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Numerical investigation for effects of actuator parameters and excitation frequencies on synthetic jet fluidic characteristics

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ABSTRACT

Numerical investigation is performed to further address the effects of geometric parameters and excitation frequency of the actuator on the synthetic jet fluidic characteristics by utilizing a two-dimensional unsteady Reynolds-averaged Navier–Stokes model. The vibrating diaphragm is modeled as a movable wall varying in sinusoidal mode. Computations are carried out by using FLUENT software with the coupled user definition function (UDF) describing the diaphragm movement. The results show that the geometric parameters of the actuator, such as the cavity depth and diameter, as well as orifice thickness and diameter, have important influences on the synthetic jet fluidic characteristics. The velocity output could be maximized if the geometric parameters of the synthetic jet actuator are designed to ensure that the cavity acoustic Helmholtz resonance frequency is coincided with the diaphragm excitation frequency. For a fixed actuator cavity, when the diaphragm excitation frequency is consistent with the Helmholtz resonance frequency of actuator cavity, the relative pressure insides the cavity is obviously great during the ejection stroke while low during the suction stroke. In the presented actuator parameters, the synthetic jet is enhanced as the decrease of cavity depth for the fixed orifice. The change of cavity diameter in the vicinity of corresponding cavity acoustic resonance diameter has relatively weaker influence on the synthetic jet. When the diaphragm is excited at high frequency, small orifice diameter will restrict the ejection and suction capacity of the synthetic jet actuator.

1. Introduction

A synthetic jet is a quasi-steady jet of fluid generated from the periodic motion of a diaphragm enclosed in a cavity with openings on one or more walls. The fluid inside the cavity is expelled through the orifice as the diaphragm is forced to move upwards. The flow separates at the edge of the orifice, inducing a vortex ring that moves outwards under its own momentum. When the diaphragm moves downwards to entrain fluid into the cavity, the vortex ring is sufficiently distant from the orifice that it is virtually unaffected by the entrainment of the fluid into the cavity. In this fashion, a train of vortex rings moving away from the orifice occurs, whereupon the coherent structures then interact, coalesce, and break down in a transition toward a quasi-steady jet [1,2]. This operational principle allows for synthetic jets to have the unique property that they are formed from the working fluid in which they are deployed. In contrast to conventional continuous jets, synthetic jets are able to transfer linear momentum without a net mass injection across the flow boundary. On the other hand, conventional jets are formed by the addition of both mass and momentum at the orifice. Unlike synthetic jets, the momentum flux in conventional jets remains conserved. Due to the difference in formation between the two jets, there is no potential core in synthetic jets as opposed to conventional jets. Additionally, the periodic vortical structures introduced into the flow exhibit an ability of synthetic jet to influence the environment at a variety of length scales. This vortex shedding phenomenon is important for many applications, such as control of separated flow [3–5], jet vectoring [6–8], mixing enhancement [9–11], thermal management and heat transfer enhancement [12–17].

A lot of studies have covered the development of the piezoelectric actuator as well as the general behavior and performance of the synthetic jet produced. Results indicated that excitation frequency and cavity orifice were important factors affecting the size

