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Experimental investigations of cavity-actuated supersonic oscillating jet

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ABSTRACT

Wind tunnel tests were 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 and two face to face cavities, to obtain its characteristics and the conditions for jet oscillating. The experimental results show that periodic flipping of the supersonic jet appears from *NPR* = 3.4 to 5.6 according to schlieren visualization and fluctuating pressures. The cross-junction mode for estimating the resonance frequency in a pipe with two closed side branches was modified and obtained comparable estimations of the frequency of jet flipping with experimental data. The coupling of the modified cross-junction mode and the Rossiter mode for cavity resonance could be the reason for the flipping of the supersonic jets. Compared to free jet, the oscillating jet achieves significant mixing enhancement based on the analysis of jet axial peak velocity and the entrainment.

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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. The innovative application of fluidic oscillators to flow control problems includes separation control, jet thrust vectoring, cavity tone suppression and so on [2,3].

One characteristic of all fluidic oscillators is that there must be some type of feedback mechanism to drive the oscillations. Based on the difference of the feedback mechanism, at least four types of fluidic oscillators have been invented so far, i.e., wall attachment, jet interaction, cavity resonating and vortex oscillators [2]. The wall attachment and jet interaction oscillators have been receiving more investigations in recent years, and the details on these two oscillators were summarized in the two latest review papers [2,3].

The cavity resonating oscillator was developed as one type of temperature sensor around the 1970s [4]. One typical design is 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 [5]. 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 distance between 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 resonant frequency (eigen frequency). Carter [4] 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 oscillations are produced until the input pressure reaches the threshold value. At this value the frequencies of oscillation produced by the flow impinging on the edges at the exhaust begin to match the cavity eigen frequencies.

The resonant frequency for the face to face cavities can be expressed by cross junction mode [6] which depends on the acoustic velocity and on the cavity length

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

where $m = 2n + 1$ ($n = 0, 1, 2, 3, \ldots$). 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. Knowles [7] tested a cavity resonating oscillator which was similar to that shown in Fig. 1, and his results showed that the experimental frequency of oscillation agrees 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

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Nomenclature

c	sound speed (m/s)
f	frequency (Hz)
H	total depth between two cavities (mm)
h_t	nozzle throat height (mm)
L	cavity length (mm)
M	Mach number
$\dot{m}$	mass flow rate (kg/s)
NPR	nozzle pressure ratio, p_a/p_v
p	pressure (Pa)
R_g	gas constant (J/(kg·K)) r recovery factor
T	temperature (K); flipping period (ms)
t	time (ms)
u	jet velocity (m/s)
γ	specific heat ratio

Subscripts

a	ambient air at nozzle entrance
c	cavity
j	jet
v	vacuum tank

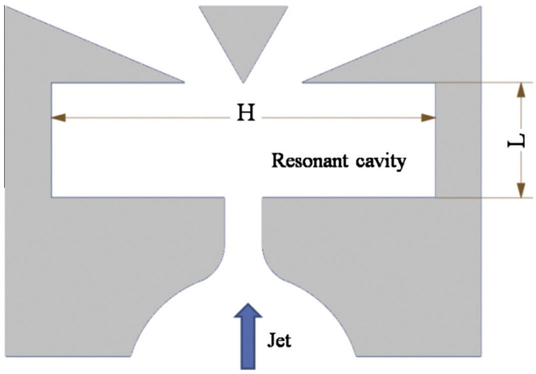

Fig. 1. Cavity resonating oscillator (redraw based on Ref. [8]).

of the temperature of the fluid which is usually constant for flow control application, which means the oscillating frequency for a certain oscillator is fixed, without considering the influence of the integer *m*. This is beneficial for flow control application [1], compared to the wall attachment oscillator in which the oscillation frequency is directly dependent on the flow rate through the device.

The several researches on cavity resonating oscillator in 1970s were limited in its subsonic operation. In recent work on wall attachment oscillators, only a few researchers investigated their operation of the supersonic flow. Raman et al. [9] published work related to the extension of a ‘flip-flop’ jet nozzle to supersonic flows. Their device operated as a supersonic flapping jet at frequencies over 300 Hz. Oscillations ceased when the pressure ratio was high enough that the internal jet expanded sufficiently to attach to both side walls. Gokoglu et al. [10] performed a computational investigation of the internal flow of a fluidic oscillator operating at supersonic conditions. Their 2D simulations were able to match the experimentally-measured oscillation frequencies across a wide range of pressure ratios for both air and helium. They were able to verify the existence of supersonic flow at the exit, with the computations revealing the complex inner interactions of vortical structures with the feedback channels and exit nozzle that lead to the oscillations. Seele et al. [11] reported schlieren images that clearly showed supersonic flow at the exit of a fluidic oscillator.

This paper will focus on the characteristics of supersonic operation of the cavity resonating oscillators with innovative designs to produce a sweeping jet. The operation limit, oscillating course and mixing characteristics of the innovative oscillator will be studied experimentally.

2. Oscillator geometry

Based on the Carter’s theory of coupling of edge-tone oscillation and Campagnuolo’s 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 are employed in this work and the wedge downstream the exit is removed. The oscillator (Fig. 2) has a nozzle throat height of 5 mm and a nozzle divergence angle of 5°, and then there are two face to face cavities with a length–depth ratio of 2.04 and a rectangular divergent exhaust after the cavity. The divergent exhaust has a divergence angle of 60° and a throat which is larger than the nozzle exit, which results in the smaller rear wall height of two cavities than the front walls. The oscillator has a width (*z* direction) of 40 mm.

3. Test facilities and instrumentations

A vacuum-type wind tunnel was used for all of the experiments. The inlet of the nozzle is exposed to the atmosphere with ambient pressure of 100.69–101.71 kPa and relative humidity of 18.0–23.2%, whereas the outlet is connected to a vacuum tank (Figs. 2 and 3). The vacuum tank has a large volume of 33 m^3 and the back pressure of the nozzle is constant at the desired value during a typical test time of 1–2 s. In this paper, the nozzle pressure ratio (*NPR*) is defined as the ratio of ambient pressure at the nozzle entrance to the pressure in the vacuum tank.

A standard schlieren system was used to visualize the transient flow inside and downstream of the oscillator (Fig. 3). A light ray

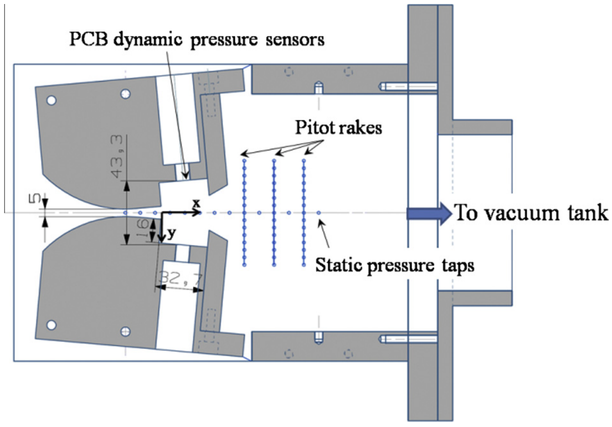

Fig. 2. Supersonic jet oscillator installed in a vacuum-type wind tunnel (dimensions in mm).

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