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Boundary Condition Effects on Piezo-Synthetic Jets

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ABSTRACT

Three circular piezoelectric actuators: Bimorph, Thunder, and Radial Field Diaphragm (RFD) function as oscillating diaphragms within a cavity to produce a zero net mass flux air jet. To characterize each diaphragm, displacement response and vibrational characteristics with varying mechanical and electrical boundary conditions were investigated using a saw tooth waveform at 5 Hz. Clamping pressure around the perimeter of each actuator and gain dampening feedback of the amplifier were varied to statistically evaluate their significance on displacement. The results showed that displacement variations due to clamping pressure for all actuators are significant, with those for RFD at the highest levels, 17–18%.

Keywords: Bimorph; Thunder; Radial Field Diaphragms; displacement

INTRODUCTION

Flow control is a key factor in optimizing the performance of any vehicle moving through a fluid [1]. Through active flow control, zero net mass flux actuators, better known as synthetic jet actuators (SJA) have demonstrated their ability to improve aerodynamic performance under laboratory test conditions [2–10]. Some of these improvements will translate into decreased fuel consumption, increased lift, and reduction in drag and hence improved vehicle maneuverability.

A SJA consist of an oscillating diaphragm inside a sealed cavity with a small orifice or slit through which an air jet enters (suctioning) and exits (blowing) due to the diaphragm's oscillatory displacement. The expelled fluid forms a shear layer with the surrounding fluid that results in a series of rolling vortices. If the

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oscillation of the diaphragm is sufficient in amplitude and frequency, the vortices have sufficient inertia to escape re-entrainment into the cavity resulting in an air jet consisting of propagating vortices [10]. Although the net mass change of fluid through the cavity is zero, the net momentum transferred into the fluid is non-zero [2–17]. Zero net mass flux synthetic jet actuators produce an air jet with unique effects not possible with steady suction or blowing and have the advantage of eliminating the need for plumbing connections and an internal air supply [11–13].

In investigating the use of synthetic jets for propulsion of fixed wing Micro Air Vehicles, that function at relatively low velocities, Whitehead and Gursul [11] demonstrated with the use of pumps and piezoelectric Unimorphs that an optimum range of Strouhal number corresponded to input frequencies less than 100 Hz.

Currently, the use of piezoelectric materials has been advantageous for the development of synthetic jet actuators [14–17]. Compared to other conventional active flow control techniques such as air pumps and voice coils, piezoelectric devices have the advantages of faster response, good reliability, low cost, and a reduction in weight and space [7]. Chen et al. [4] have attained a maximum air jet velocity of approximately 40 m/sec using a 23 mm diameter Murata piezoelectric type 7BB-50M-1 bonded to a 50 mm diameter brass shim driven with a sine wave at a frequency of 1160 Hz. Their study shows that for limiting cases, the jet velocity may be scaled by the peak-to-peak displacement of the actuator. Using a sine wave as the driving input requires relatively high frequencies to match the actuator's resonance frequency to enable a synthetic jet formation with a significant velocity [2–4, 7, 17]. High frequencies, however, consume more power and also physically limit the oscillation amplitude of the piezoelectric diaphragm. This in turn limits the volume of air volume displaced.

To overcome these limitations three low frequency, three high displacement actuators were chosen for this study, the Bimorph, Thunder® and RFD. These actuators are similar in that they are circular with a diameter of 6.35 cm and use the same active element, Lead Zirconate Titanate (PZT) type 5A. The geometry and overall free displacement characteristics of these piezoelectric actuators make them easy to incorporate into a relatively simple design [18]. The Bimorph model T216-A4NO-573X manufactured by Piezo Systems Inc., has the largest capacitance of 130 nF and is 0.41 mm thick consisting of two bonded piezoelectric layers with nickel electrodes. Thunder® is a pre-stressed curved Unimorph composed of three layers that include a 0.254 mm thick layer of stainless steel, a 0.254 mm thick layer of PZT type 5A and a .0254 layer of perforated copper, laminated with a polyimide adhesive between the layers [19]. The resulting actuator, Thunder is saddle shaped with a capacitance of 80 nF. The RFD, manufactured by NASA Langley Research Center consists of one PZT layer laminated between Kapton® films with etched inter-circulating copper electrodes. This electrode design is responsible for the device's low capacitance, 14 nF, and its characteristic high displacement and dome topography [19].

