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Towards the noise reduction of piezoelectrical-driven synthetic jet actuators

Mark Jabbal [a,*], Jonne Jeyalingam [b]

[a] Faculty of Engineering, University of Nottingham, NG7 2RD, UK
[b] College of Engineering, Design and Physical Sciences, Brunel University London, UB8 3PH, UK

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ABSTRACT

This work details an experimental investigation aimed at reducing the noise output of piezoelectrical-driven synthetic jet actuators while minimising peak jet velocity reduction. The study considers double-chamber actuator for anti-phase noise suppression and lobed orifice as a method to enhance jet turbulent mixing to suppress jet noise. The study involved the design, manufacture and bench test of interchangeable actuator hardware. Hot-wire anemometry and microphone recordings were employed to acquire velocity and sound pressure level measurements respectively across a range of excitation frequencies for a fixed diaphragm clamping and input voltage. The data analysis indicated a 26% noise reduction (16 dB) from operating a single-chamber, round orifice actuator to a double-chamber, lobed orifice one at the synthetic jet resonant frequency. Results also showed there was a small reduction in peak jet velocity of 7% (~3 m/s) between these two cases based on orifices of the same discharge area. The electrical-to-fluidic power conversion efficiency of the double-chamber actuator was found to be 15% for both orifice types at the resonant frequency; approximately double the efficiency of a single-chamber actuator.

1. Introduction

A synthetic jet actuator (SJA) is a zero-net mass flux device that negates the need for a network of pneumatic ducts. Instead, it generates fluidic power through an orifice on one side of a chamber using an oscillating diaphragm on the opposite side. In the case of a piezoceramic diaphragm, an input electrical supply is required to create the oscillatory motion. The momentum that a SJA imparts to a fluid flow can delay boundary layer separation, which could be used to improve the effectiveness of aircraft high-lift and control surfaces [1,2].

One of the major limitations of a SJA for aircraft application is its high noise output generated from the motion of the diaphragm and jet stream mixing with the atmosphere. Unfortunately SJA effectiveness often dictates operation at the actuator resonant frequency to maximise authority, which coincides with the highest tonal noise output. Since SJAs generate discrete high-momentum jets, then to introduce significant effects in large scale flow they must be used in large numbers, e.g. in arrays along the span of the wing. Although there has been much research on optimising SJAs for peak jet velocity, there has been far fewer studies on minimising SJA noise.

Table 1 summarises noise reduction methods employed for SJAs. It was observed by Arik [3] that the sound pressure level (SPL) from a SJA can be as high as 73 dB when operating at a resonant frequency, $f = 3.6$ kHz for a peak jet velocity, $U_{peak} = 90$ m/s out of a round orifice of diameter, $d = 1$ mm. Noise abatement using passive mufflers was shown to reduce SPL to 30 dB, but at a cost of significantly increasing the actuator volume to a level that is unviable for aircraft implementation. Lasance et al. investigated the influence of pipe length [4] and actuator power [5] on SJA noise (the SJA featured a cavity backed with a vibrating loudspeaker and two adjacent protruding pipes for the jet outflow). As might be expected, SPL increased with power however the influence of pipe length was less clear with reduced noise reported for increasing pipe length at $d = 3$ mm and the reverse trend at $d = 4$ mm. Although the two pipes were in an acoustic dipole, no noise reduction results of this arrangement were reported relative to a single monopole pipe. Bhapkar et al. investigated the influence of orifice diameter [6] and orifice height [7] on SJA noise. SPL was reduced for smaller orifice diameters and smaller orifice height, i.e. thinner orifice plates. Mangate and Chaudhari [8] recorded SJA noise as high as 68 dB for an operating frequency of 0.4 kHz out of a 8 mm round orifice. Noise

* Corresponding author.
E-mail address: mark_jabbal@hotmail.com (M. Jabbal).

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Table 1
Noise reduction methods employed for synthetic jet actuators.

Study	Orifice	d (mm)	f (kHz)	U_{peak} (m/s)	SPL (dB)	Noise abatement	SPL (dB)
Arik [3]	Round hole	1	3.6	90	73	Passive muffler	30
Lasance et al. [4]	Round hole	3	0.11	6.5	43.1 (l = 30 mm)	Pipe length	41.5 (l = 90 mm) 36.9 (l = 120 mm)
		4	0.11	6.5	49 (l = 120 mm)		46.4 (l = 30 mm) 48.1 (l = 90 mm)
Lasance et al. [5]	Round hole	4 8	0.03 0.08	... ...	37 (P = 1 W) 52 (P = 0.3 W)	SJA power	32 (P = 0.4 W) 46 (P = 0.1 W)
Bhapkar et al. [6]	Round hole	14	0.1	21	58	Orifice diameter	48 (d = 8 mm) 53 (d = 10 mm) 55 (d = 12 mm)
Bhapkar et al. [7]	Elliptical hole	12	0.1	21	58 (h = 5 mm)	Orifice height	54 (h = 2 mm)
Mangate & Choudhari [8]	Round hole	8	0.4	...	68	Orifice shape	57 (oval) 64 (diamond)

was reduced to 64 dB and 57 dB respectively for diamond and oval orifices of equivalent diameters.

