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High-Bandwidth Pulsed Microactuators for High-Speed Flow Control

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A systematic study on the design, development, and characterization of high-momentum, high-bandwidth microactuators for high-speed flow control is described in this paper. Beginning with building-block experiments, multiple resonant flow phenomena are used in the actuator design to arrive at an actuator configuration that provides the desired flow properties. The first-generation actuator design consists of an underexpanded source jet incident upon a cavity. The lower surface of this cavity contains micronozzles through which the unsteady microjets (400 μm) issue. Results show that microjets produced by this actuator have a high mean momentum (300–400 m/s) and a significant unsteady component (20–30% of the mean). Experiments were conducted over a large range of parameters in terms of cavity length, source jet nozzle pressure ratio, and impingement distance. The results unequivocally demonstrate the ability to vary the frequency and the amplitude of the mean and unsteady momentum of microjets issuing from this actuator. By varying the dimensions of the actuator by few hundred microns and/or source jet pressure by roughly 1 atm, one is able to vary the frequency rather precisely over a range of 5–20 kHz. A correlation based on Strouhal number and jet column length is suggested for the design of actuators. Actuators in the frequency range of a few to well over 50 kHz have been designed and characterized. It is believed that the frequency range may be extended down to $\mathcal{O}(100\ \mathrm{Hz})$ and up to $\sim\mathcal{O}(100\ \mathrm{kHz})$ using this actuator approach.

I. Introduction

DESIGN and development of active flow control systems have received wide attention in the recent years due to their ability in reducing or eliminating a number of adverse and parasitic effects associated with aerodynamic flow and providing potentially substantial gains in performance. A number of such systems have been developed and tested over the years by many researchers, some of which were found promising in a limited range of flow conditions. Ideally, the desired control effect (e.g., noise reduction, flow separation control, and turbulent mixing) must be achieved with minimal energy input. Active control of high-speed flow demands high-amplitude and high-bandwidth actuation techniques for the effective and efficient manipulation of such high-energy/high-momentum flows and structures that are often responsible for the adverse flow characteristics. An example of such a flowfield is associated with a supersonic cavity. Various active and passive control strategies have been explored to control the aeroacoustically induced cavity flow oscillations (Zhuang. et al. [1] and Ukeiley et al. [2]). Another high-speed flowfield that requires proficient active control is associated with supersonic impinging jets (Krothapalli et al. [3], Alvi et al. [4], and Kumar et al. [5]). A short takeoff and vertical landing aircraft during its hovering mode, especially in close proximity to the ground, produces a highly unsteady flowfield that produces intense unsteady aeroacoustic loads that can lead to ground erosion and structural damage to the near-field structures. The above examples point to the necessity of developing energy-efficient and effective actuator systems for a number of aeroacoustic problems. In addition, progress in the area of microelectronics has given rise to more challenging problems associated with the thermal management of microdevices (Ro and Loh [6]). Development of effective micro-actuator systems that are scalable and capable of addressing some of these issues may potentially be beneficial toward solving these problems as well.

Flow control methods are generally classified into active and passive based on the involvement of external energy in the control process. Passive methods do not require external energy input but make use of the energy associated with the primary flow for the purpose of control. Variations in nozzle geometry, i.e., rectangular, triangular, elliptic, etc. (Sfeir [7], Sforza et al. [8], and Schadow et al. [9]), use of mechanical tabs of different shapes and the use of splitter plates (Zaman et al. [10] and Reeder and Samimy [11]) are examples of various passive control methods adopted for the control of jet noise. On the other hand, in active flow control schemes, an external energy source is used for tailoring the natural behavior of a shear-layer or a boundary-layer flow according to the control objectives. The ability to efficiently adapt to changing flow conditions (the ultimate goal of active control schemes) makes them more attractive than passive methods.

Mechanical systems such as vibrating ribbons and cantilevered beams and electromechanical devices such as piezoelectric diaphragms, voice coils, and speakers are used as external energy sources in various active flow control schemes. The vibration of a piezoelectric material is used for generating a low-momentum air jet with zero net mass flux (synthetic jets) for the control of cavity flows (Cattafesta et al. [12]) and shear flows (Wiltse and Glezer [13]). Actuators based on synthetic jets have also been used for separation control over airfoils and cylinders (Amitay et al. [14]). A number of researchers in the past modified the Hartmann tube and used it as a flow actuator, demonstrating reasonable success over a limited range of flow conditions (Raman and Kibens [15], Kastner and Samimy [16], and Dziuba and Rossmann [17]). Although relatively successful at low speeds, many actuators are not very efficient when the primary flow velocities are high, in particular supersonic. Optimal manipulation of the shear or boundary layer of high-speed flows requires aeroacoustic disturbances with high momentum or energy, and actuators whose steady and unsteady components can be manipulated. A simple and robust actuator, with high mean and unsteady momentum that can be easily integrated into practical high-speed flow applications and subsystems is essential for efficient active flow control schemes. The present studies are motivated and driven by this goal.

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