Mossi and Bryant performed a preliminary study with these actuators for displacement and jet velocity. The study showed that the brittleness of the Bimorph and the heat buildup of the RFD limited the frequency to 290 Hz and 100 Hz respectively, while the Thunder device frequency range is limited by available power [18]. Further experiments showed that a saw-tooth wave input provided significantly higher jet velocities though instabilities were present [20]. Reported results showed significant velocity fluctuations with time when the actuators were driven at frequencies ranging from DC to 100 Hz. These velocity fluctuations were less noticeable at the low frequency range, and hence a 5 Hz driving frequency was chosen for this study.

To determine the origin of the variations with time in air jet velocity, an investigation was carried out on parameters, which may have some effect on displacement. A frequency of 5 Hz was chosen to minimize any random variations on jet velocity. In this manner, only boundary condition factors are considered when measuring the displacement response of the actuators since displacement response is believed to have a significant effect on maximum jet velocity.

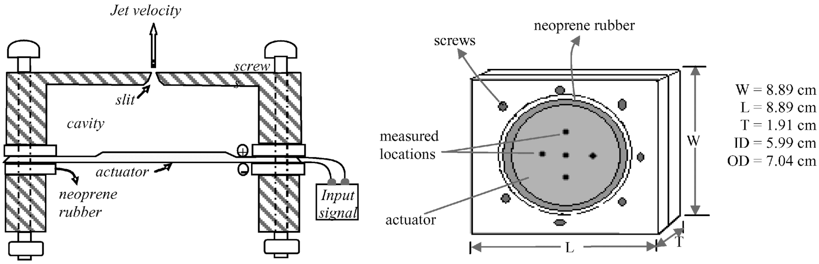
Displacement response of each actuator was monitored under various input voltages and boundary conditions. Different ranges of input voltages using a saw-tooth waveform are used for each actuator to see the effects on the actuator behavior. Boundary conditions, such as the applied force on the perimeter of the diaphragms, were also varied. These results are fundamental in identifying relevant parameters in the design of a synthetic jet.

EXPERIMENTAL SETUP

The equipment utilized in the experiments included a 9350L LeCroy oscilloscope, PZD700 TREK amplifier with a feedback damping system, HP33120 signal generator, and a dual channel Angstrom Resolver model 201R with a fiber optic sensor. The output voltage from the Angstrom Resolver and the amplifier were monitored with the oscilloscope that is controlled through a PC equipped with a National Instruments data acquisition card that allows the data to be recorded using LabView® software.

The cavity housing $8.89 \times 8.89 \times 1.91$ cm, was composed of two identical rectangular plastic pieces that have a 0.318 cm deep circular groove with a circular aperture as shown in Figs. 1a and b.

The actuator was placed between the described pieces with neoprene rubber around the perimeter of the actuator on either side. Seven 0.318 cm screws hold the two plastic pieces together and clamp the actuator in place. The assembled cavity was mounted onto an adjustable height gauge with the actuator's surface perpendicular to the fiber optic sensor used to measure displacement at the indicated locations.



(a) (b)

Figure 1. (a) Synthetic Jet Cavity Cross Section, (b) Posterior View of the Synthetic Jet Cavity.

The parameters tested were the torque applied to the screws, the voltage magnitude and the gain on the feedback dampening system. Applying a known torque to the clamping screws with an adjustable torque screwdriver adjusted clamping pressure around the perimeter. The torque range for the Thunder and RFD actuators was 141 to 706 N-mm. Due to the Bimorph's fragility, its the applied torque was limited to a maximum of 424 N-mm as higher torque results in fracture of the actuator.

