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Pressure Loading of Piezo Composite Unimorphs

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ABSTRACT

Over the past decade synthetic jets have emerged as a promising means of active flow control. They have the ability to introduce small amounts of energy locally to achieve non-local changes in the flow field. These devices have the potential of saving millions of dollars by increasing the efficiency and simplifying fluid related systems. A synthetic jet actuator consists of a cavity with an oscillating diaphragm. As the diaphragm oscillates, jets are formed through an orifice in the cavity. This paper focuses on piezoelectric synthetic jets formed using two types of active diaphragms, Thunder® and Lipca. Thunder® is composed of three layers; two metal layers, with a PZT-5A layer in between, bonded with a polyimide adhesive. Lipca is a *L*ight We*I*ght *P*iezo *C*omposite *A*ctuator, formed of a number of carbon fiber prepreg layers and an active PZT-5A layer. As these diaphragms oscillate, pressure differences within the cavity as well as average maximum jet velocities are measured. These parameters are measured under load and no-load conditions by controlling pressure at the back of the actuator or the passive cavity. Results show that the average maximum jet velocities measured at the exit of the active cavity, follow a similar trend to the active pressures for both devices. Active pressure and jet velocity increase with passive pressure to a maximum, and then decrease. Active pressure and the jet velocity peaked at the same passive cavity pressure of 18kPa for both diaphragms indicating that the same level of pre-stresses is present in both actuators even though Lipca produces approximately 10% higher velocities than Thunder®.

INTRODUCTION

Methods that attempt to control the motion of fluids have been extensively explored in the past. Some of these methods can be passive or active or both [1]. Passive flow control is usually achieved using steady state tools such as wing flaps, spoilers, and vortex generators, among others. These techniques though effective have marginal power efficiency and are not capable of adjusting to the instantaneous flow conditions experienced during flight. Active flow control (AFC) methods however, are much more efficient as they can adapt to the constantly changing conditions by introducing small amounts of energy locally to achieve non-local changes in the flow field with large performance gains [2,3,4]. The simplification of conventional high lift systems by AFC could possibly lead to providing 0.3% airplane cost reduction, up to 2% weight reduction and about 3% cruise drag reduction [5]. In spite of all the advantages, using active flow control devices usually adds complexity in design, and increases manufacturing and operation cost of the system preventing their use. For this reason, many researchers have focused on designing better active flow control devices that are easy to manufacture, are small in size and require little power to operate. One of the devices that fulfill all of these qualities is called synthetic jets.

Synthetic jets consist of a cavity with an oscillating diaphragm. When the diaphragm oscillates air is pushed out an orifice forming a jet [6]. The interaction of the jets with an external flow leads to the formation of closed re-circulating flow regimes near the surface. These flow regimes can act as a "virtual surface" and consequently add an apparent modification of the flow boundary [4].

The oscillating diaphragm used in the synthetic jet cavity is usually driven using electrical or mechanical power. In the past, researchers have used compressed air or regulated blowers as a means of supplying steady or oscillating flow [7,8]. This adds to the complexity and weight of the system. Piezoelectric disks oscillate in the same manner as a piston or a shaker when driven using an AC electric signal. Eliminating the shaker or a piston reduces the number of moving parts, eliminates tribology issues and reduces weight. Hence, several investigators have adopted piezoelectric disks as oscillating diaphragms in synthetic jets [6,9]. The most commonly used diaphragm consists of a Lead Zirconate Titanate (PZT) disk bonded to a metal shim using a conductive epoxy, a Unimorph. Although these disks have been successful in generating high velocities, the devices operate at high off resonant frequencies, consequently requiring high amounts of power. In addition, driving the actuator at resonant frequencies causes debonding and heating of the individual layers shifting the resonance and causing the output of the device to drop and fail [9].

In the current study, piezoelectric composites that are more durable are used as active diaphragms in the jet cavity. In addition to active piezoelectric layers, they have reinforcing layers of metal or other stronger materials that give them added durability. These lightweight devices have the ability to produce micro scale displacements at fast response times. Such advantages make them suitable for flow control purposes as demonstrated by Mossi et al. [10,11]. In practical applications synthetic jets will be subjected to various pressure differentials within the cavity and also outside the cavity. In this study, the pressure differentials within the cavity are studied as the understanding of these internal pressures plays a crucial role in cavity design and jet performance.

