EXPERIMENTAL TESTING OF A PIEZOAEROELASTIC ENERGY HARVESTER IN A WIND TUNNEL

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ABSTRACT

Aeroelastic energy harvesting in Heating, Ventilation, and Air Conditioning (HVAC) ducts has the potential to provide buildings with wireless security, air quality, temperature, and humidity monitoring. The energy generated could power a sensor, an on-board microprocessor, and Wi-Fi communications without the need for power and communication wiring. The sensor could work for years without the need for maintenance (e.g. battery changing). This work investigates the effect that certain variables have on the power and voltage output of a piezoelectric energy harvester that is placed in a wind tunnel. The harvester uses a unimorph cantilever that consists of a layer of piezoelectric material, PVDF, and a base material, Mylar. The cantilever is mounted on the face of a box that is perpendicular to the flow of the wind in the tunnel, and the air is allowed to pass through small gaps around the cantilever of varying widths, causing the cantilever to vibrate. The experiment demonstrates the effect that this gap width, the wind speed, and the applied load resistance has on the amount of power and voltage that the energy harvester can generate. Analysis of the collected data suggests that power and voltage increase with increasing gap width. Realistically, power would not continue to rise as gap size continued to grow, as there would be an optimal value for gap width. Optimization of gap width, however, is not within the scope of this thesis. There is also a clear trend of power and voltage increase as wind speed and electrical load resistance increase. The experiments test power and voltage outputs for 8 wind speeds, 3 load resistances, and 3 gap widths. Further experimentation should include additional load resistances and at least one gap width larger than 5 mm to verify the trends that are observed in this thesis.
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Chapter 1

Introduction

Piezoelectricity, defined as the electrical charge that forms in certain materials in response to mechanical stress, is a form of energy that has recently received much attention in regards to its ability to be harvested for practical uses. Methods of harnessing this energy have appeared all over the world spanning a wide range of sizes and power outputs. The East Japan Railway Company, for example, was one of the first companies to experiment with piezoelectric energy harvesting on a large scale by incorporating piezo elements into the floors of the ticket gates at Tokyo Station’s North Exit [1]. These floors harnessed the energy created by people’s footsteps as they walked through the ticket gates, and they found that they were able to produce a maximum of 10,000 watt-seconds per day of electricity with only 6 square meters of power-generating flooring. On the opposite end of the spectrum, experiments have been performed that fix piezoelectric generators to the wings of June beetles that are able to produce up to 115 microwatts of power [2]. This thesis will focus on these smaller power outputs, as the size of the tested material in the experiment and the material itself do not allow for power outputs on a scale much larger than microwatts.
Piezoelectric Materials Background

The use of piezoelectric materials to harvest ambient energy has quickly gained popularity in the last decade or so. These materials are so attractive to engineers because of their unique ability to efficiently transfer mechanical energy into electrical energy. There are numerous materials that exhibit the piezoelectric effect, but the majority are classified as either crystals, ceramics, or polymers. The most well-known piezoelectric crystal is quartz (SiO2), and its piezoelectric properties have been utilized to power such devices as radio transmitters and receivers, cigarette lighters, and watches [3]. Some lesser known crystals that exhibit the piezoelectric effect are lithium niobate (LiNbO3) and lithium tantalite (LiTaO3), which are commonly used in various sensors, frequency stabilized oscillators, and surface acoustic devices [4]. These crystals exhibit fantastic piezoelectric properties, however they are fairly limited in their applications. The piezoelectric ceramics and polymers are much more flexible and can be incorporated into a vast number of mechanical and electrical systems. The most commonly used ceramic is lead zirconate titanate (PZT) due to its large piezoelectric charge constants in comparison to other ceramics, where the piezoelectric charge constants indicate how much mechanical strain is experienced by a material per unit of applied electric field [5]. The majority of experiments that have been conducted on piezoelectric wind harvesting have been done using PZT as the piezoelectric material, and the literature review below details some of the studies that have already been done.
Literature Review

Harvesting energy from the environment to power small electronic devices such as wireless sensors, data transmitters, and medical implants has become extremely popular in recent years. The rise in popularity can be contributed to two main factors. Firstly, these devices have become more and more energy efficient, with some sensors requiring power only on the order of microwatts to function. Secondly, the small batteries that have typically powered these devices require time-consuming and expensive maintenance. These two factors have opened the door for research into using ambient energy to power such devices because energy harvesters can be made cheaply and are easily integrated into a variety of systems. There are a number of methods available to harness this ambient energy, such as electromagnetic, electrostatic, and piezoelectric transduction, with piezoelectric transduction receiving the most attention recently because of its compatibility with MEMS devices and wireless sensors.

