Synthetic jets with piezoelectric diaphragms

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ABSTRACT

Piezoelectric diaphragms are used as synthetic jets because of their size, rapid time response, and relatively low power consumption. Among the piezoelectric diaphragms used are unimorphs and Bimorphs. In this study, a bimorph diaphragm, a thin Unimorph pre-stressed device and a Radial Field Diaphragm (RFD) are compared. A bimorph consists of two bonded PZT discs, a thin Unimorph pre-stressed device consists of copper, PZT, and stainless steel and a Radial Field Diaphragm consist of a layer of PZT with inter-digitized electrodes encapsulated in Kapton film. The effects of driving waveform on jet velocity are studied for each of these actuators. The actuators are driven at varying frequencies and the differential pressure in the cavity is monitored.

Keywords: flow control, synthetic jet, piezoelectric diaphragm, unimorph, bimorph, thunder, RFD

1. INTRODUCTION

Prandtl in 1904 used active control of the boundary layer, to show the influence such a control exerted on the flow pattern by suppressing transition or delaying separation[1, 2]. Since then significant research has been conducted towards developing flow control methods and techniques[1-24]. The capability to actively or passively control and manipulate the evolution of a flow field is of enormous scientific and industrial significance[1-24]. In addition to saving billions of dollars in fuel costs for land, air and sea vehicles, such technological advancements can lead to the development of economically and environmentally more viable industrial processes involving fluidic flow.

In recent years synthetic jets have shown promise as an effective device for actively controlling the boundary layer flow[3-24]. A unique feature of these jets is that they are formed entirely from the working fluid of the flow system in which they are deployed. The use of synthetic jets for flow control was first demonstrated by Smith and Glezer[3,8] and, again in more detail, by Smith[9]. Since then it has been adopted in many applications including the modification of aerodynamic characteristics of bluff bodies [4, 5], control of lift and drag on airfoils [10-12, 14], reduction of skin friction of a flat plate boundary layer [15], mixing in circular jets [16, 20], control of internal flow separation [13] and control of cavity oscillations [17, 18].

A typical synthetic jet cavity consists of an oscillating diaphragm in a circular void with an orifice in the face opposite the diaphragm. As the diaphragm oscillates, there are regular ingestion and exhaust strokes through the orifice. During the ingestion cycle, the flow separates at the orifice leading to the formation of a vortex sheet. The sheet rolls into a single vortex as it moves away from the orifice under its own self induced velocity. If the velocity is high enough, entrainment into the cavity is prevented leading to the formation of a jet of air [19]. Thus linear momentum is transferred into the flow system even though net mass injection is zero. Consequently, these jets are also called “zero net mass flux” jets.

The key component of the synthetic jet actuator is the oscillating diaphragm or actuator. In recent studies, piezoelectric actuators have been used as the active diaphragms in synthetic jets [21-24]. They have the advantage of low-weight, low-cost, reliability, and lower-power consumption in comparison with other actuators [25].

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The objective of this project is to study some of the factors affecting the performance of a synthetic jet actuator based on piezoelectric actuators. The results from this study will be used to design a synthetic jet that affords a maximum jet velocity. For this purpose, synthetic jets formed using three different piezo actuators the Bimorph, the Thunder® and the RFD were studied. The actuators used are distinct from each other but share two common characteristics, their diameters of 6.35cm and the active material element used in their construction. The active element used is Lead Zirconate Titanate (PZT) type 5A. The geometry and overall free displacement characteristics of these piezoelectric actuators make them easy to implement into a relatively simple design [23]. A detailed description of their construction is described in the experimental section.

Previous work by Mossi and Bryant showed displacement and frequency characteristics of the three actuators [26-28]. It was observed that even though the Bimorph had the smallest overall displacement, its velocity was the highest. It was hypothesized that this may be due to the total volume displaced. Further studies by Mossi and Bryant suggested that the driving waveform affects the maximum velocity obtained from a synthetic jet [23, 24]. As a continuation of that research, the current study investigated the effects of conditions such as driving signal, frequency and pressure on the synthetic jet performance. The three driving signals used were sine, sawtooth, and square with frequency ranges limited to below resonant frequencies [27-29].