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and formation of coherent structures in synthetic jet flow. Crook et al. [18] studied the development of a round jet using an analytical model and compared his results with hot-wire measurements. The study was focused on the maximum velocity from the jet as function of actuator geometry and operation parameters. It was found that the peak velocity was originated at operating frequency of about 1400 Hz. Chen et al. [19] measured velocity profiles at the centerline of a plane jet, and jet exit velocity profiles along and across the jet slot with a single component hot-wire. They used an actuator with a diaphragm oscillating at a frequency ranging from 500 to 1000 Hz. Guy et al. [20,21] studied a plane synthetic jet produced by piezo-diaphragm with hot-wire measurements. Similar to Chen et al. [19], they observed two resonance frequencies, in this case, 700 and 1160 Hz. Furthermore, it was suggested that there was an optimum combination of all geometric parameters at which the actuator would operate at its full capacity. To address the response of a cavity, Gallas et al. [22,23] presented a simplified lumped element model (LEM) of a piezoelectric-driven synthetic jet actuator. In this model, the individual components of a synthetic jet were modeled as elements of an equivalent electrical circuit using conjugate power variables (i.e. resistor, inductor, and capacitor). Based on the lumped element model, they deduced that the output velocity versus actuation frequency curve had two local maxima corresponding to the actuator cavity acoustic resonance (Helmholtz resonance, f_H) frequency and the diaphragm structural resonance frequency (f_D). Persoons and O'Donovan [24] presented an analytical model derived from simplified gas dynamics, for estimating the synthetic jet velocity and actuator deflection, based on a cavity pressure measurement. It was concluded that low-power operation was achieved by matching actuator and Helmholtz resonance frequencies. Lockerby et al. [25] made numerical-simulation studies to describe the methodology on how Helmholtz resonance affected the interaction of active and nominally inactive micro-jet actuators with a laminar boundary layer. It was previously shown that the conditions for Helmholtz resonance were identical to those for optimizing actuator performance for maximum mass flux. The velocity output could be increased significantly if the synthetic jet actuator could be designed so that the acoustic and structural resonances coincided in order to increase output velocity. This approach had been verified by some following works [26–29]. Pavlova and Amitay [26] experimentally investigated the efficiency and mechanism of cooling a constant heat flux surface by impinging synthetic jet; also, comparison with continuous jet was presented. In their measurements, high frequency (1200 Hz) jets were found to be more effective at smaller axial distances and the low frequency (420 Hz) jets were found to be more effective at larger axial distances. Zhang and Tan [27] investigated experimentally the flow and heat transfer characteristics of a synthetic jet driven by piezoelectric actuator by utilizing particle image velocimetry, hot-wire anemometry and infrared camera. Two resonance frequencies of 540 Hz and 1140 Hz were easily identified. It was evident that the actuator produces fairly high velocities even when operated off-resonance and the synthetic jet could not be formed under some frequencies. Chaudhari et al. [28] made a detailed experimental investigation wherein the effect of excitation frequency on the synthetic jet flow was studied for cavities of different depths and for orifices of different diameters. The exit velocity averaged over an excitation cycle indicated a lower and an upper bound on the frequency for the formation of a jet, and showed resonance at two frequencies. The resonant frequencies had been identified as being close to the diaphragm and the Helmholtz frequencies. Jain et al. [29] performed a numerical simulation to investigate the effect of various cavity parameters and orifice/cavity shapes on the ensuing synthetic jet flow. The simulation results showed that synthetic jets are more affected by changes in the geometric parameters of the orifice than those of the cavity.

The momentum carried by the fluid away from the actuator cavity is strongly dependent on its design, which makes the operating frequency and the geometric parameters of the synthetic jet actuator very crucial aspects in the synthetic-jet assembly. However, the detailed knowledge about the design aspects on the ensuing jet deserves further illustrated, especially on the relationship between the cavity Helmholtz resonance frequency and the diaphragm excitation frequency. In order to further address the effects of actuator parameters and excitation frequency on the synthetic jet fluidic characteristics, a numerical investigation utilizing a two-dimensional unsteady Reynolds-averaged Navier–Stokes model on the synthetic jet actuator fluid field was performed in this study. The synthetic jet fluidic characteristics were explored under the different design parameters of the synthetic jet actuator that include radius and thickness of the orifice, as well as radius and depth of the cavity. The relationship between the cavity Helmholtz resonance frequency and the diaphragm excitation frequency was analyzed.

2. Numerical simulation procedure

2.1. Physical model and computational domain

The physical model of a synthetic jet considered in the present is illustrated schematically in Fig. 1. It is composed of a vibrating diaphragm located at the bottom of a cavity, on the opposite face of which is a round orifice. The diaphragm is oscillating up and down in the sinusoidal or cosinoidal mode. The main geometric parameters of the synthetic jet actuator include diameter (d_o) and thickness (h_o) of the orifice, as well as diameter (d_c) and depth (h_c) of the cavity. The computational domain consists of three zones including the cavity, the orifice, and the surrounding region into which the jet exits. According to the study of Jain et al. [29], the surrounding size of 30 orifice diameters (in the lateral direction) and 20 orifice diameters (along the axis) is chosen. For this surrounding size, jet near field parameters are not affected by pressure outlet boundary condition applied at the end of the outer region.

In the present, a group of baseline geometric parameters are outlined as: $d_c = 45$ mm, $h_c = 7$ mm, $d_o = 3$ mm, and $h_o = 2.5$ mm. To address the effects of actuator parameter on the synthetic jet fluidic characteristics individually, one of the geometric parameters is varied in a certain range while the other geometric parameters are maintained as their baseline values.

2.2. Numerical methods

The unsteady Reynolds-average Navier–Stokes (RANS) equations are chosen as governing equations for the synthetic jet problems. The flow is assumed to be compressible and turbulent. The compressibility effects come into picture because of the rapid change in pressure/density due to the movement of the diaphragm. The computation is carried out by using the commercial CFD software FLUENT coupled with the user definition function (UDF) describing the diaphragm movement. The segregated, unsteady, symmetric solver is chosen with first-order implicit time scheme that is unconditionally stable with respect to time step size. Pressure-implicit with splitting of operators (PISO) based on a higher degree of approximation between the iterative corrections for pressure and velocity is chosen. Second-order upwind spatial discretization is used for the momentum, turbulent kinetic energy, and turbulent dissipation rate. According to Yoo and Lee [30], Menter's k–ω shear stress transport (SST) turbulence model is used to account for the turbulent nature of the synthetic jet flows.