EXPERIMENTAL SETUP

The two diaphragms used in this study are PZT based piezoelectric composites, Thunder® and Lipca. Both diaphragms are mechanically pre-stressed, due to a coefficient of thermal expansion mismatch between their layers. Thunder®, developed at NASA Langley Research Center, is composed of three layers; a 0.254 mm thick PZT-5A layer is sandwiched between a 0.0254 mm thick layer of chemically etched copper, type ASTM B152 Alloy 110, and a 0.254 mm thick layer of stainless steel, Type 304, bonded with a polyimide adhesive, LaRC-SI [12]. The PZT and copper layers have an overall diameter of 63.5 mm, and the steel layer has a slightly larger diameter, 68.5 mm, to allow clamping of the device, Figure 1a. The Lipca actuator, developed by Konkuk University, Korea [13], is composed of a top layer of glass/epoxy with a diameter of 66.0mm and thickness of 0.09 mm, followed by a unidirectional carbon/epoxy layer with a diameter of 66.0 mm and thickness of 1.0 mm, a layer of PZT 5A ceramic with diameter of 50.0 mm and thickness of 0.18 mm, and a final layer of glass/epoxy in the bottom with the same dimensions as the top layer, as shown in Figure 1b.

The synthetic jet cavity is constructed of two 88.0 x 88.0 x 19.1 mm Plexiglas™ pieces. The plastic pieces have a 60.5 mm circular aperture in the center. The actuators are placed in between the two pieces reinforced with a neoprene rubber ring, on both sides, to provide a cushion and a seal at the same time. Screws are used to seal the plastic pieces along with a 1.6 mm thick covering plate which provides a 3.67 mm axisymmetric orifice in the center.

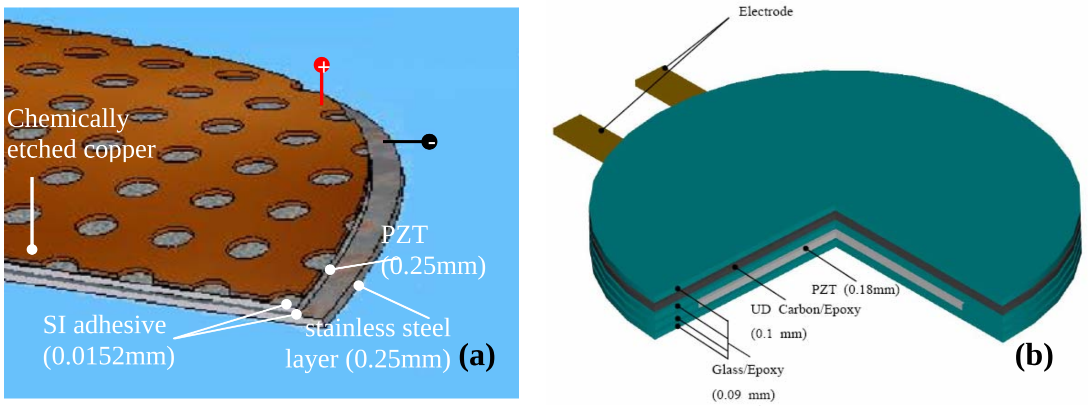

Figure 1. Layer Arrangement, (a) Thunder®, (b) Lipca

Equal torque of 424N-mm is applied on each screw using a torque screwdriver to ensure constant pressure along the perimeter of the actuator. The final cavity assembly is shown in Figure 2a.

The assembled actuator-cavity is mounted onto an adjustable height gauge, with the actuators surface perpendicular to an IFA100 hot-wire anemometer of 3.2 mm in diameter, used to measure average maximum velocity of the jet. The hot-wire anemometer is traversed through the diameter of the synthetic jet orifice while the diaphragm is driven with a sine and sawtooth driving signals at varying voltages and frequencies. Magnitude of the applied signal and frequency are kept below their allowable maximum driving fields and their respective resonant frequencies in order to prevent electrical and mechanical failure of the diaphragms. A signal generator, an HP model HP33120, connected to an amplifier, TREK model PZD700 is used for generating the driving waveforms. The synthetic jet cavity is divided by the diaphragm into active and passive cavities, Figure 2b. Pressure in the active cavity, Figure 2b, is monitored using an Endevco 8510 B-2 dynamic pressure transducer.

