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Variable-Frequency Fluidic Oscillator Driven by a Piezoelectric Bender

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A new actuator for aerodynamic flow control applications is described and evaluated in this paper: the piezo-fluidic oscillator. This actuator is a fluidic device based on wall attachment of a fluid jet and modulated by piezoelectric devices. The piezo-fluidic oscillator successfully decouples the operating frequency from the flow characteristics of the device. The frequency is specified by an input electrical signal that is independent of pressure, making this actuator ideal for closed-loop flow control applications. The oscillator exhibits high bandwidth (up to 1.2 kHz), modulation rates up to 100%, and a velocity range reaching sonic conditions. Furthermore, the bistable actuator may be operated in a steady state, with momentum flux in one of two desired directions for flow vectoring purposes. The piezo-fluidic oscillator may be used in flow control applications in which synthetic jets or plasma actuators cannot provide enough momentum for control authority. This paper details the design and characterization of the piezo-fluidic oscillator. The dynamic response characteristics are evaluated with flow visualization and hot-film probe measurements on the output.

I. Introduction

FLOW control is a rapidly developing field in applied fluid dynamics, with much of the work focused on actuator development, sensor systems, control logic, and applications. Flow control actuators are devices that are used to enact large-scale changes in a flowfield. Often these changes are focused on improving the performance of a flight vehicle: by delaying stall, reducing drag, enhancing lift, abating noise, reducing emissions, etc. In many flow control situations, unsteady actuation is required for optimal performance. Unsteady actuators are particularly beneficial in closed-loop control applications when the unsteady actuation can be controlled and synchronized with characteristic time scales of the flowfield. Common flow control actuators include synthetic jets [1], piezoelectric benders for direct excitation [2,3], powered resonance tubes (also known as Hartmann whistles) [4–6], plasma actuators [7–9], pulsed combustion actuators [10–12], pulsed jets [13,14], and steady blowing [15] or suction [16]. These devices and concepts all have inherent strengths and some limitations. Thus, the selection of a flow control actuator is often driven by the requirements of the application.

The ideal actuator will have a high-frequency bandwidth and direct control by an electrical signal for closed-loop applications. The device should be simple and robust for reliable flight operations: devices with few moving parts are desirable for mechanical reliability. The ideal actuator should also be capable of a large range of flow rates, but should only provide enough momentum input for sufficient control authority. Some applications require large flow rates that current actuators cannot deliver. Jet thrust vectoring on a flight vehicle is one such example. Miller et al. [17] and Yagle et al. [18] specified that the ideal actuator for this application is a pulsed jet that operates at 1 kHz with 100% modulation of the jet at sonic conditions. The focus of the present work is on the development of a fluidic oscillator toward the following design goals: high bandwidth, high mass flow rates, and an operating frequency that is decoupled from the flow rate.

The fluidic oscillator is a device that generates an oscillating or pulsed jet when supplied with a pressurized fluid, as shown in Fig. 1. The development history of fluidic oscillators is very rich and extensive, being grounded in the field of fluidic amplifiers [19–22]. Typical oscillators are bistable devices that operate on the principle of wall attachment, as shown in Fig. 2. When a free jet of fluid is adjacent to a wall, entrainment of flow around the jet causes a low-pressure region between the wall and the jet that draws the jet closer to the wall. Thus, the jet will deflect until it has attached to the wall. This principle was observed by Coanda [23] in the 1930s and was later named the Coanda effect [24]. Coanda [23] originally appropriated this phenomenon for steering streams of fluid.

If there are two adjacent walls, such as the symmetric configuration shown in Fig. 2, the jet will arbitrarily attach to one wall or the other, based on random disturbances in the flow. Traditional fluidic devices employ a control port at the nozzle, where injected mass flow can force the jet to detach from the wall and reattach to the opposite wall. This occurs through the creation of a separation bubble between the jet and the wall. As more fluid is injected from the control port, the separation bubble enlarges and extends downstream until the jet has entirely separated. The pressure differences and momentum of this separation process then carry the jet over to the opposite wall, where it reattaches. The primary advantage of this arrangement is that the

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