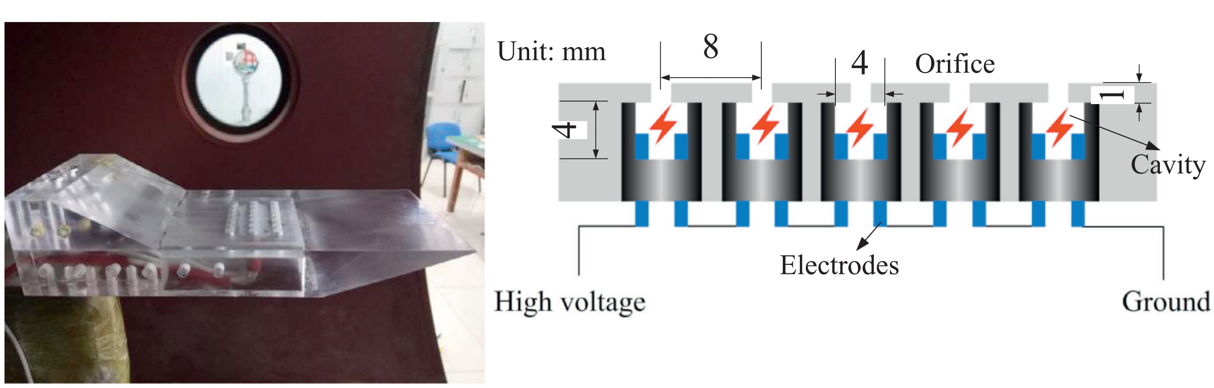

Fig. 2. Test model (a) and actuators (b).

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