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Technical Notes

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New Generation of Synthetic Jet Actuators

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Introduction

In the last 20 years, much attention has been given to developing microfluidic systems [1]. Among them, synthetic-jet actuators (SJA) have been intensely studied recently [2]. Synthetic-jet actuators have many potential applications such as jet vectoring [3,4], boundary-layer control [5,6], combustion control [7], and micro-pumps [8], etc. A synthetic-jet actuator is a zero net mass flux device. Figure 1a shows a typical structure of an existing SJA, which is composed of an exit slot (or orifice) and a diaphragm (or double diaphragms [9]) mounted to enclose a volume of fluid in a cavity. Piezoelectric (PZT) diaphragms are used in most mini- or micro-SJAs because of their size, rapid time response, and relatively low power consumption. The PZT-driven SJA also fits within the microelectromechanical system (MEMS) discipline and can be coupled with MEMS sensors, control and logic electronics into a single very lightweight and compact device. Unfortunately, the pressure loading limits to obtain a small deflection of the PZT-diaphragm on the existing SJA requires a high power to drive the PZT-diaphragm when the pressure differential between the base flow (to be controlled by the SJA) and the environment is large. This limits applications of the SJA. In addition, the diaphragm of the existing SJA (as shown in Fig. 1a) has one surface exposed to the fluid drawn from the base flow and the other surface exposed to the environment, which indicates that half of the radiation energy of the vibrating diaphragm is wasted in the environment. Keeping the advantages of a PZT-driven SJA, while resolving the major problems of pressure loading and energy inefficiency, is the main impetus for designing a new generation SJA.

A new SJA prototype is schematically shown in Fig. 1b. It consists of two cavities, a PZT-diaphragm, two exit slots, and a slide block (SB). In the new SJA concept, two adjacent jets are established under the two exit slots and are driven by the motion of the same PZT-diaphragm. The slide block regulates the two jets (as shown in Figs. 1b–1d), and then two adjacent jets merge into a single, larger synthetic jet.

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In this Note, numerical simulations are conducted to study the new SJA. We include a discussion focused on the novelty and merits of the new SJA in comparison with the existing SJAs.

Computational Method

The Knudsen number expresses the degree of gas rarefaction. For the present application in this Note, the characteristic length is taken to be the slot width $d = 1$ mm and the mean free path of air as $\lambda = 0.065\ \mu$m. This gives a Knudsen number $Kn = \lambda/d = 0.000065$, thus satisfying the continuum criterion and allowing the Navier–Stokes equations to be used. An incompressible flow solver is used for the simulations at very low Mach numbers. For a high aspect ratio of the SJA exit slot, the numerical simulations in this Note are based on CFD techniques using a Reynolds-averaged Navier–Stokes two-dimensional code with a $k-\varepsilon$ turbulence model. The X-L model, a computing model for the SJA, is adopted. The PZT-diaphragm is excited by a voltage; f is a forcing frequency, A denotes the amplitude of the vibrating diaphragm, r is a radius of the diaphragm, and Φ_0 is the original phase of diaphragm. For an arbitrary point on the diaphragm (x, l), the velocity of this point is composed of an axial velocity $u_x(l,t)$ (x-direction, normal to the original diaphragm) and a radial velocity $u_l(l,t)$. The function is induced as follows: $u_x(l,t) = -2\pi f A \cdot (1 - l^2/r^2) \cdot \sin(2\pi f t + \Phi_0)$, $u_l(l,t) \approx 0$. For the present application, $\Phi_0 = 0$, $f = 500$ Hz, $A = 0.2$ mm, and $r = 23$ mm.

Four representative SJAs, as shown in Fig. 1, are investigated numerically in this Note. Table a provides domain sizes and grid distributions. The fluid media simulated is air and numerical accuracy has been validated in Ref. [8].

Results and Discussion

Figure 2 shows the velocity magnitude maps of the synthetic jets for the four representative cases. Comparing the new SJA (Fig. 1b) with the existing SJAs (Fig. 1a), there are two differences in structure. The new SJA has two cavities sharing the same wall equipped with a single PZT-diaphragm and it has the slide block separating the two exit slots at an appropriate distance. The differences bring many merits to the new SJA that the existing SJAs do not have. The following are the merits of the new SJA.

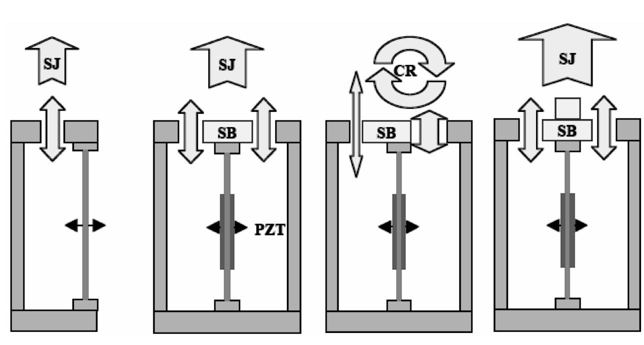
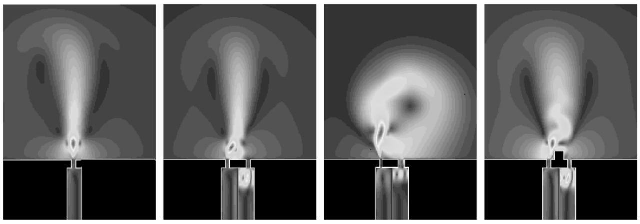


Fig. 1 Schematic diagrams of SJAs: a) an existing SJA, b) a new SJA, c) a new SJA, in which a slide block shifts to the left, and d) a new SJA, containing a slide block with an extended step.

