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Research paper

A novel ram-air plasma synthetic jet actuator for near space high-speed flow control

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ABSTRACT

As a promising high-speed flow control technique, plasma synthetic jet actuator (PSJA) has the superiorities of requiring no moving parts or flow supplies, extremely fast response, wide frequency band and high efflux speed. However, it has limitations for application: in near space, the air in the cavity which is used to generate the puled plasma jet becomes rare, and the low refill rate often leads to insufficient recovery which limits the working frequency. In order to overcome these limitations, a novel actuator called ram-air plasma synthetic jet actuator (RPSJA) is proposed. Inspired by the ramjet, the principle of this actuator is to take advantage of the tremendous dynamic pressure of the high-speed inflow using an added ram-air inlet. Numerical investigations were conducted to demonstrate the feasibility of such an actuator. The results show that, compared with PSJA, the air in the chamber becomes denser and the refill rate is notably increased owing to the "ram-air effect" of RPSJA. Based on the flow characteristic analysis, a revised actuator with a stepped ram-air inlet is proposed and investigated as well, and the results show that the performance is improved as the stepped height rises.

1. Introduction

Due to considerable potential uses in a number of areas, such as flow separation control, boundary layer transition, mixing enhancement, drag and heat reduction et al., active flow control (AFC) methods (jet blowing [1,2], synthetic jet [3,4], plasma actuator [5–7] et al.) have become one of the hotspots in fluid mechanics. As a new type of plasma actuator, plasma synthetic jet (also called sparkjet or pulsed plasma jet) is one of the enabling AFC methods which show the promise of manipulating high-speed flows [7–11]. It is created by the energy deposition from a pulsed arc discharge in a small cavity with an orifice. The operation cycle of plasma synthetic jet actuator (PSJA) consists of three distinct stages: energy deposition, air expulsion and air recovery. PSJA has the favorable features of both plasma actuator and zero net mass flux (ZNMF) jet. Its unique properties, such as requiring no moving parts and flow supplies, extremely fast response [12,13], wide frequency band (from zero to several kHz) [14–16] and high efflux speed (several hundred m/s) [17,18] et al., make PSJA most suitable for high-speed flow control.

Various experimental and numerical methods have been used to investigate the characteristics of PSJA. The mostly used experimental techniques include voltage-current measurement, high-speed schlieren [14] or shadowgraphy [18], quantitative schlieren [19], optical emission spectroscopy [15], particle image velocimetry (PIV) [17], thrust measurement [20], short-exposure-time ICCD photograph [21], pressure measurement in the cavity [22], total pressure measurement of the jet [14], digital speckle tomography (DST) [23], infrared camera [14] and so on. For numerical investigations, the useful numerical methods include analytical model [26], instantaneous energy deposition model [7], source term model [10], non-confined arc simulation [27] and plasma kinetic models [24].

To date, research achievements on the performance of PSJ actuator are abundant. Contrasting research into inductive discharge and capacitive discharge shows that capacitive discharge produces a more powerful jet (higher velocity, shorter expulsion time), and probably heats the gas and the cavity less significantly than inductive discharge [25]. Compared with the two-electrode actuator, a novel three-electrode actuator increases the cavity volume as well as input energy and keeps a relative low disruptive voltage [18]. With the same energy deposition, there exists a saturated frequency, above which the total mechanical energy of the pulsed jet drops sharply [26]. The discharge energy, cavity volume and ambient pressure determine the dimensionless energy deposition of the actuator (i.e. the ratio of discharge energy to the internal energy of gas in the cavity) which influences the performances of PSJ. As the dimensionless energy deposition rises, three typical flow field evolution patterns (shock wave, weak jet with vortex rings and strong jet without vortex rings) appear successively [9]. As the orifice diameter enlarges, the peak jet front velocity

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increases while the jet duration time and the jet delay time drop [28].

In spite of many good properties, PSJA still has limitations in application. First, when the actuator is working in near space, the environment pressure decreases so the air in the cavity which is used to generate the puled plasma jet becomes rare. This degrades the performance of PSJA at high altitudes. Second, the refill rate is very low in the third stage of the operation (i.e., the air recovery stage which mostly depends on the negative pressure in the chamber caused by the jet expelling). This low refill rate often leads to insufficient recovery which limits the jet energy and working frequency. Previous studies by Zong et al. show that as the working frequency increases, the mechanical energy and the expelled mass incorporated in single pulsed jet decrease [26]. And the experiments conducted by Narayanaswamy et al. in the quiescent flowfield show that though the circuitry can work reliably over 100 kHz, PSJA will begin to miss pulses at about 5 kHz due to the air recovery timescale being longer than the interpulse period and hence the lack of air in the chamber [15]. What's more, the situation gets worse when the actuator is working in the high-speed flow. The large inertia and injection of the high-speed crossflow make it even more difficult for the chamber to inhale the outer air [29].

Some efforts have been made in order to overcome these limitations. Emerick et al. [13] developed a non-ZNMF version of the actuator which incorporates an active refill supply pressure port. It utilizes compressed air and a one-way poppet check valve to supply air to the chamber of the actuator. Liu et al. [30] developed a similar air supplementing type PSJA which utilizes different kinds of one-way check valves connected to the atmosphere to improve the air refill.

In this paper, a novel actuator called ram-air plasma synthetic jet actuator (RPSJA) is proposed in an attempt to improve the performance of PSJA in the near space high-speed flow control. The configuration and working process of RPSJA are described in Section 2. Numerical investigations were conducted to demonstrate the feasibility of such an actuator. The performances of both PSJA and RPSJA are compared. And based on the analysis of the flow characteristics, an improved design of RPSJA with a stepped ram-air inlet is investigated as well. The numerical simulation methods are described and validated in Section 3. And the simulation results are presented and discussed in Section 4.