2. EXPERIMENTAL SETUP

The diaphragms are fabricated into a composite with an active piezoelectric ceramic layer and additional layers of different materials depending on each actuator. The Bimorph, model T216-A4NO-573X is manufactured by Piezo Systems Inc. This device consists of two bonded piezoelectric layers with nickel electrodes. It is 0.41 mm thick and has a large capacitance of 130nF. The Thunder® is a pre-stressed curved Unimorph composed of three layers that include a 0.254mm thick layer of stainless steel, a 0.254mm thick layer of PZT type 5A and a 0.0254 layer of perforated copper, respectively. The layers are laminated with a polyimide adhesive[25]. The resulting actuator is saddle shaped with a capacitance of 100nF. The RFD, manufactured by NASA Langley Research Center consists of one PZT layer laminated in between Kapton® films with etched inter-circulating copper electrodes. This electrode design is responsible for the devices low capacitance, 14nF, and its characteristic high displacement and dome topology [26].

The two parameters measured were jet velocity and cavity pressure. Velocity of the jet formed in quiescent air is measured at several locations along the diameter of the orifice. The differential pressure in the front cavity is measured with reference to the pressure in the back cavity. In all cases, the driving waveform and frequency were varied. The sine, saw-tooth, and square waveforms were applied at varied driving fields to each actuator. Voltage applied to the Bimorph was 140Vpp, Thunder 400Vpp, and RFD 800Vpp. In order to prevent the failure of the diaphragms the voltages were kept below their allowable maximum driving fields. Frequency ranges were different for each actuator depending on their properties and power supply capabilities. Maximum frequencies used were 100Hz for the Bimorph, 150Hz for the Thunder and 90Hz in the case of the RFD. The frequencies applied were below their respective resonant frequencies.

The setup utilized in the experiments is shown in Figure 1. The cavity housing 88.9 x 88.9 x 19.1 mm is composed of two identical rectangular plastic pieces with a circular aperture and a cover plate with a circular orifice. The synthetic jet formed through this orifice has a diameter of 3.67mm. The two plastic pieces have a 3.18mm deep circular groove along the circumference of the aperture. The actuator is placed in this groove between the two pieces with neoprene rubber around the perimeter of the actuator on either side. Seven 3.18mm screws hold the two plastic pieces and the cover plate together and clamp the actuator in place. The assembled cavity was mounted onto an adjustable height gauge with the actuators surface perpendicular to the hot-wire anemometer used to measure velocity of the jet from the orifice.
The equipment utilized in the experiments included a 9350L LeCroy oscilloscope, PZD700 TREK amplifier, HP33120 signal generator, a TSI 1210-T1.5 hot-wire anemometer, an IFA 100 signal conditioner and an Endevco 8510 B-2 dynamic pressure transducer. All the equipment was monitored using LabView® software through a PC equipped with a National Instruments data acquisition card.

The velocity was measured along the *r-axis* using a hot-wire anemometer, at a distance of 0.5*d* along the *z-axis* where *d* is the orifice diameter. It was assumed that effects such as inherent harmonics of the applied signal and noise do not have

a significant effect on the flow field. Pressure differential across the diaphragm that is the pressure differential between the front and back cavity, was also monitored and recorded.

3. RESULTS

The results presented below are divided into two sections. The first section describes velocity measurements and the second talks about the pressure differential measurements across the cavity with the three different diaphragms. To investigate the effects of applied waveform, each diaphragm was driven with three different waveforms, sine, saw-tooth, and square wave at their respective maximum voltages and varying frequencies. The obtained results are presented in the following sections.

3.1 Velocity Measurements

A typical voltage and velocity profiles for a diaphragm, in this case a RFD, are shown in Figure 2a through 2c. In this figure, the velocity signal is triggered by the applied waveform in order to capture phase differences between obtained signals. It is observed that the square waveform and the sinusoidal waveform both produce two velocity peaks of different magnitudes, per cycle. As seen in Figure 2(c), the larger peak follows the leading edge of the driving signal and as the voltage drops, the smaller peak follows the trailing edge. The saw-tooth produces a single velocity peak with magnitude similar to the square wave. These trends are observed in all three actuators tested with the driving signals at different magnitudes.

