An adjustable synthetic jet by a novel PZT-driven actuator with a slide block

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Abstract. Synthetic jets have been identified and utilized widely in flow control applications. The synthetic jets are usually created by a traditional PZT-driven actuator, which consists of a small cylindrical cavity that has an emitting orifice and a PZT-diaphragm or two PZT-diaphragms. A novel synthetic jet actuator is composed of two emitting slots, two sealed cavity bounded on one end by a single PZT diaphragm, and a slide block. The flow fields of the novel synthetic jet actuator in the quiescent air and the cross-flow conditions were simulated. The results show the slide block of the novel synthetic jet actuator has an important regulating function and a unique adjustable synthetic jet can be generated with slight modifications of the slide block. The adjustable synthetic jet may potentially replace the traditional synthetic jets in various applications, and also extend the applications of the synthetic jet to more flow control systems that can’t be implemented by the traditional synthetic jets.

1. Introduction

The synthetic jet has attracted much attention in recent years because of its potential application in areas such as active flow control, micro-pump, and thermal management in microelectronic devices [1-10]. A synthetic jet is a zero mass flux device that converts electrical energy into momentum. These devices are being explored for use in several different fields, including aerospace and electronics. A schematic and a photograph of a traditional synthetic jet actuator are shown in Figure 1. The traditional synthetic jet actuator consists of an emitting slot and a small cavity bounded by one or two piezoelectric (PZT) diaphragms. Applying voltage to the piezoelectric element causes it to vibrate, and outside air is rapidly pulled into the chamber through the orifice then expelled. The synthetic jet is referred to as a "zero mass flux" device because the net mass flowing from the jet to the outside air is zero. The mass of the air drawn in is equal to the mass of the air expelled. An example: Imagine sitting on a frictionless surface. Make an "O" shape with your mouth, and then breathe in. You don't move. Breathe out through your mouth, still making an "O" shape, and you will move opposite the direction you are breathing, per Newton’s Third Law of Motion. Repeat this processes several thousand times per second, and you will be a synthetic jet.

High performance synthetic jet actuator is a key of flow control using synthetic jet. PZT-diaphragms are used in most mini- or micro synthetic jet actuators because of their size, rapid time response, and relatively low power consumption. The PZT-driven synthetic jet actuator also fits within the 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 for the validity of small deflection of the PZT-diaphragm, that’s to say, the traditional synthetic jet actuator (as Figure
1) require a high power to drive the PZT-diaphragm when the pressure differential between the base flow to be controlled by the synthetic jet actuator and the environment is large, which limits applications of the traditional synthetic jet actuator. In addition, the diaphragm of the traditional synthetic jet actuator has one surface exposed to the fluid drawn from the base flow and the other surface exposed to the environment, which indicates half radiation energy of the vibrating diaphragm is wasted in the environment.

The novel synthetic jet actuator has provided by us [11], the schematic and a photograph of a novel synthetic jet actuator are shown in Figure 1. the prototype is schematically shown in Figure 2, it consists of two emitting slots, two-sealed cavities bounded on one end by a single PZT-diaphragm, and a slide block. In the novel synthetic jet actuator concept, two adjacent jets are established downstream the two exit slots and are driven by the motion of the same PZT-diaphragm, and then two adjacent jets merge a single, larger synthetic jet. The novelties of the novel synthetic jet actuator lie in that the two cavities share the same wall equipped with a PZT-diaphragm and the slide block regulates the two synthetic jets. The novelty of the two cavities sharing the same PZT-diaphragm make the novel synthetic jet actuator not only doubled the function of the traditional synthetic jet actuators with a single diaphragm but also resolved the problems of pressure loading and energy wasting of the traditional synthetic jet actuators.

To promote the applications of the novel synthetic jet actuator, a groundwork study is required. This includes the characteristics of the novel synthetic jet actuator in a quiescent air and a cross-flow condition.

2. Numerical simulation

The Knudsen number expresses the degree of gas rarefaction. $Kn$, which is defined by the mean free path of gas $\lambda$ and the characteristic length of the flow $L$ as followed: $Kn = \lambda / L$. The flow is divided four different regimes by Tsien H S [13]: the continuum assumption and the Navier-Stokes
equations are valid only when $Kn < 0.01$; beyond this, the slip flow regime is encountered ($0.01 < Kn < 0.1$), where the no-slip condition at wall interfaces is no longer satisfied; the transition regime is when $0.1 < Kn < 10$; and then completely rarefied or free-molecular flow occurs for $Kn > 10$. For the present application in this paper, the characteristic length is taken to be the slot width $L = d = 0.5 \text{mm}$ and the mean free path of air as $\lambda = 0.065 \mu\text{m}$. This gives a Knudsen number $Kn = 0.000125 < 0.01$, thus satisfying the continuum criterion and allowing the Navier-Stokes equations to be used.

An incompressible flow solver, INS2D is used for the simulations at very low Mach numbers. An incompressible code has the advantage of running more efficiently than a compressible code, since compressible codes run at very low Mach numbers require very small time steps to maintain stability. Accordingly, the unsteady, incompressible, Reynolds-averaged Navier-Stokes (RANS) equations are solved. And the turbulence model used is based on the $k-\varepsilon$ model

X-L model [12], a computing model for SJA is adopted, it considers the actuator cavity, the exit throat, and the external flow field as a single computational region. The PZT-diaphragm is excited by voltage, $f$ is a forcing frequency, $A$ denotes the amplitude of the vibrating diaphragm. $r$ is a radius of the diaphragm, and $\Phi_0$ is the original phase of diaphragm. For $(x, l)$ is an arbitrary point on the diaphragm, the velocity of this point is composed of axial velocity $u_x(l, t)$ (x-direction, normal to the original diaphragm) and radial velocity $u_r(l, t)$.