2. RPSJA description

The schematic and operation circle of RPSJA are shown in Fig. 1. The actuator is implanted in the aircraft body. Its compositions such as the chamber, electrodes, and jet orifice are similar to PSJA, except that a ram-air inlet toward the incoming flow is added. The operation circle of RPSJA, as shown in Fig. 1, also consists of three stages: 1) ram-air charge, during which a high-speed flow is introduced into the actuator, and the chamber is refilled and pressurized quickly; 2) energy deposition, during which an arc discharge is struck inside the chamber, and

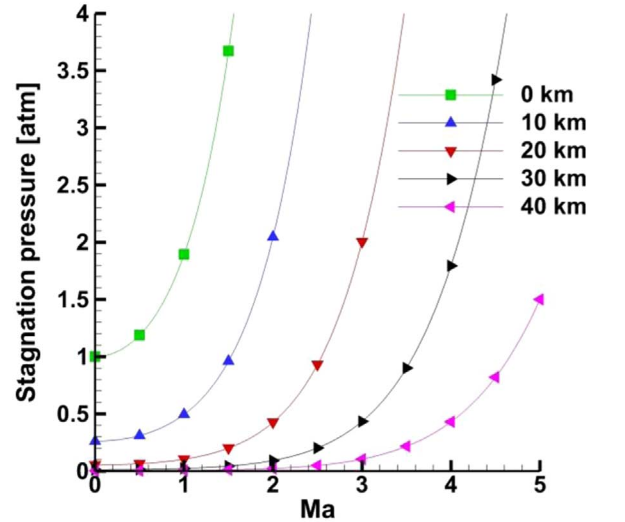

Fig. 2. The stagnation pressure as a function of *Ma* at 0–40 km flight altitudes.

the air inside the chamber is heated and pressurized further; 3) air expulsion, during which the hot and pressurized air spurts out, and a high-speed jet is “synthesized”.

The idea of RPSJA is inspired by the ramjet. Like a ramjet, its basic principle is to take advantage of the tremendous dynamic pressure of the high-speed inflow. The stagnation pressure of the high-speed inflow P_s can be described as

$$P_s = P + P_d = P\left(1 + \frac{\gamma - 1}{2}Ma^2\right)^{\frac{\gamma}{\gamma-1}} \tag{1}$$

where P represents the freestream static pressure, P_d represents the dynamic pressure, γ is the specific heat radio and Ma is Mach number. The stagnation pressure P_s as a function of Ma at different flight altitudes (0–40 km) is given in Fig. 2. It is seen that the static pressure drops greatly as the altitude increases. For example, at the high altitude of 20 km, the static pressure drops to 5.5 kPa which is about one twentieth of the standard atmosphere pressure. In this rarefied air environment, the intensity and control effect of plasma synthetic jet will decrease greatly. On the other side, the dynamic pressure increases significantly with the rise of Ma, which suggests the utilization of the dynamic pressure to improve the performance of PSJA.

As shown in Fig. 1, the chamber of RPSJA is like the combustor of the ramjet in some sense, and the ram-air inlet is like the inlet. Through the ram-air inlet, a high-speed airflow is introduced into the chamber where the electrical energy is input and transformed to the internal energy of the air by pulsed arc discharge (acts like the combustion of the ramjet that transforms the chemical energy to the

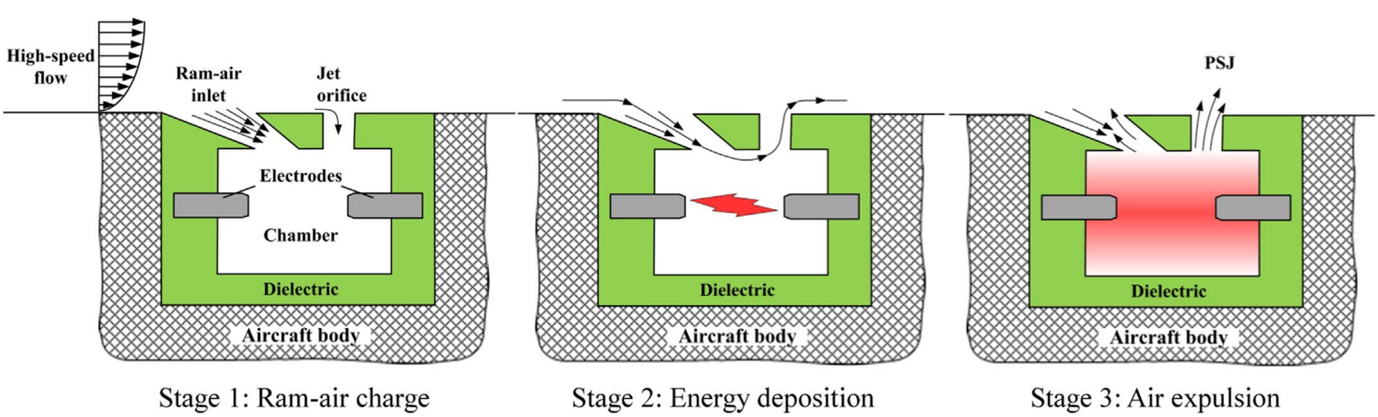

Fig. 1. The schematic and operation circle of RPSJA. Stage 1: Ram-air charge Stage 2: Energy deposition Stage 3: Air expulsion.