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Characteristics of pulsed plasma synthetic jet and its control effect on supersonic flow

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Abstract The plasma synthetic jet is a novel flow control approach which is currently being studied. In this paper its characteristic and control effect on supersonic flow is investigated both experimentally and numerically. In the experiment, the formation of plasma synthetic jet and its propagation velocity in quiescent air are recorded and calculated with time resolved schlieren method. The jet velocity is up to 100 m/s and no remarkable difference has been found after changing discharge parameters. When applied in Mach 2 supersonic flow, an obvious shockwave can be observed. In the modeling of electrical heating, the arc domain is not defined as an initial condition with fixed temperature or pressure, but a source term with time-varying input power density, which is expected to better describe the influence of heating process. Velocity variation with different heating efficiencies is presented and discussed and a peak velocity of 850 m/s is achieved in still air with heating power density of 5.0×10^{12} W/m^3. For more details on the interaction between plasma synthetic jet and supersonic flow, the plasma synthetic jet induced shockwave and the disturbances in the boundary layer are numerically researched. All the results have demonstrated the control authority of plasma synthetic jet onto supersonic flow.

1. Introduction

Flow control technology is one of the hotspots in aeronautics and astronautics, which is expected to bring significant benefits for aircraft such as improved performance, payload, maneuverability and lower cost. For future flight control units, the criteria mainly include the following aspects: easy to integrate, adjustable, high reliability and low energy consumption.

Compared with other solutions like mechanical deflection and mass injection, synthetic jet actuation could achieve the manipulation of flow field without complex mechanical devices and extra gas supply, thus has drawn much attention worldwide. Smith and Glezer described the formation and evolution of typical piezoelectric-based synthetic jet,[1] and the working mechanism concluded by Glezer indicated that through manipulating the interaction between synthetic jet and cross

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flow, the localized "trapped" vortices' concentration could be achieved near the actuating area, by which the virtual shape was generated so as to change the aerodynamic force.[2] Mane et al. systematically analyzed the influence of various factors, including the diaphragm and the cavity geometry, on the performance of the synthetic jet.[3] Experimental investigations respectively validated the control authority of synthetic jet to a shear layer,[4] the flow over a two-dimensional cylinder[5] and separated flow on an unconventional airfoil.[6] Another combustion-driven jet actuator was believed to create jets with high impulse momentary,[7] but the fuel/air supply and valves would bring other problems in installation.

Based on the concept of combustion-driven jet, the Applied Physics Laboratory of Johns Hopkins University initiated a new type of synthetic jet, which was called spark jet.[8] This kind of actuator generally includes a cavity, a pair of electrodes and an orifice. The working process is divided into three stages: energy deposition, discharge and recovery. Inside the cavity the electrodes are fixed with certain distance; at the first stage, when the input voltage exceeds breakdown value, an arc filament is initiated and electrothermally heats the gas within a very short time. With the sharp increase of pressure, the gas will erupt from the orifice and forms plasma synthetic jet, which is called discharge stage. At the recovery stage, the gas outside will be drawn back into the cavity because of the lower pressure, and the actuator is refilled for the next pulse.