The above described experiments were carried out for a range of frequencies. Table 1 shows the maximum velocities measured in m/s for each actuator. For a sinusoidal waveform the maximum measured velocity was at the maximum applied frequency. For a sawtooth and a square wave the maximum measured velocity was in the range of 40-100 Hz. The Bimorph appears to produce the highest velocity followed by the RFD and finally the Thunder gives the lowest velocity.

Table 1. Maximum Velocities Measured in m/s

Waveform/Diaphragm	***Sine***	***Saw-tooth***	***Square***
Bimorph	7 ± 2	35 ± 6	36 ± 5
Thunder	5 ± 2	26 ± 4	27 ± 4
RFD	6 ± 2	28 ± 5	32 ± 3

The velocity was also measured at various locations along the center of the orifice in the *r* direction. A typical velocity profile produced by a synthetic jet in quiescent flow is shown in Figure 3. The figure shows velocity profiles for all three actuators at 32Hz with a sine wave. The profiles follow a Gaussian like distribution as shown by the results obtained by Carter and Soria [30]. They studied the evolution of circular synthetic jets formed using a piston. The jet was formed through a circular orifice by oscillating a piston like a sine curve.

Next the frequency effects on the maximum velocity were investigated. For the Bimorph, the frequency was increased up to 100Hz, Thunder 150Hz and the RFD 90Hz. In the case of the square and the sawtooth wave, the velocity increases up to about 20Hz and then remains constant as the frequency increases. For the sine wave the velocity continues increasing as the frequency increases. This pattern is observed for all three actuators. Figure 3 shows the trend followed by a Thunder actuator as the frequency is increased. The graph shows data for all three driving signals.

To test the significance of the variations seen in the actuators due to driving signal, statistical analysis was required. A two-way ANOVA with interactions was performed at selected frequency values [30]. Results shown in Table 2 indicate that there are significant differences due to the applied waveform. However the differences between the actuators appear

to be trivial. Such results may be an indication that cavity shape has a higher effect on maximum velocity than the diaphragm alone. However, the current study does not test this hypothesis.

Table 2. Two-way ANOVA with interactions

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Diaphragm Effect	5.6	2	2.8	0.04496	0.9561389	3.5545571
Waveforms Effect	2824.7	2	1412.3	22.86151	1.145E-05	3.5545571
Interaction Effect	4.4	4	1.1	0.01799	0.9993018	2.9277442
Error	1112	18	61.8			
Total	3946.7	26				

3.2 Pressure Measurements

The synthetic jet is formed due to cavity pressure variations across the diaphragm. As the diaphragm oscillates the pressure in the cavity also changes. As shown in Figure 1(b), the differential pressure in the front cavity was measured with reference to the pressure in the back cavity. Since the same trend is observed in all three actuators, a typical result is shown in Figure 5 for a RFD at 35Hz, driven by a sine wave. The pressure and the velocity are measured simultaneously triggered by the applied voltage to the diaphragm. It is observed that the pressure and the velocity are 120 degrees out of phase. Similarly, displacement, voltage, and velocity are monitored and the results are shown in Figure 6. This figure shows that the phase difference between the velocity and the applied diaphragm voltage is approximately 40 degrees, and between the voltage and the displacement is 25 degrees. These results are valid only for a RFD at 35 Hz sinusoidal waves. Other waveforms and frequencies are under investigation.

To assess the effects of frequency on the pressure in the cavity the diaphragm frequency was varied. The maximum differential pressure in the cavity was recorded at each frequency. As observed in the velocity measurements, the pressure increases until approximately 20Hz, remaining constant for all other frequency values. Typical results of the trend described are shown in Figure 7 using a Bimorph. The figure shows both the pressure and the velocity at different frequencies for a saw-tooth driving signal. Similar trends are observed for all the actuators with a square waveform.

4. CONCLUSIONS

The objective of this project was to investigate the relevance of certain factors affecting the performance of a synthetic jet actuator activated by a piezoelectric diaphragm. The parameters considered were type of piezoelectric diaphragm, driving waveform and frequency of the diaphragm. Three types of piezoelectric diaphragms, Bimorph, Thunder and RFD, were driven with three waveforms, square, saw-tooth and sine, at varied frequency ranges. Amongst the three driving signals used, the square wave produced the highest velocity and the sine wave produced the lowest velocities regardless of the piezoelectric diaphragm utilized. It was also observed that the square and the sine wave formed two velocity peaks per applied voltage cycle, which may be an indication of maximum and minimum cavity volume. The saw-tooth wave produces a single velocity peak per applied voltage cycle and also its magnitude is similar to the square wave.

