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A novel optimal design for an application-oriented synthetic jet actuator

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Abstract The evaluation indicator for the performance of a synthetic jet actuator (SJA) is well-defined because of its various applications, which require optimal design to improve its performance and extend its field of application. This paper presents a novel approach to the optimal design of an SJA applied to enhance fuel/air mixture. It optimizes the combination of an actuator's geometric parameters by selecting the strength of vortex pairs as the evaluation indicator, coupled with orthogonal experiments and analysis of variance (AOV). The results indicate that slot width is the most notable factor influencing the strength of vortex pairs, followed by cavity height and slot depth. The optimal value of the strength of vortex pairs increases by 32.5% over the experimental data of the base case, and more than 8.4% compared with the simulation results of the orthogonal experiments. It is concluded that the optimal method can effectively improve the performance of an SJA applied in mixing enhancement, reducing the test numbers and the associated design cycle and cost.

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1. Introduction

With the advantages of a compact structure, requiring no flow supply and moving mechanical devices, low energy consumption and fast time response,[1,2] synthetic jet actuators (SJAs) are widely recognized as offering significant potential as practical flow control actuators, including control of flow separation,[3,4] aerodynamic force,[5–7] jet vectoring,[8–10] noise suppression,[11,12] mixing enhancement,[13–15] augmenting heat and mass transfer.[16–18] Therefore, SJAs have become an active topic of recent research in the community of aeronautics and astronautics.

The performance requirement of an SJA differs according to its various applications, and it needs to select appropriate indicators to evaluate its performance. It is important to carry out optimal design of an application-oriented SJA to improve its performance. Rathnasingham and Breuer[19] proposed a zero-dimensional model (dynamic incompressible model) for a resonant actuator. With this model, they found an optimal operating Stokes number for the actuator, at which the maximum jet velocity was generated for a given power input. However, the model was only capable of predicting the magnitude of jet velocity which qualitatively agreed with the measurement. The basic concept in the above model was later adopted by Lockerby and Carpenter,[20] who developed a one-dimensional

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model (static compressible model). They studied the effect of geometrical parameters and the driven frequency on the performance of an actuator, and acquired an optimal magnitude for peak jet velocity which was predicted over the experimental counterpart. By representing a speaker-driven actuator with an equivalent electrical circuit, McCormick[21] employed the lumped-element method (LEM) to analyze the characteristics of SJAs. This method was further developed by Gallas et al.[22–24] to establish the model of a piezoelectric SJA by introducing an electro-acoustic transforming factor. They obtained an optimal combination of orifice diameter, depth and cavity volume based on two objective functions, i.e., the integration of jet velocity over a frequency range and the jet velocity at a specific frequency. Oyarzun and Cattafesta[25] optimized orifice sizes using LEM in conjunction with MATLAB® optimization toolbox, and performed corresponding verification with numerical simulations and experiments.

Synthetic jets are observed to spread faster and decay more rapidly than the continuous jet under same conditions, which indicates that synthetic jets are capable of mixing enhancement. A piezoelectric SJA with a cavity–diaphragm setup is a coupled system consisting of an electromechanical domain in the form of the vibrating diaphragm, and a fluidic/acoustic domain in the form of the resonant cavity, causing strong nonlinearity. Therefore, it is difficult to build an exact model. The three aforementioned models of an SJA merely predict the space-average velocity at the exit, or other physical quantities derived from it, which do not consider the exit velocity profile and cannot describe the characteristics of synthetic jets, such as the formation and convection of vortex structures, strength and distribution of vortex pairs. Accordingly, they are not properly used to execute optimal design for an SJA applied in mixing enhancement, which is evaluated using the strength of vortex pairs. Briefly, optimal methods based on the exit jet velocity models are not suitable considering the limitations in selecting evaluation indicators appropriate to the applications. However, numerical simulations, generally used to analyze flow-field features, can provide profound insights into flow field, and are thus helpful in carrying out an optimal design for an SJA based on diverse evaluation indicators.

Because of the drawbacks of the above optimal methods and high cost of manufacture and testing, a novel approach to the optimal design of an application-oriented SJA with numerical simulations is proposed, and is then validated to be efficacious and feasible compared with particle image velocimetry (PIV) experiments.

2. Computational analysis

2.1. Choice for geometrical parameters

The overall performance of an SJA is dependent on its internal geometric configuration (i.e., slot depth and width, and cavity volume), and how much volume is swept inside the cavity. The latter is related to how the diaphragm is driven (e.g., power and driven frequency applied on the vibrating diaphragm). Moreover, the flow-field features (e.g., Reynolds number and Strouhal number), as well as intensity and thickness of vibrating diaphragm, also have an impact on synthetic jets.

A typical piezoelectric SJA consists of a small cavity with a vibrating diaphragm and a slot on two sides. The independently geometrical parameters of the investigated SJA include equivalent cavity diameter D and height H, slot depth h and width a in a two-dimensional plane, as shown in Fig. 1. Correspondingly dimensionless parameters are defined as follows:

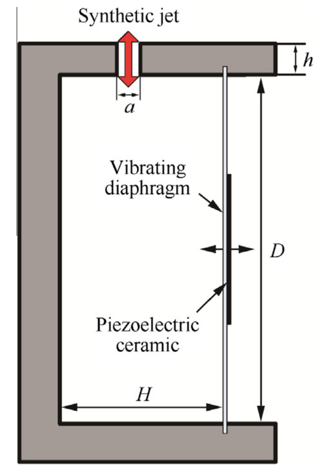

Fig. 1 Schematic of an investigated SJA.

$$\begin{cases} \pi_1 = H/D \\ \pi_2 = h/D \\ \pi_3 = a/D \end{cases} \quad (1)$$

where π_1 is dimensionless cavity height; π_2 is dimensionless slot depth; π_3 is dimensionless slot width.

In this paper, considering the allowable space for installing an SJA and appropriate comparisons with existing data, the equivalent cavity diameter determined by the diameter of vibrating diaphragm is a constant at 50 mm, and the remaining dimensionless parameters to be studied are π_1, π_2, and π_3. In addition, a practical SJA should work at its optimal level with greater efficiency and minimal electric power consumption. As a result, the electrical control factors including the excitation amplitude and the driven frequency (approximating to the Helmholtz resonance frequency of the cavity) are adjusted to prior values and no longer varied.

In summary, the collective expression for the geometrical parameters is (π_1, π_2, π_3). Several constraints on factors must be considered to make sure that the optimal result is physically achievable, for instance, $H \geqslant a$, that is $\pi_1 \geqslant \pi_3$.

2.2. Analysis of evaluation indicator

The evaluation indicator of an SJA should be properly selected to represent its performance. At present, it is a key to efficiently combusting the fuel and improving the performance of ramjet engines by enhancing fuel/air mixture. Fortunately the capability of synthetic jets to enhance fuel/air mixing has already been validated using numerical simulations[13]and experiments.[26] The main task for this study is to execute an optimal design for an SJA to enhance fuel/air mixture.

The formation, advection and mutual interactions between trains of unsteady vortex pairs are the essential feature of a synthetic jet, which make the strength of vortex pairs an appropriate parameter for determining the degree of mixing enhancement. The impact domain of synthetic jets for mixing enhancement is not only associated with single vorticity, but also influenced by the distribution of vortex pairs. Thus, the evaluation indicator must be selected to represent the mutual

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