The aforementioned studies are all focused on using SJAs to enhance heat transfer for thermal cooling applications. With the exception of [3], the rest incorporate orifice diameters which are an order of magnitude larger or orifice lengths that are upto two orders of magnitude larger than those required for aircraft separation control. In addition, actuation frequencies are an order of magnitude lower and hence peak exit velocities are much lower than those required for separation control. The aim of the present work is to explore methods of reducing the noise generated by piezoelectrical-driven SJAs without decreasing peak jet velocity relative to a round orifice SJA baseline. Emphasis is given to such methods which are conducive for use in an aircraft separation control setting.

A SJA has two main sources of noise: jet noise and diaphragm noise. Jet noise is generated from the turbulent mixing of the flow exiting the orifice with the surrounding air. A potential core is formed just aft of the orifice exit containing laminar flow. The length of the core is typically 4–5 times the diameter of the orifice [9,10]. The mixing of the synthetic jet with the ambient air occurs at a region around the potential core. Further downstream of the orifice exit, the jet spreads out at a wider angle, forming a fully-developed flow region. The vortex rings formed at the edges of the orifice increase in size and decrease in velocity as they propagate away from the SJA. The frequency of sound generated is inversely proportional to the size of the vortex rings. This means that high frequency sound is generated close to the orifice and low frequency sound derives from the fully-developed jet far from the orifice exit [11]. The continuously vibrating diaphragm creates acoustic waves inside the chamber, which bounce between the walls and finally escape through the orifice exit in to the external ambient [12].

A double-chamber SJA consists of two chambers and two orifices. The two orifice plates are located perpendicular to the shared oscillating diaphragm (Fig. 1). The double-chamber SJA design has the ability to offer reduced noise output. Firstly, the presence of a second chamber on the other side of the diaphragm acts as a sound barrier preventing sound waves from propagating in to the atmosphere. It is also possible that the two orifices of a double-chamber SJA can act as a fluid mechanical dipole source. The orifice of a SJA can be characterized as a monopole source of sound (Fig. 2a). This source radiates sound in all directions; in this case, jet noise is radiated to the atmosphere. A dipole source is the close placement of two monopole sources of equal strength and exactly opposite phase [13]. When one source produces a net outflow, the other one produces an exactly opposite inflow. In contrast to a single monopole, the net fluid flux is zero. However, a net fluctuating force is produced because of the 180° out-of-phase oscillation. In the case of a

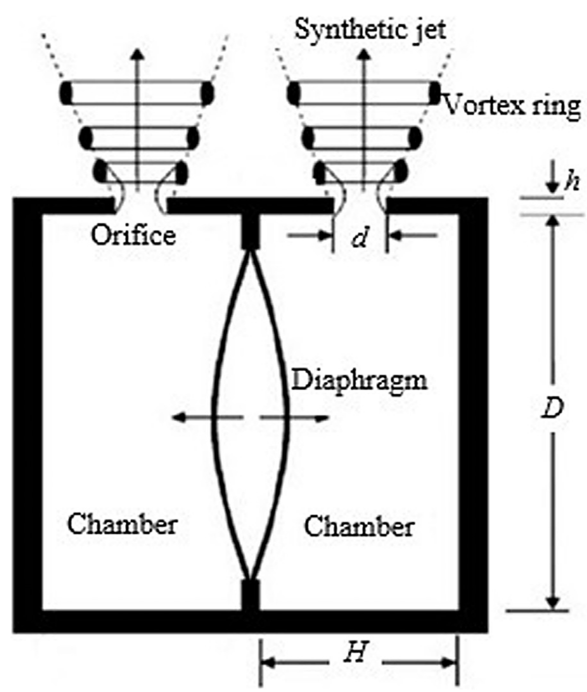

Fig. 1. Double-chamber SJA.

double-chamber SJA, the two orifice plates have the same dimensions (orifice diameter and depth) and are situated close to each other. As the diaphragm oscillates back and forth, flow from one orifice is exhaled while at the same time ambient air is inhaled in the other orifice. This indicates that the two orifices produce a net fluctuating source and are 180° out-of-phase. The propagating sound waves produced interact with each other and cancel out at 90° and 270° from the sound sources (Fig. 2b).

There have been several nozzle design modifications devised in an effort to reduce jet exhaust noise. Research has been conducted by the aviation industry in order to specifically reduce the noise produced by aircraft jet engines. Such design modifications include chevron and corrugated nozzles. These nozzles reduce jet noise by inducing streamwise vorticity along the shear boundary layer in the jet flow. The added vorticity causes smoother mixing of the jet core with the ambient air, reducing the rapid pressure fluctuations responsible for jet noise. Enhanced mixing slightly increases the high frequency noise ranging from 7.5 kHz to 30 kHz [15]. However due to the breakdown of the larger scale turbulence into small scale, this mixing reduces the low frequency noise (below 7.5 kHz) resulting in reduction of the overall sound pressure level [16].