All three piezoelectric diaphragms followed the same velocity trends in spite of the fact that each diaphragm has unique features and characteristics. The Bimorph produced the highest velocity followed by the RFD and the Thunder. The RFD produces velocities slightly higher than the Thunder. To verify the velocity profile shape along the length of the orifice, velocity was measured for all the diaphragms at varied frequencies. The profiles shape regardless of the waveform showed a Gaussian curve for all the actuators as previously shown by other researchers. When varying frequency, the square and the saw-tooth wave produce a maximum constant value at low frequencies. For the sine wave, the velocity

increases gradually with frequency without reaching a maximum value. To statistically compare all the varied parameters a two-way ANOVA test with interactions was performed on the data were waveform type, frequency, and actuator were considered as independent variables, and the velocity as dependant. The results showed that the variations due to waveform were statistically significant but the variations amongst the actuators were not statistically significant. These tests could imply that in a quiescent flow the cavity physical attributes play a more important role than the actuator utilized.

Pressure differences across the diaphragm were also monitored. It was observed that there are phase differences between the pressure, velocity and voltage that vary depending on the waveform and actuator type. Further tests are needed to verify the effect of pressure on velocity. Frequency effects on pressure were also investigated. As observed in the velocity measurements, the pressure increases until it reaches a maximum value, remaining constant for all other frequency values with all the actuators tested when using a saw-tooth wave and a square waveform. The results were inconclusive for a sine wave. Further tests need to be conducted.

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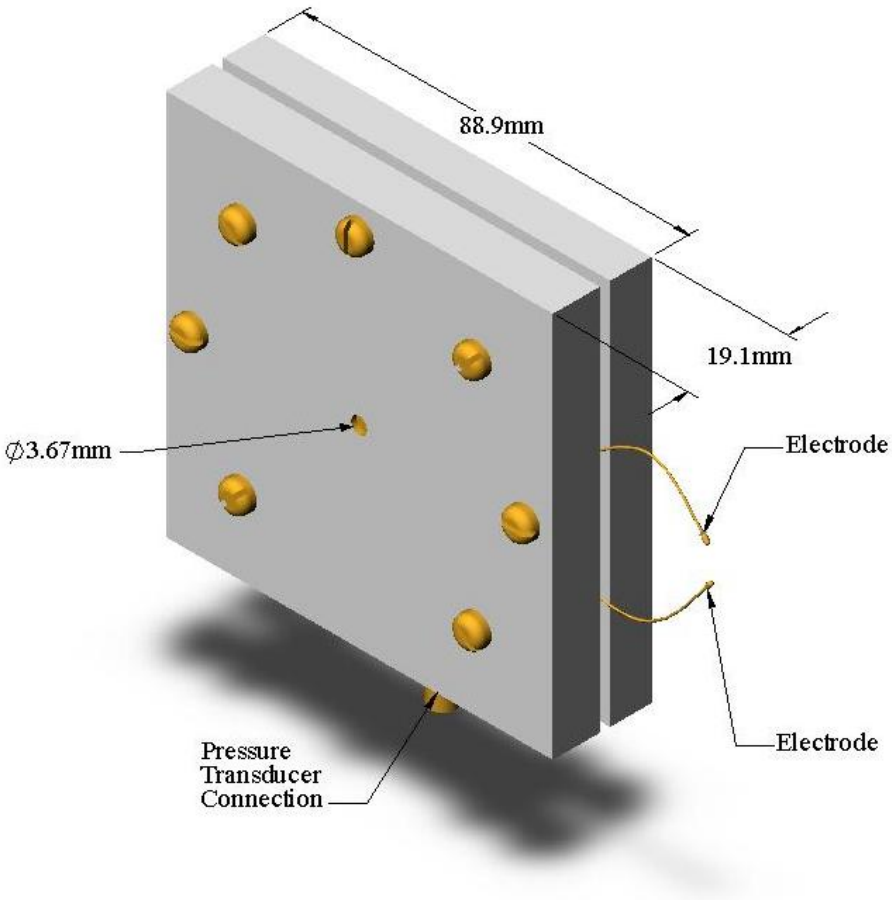
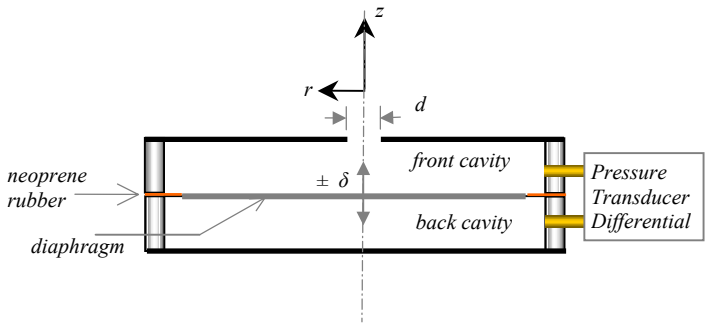