The function is induced as follows:

\[ u_x(l, t) = -2\pi f A \cdot \left(1 - l^2 / r^2\right) \cdot \sin \left(2\pi f t + \Phi_0\right), \quad u_r(l, t) = 0. \]

For the present application, $\Phi_0 = 0$, $f = 500\text{Hz}$, $A = 0.1\text{mm}$, $r = 23\text{mm}$.

The fluid media simulated is air. And the numerical accuracy has been validated in the Ref.9.

3. Results and Discussion

The computational domain and grid of the novel synthetic jet actuator are illustrated in Fig.3. Table.1 provides detail domain sizes and grid distributions.

The novel PZT-driven actuator in a quiescent air and a cross-flow condition are numerically simulated. For brevity, we discuss the baseline case (Case1), five representative cases with different slide block configurations (Case2-6) in quiescent air, and four representative cases with different cross flow velocities (Case7-10); the computational cases are summarized in Table 2.
Table 1: Computational domain and grid distribution for the baseline case (Case 1)

| Designation       | Domain (x×y)/mm | Grid (x×y) | Remarks                                      |
|-------------------|-----------------|------------|----------------------------------------------|
| SJA Cavity        | 4×46            | 40×80      | Divided evenly in x-direction, dense to exit |
| SJA Exit Slot     | 1×2             | 10×20      | Divided evenly                               |
| External Surroundings | 100×100     | 240×100    | Dense in center and to wall                  |

Table 2: Computational cases for the novel PZT-driven actuator with a slide block in different conditions

| Conditions | In quiescent air | In cross-flow |
|------------|------------------|---------------|
| Cases      | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 | Case 7 | Case 8 | Case 9 | Case 10 |
| Configurations of slide-block | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) | ![Image](image10.png) |
| Velocity of cross flow/m/s | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 3 | 5 |

3.1. In quiescent air

Figure 4 shows the velocity magnitude maps of synthetic jets by the novel PZT-driven actuator with different slide blocks.

![Image](image1.png)

(a) Case 1  (b) Case 2  (c) Case 3

![Image](image4.png)

(d) Case 4  (e) Case 5  (f) Case 6

Fig. 4. Velocity magnitude maps of ASJs by the novel PZT-driven actuator with different slide blocks.

As shown in Figure 4a (see also Ref. 11), the slide block is even with the exit, two fluid puffs out of phase are forced out of the actuator in every vibrating circle of the PZT-diaphragm, instead of a fluid puff every vibrating circle from a traditional synthetic jet actuator, and the two jets merge a single, larger synthetic jet, and the sum momentum of the larger synthetic jet is more higher than that of a traditional synthetic jet actuator. In Figure 4b and 4e, the slide blocks are in a lower position than the exit, and the synthetic jets are vectored to the left. In Figure 4c and 4d, the slide blocks are extended in
higher position than the exit, for the extending step can restrict the suction flow from the other jet and lead to an increase in the flow rate from the surroundings, and it induces the two jets to merge a more larger synthetic jet, and the synthetic jets are larger than that of Case1. In Figure 4f, the two jets entrain fluid from the surroundings and interact each other downstream, and the flow field is more complex. So the synthetic jet by the novel PZT-driven actuator can be adjusted by altering the configuration of the slid block. These unique characters make the novel PZT-driven actuator extended the applications of the synthetic jets to more flow control systems that can't be implemented by the traditional synthetic jets.

3.2. In cross-flow
Figure 4 shows the velocity magnitude maps of synthetic jets by the novel PZT-driven actuator with different cross flow velocities.

As shown in Figure 5a, in a quiescent air, when the slide block shifts, for example to the left, the similarities of the two jets are destroyed, and the left jet momentum increases but the right jet momentum decreases, which changes the interaction of two jets and the downstream synthetic flow field is altered. A circumfluence region is synthesized and founded under the two exit slots at appropriate conditions, such as the exciting frequency of the PZT diaphragm and the location of the slide block. The circumfluence region has a potential to be used in flow control applications, such as ignition and mixing etc. so it is necessary to investigate the circumfluence region in a cross flow.

As depicted in Table 2, the velocity of the cross flow for case 6-10 is increased from 0, to 1, 3, and 5m/s, and the size of the circumfluence regions is decreased monotonously (as shown in Figure 5a-e). Which implies the circumfluence region cannot be synthesized when the velocity of the cross flow is high.

4. Conclusions
The flow fields of the novel synthetic jet actuator in the quiescent air and the cross-flow conditions were numerically simulated.

An adjustable synthetic jet can be generated with slight modifications of the slide block of the novel PZT-driven actuator. These unique characters make the novel PZT-driven actuator extended the applications of the adjustable synthetic jets to more flow control systems that can't be implemented by the traditional synthetic jets.

A circumfluence region is synthesized and founded when shifting the slide block of the novel PZT-driven actuator. The circumfluence region has a potential to be used in flow control applications, such as ignition and mixing etc, but it is limited in a cross flow at very low Mach numbers.

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