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Experimental investigation on a cavity-step-actuated supersonic oscillating jet

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Abstract Wind tunnel testing is conducted at different back pressures in a vacuum-type wind tunnel for a novel supersonic fluidic oscillator which consists of a two-dimensional Laval nozzle, a rectangular cavity and a backward step, to obtain its characteristics and the conditions for jet oscillating. The experimental results show that periodic asymmetrical flipping of the supersonic jet appears over certain nozzle pressure ratio (NPR) range according to schlieren visualization and pressure fluctuations. The jet flipping appears only when the jet is over expanded. The normalized average amplitude of the lateral pressure difference acting on the roofs of the cavity and the step varies around 0.2 while the periodic flipping appears. The supersonic jet periodic flipping frequencies obtained from the experiments agree well with those from the modified Rossiter mode for cavity-step acoustic resonance, but further investigations are needed to discover the underlying mechanism for the jet flipping.

1. Introduction

Fluidic oscillators, which produce an oscillating jet (sweeping or pulsing jet) at high frequency, are attracting increased attention in recent years due to their application potentials as flow control actuators.[1] The attractive features of fluidic oscillators for flow control are their characteristics of unsteady blowing, wide range of operating frequency, and the distributed nature of momentum addition. Innovative applications of fluidic oscillators to flow control problems include separation control,[2] jet thrust vectoring, cavity tone suppression, and so on.[3,4]

One characteristic of all fluidic oscillators is that there must be some type of feedback mechanism to drive the oscillations. Based on the difference in the feedback mechanism, at least four types of fluidic oscillators have been invented so far, i.e., wall attachment,[5] jet interaction,[6] cavity acoustic resonance, and vortex oscillators.[3] Wall attachment and jet interaction oscillators have received more investigations in recent years, and details on these two oscillators were summarized in two latest review papers.[3,4]

The cavity resonating oscillator was developed as one type of temperature sensor around the 1970's.[7] One typical design is

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shown in Fig. 1. As a fluid jet issues from the inlet nozzle and impinges on a wedge, it is subjected to an oscillation transversely to the jet issuing direction. This oscillation has traditionally been called edge tone oscillation.[8] The edge-tone oscillation is caused by inherent shear layer instabilities, vortex shedding, and acoustic feedback characteristics of the jet-edge configuration, and is dependent upon the jet velocity and the distance from the nozzle exit to the wedge.

The cavity in which the fluid runs from the inlet nozzle to the discharge exhaust has a characteristic or acoustic resonance frequency (eigen frequency). Carter[7] pointed out that this cavity eigen frequency is excited by the edge tone oscillations beginning at an input pressure corresponding to the threshold point. No distinct oscillation is produced until the input pressure reaches the threshold value. At this value, the frequencies of oscillations produced by the flow impinging on the edges at the exhaust begin to match the cavity eigen frequencies.

The acoustic resonance frequency for face-to-face cavities can be expressed by the cross junction mode[9] which depends on the acoustic velocity c and the cavity height H as follows:

$$f = mc/2H \tag{1}$$

where $m = 2n + 1$ $(n = 0, 1, \ldots)$. Since the sound speed is a function of temperature, the output frequency can be expressed by

$$f = \frac{m\sqrt{\gamma R_g T}}{2H} \tag{2}$$

where T is the temperature of the fluid in the cavity, γ is specific heat ratio and R_g is gas constant. Knowles[10] tested a cavity acoustic resonance oscillator which was similar to the one shown in Fig. 1 (L denotes the cavity length), and his results showed that the experimental frequency of oscillation agreed well with the prediction by Eq. (2).

As can be seen from Eq. (2), for a certain oscillator (i.e., H is fixed), the oscillation of the fluid in the cavity is a function solely of the temperature of the fluid which is usually constant for flow control applications, which means that the oscillating frequency for a given oscillator is fixed, without considering the influence of the integer m. This is beneficial for flow control applications,[1] compared to a wall attachment oscillator in which the oscillation frequency is directly dependent on the flow rate through the device.

Several researches on cavity resonating oscillators in 1970's were limited in their subsonic operation. In recent work on wall attachment oscillators, only a few researchers investigated their operation of the supersonic flow. Raman et al.[12] reported their research on the extension of a " flip-flop" jet nozzle to supersonic flows. They made their device operate as a supersonic flapping jet at frequencies over 300 Hz. Oscillations stopped when the pressure ratio increased high sufficiently that the internal jet expanded enough to touch both side walls. Gokoglu et al.[13] reported their work related to the computational investigation of the internal flow in a fluidic oscillator (Fig. 2) working at supersonic conditions. Their two-dimensional (2D) simulations matched the oscillation frequencies measured from experiments across a wide range of pressure ratios. The existence of supersonic flow at the exit was verified, and the complex inner interactions between vortical structures and the feedback channels as well as the exit nozzle that led to oscillations were revealed by their computations.

Seele et al.[14] published schlieren photos in which a supersonic flow at the exit of a fluidic oscillator was clearly shown. We conducted supersonic jet flipping research on two novel symmetric supersonic fluidic oscillators which consisted of a 2D nozzle and two face-to-face cavities. The difference between these two is that one consisting of a 2D convergent nozzle and the other of a 2D Laval nozzle. Both oscillators were studied through wind tunnel tests to analyze the jet flipping. It was found that periodic supersonic jet flipping appeared under certain pressure condition and the oscillating jet achieved significant mixing enhancement.[15,16]

This paper focuses on the characteristics of supersonic operation of a cavity acoustic resonance oscillator with an innovative design to produce a sweeping jet. Different from our previous research, this supersonic fluidic oscillator is asymmetric. The operation limit and oscillating course of this innovative oscillator have been studied experimentally.

2. Oscillator geometry

Based on Carter's theory of coupling of edge-tone oscillation and Campagnuolo's[11] design (Fig. 1), an oscillator was designed and fabricated for the test. Different from the oscillator with a convergent nozzle from Carter's design, convergent-divergent nozzles were employed in this work and the wedge downstream from the exit was removed. The oscillator

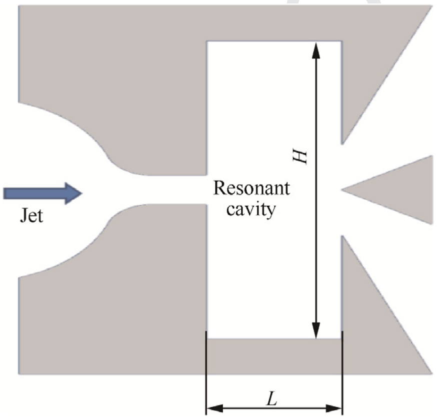
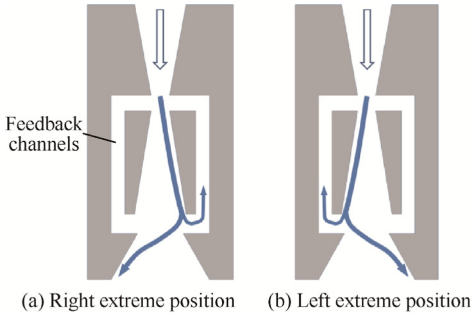


Fig. 1 Cavity resonating oscillator (redrawn based on Refs. 10,11).



(a) Right extreme position (b) Left extreme position

Fig. 2 Typical wall attachment oscillator (redrawn based on Ref. 13).

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