(a)



(b)

Figure 1. (a) Synthetic Jet Cavity (b) Cross-Sectional View of the cavity

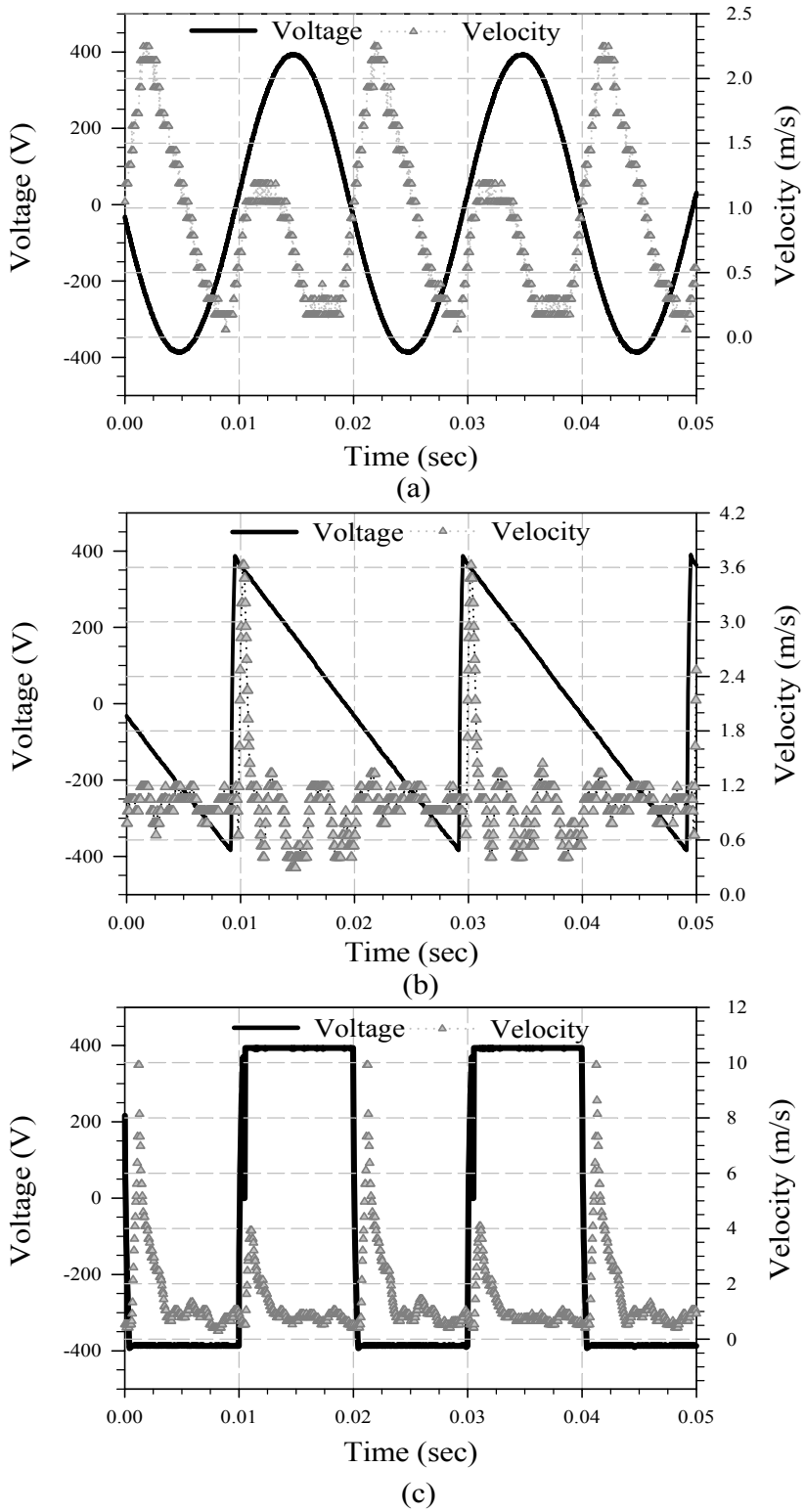


Figure 2. Typical Voltage and Velocity vs. Time at 50Hz and 800 Vpp (a) Sine, (b) Sawtooth, (c) Square for a RFD