Cybyk et al. established a three-dimensional analytical model to assess the performance of the actuator, and the impact of some parameters like cavity volume and deposited energy was also discussed.[9,10] Through experiments the peak pressure of the cavity was measured to be about 1.8×10^6 Pa,[11] with high-resolution particle image velocimetry (PIV) the propagation of plasma synthetic jet was quantified.[12] Besides, the temperature distribution of jet plume was acquired with digital speckle tomography (DST), and the maximum value reached over 1600 K within 75 μs after jet release.[13] Narayanaswamy et al. experimentally researched the performance of pulsed plasma jet both in Mach 3 flow and stagnant air.[14] Some efforts have been made to explore its application to the control of shockwave boundary layer interaction;[15,16] when jet actuation was adopted at $St_L \approx 0.04$ (where the Strouhal number $St_L = fL/U_\infty$ is defined by the characteristic length L, the frequency f and the freestream velocity U_∞) and actuation frequency $f = 2$ kHz, the separation shock unsteadiness was locked to the pulsing frequency of the actuator, and the overall magnitude of the pressure fluctuations reduced by about 30%.[17,18] Reedy et al. discussed the influence of capacitor size on plasma synthetic jet velocity, and both velocity contours and vectors are acquired with PIV at different delay times.[19] Shin described the evolution of electro-thermal jet through schlieren images; it was noted that the enlargement of discharge current or duty time would lead to the peak value of the jet. But further increase of duty cycle or pulse frequency may weaken the jets since there was not enough time for the recharge of capacitor or the recovery of jet cavity.[20] Belinger et al. focused on the impact of the power supply on the plasma synthetic jet; a comparative study between plasma synthetic jets created by an inductive power supply and a capacitive one was introduced and the role of the rate of energy dissipation in the discharge was particularly discussed.[21] Barricau et al. tested the operating characteristics of plasma synthetic jet actuator. In the field of flow control application, both experimental and numerical results showed its effectiveness when applied as fluidic vortex generator, besides, it was reported that the plasma synthetic jet could thicken the mixing layer of high subsonic jet in the exit of nozzle, which was believed to mitigate the jet exhaust noise.[22,23] Efforts on numerical simulation from Anderson and Knight evaluated the force and impulse generated by plasma synthetic jet; analysis showed that the force from a plasma synthetic jet array is sufficient to replace the conventional aerodynamic flap.[24] Wang et al. investigated the energy efficiency and performance of plasma synthetic jet, and the characteristic of a three-electrode plasma synthetic jet actuator is studied.[25,26] Jin et al. experimentally researched the influence of discharge voltage and frequency on the velocity of pulsed plasma synthetic jet.[27]

In this paper, the characteristics of plasma synthetic jet and its control effect on supersonic flow are studied. Through time resolved schlieren method the formation of plasma synthetic jet and its precise structure are acquired, which help to accurately measure the velocity of jet front. In numerical simulation, the arc domain is no longer defined as a heating block with constant pressure or temperature, but described with time varying power density, which comes from experimental diagnose. That will be definitely closer to the reality, with this the influence of heating process can be considered, so the dynamic evolution of plasma synthetic jet and its coupling with supersonic flow will be better reflected.

2. Experimental setup

Fig. 1 gives the schematic of small-scale Mach 2 wind tunnel test section. The compressed air from plenum tank and inter-

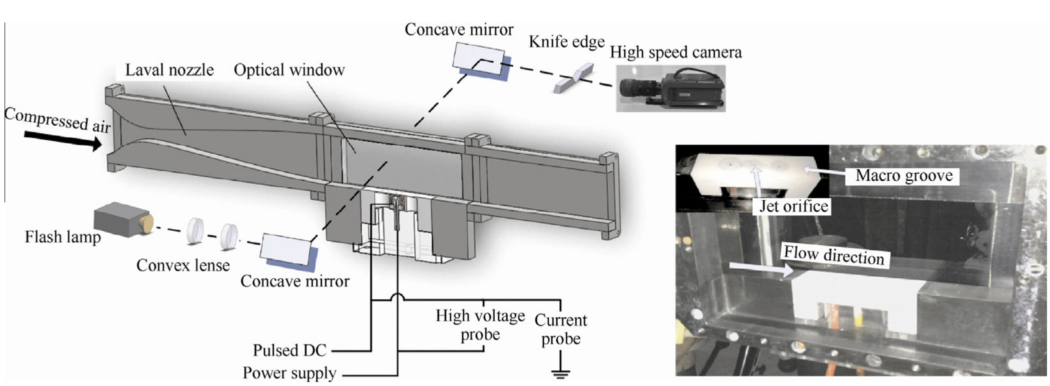

Fig. 1 Schematic diagram of experiment setup.