Velocities are measured in quiescent air in the *z*-direction at 2 mm from the orifice. The passive cavity is pressurized using a pressure regulator connected to a compressed air supply, as shown in Figure 2b. As the passive cavity is pressurized to various levels, the effects on the jet velocity are monitored. Average maximum velocity, voltage signals, and dynamic pressure are monitored and recorded using an oscilloscope, LeCroy model 350L, National Instruments data acquisition hardware, and recorded using Labview® data acquisition software.

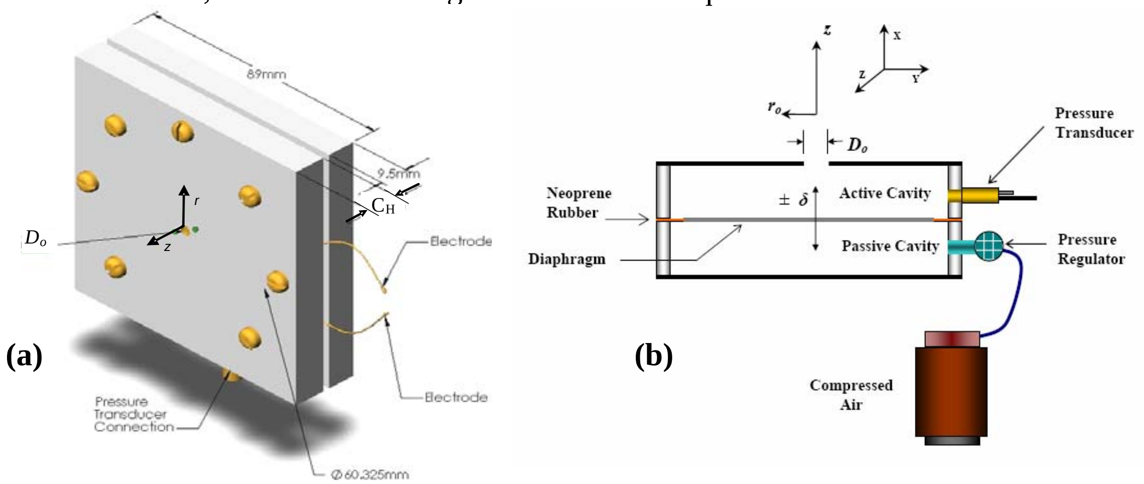

Figure 2. Synthetic Jet Cavity Assembly (a) Final Assembly, (b) Pressure Setup

RESULTS

Average maximum jet velocities and active cavity pressures are measured at various frequencies and voltages for each actuator. Driving waveform, in the case of both actuators, has a significant effect on the measured pressures and velocities. A sinusoidal waveform produces small pressure variations that may be below the resolution of the pressure transducer (±0.14kPa). A sawtooth waveform however, produces higher dynamic pressures, as shown in Figure 3 for a typical Thunder® device at 400Vpp. It is also observed that with a sinusoidal waveform, the active pressure increases with frequency while for a sawtooth waveform the pressure reaches a steady value after approximately 10Hz. The same trend is observed for average maximum jet velocity as shown in Figure 4. These results indicate that the flow inside the cavity reaches a saturation point with a sawtooth waveform. A similar phenomenon is observed in nozzles for compressible flow and is called a choked condition [14]. It is feasible that a similar choking condition occurs in the synthetic jet cavity, when the diaphragm is driven with a sawtooth waveform at high frequencies. This indicates that there may be a coupling between pressure and velocity for both actuators, and that this coupling is related to the waveform applied to the actuator. This phenomenon is not observed with a sinusoidal waveform at the frequencies tested.