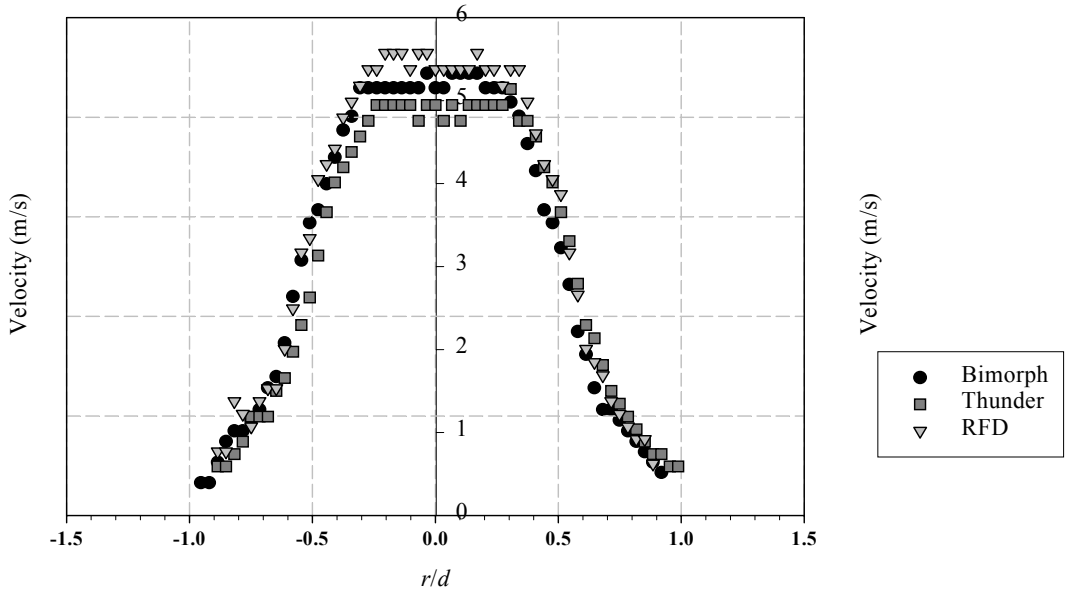


Figure 3. Velocity Profiles with a Sine Waveform at 32Hz

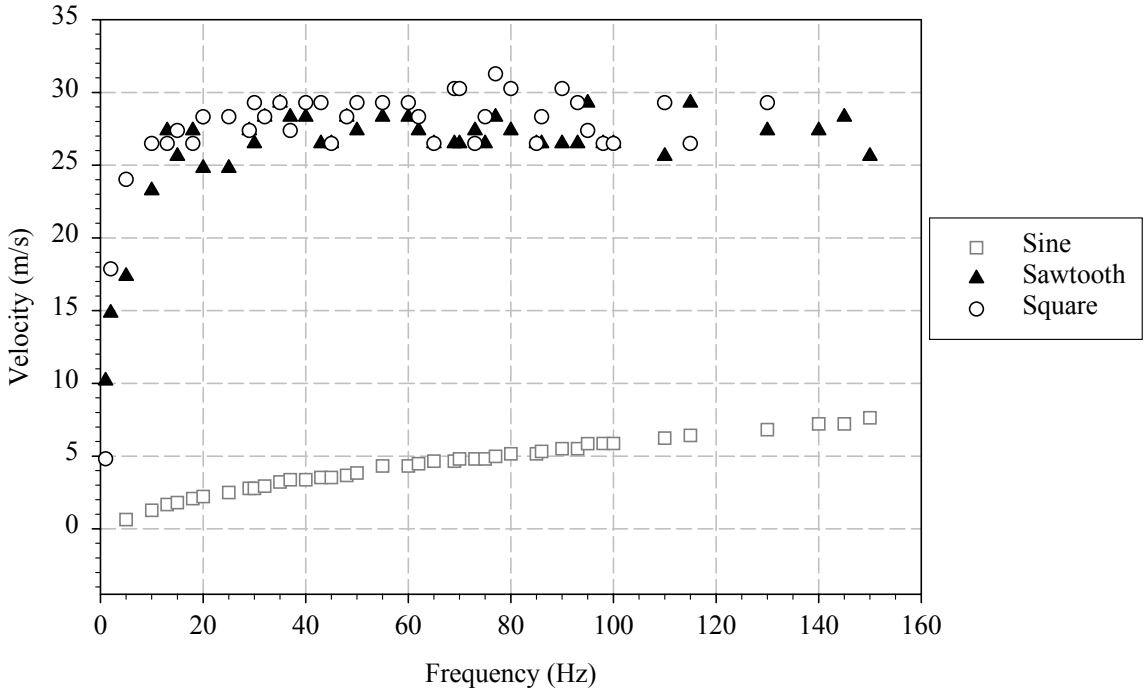


Figure 4. Typical Maximum Velocity vs. Frequency for Thunder

