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Numerical study of nozzle design for the hybrid synthetic jet actuator

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ABSTRACT

This paper presents a numerical study on the influence of the geometrical arrangement of the hybrid synthetic jet (HSJ) actuators. We study five variants of the HSJ actuators. The laboratory experiment by using water as the working fluid has been conducted for comparison and validation of the numerical simulation. The numerical results reveal the formation and propagation of vortices during the operating cycle in detail. It is identified that the internal vortex within the HSJ actuator plays essential roles on the flow mass exchange during the operating cycle. Our results show that the flow pattern of synthetic jet is highly sensitive to the internal geometrical design, which leads to significant difference in efficiency for different actuators.

1. Introduction

The synthetic jet (SJ) is a fluid flow producing by moving the fluid back and forth periodically through an orifice or nozzle by the reciprocating changes of a cavity volume (Smith and Glezer [1]). A typical SJ actuator contains a closed chamber with an orifice opened at one end and with a reciprocating driven mechanism at the other end. The mechanism drives a diaphragm or a piston to suck and pump fluid into and from the cavity, respectively. The typical SJ actuator operates as a single-acting displacement pump. The working fluid is pumped from the cavity during the pump stroke and the same fluid volume is sucked back into the cavity during the subsequent suction stroke. The time-mean mass flux through the nozzle is zero, and SJ is frequently named as the zero-net-mass-flux jet (Cater and Soria [2]).

The first SJ actuator was a laboratory air-jet generator by Dauphinee [3]. The topic then started to be extensively investigated in connection with the active control of thermal and flow fields (e.g., Yassour et al. [4] and Meier and Zhou [5]). The SJs have become popular since the end of the last century, when the term "synthetic jet" was introduced by James et al. [6]. Since then, experimental, theoretical and numerical investigations have conducted in numerous studies [7–12]. Due to its advantage of simplicity in design, SJs have been studied for various applications such as jet flows [13–16], external flows [17–20], internal flows [21] and heat transfer [22–31] intended for cooling of electronic components and turbine blades.

Besides the aforementioned typical SJ actuators that are single-acting and generate zero-net-mass-flux jets, advanced arrangements can be designed based on following principles:

- *A double-acting operation* known from a reciprocating pump. The double-acting SJ actuator contains two cavities that are formed on two sides of one diaphragm (or a piston). If the working fluid is pumped from one cavity to the surroundings, the other cavity is in a suction phase. In other words, both cavities at each side of the diaphragm (or piston) generate two SJs with an anti-phase behavior.
- *A rectification effect of fluidic diodes*. The fluidic diodes are fluidic element having a hydraulic resistance in one (forward) flow direction smaller than in the opposite (reverse) flow direction [32–37]. This feature causes the fluidic diode to rectify oscillating flow to the low resistance direction. The fluidic diodes can be used in valve-less pumps [38–40]. In the same manner, the hybrid synthetic jet (HSJ) actuator is equipped with a fluidic diode which enhances fluid entrainment from surroundings into the actuator cavity. The rectification effect enhances the volume flux during the pump stroke, therefore the resultant HSJ is a non-zero-net-mass-flux SJ.

The present paper focuses on the double-acting HSJ actuator, as shown in Fig. 1, which was introduced by Wang et al. [40], Trávníček et al. [41,42]. The actuator contains two cavities, namely the front

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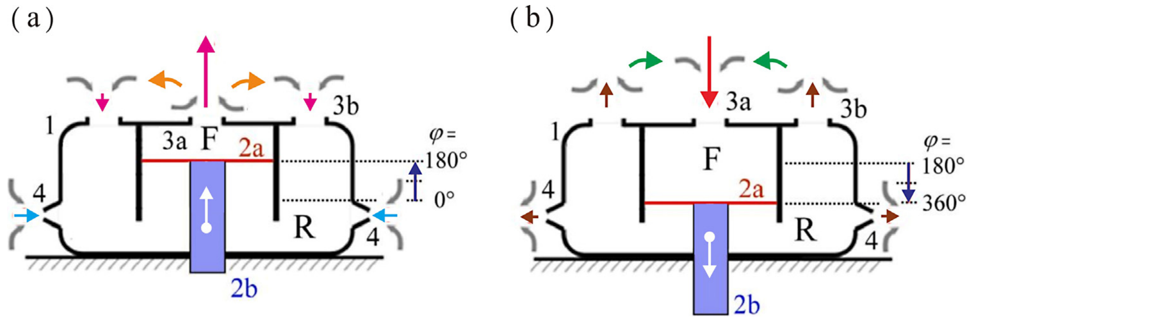

Fig. 1. Double-acting HSJ actuator in (a) upward and (b) downward strokes; F: front cavity, R: rear cavity, 1: chamber; 2a: diaphragm, 2b: drive unit, 3a: central nozzle, 3b: annular nozzle, 4: fluidic diodes shaped as conical ducts.