To further study the effects of pressure on jet velocity, the opposite face of the diaphragm or the passive cavity is pressurized, that is, uniformly loaded from 0 to 55kPa. In this manner, additional mechanical pre-stress and curvature is added to the actuator, simulating a real world condition. Active cavity pressure and the jet velocity are measured at various voltages and frequencies as previously described with and without additional pressure in the passive cavity. Figure 5 shows the typical effects of passive cavity pressure on the active cavity pressure at 350Vpp for a Lipca. As the passive cavity pressure increases, the active cavity pressure also increases to a maximum, followed by a pressure decrease. The pressure peak is observed to be at approximately 18kPa. A similar peak is seen with the Thunder® device at the approximately the same passive cavity pressure. In the case of average maximum jet velocity, a similar trend is observed, the velocity increases until approximately 18kPa and then drops as the passive cavity pressure is increased, as shown in Figure 6. The Lipca device performs in a similar manner with the velocity peaking at approximately 18kPa passive cavity pressure. This behavior is noticed at all frequencies and voltages as shown in Figures 5 and 6 for a few selected frequencies.

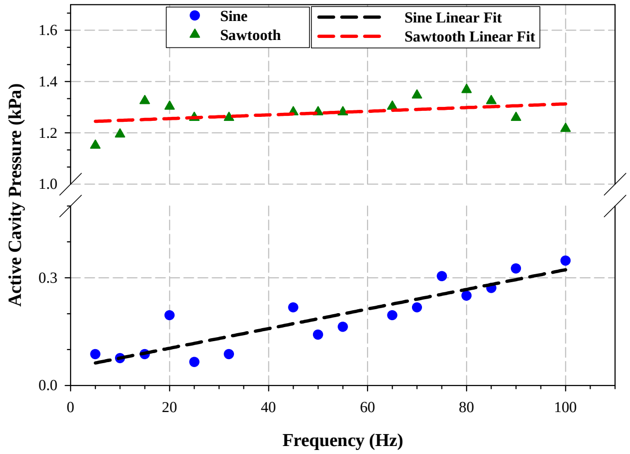

Figure 3. Thunder® Active Cavity Pressure

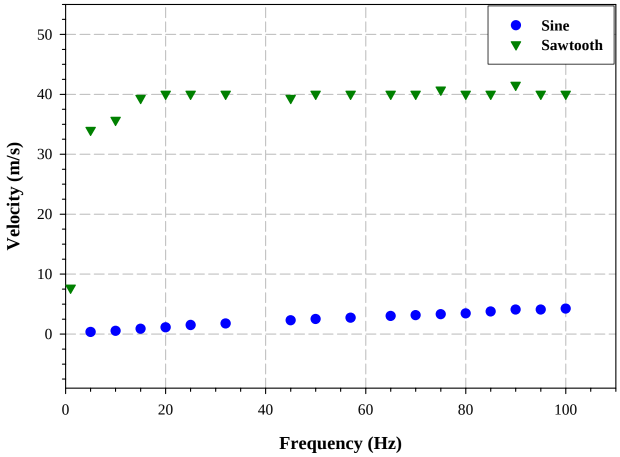

Figure 4. Lipca Synthetic Jet Velocity

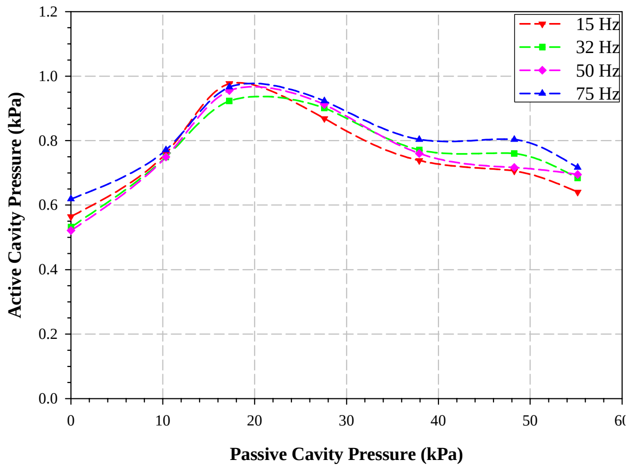

Figure 5. Lipca Sawtooth Pressure Comparison

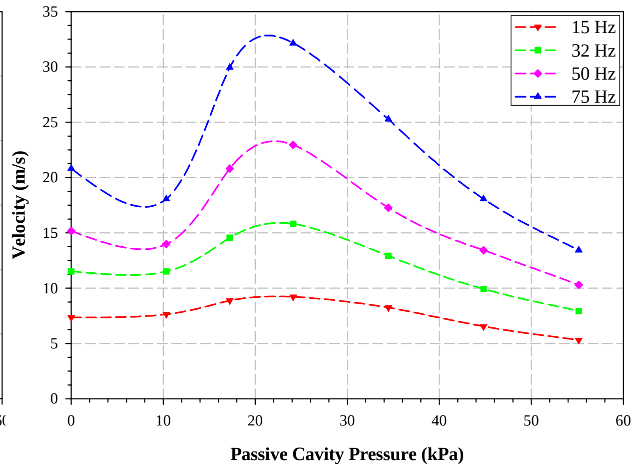

Figure 6.Thunder® Sine Pressure Effects

