CHARACTERIZATION OF PIEZOELECTRIC ACTUATORS FOR FLOW CONTROL OVER A WING

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Abstract:
During the past decade, piezoelectric actuators as the active element in synthetic jets demonstrated that they could significantly enhance the overall lift on an airfoil. However, durability, system weight, size, and power have limited their use outside a laboratory. These problems are not trivial, since piezoelectric actuators are physically brittle and display limited displacement. The objective of this study is to characterize the relevant properties for the design of a synthetic jet utilizing three types of piezoelectric actuators as mechanical diaphragms, Radial Field Diaphragms, Thunders, and Bimorphs so that the shape cavity volume does not exceed 147.5 cm^3 on a 7cm x 7cm aerial coverage. These piezoelectric elements were selected because of their geometry, and overall free-displacement. Each actuator was affixed about its perimeter in a cavity, and relevant parameters such as clamped displacement variations with voltage and frequency, air velocities produced through an aperture, and sound pressure levels produced by the piezoelectric diaphragms were measured.

Keywords: pre-stressed, piezoelectric, actuators, synthetic jets, free displacement, velocity

Introduction

Synthetic jets for flow control devices have been proven to be an effective tool to reducing drag and enhancing mixing [1]. Synthetic jet systems have been produced with speakers, compressed air, air pumps, and bimorph diaphragms among others. All of the above techniques add weight, require real estate, and add complexity to an airplane making these options impractical. Piezoelectric actuators are an attractive solution because of their light weight, and fast-time response though piezoelectric actuators as part of complete mechanisms, machines, or devices are rare. One of the main reason for failure to find a suitable application for these devices is the boundary conditions dictated by the environment that the device would be used [2, 3]. Piezoelectric actuators such as moonies [4], rainbows [5,6], unimorphs [7], thunders [8,9,10], bimorphs [11,12] and radial field diaphragms, RFD, [13,14] have been investigated for particular applications and some of their relevant properties are well documented. Based on their documented properties, specifically geometry and free-displacement, three actuators were chosen for a synthetic jet application with a zero net mass flow rate production. Thunder, Bimorph, and RFD circular actuators were selected and tested in a cavity of constant size equipped with a slot. The actuators were driven with different types of waveforms and frequencies. Relevant parameters such as clamped displacement, frequency, and capacitance were measured in a previous study and the limitations and advantages were described [15]. These preliminary results demonstrated that none of the three actuators possessed all of the characteristics needed to design a synthetic jet to be used for an effective flow control mechanism and that a combination of actuators are needed to achieve all the ideal characteristics of a synthetic jet. In order to better understand the performance of these actuators, jet velocity was measured with the actuators in a cavity. A baseline data of their performance was measured by quantifying the jet velocity through an aperture.

Experimental Setup

The three types of elements used for testing were; bimorphs, pre-stressed curved Unimorphs (Thunder), and Radial Field Diaphragms (RFD). All of the devices had a diameter of 63.5 mm. The bimorph utilized consisted of two bonded piezoelectric layers manufactured by Piezo Systems, Inc. model number T216-A4NO-573X utilizing a type 5A material with nickel electrodes and a total thickness of 4.1 mm (each PZT layer 1.9 mm thick). The Thunder® devices manufactured by Face International Corporation consisted of layers of stainless steel type 304, 0.254 mm thick, PZT type 5A, 0.254 mm thick and copper, 0.0254 mm thick, laminated using SI adhesive. The last group was the RFDs, manufactured by NASA Langley Research Center. These devices consist of one PZT wafer laminated with epoxy between Kapton® films having etched copper inter-digitized electrode patterns. A schematic of the layout of these three types of devices is shown in Figure 1a, 1b, and 1c.

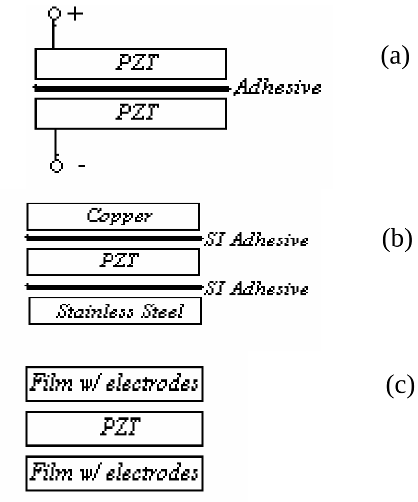

Fig. 1: *Actuators Schematic for (a) Bimorph, (b) Thunder, and a (c) Radial Field Diaphragm*

Due to the fragility of each actuator, and their performance under specific boundary conditions (torque applied and placement), careful consideration to the design of a specific-device clamping mechanism was utilized. It has been proven that the boundary conditions a piezoelectric actuator is subjected to in an application has a significant impact on the final performance of the device. For instance, Liew states that different boundary conditions and applied voltages affect the shape control of piezo-laminated composite beams [3]. The clamping torque on the device is constant and the placement in the cavity is tailored to each-actuator. For details see Mossi, et al. [15]. The cavity dimensions consist of two plates with a total height of 1.0 cm, length of 8.89 cm, and width of 8.85 cm with a top plate cover. The top cover plate shown on the schematic of Figure 2, has a top plate with a slot width of 0.5207mm by 3.49cm for producing the air jet. For this study, only one size slot was tested. All of the actuators were fastened between the top and bottom layer of the cavity as described above depending on the actuator type leaving one side open to the atmosphere.