Table 1 Computational domain and grid distribution

Designation	Domain ($x \times y$)/mm	Grid ($x \times y$)	Remarks
SJA cavity	4×46	40×80	Divided evenly in x-direction, dense to exit
SJA exit nozzle (case 1, 2, 4)	1×2	10×20	Divided evenly
External surroundings	100×100	240×100	Dense in center and to wall

[a]Note: In case 3, SB shifts 0.5 mm to left, the left exit nozzle domain is 0.5×2 mm, the grid is 5×20, the right exit nozzle domain is 1.5×2 mm, and the grid is 15×20.



a) b) c) d)

Fig. 2 Velocity magnitude maps of synthetic jets: a) case 1, existing SJA, b) case 2, new SJA, c) case 3, new SJA with slide block shifting 0.5 mm to the left, and d) case 4, new SJA with a 2 × 2 mm extended step.

There are two types of existing SJAs, one with a single piezoelectric diaphragm (as shown in Fig. 1a) and the other with double piezoelectric diaphragms. The velocity magnitude map of the synthetic jet for the existing SJA with a single PZT-diaphragm is shown in Fig. 2a; only one jet is forced out of the SJA in one period of the PZT-diaphragm's vibration. The synthetic jet for the other type with double PZT-diaphragms is the same as that of the existing SJA with a single PZT-diaphragm, but it requires double power or a control of the phase differential between the two diaphragms. As mentioned in the "Introduction," the existing SJAs require high power to drive the PZT-diaphragm when the pressure differential between the two different fluid environments is large, which is a limitation of the existing SJA. The new SJA is schematically shown in Fig. 1b, and 2b shows the jet velocity magnitude of the new SJA. For the two cavities sharing the same PZT-diaphragm, the compression in one cavity of this new SJA results in the expansion stroke of the other cavity and two jets out of phase are forced out of the SJA in one period. The two jets entrain fluid around them and interact with each other and then the two jets merge into a single, larger synthetic jet downstream. As the diaphragm of the new SJA is only surrounded by the fluid drawn from the base flow, the new SJA makes the most of the energy of the vibrating diaphragm and also avoids the high power required to drive the diaphragm when the pressure differential between the base flow (to be controlled by the SJA) and the environment is large.

The shift of the slide block can regulate the synthetic jet flow of the new SJA. When the slide block shifts to the left, for example, as shown in Fig. 1c (the jet velocity magnitude is shown in Fig. 2c), the similarities of the two jets are destroyed. The left jet momentum increases but the right jet momentum decreases, which changes the interaction of the two jets and the downstream synthetic jet flow is regulated and altered. An important finding of the present work is that a circumfluence region (CR) is synthesized downstream of the two exit slots at appropriate conditions, depending on the exciting frequency of the PZT-diaphragm and the location of the slide block. This is a new and interesting phenomenon, which may have a potential to be used in flow control applications, such as ignition and mixing, etc. The configuration of the slide block also influences the synthetic jet flow. Figure 1d shows a configuration of the slide block with an extended step and the jet velocity magnitude is shown in Fig. 2d. The symmetry of the synthetic jet can be regulated by the step configuration [4]. The extended slide block restricts the suction flow from the other jet and leads to an increase in the flow rate from the surroundings. This induces the two jets to merge and form a larger synthetic jet (as shown in Fig. 2d).

Conclusions

A new generation of SJA is provided. It consists of two cavities bounded on one end by a single PZT-diaphragm with two exit slots and a slide block. In the new SJA concept, two adjacent jets are established downstream of the two exit slots and are driven by the motion of the same PZT-diaphragm. The slide block regulates the two jets and then the two adjacent jets merge into a single, larger synthetic jet.

The novelties of the new generation of SJA are that the two cavities share the same wall equipped with a PZT-diaphragm and the slide block regulates the two synthetic jets. These novelties bring the major advantages and functions of this new SJA that the existing SJAs do not have. The new SJA may not only double the function of the existing SJAs with a single diaphragm but also resolve the problems of pressure loading and energy inefficiency of the existing SJAs. The slide block of the new SJA has an important regulating function and different types of synthetic jets can be generated with slight modifications of the slide block. These indicate that the new SJA may potentially replace the existing SJA in various applications and also extend the applications of the SJAs to more flow control systems that cannot be implemented by the existing SJAs.

To promote the applications of the new generation of SJA, future work is required. This includes a groundwork study on the characteristics of the new generation of SJA in a crossflow and the control rules of the new generation of SJA adjusted due to the slide block.

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