In Figures 7(a) and (b) active cavity pressures and velocities are simultaneously shown at different passive cavity pressures for a Thunder® and a Lipca when driven with a sawtooth waveform. As the passive cavity is pressurized to up to 55kPa, the diaphragm is further pre-stressed, influencing the resulting active cavity pressure and jet velocity. Both diaphragms exhibit similar trends however Lipca produces a higher velocity than the Thunder® (approximately 10%).

CONCLUSIONS

Pressure effects on a synthetic jet actuator, active and passive cavities, were studied for the Thunder® and Lipca devices. For both devices, the active cavity pressure increases with frequency for a sinusoidal waveform. However, a sawtooth waveform pressure stabilizes to a constant value at approximately 10Hz.

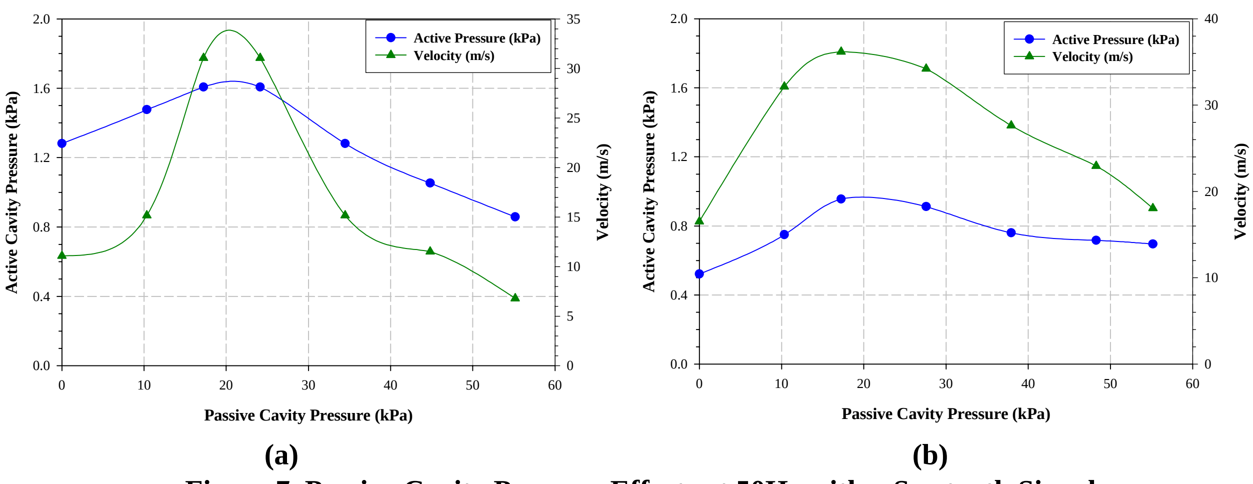

Figure 7. Passive Cavity Pressure Effects at 50Hz with a Sawtooth Signal; (a) Thunder® and (b) Lipca

This trend is similar to the one observed in compressible flows indicating that compressibility effects are significant when using a sawtooth waveform. Average maximum jet velocities follow a similar trend to the active pressures for both devices. Active pressure and jet velocity increase with passive pressure to a maximum followed by a decrease. In addition, active pressure and the jet velocity peaked at the same passive cavity pressure of 18kPa for both diaphragms indicating that the same level of pre-stresses is present in both actuators. Though both diaphragms exhibit similar performance with respect to the trends with pressure and velocity, Lipca produces approximately 10% higher velocity than Thunder®.

ACKNOWLEDGEMENTS

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