Piezoelectric energy harvesting can be broken up into two major categories based on the method of inducing vibrations: base and aeroelastic. The majority of studies and research to date have used base excitation as the source of vibration. This is because base vibrations have easily controlled inputs, such as shaker frequency, with hardly any uncontrollable variables. In contrast, there have only been a handful of studies done on piezoelectric energy harvesting from vibrations induced by aeroelastic instabilities. These systems are more difficult to model due to their nonlinear nature, but there have still been several papers published on aeroelastic energy harvesting, taking advantage of various fluid flow phenomena. Flutter of airfoils, vortex-induced vibrations of circular cylinders, galloping of prismatic structures, and wake galloping of parallel cylinders are examples of several phenomena that have been studied for use in piezoelectric energy harvesting systems. Most studies done on aeroelastic energy harvesting using a
piezoelectric transducer feature a beam of piezoelectric material that is fixed on one end to create a cantilever.

A study done by Nan Wu, Quan Wang, and Xiangdong Xie of the University of Manitoba illustrates the potential power output generated by the vibrations of a cantilever as a result of the vortex shedding phenomenon that occurs on the backside of the cantilever [6]. Their theoretical model, developed in 2013, features a cantilever beam made of polysulfone (PES) with piezoelectric patches on either side of the beam and a proof mass at the end of it. PES is used for the base material because of its low Young’s modulus and high tenacity, and PZT4 is used as the piezoelectric element because of its excellent piezoelectric properties mentioned earlier. They model a wide range of voltage and power outputs by adjusting the value of the proof mass, the vertical position of the PZT4 patch on the cantilever, and the size of the PZT4. The setup for their model is seen in figure 1.

![Figure 1: Piezoelectric harvester subjected to a wind load (Wu, Wang, and Xie, 2013)](image-url)
The simulation that is performed is driven by the Euler-Bernoulli beam theory, which governs the vibrations of the cantilever section by section. What the simulations show is that the magnitude of the RMS power output varies greatly with the location and size of the PZT, as well as the value of the proof mass. For smaller proof masses, the output power is not as sensitive to changes in location and size, but they find sizable fluctuations in generated power with only the slightest change in position when using a larger proof mass. They also discover that much more power can be generated when using a large proof mass.

For a 0.5 kg proof mass, the highest RMS power output is 0.019 W, which is accomplished when the length of the PZT4 is between 0.4 and 0.6 m and placed between 0.2 and 0.3 m from the base of the cantilever. With the heavier proof mass of 12 kg, they find that they can theoretically achieve 2 W of power when the length of the PZT4 is 0.54 m and positioned 0.22 m above the base of the cantilever. Both of these simulations run under the assumption that the beam is 1.2 m long, 0.012 m thick, and 0.15 m thick. The power output generated through these simulations exemplifies the potential that piezoaeroelastic energy harvesters have moving forward.

While the Wu, Wang, and Xie experiment was able to produce a large amount of power, the length of the beam (1.2 m) is not practical for many applications. A recent study by Jin Zhu and Wei Zhang of the University of Connecticut explores aeroelastic energy harvesting on a much smaller scale. Although their piezoelectric elements are not as large as the elements used in the study done by Wu, Wang, and Xie, it still has many similarities with the simulation performed by the aforementioned. Both models use PZT as the piezoelectric material, fix the PZT to cantilever beam(s), and model the simulation using Euler-Bernoulli beam theory.
The study performed by Zhu and Zhang is inspired by the failure of the Tacoma Narrows Bridge in 1940 due to aeroelastic flutter and a poor bridge design that featured a slender H-shaped deck [7]. While the H-beams used in this bridge proved to be disastrous in terms of bridge stability, the ease of which these beams can be triggered to vibrate is favorable in regards to energy harvesting. For this reason, Zhu and Zhang choose to model their energy harvester as an H-beam secured to eight vertical springs, one on the top and bottom of each corner of the beam. The vertical edges of both flanges of the beam are fixed with equally spaced teeth that come in close contact with a bimorph cantilever beam at each corner. As the H-beam moves up and down in response to the wind passing over it, the teeth strike the bulged tip at the end of each bimorph cantilever, causing the PZT to deflect and vibrate in a steady manner. The setup for this experiment can be seen in figure 2.

![Figure 2: Drawing of piezoelectric multi-impact wind harvester (Zhu and Zhang, 2015)](image)

The cantilever beams that are found on each corner of the H-beam are bimorph with a PZT patch bonded on each side of an aluminum beam. The piezoelectric patches are connected in series, which helps to increase the overall power output of the system. In order to calculate how much power can be generated by this energy harvesting system, a numerical simulation is run that consists of iterative complex eigenvalue analysis in order to obtain the voltage and
power response of the bimorph cantilever beams. Many iterations are performed with slight adjustments in the time interval and the wind speed until the critical flutter speed is reached. This simulation is done using MATLAB, and the results suggest that a heavier H-shape beam and higher wind speeds lead to higher average power output.