(F) and rear (R) cavities, as indicated by F and R, respectively. The cavities are separated by a diaphragm (denoted as 2a in Fig. 1), which is driven by the driving unit (2b in Fig. 1). Fig. 1(a) shows that during the first half of the actuation period ($\phi = 0^\circ - 180^\circ$, i.e., the upward stroke of diaphragm or simply upward stroke thereafter), while the F cavity pumps fluid out of the actuator through the central nozzle (denoted as 3a in Fig. 1), the R cavity sucks fluid inward through the annular nozzle (3b in Fig. 1) and the fluidic diodes (4 in Fig. 1). As a result, flows from the annular nozzle and the fluidic diodes are mixed in the R cavity. In the second half of the actuation period ($\phi = 180^\circ - 360^\circ$, the downward stroke of diaphragm or simply downward stroke thereafter), part of the flow in the R cavity moves into the F cavity through the annular nozzle (green arrows in Fig. 1(b)) and gets mixed with the flow sucked through the central nozzle. The mixed fluid in the F cavity is then pumped out at the next half cycle. The key feature that the flow gets twice mixing (from both central and annular nozzles) in the double acting operation leads to an enhancement of cooling efficiency in comparison to the single-acting operation.

It is worth mentioning that the central nozzle (3a) generates zero-net-mass-flux SJ, while the annular nozzle (3b) generates non-zero-net-mass-flux HSJ. The two jets interact in the near field, which was visualized and measured in previous papers [42,43].

In general, advantages and possible applications of HSJs are the same as those mentioned for SJs. However, the HSJs can achieve higher volume fluxes than SJs because of the flow enhancement [44,45] resulting from rectification effect of the fluidic diodes (convergent/divergent elements). Besides, another advantage for cooling applications is that entrained air can be taken via fluidic diodes from the colder surroundings, i.e., fresh air sucked from the fluid diodes without preheating can be introduced into the heat exchange zone at the downstream of the central nozzle.

While most of the aforementioned studies focus on experimental observations, numerical simulations are conducted in the present study. This allows for an efficient comparison study of different actuator geometry without any time-consuming manufacturing. Moreover, numerical results reveal detailed flow features that benefit the evaluation of the resulting actuator performance.

During the last two decades, computational fluid dynamics (CFD) has become a powerful tool to study the SJ. It does not only provide precious physical insights but also gives effective prediction to achieve several practical purposes. For example, Kral et al. [7] and Lee and Goldstein [9] used a simplified 2-D model to study the influence in the surrounding field. However, 2D model usually overpredicts the flow field in comparison with experiments, which is due to its incapability to resolve 3D flow features. More recently, owing to the advances of computational power, 3D numerical simulation has become more prevalent as it can reveal more realistic flow features, such as flow instability and turbulence. Rizzetta et al. [46] and Wang [47] used the 3D model and successfully showed the

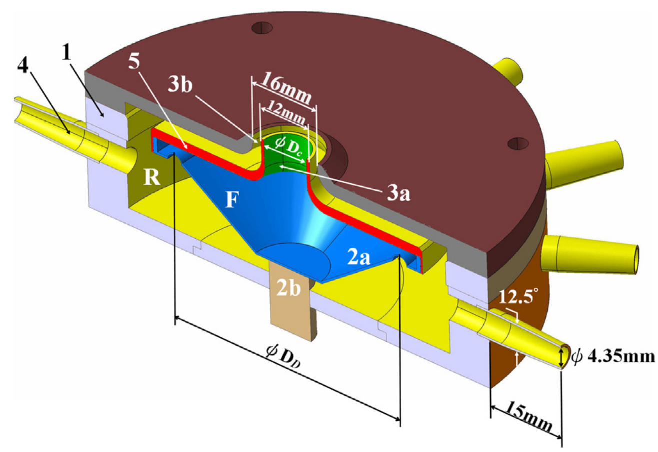

Fig. 2. Geometry of the reference double-acting HSJ actuator (from [43]); F: front cavity, R: rear cavity, 1: camber, 2a: diaphragm (ϕ D_D = 56 mm), 2b: drive unit (20 mm in diameter), 3a: central nozzle (ϕ D_C = 10.6 mm), 3b: annular nozzle (ϕ D_{A1} = 12 mm, ϕ D_{A2} = 16 mm), 4: twelve fluidic diodes shaped as conical ducts, 5: fixed common interface.

flow transition to turbulence, which was comparable with experimental results. In the present study, numerical simulations are conducted with the aim to allow for an efficient comparison of different actuator geometry without any time-consuming manufacturing. Moreover, the present numerical results reveal insightful flow features that help evaluating the actuator performance.

2. Numerical modeling

2.1. Actuator setup and its variants

Fig. 2 shows the basic design of double-acting HSJ actuator that was modified from Trávníček et al. [41,42] in the present work (i.e., Type 0 in Table 1). The actuator was investigated experimentally in the recent study by Hsu et al. [43]. The actuator is driven by a

Table 1
Dimensions of investigated HSJ actuators.

Variants		Dimensions in mm				
Type	Fig.	D_C	D_{A1}	D_{A2}	E	G
0 – reference	Figs. 2 and 4(a)	10.6	12.0	16.0	0	3.0
I	Fig. 4(b)	10.6	12.0	16.0	5.3	3.0
II	Fig. 4(c)	10.6	–	10.6	9.0	3.0
III	Fig. 4(d)	21.2	–	10.6	9.0	3.0
IV	Fig. 4(e)	10.6	–	10.6	9.0	3.0