The measurements performed included air jet velocity at approximately 2 mm from the center slot exit, displacement of the actuator at the opposite end at the center as well, and applied voltage, frequency and waveform. The equipment utilized included a hot wire anemometer coupled with an IFA-1000 flow analyzer, a LeCroy oscilloscope; a TREK voltage amplifier model PZD700, an HP33120A signal generator, a positioning system, and a non-contact Laser Nais LM10 system, and sound meter. All the instruments were controlled and monitored through a PC using LabView® software.

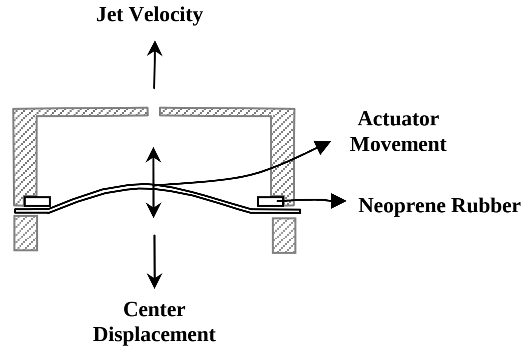

Fig. 2: *Cross-Sectional Schematic of the Synthetic Jet Cavity*

Results

A sinusoidal, square, and a saw tooth driving signal was utilized for the three actuators at their respective driving fields (thickness dependant). It was observed that the velocity of the produced jet, independently of the type of actuator utilized, was stronger during exhaling and inhaling by using a saw tooth drive form. To illustrate this effect, displacement was also monitored using a non-contact laser simultaneously with the hot-wire anemometer (See Fig. 3).

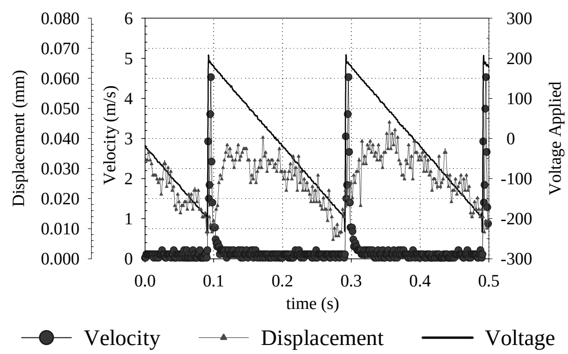

Fig. 3: *Saw Tooth Waveform at 5 Hz for a Typical Actuator*

Once the driving waveform was selected, air jet velocities produced were measured for the three types of devices at the appropriate driving voltages and frequencies in a one size cavity with a one size slot jet were measured for the three types of devices at the appropriate driving voltages and frequencies – actuator dependant. When performing these velocity measurements in the cavity with the different actuators, erratic velocity measurements were obtained at all driving frequencies independent of the driving voltage. In order to investigate the source of variability, each actuator was tested by varying the applied torque, 28.25 N-cm, 42.37 N-cm, and 70.62 N-cm to asses the variability of the results under different clamping forces. The resulting velocities continued to be erratic independent of the clamping torque and type of actuator. It was observed that the resulting velocities fluctuated at audible tones so that a sound meter reproduced the variations observed with the hot-wire anemometer (See Fig. 4).

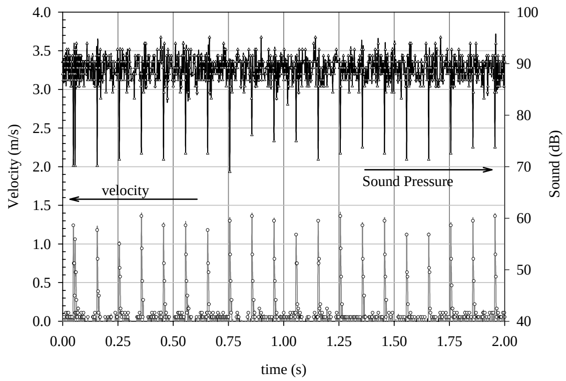

Fig. 4 *Sound Pressure Level variation with Sound for a Typical Air Jet produced by a Piezoelectric Actuator.*

This is expected as sound is produced by the change in pressure levels, with some frequencies producing more noise than others. All testing was performed at low frequencies and the variations were not believed to be part of the Helmholtz cavity resonance since the theoretical values calculated for a cavity of this size is above 200 Hz [16]. Furthermore, jet velocities variations at some frequencies were not as evident, namely 5, 10, 20Hz, etc. To attempt to identify the source of the larger variations, the velocity was monitored over a period of 4 minutes by taking a snapshot of the jet's velocity every minute at a frequency where fluctuations are minimal. A typical output for any of the three actuators is shown in Fig. 5.