The voltage amplitude was varied according to the maximum allowable electric field of each actuator; five peak-to-peak input voltages were applied to each actuator with no DC bias (i.e. 80 Vpp is from −40 to +40 Volts). The ranges applied to each actuator were; Bimorph: 80 to 160 Vpp at 20 Volt intervals; Thunder: 300 to 500 Vpp at 50 Volt intervals; RFD: 600 to 1000 Vpp at 100 Volt intervals. The gain dampening feedback system of the applied signal is adjusted through a potentiometer. The potentiometer controls the AC response characteristics of an amplified voltage when applied to a capacitive load. For these experiments, the potentiometer was set to a minimum, and maximum values that correspond to a resistance of 0 and 20 KΩ respectively [21]. For instance, a typical signal applied to a Bimorph, Fig. 2a, shows that at minimum setting, there is a significant overshoot in the applied signal; while at a maximum setting there is a small undershoot, as shown in Fig. 2b.

Similar overshoots are observed on displacement. The displacement of the actuator was measured at five locations, the center and four other positions at 10 mm from the center at 0, 90, 180, and 270 degrees. First with the potentiometer set at 0 kΩ, and one torque, displacement is monitored for all voltages. This process is repeated for each of the locations. Next, the Angstrom Resolver was calibrated and the actuator was discharged to remove any remnant charge. This procedure was repeated with a potentiometer set to 20 kΩ for all voltages, torques, and locations.

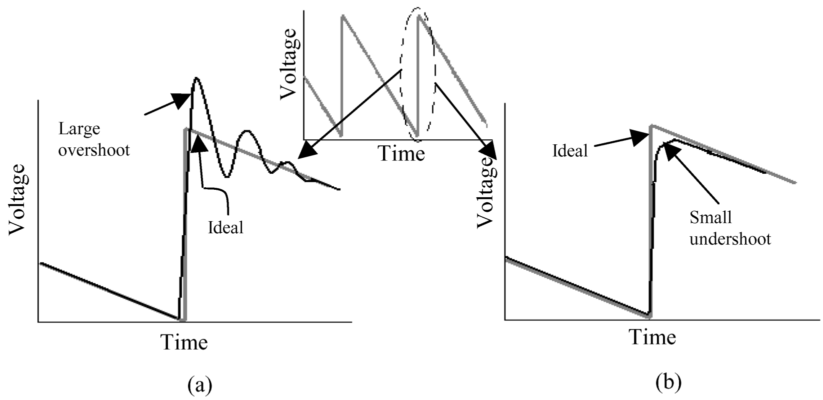


Figure 2. Potentiometer Setting Effects (a) minimum at 0 kΩ (b) maximum at 20 kΩ.

The Bimorph and RFD produce displacement in phase with the driving voltage signal, while the Thunder displacement is out of phase. *In phase* indicates that displacement is positive, with a positive voltage input or that the device increases in dome height. *Out of phase*, the device becomes flatter. Figure 3a shows an *in phase* displacement and 3b shows an enlarged view of the voltage input and actuator displacement versus time. The shape of the waveform shown in Fig. 3b is characterized by the following variables: *Total Displacement*, $\Delta\delta$, is the peak to peak displacement in mm; $\Delta\bar{\delta}_{\max}$, is the maximum displacement average; $\Delta\bar{\delta}_{\min}$, is the minimum displacement average. In order to plot and compare the displacement of the tested actuators, applied voltages are divided by respective maximum voltage applied to each actuator, by using

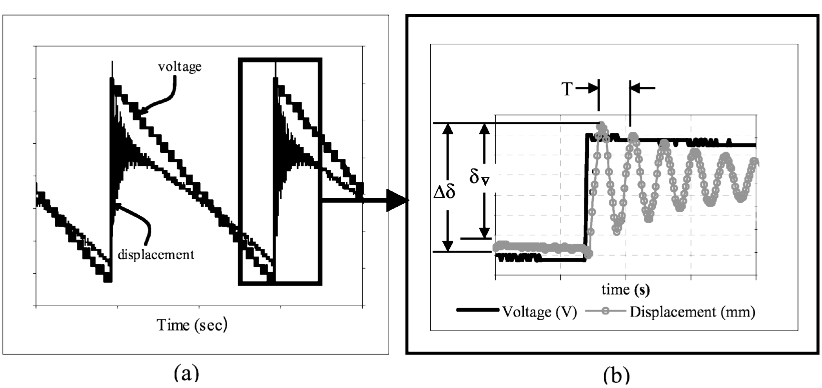


Figure 3. Voltage and Displacement vs. Time, (a) In-phase voltage and displacement (b) Time Magnification.

the relationship shown in Eq. (1).

$$V_r = \frac{V_a}{V_{max}} \quad (1)$$

V_r, represents voltage ratio, V_a is the applied voltage, and V_{max} is the maximum applied voltage.