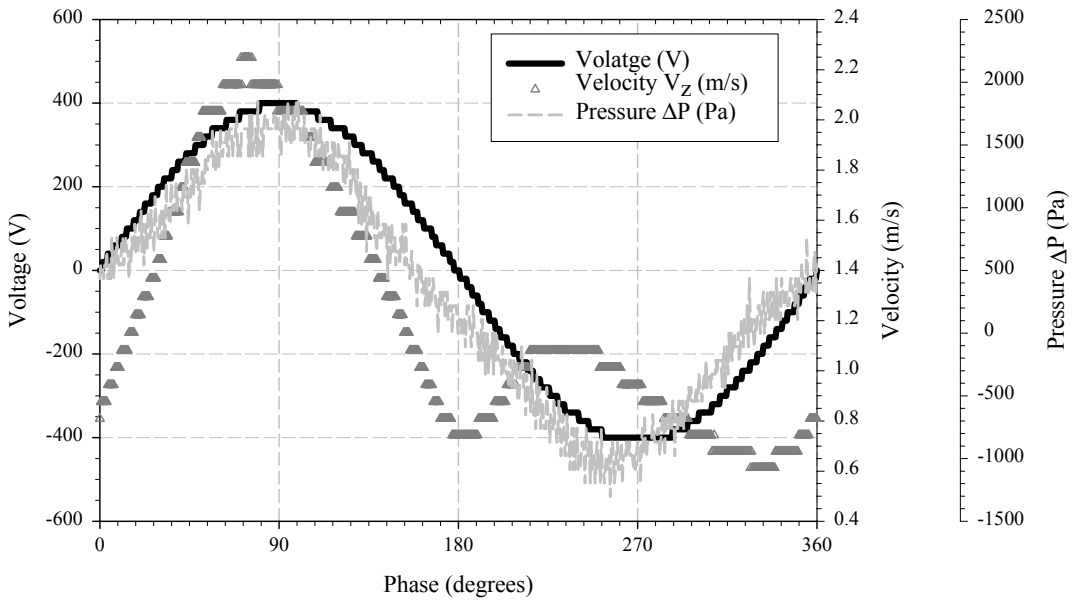


Figure 5. RFD - Pressure and Velocity Vs Voltage for a Sine Waveform at 35Hz

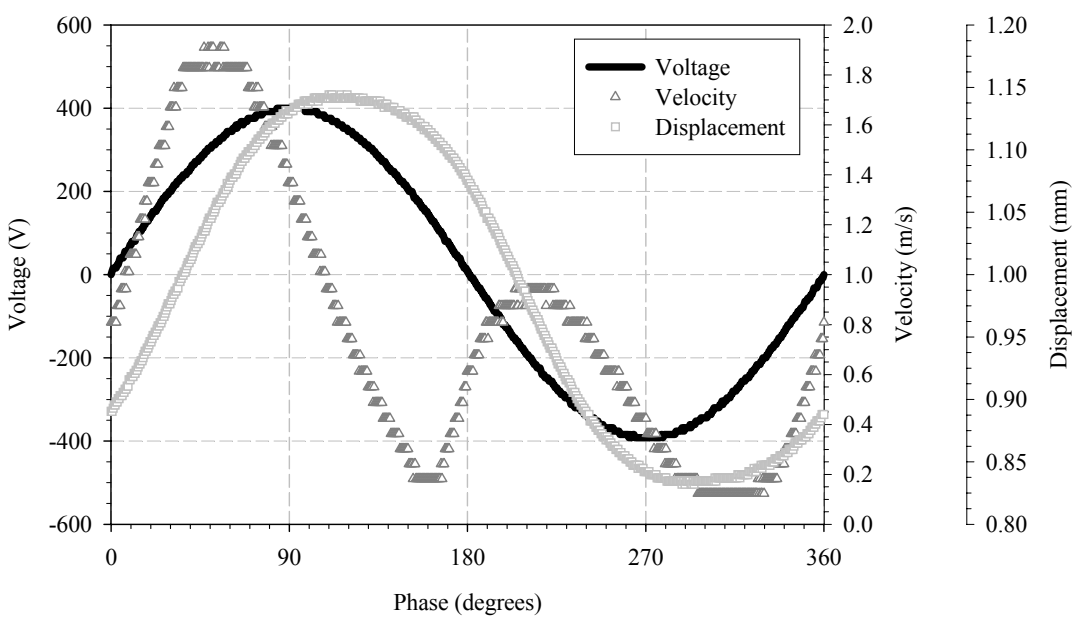