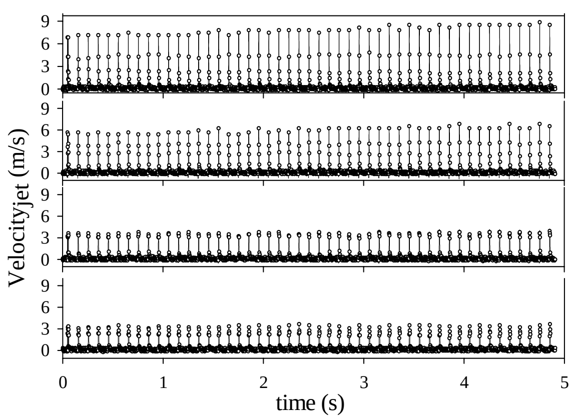

Fig. 5 *Typical Variations of Jet Velocity with time at the same driving voltage and frequency for a Thunder Actuator*

Note that velocity varied from 4 m/s to 8 m/s during the 4 min span, so that a peak velocity is difficult to record. To isolate the factors that produce this erratic behavior temperature was monitored for all actuators during testing. No significant change in temperature, above or below ambient, was noted. After careful monitoring, it was observed that the variations could be caused by mechanical factors such as the boundary conditions (type of grooves machined in the cavity) and the applied torque to the holding mechanism and its effects on the saw-tooth waveform and the inherent harmonics of the waveform itself. All three actuators were tested with different torques around their perimeter and displacement outside the cavity was measured in order to eliminate cavity frequency effects. The same variations over time observed in speed where also observed in displacement and applied voltage outside the cavity. These results indicate that clamping maybe the cause of the variations since the three actuators had similar responses. A typical radial field diaphragm held at three different torque values is shown in Fig. 6 which consists of a magnification of the top portion of the monitored displacement waveform at different torques. Peak displacement varies and number of peaks varies before stabilizing depending on the applied torque. For instance, at 70.62 N-cm, the highest torque applied, more peaks are observed than the other applied torques corresponding to smaller vibrations. Vibrations produced in this manner have an impact on the applied voltage that the amplifier provides to the actuator (feedback). This excess voltage eventually returns to the actuator producing different displacements that translate into the erratic jet velocities shown in fig. 5. One solution to this problem is to change the boundary conditions to a more compliant material or change the driving waveform and avoid sharp changes to limit the number of mechanical vibrations of the device.

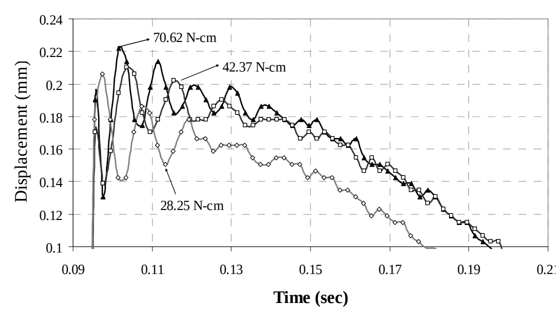

Fig. 6 *Sample Peak Variations with Torque using a Saw-Tooth Waveform*

The erratic performance observed is more pronounced at specific frequencies and more investigations are under way to assess the source of the vibrations that are beyond the scope of this paper. Selecting one frequency where variations are small to illustrate the capabilities of one of the actuators tested, fig. 7 is shown with velocity and displacement monitored simultaneously at 5 Hz. In this figure it is evident that a maximum jet velocity is approached before reaching maximum voltage, reaching a saturation value. This particular characteristic may be useful when designing a multiple-actuator synthetic jet in terms of power needed to drive the actuators.

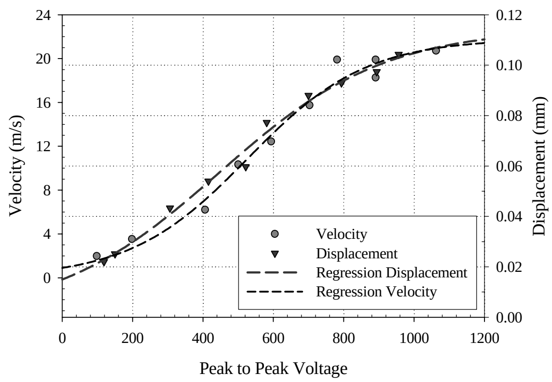

Fig. 7 *Typical Variations of Velocity with Voltage peak to peak for a Radial Field Diaphragm at 5 Hz.*

Conclusions and Future Work

A preliminary study was conducted to characterize the capabilities of three actuators, a Bimorph, a Radial Field Diaphragm, and a Thunder device as diaphragms for a synthetic jet actuator. Jet velocity displacement and sound were performed on the cavity with a pre-determined volume and slot size. The results showed velocity and sound fluctuations with sound at a constant frequency with all the actuators. These fluctuations may be inherent to cavity design. Temperature and clamping torque were closely monitored as an attempt to eliminate some of the sound variations from the velocity readings. Further measurements of the devices under a saw-tooth waveform were performed to further investigate the cavity effects on the sound and velocity variations. Preliminary results seem to suggest that the vibrations are due to mechanical design and inherent harmonics due to the driving waveform and the applied torque when clamping the devices. Future work involves different clamping mechanisms as well as the use of an arbitrary driving waveform.

Acknowledgements

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