RESULTS

The following sections describe the effect of pressure applied around the perimeter of each actuator and the gain dampening feedback system of the amplifier on displacement. The total displacement average versus voltage ratio for each actuator is shown in Fig. 4 for two tested potentiometer settings and a Torque of 424 N-mm. Results show that the Bimorph and the RFD have significantly higher displacement than the Thunder actuator when driven at the conditions tested in this study. At maximum applied voltage, the Bimorph displacement is four times that of Thunder, and the RFD displaces five times that of Thunder. Next the clamping pressure effects are discussed.

CLAMPING PRESSURE EFFECTS

By varying the torque on the screws and potentiometer settings on the amplifier, clamping pressure around the perimeter and vibrational characteristics were altered. To measure these effects, displacement for each actuator was measured at each location for every applied torque and each potentiometer setting tested. A typical center displacement versus torque for each applied voltage at a po-

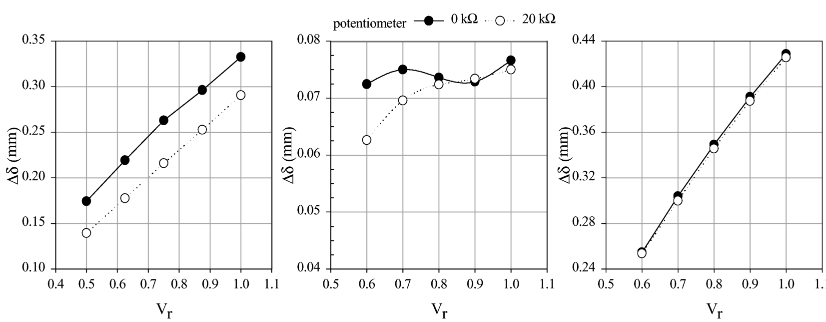


Figure 4. Actuator Displacement vs. Voltage Ratio at constant Torque for (a) Bimorph, (b) Thunder, (c) RFD.

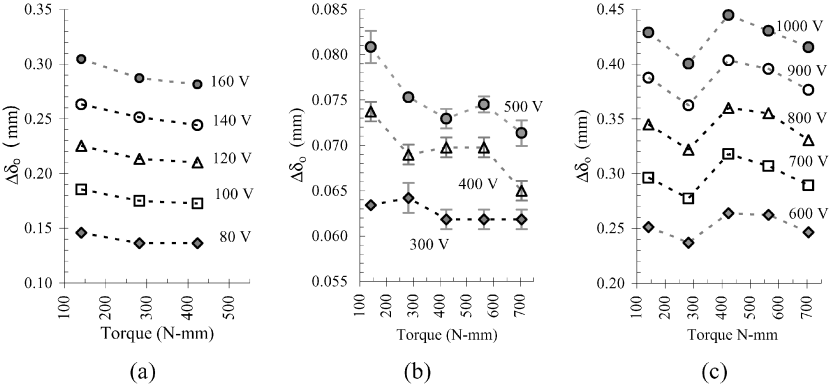


Figure 5. Center Displacement vs. Torque, (a) Bimorph, (b) Thunder, (c) RFD.

tentiometer setting of 20 kΩ is shown in Figs. 5a, b, and c for the Bimorph, Thunder, and RFD, respectively.

Each one of the points presented is an average of five points; one standard deviation displacement error bars were calculated and plotted for all actuators. Due to the low magnitude displacement of the Thunder device, Fig. 5b is the only one showing visible errors.

Since the results shown in Fig. 5 only represent one potentiometer setting, statistical analysis tools are utilized to assess the relevance of torque and potentiometer setting on displacement. One of these statistical tools is an analysis of variance, two-way ANOVA, which evaluates the significance of the tested parameters and the possibility of the two factors simultaneously interacting to have a significant effect on displacement [23]. Results of the significance are given a p-value. If the p-value is less than 0.001, the possibility of the differences being chance is less than 0.1%. In this study, the two tested parameters are torque and potentiometer setting. The test is performed for each actuator at three chosen voltages, lowest, middle, and maximum with five repetitions each.