Figure 6. RFD – Displacement and Velocity Vs Voltage for a Sine Waveform at 35Hz

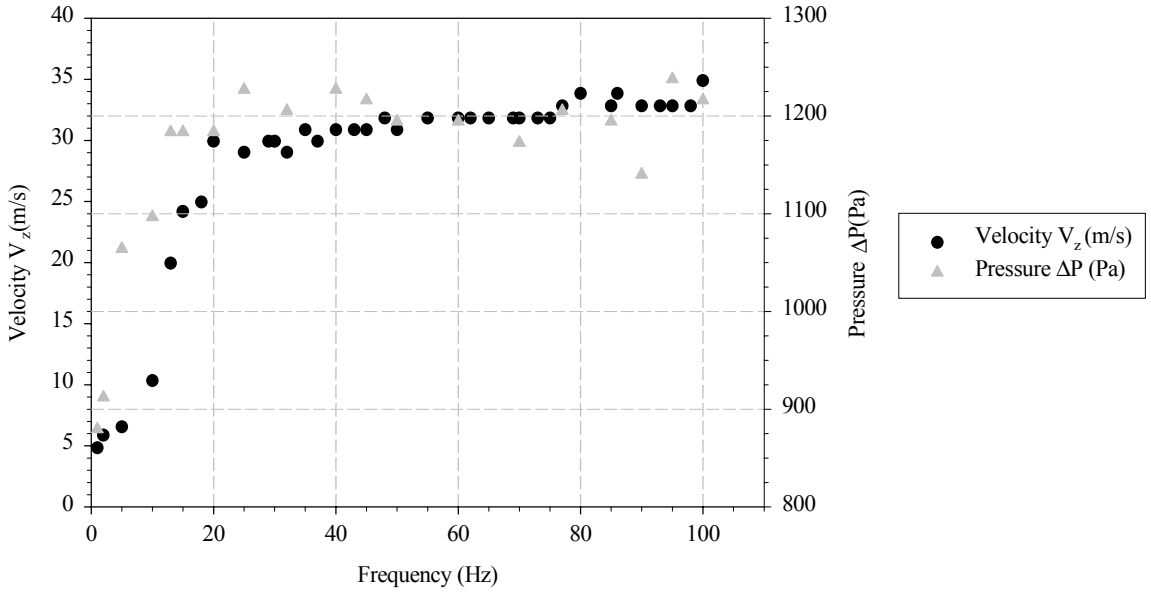


Figure 7. Frequency Effects on Pressure and Velocity for a Bimorph with a Sawtooth Waveform