For the first parameter, the relevance of torque on displacement, the analysis showed the results were statistically significant for all three actuators since all p-values are less than 0.001. However, for the Bimorph, the relevance of torque varies with location. For the second parameter, gain dampening feedback effects through the potentiometer, the ANOVA showed that the results were statistically significant for all locations for both the Bimorph and RFD. For Thunder, the ANOVA test results showed that potentiometer settings are significant parameter at the lowest voltage of 300, only but not higher voltages. The significance of the interaction between parameters on displacement also evaluated by the ANOVA analysis, that is a combination of gain feedback and torque, was not evident. For the Bimorph and Thunder, the interaction between parameters was not significant for most locations. For the RFD, there was evidence of some interaction between both parameters at specific locations however no definitive conclusion could be reached since the p-values ranged from 0.2 to less than 0.0001.

All the analysis done shows that the maximum displacement average, $\Delta\bar{\delta}_{\max}$, for all voltages and potentiometer setting occurs at the lowest torque setting of 141 N-mm for both the Bimorph and Thunder, and a minimum displacement average, $\Delta\bar{\delta}_{\min}$, at the maximum torque applied. This is expected since less applied torque is equivalent to less applied clamping force on the actuator perimeter. For the Thunder and Bimorph, this lowered restriction allows for higher displacement. This is not the case for the RFD. For all voltages and potentiometer settings, $\Delta\bar{\delta}_{\max}$ for the RFD occurs at the highest torque of 706 N-mm. One possible explanation for the performance of the RFD may be a consequence of the strain distribution on the device. It is hypothesized that as the torque is increased, the RFD is prevented from straining radially, forcing all the displacement out of the plane, thus giving higher displacement at the highest torque of 706 N-mm. The minimum displacement average for the RFD occurs at 282 N-mm.

The percentage difference, P_T, between the maximum average, $\Delta\bar{\delta}_{\max}$, and the minimum average, $\Delta\bar{\delta}_{\min}$, for each voltage was defined by Eq. (2).

$$\mathrm{P_T} = \left(\frac{\Delta\bar{\delta}_{\max} - \Delta\bar{\delta}_{\min}}{\Delta\bar{\delta}_{\max}}\right) \cdot 100 \tag{2}$$

The percentage difference due to torque is highest for the RFD at 17 to 18%. For Thunder the difference is 10 to 12% while for the Bimorph it is only 4 to 5%.

CONCLUSIONS

In this experimental study, displacement responses of three circular piezoelectric actuators, Bimorph, Thunder and RFD, driven with a 5 Hz saw-tooth waveform were examined to determine the effects and relevance of varying mechanical boundary conditions and electrical parameters. Mechanical boundary conditions were varied, by altering the applied clamping pressure around the perimeter of the actuator. Electrical parameters were varied throughout the amplitude of the applied voltage and the gain dampening feedback system in the power amplifier. Displacement and vibrational parameters at five different locations on the actuators were used to evaluate the relevance and significance of these variables. To that end, several parameters were calculated and evaluated statistically to investigate their relevance.

To evaluate the significance of the parameters, a 95% confidence interval two-way ANOVA, or analysis of variance, was performed for each test location with five repetitions at the low, mid, and high voltage range chosen for each actuator. In this manner, the ANOVA analysis indicated if the differences observed on displacement and amplitude of the vibration were a consequence of either clamping pressure, gain dampening feedback, an interaction of both, or completely random. Results showed that the effects of clamping pressure on displacement were significant for all three actuators, although for the Bimorph, the relevance of torque varied with location. The percentage difference, however, between the maximum and minimum tested values was highest for the RFD at a range of 17–18%, thunder 10–12%, and Bimorph 4–5%. Gain dampening feedback effects through the potentiometer, showed that the results were statistically significant for both the Bimorph and RFD but not for Thunder and there was no apparent interaction between torque and potentiometer setting. Hence, mechanical boundary conditions, in this case clamping force, are a relevant factor on the displacement performance of the actuators, having more relevance for the RFD and Thunder device.

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