The average power output for the bimorph cantilever reaches 11.77 mW at a wind speed of 10 m/s, which is a very good result considering the small size of the piezoelectric patches. The average power is very low at wind speeds below 4 m/s because this wind speed does not create a large enough displacement in the H-shape beam to cause contact between the teeth and the tip bulge. Once the 4 m/s threshold is broken however, the average power drastically increases. Overall, this simulation proves that bimorph piezoelectric cantilevers are capable of harvesting a useful amount of power from wind, despite their small size.

Another example of the use of a piezoelectric cantilever to harness wind energy is found in a study performed by Amin Bibo, Gang Li, and Mohammed Daqaq of Clemson University in 2011 [8]. They develop and experimentally validate a device that embeds a piezoelectric unimorph cantilever in a cavity that generates electric power when subjected to an air flow. The model is intended to imitate the vibrations of the reeds in a harmonica when the instrument is played. In their model, air enters the chamber at a certain velocity and tries to escape through the small gaps between the cantilever and the PVC pipe. The velocity of the air increases upon leaving the small aperture, which causes a pressure drop that bends the cantilever. The mechanical restoring force returns the cantilever back to its initial position, and the process continuously repeats as long as the air flow remains active. This periodic phenomenon is known as a self-sustained oscillation.
The theoretical model utilizes several principles and equations to develop expressions for output voltage and power. It uses a combination of Euler-Bernoulli beam theory, Hamilton’s principle, steady Bernoulli’s equation, and Galerkin expansion to create differential equations that can be solved to find the values of interest. The theoretical model is validated through experiment, and the experimental setup can be seen in figure 3.

![Experimental Setup](image)

**Figure 3: Self-sustained oscillations experimental setup (Bibo, Li, Daquq, 2011)**

The theoretical and experimental values for output power and voltage are in very close agreement. The model is run at wind speeds varying from 0 m/s to 13 m/s, which corresponds to threshold pressures of 0 Pa to 100 Pa. The voltage outputs range from 0 V at 0 m/s wind speed to 7.5 V at 13 m/s wind speed. The power outputs range from 0 mW at 0 m/s to 1.1 mW at 13 m/s. This power output may not seem like much, but it is sufficient to power small devices such as wireless sensors, health monitors, and many other MEMS devices. These results also show that a bimorph cantilever is not always necessary, as just a unimorph can produce an adequate amount of power.

While the majority of the piezoaeroelastic energy harvesters that have been modeled involve the use of a cantilever beam, there are some exceptions. A paper published in 2011 by A. Abdelkefi, A.J. Nayfeh, and M.R. Hajj models a piezoaeroelastic system that uses an airfoil that
can translate vertically (plunge motion) and rotate about the elastic axis (pitch motion) [9]. A piezoelectric coupling is connected to the plunge degree of freedom so that the coupling will experience cycles of compression and tension to produce a voltage. The study varies the linear and nonlinear spring coefficients and the electric load resistance to see the effect that they have on output power and voltage. A schematic of their model is shown in figure 4.

![Figure 4: Schematic of piezoaeroelastic energy harvester with airfoil profile (Abdelkefi, Nayfeh, Hajj, 2011)](image)

They come up with both a numerical and analytical prediction for the power and voltage, and they are in very close agreement. They find that there is an optimal electrical load resistance of $10^6$ ohms. They run the simulation up to wind speeds of 10 m/s, and they are able to achieve a power output of 23 mW and a voltage output of 150 V at this speed and at the optimal resistance.

The studies reviewed above give great insight into the capabilities that piezoelectric energy harvesters have moving forward. Through various sizes and shapes of the material used, as well as the method in which vibrations are induced, a vast range of power outputs are achievable. The papers outlined above all use PZT or a similar piezoelectric ceramic as the energy harvesting material, but hardly any research has been done on piezoaeroelastic systems using piezoelectric polymers instead. The experiment conducted for this thesis uses the polymer polyvinylidene fluoride (PVDF), and the properties of this material are outlined in the next section.
PVDF Film Properties

Piezoelectric ceramics and polymers have their advantages and disadvantages, and in order to understand these advantages and disadvantages, it is necessary to define some important constants that describe the piezoelectric properties of the material.

The piezoelectric constants that relate the mechanical strain on the material to the induced electric field are known as the “d” constants, and they are typically listed with units of meters per volt followed by a subscript that describes the direction of the mechanical displacement and the electric field. The two most commonly listed “d” constants are $d_{33}$ and $d_{31}$. $d_{33}$ refers to the case when the force is applied along the polarization axis of the piezoelectric material and on the same surface that the charge is collected, and $d_{31}$ refers to the case when the force is applied at right angles to the surface that the charge is collected. This constant, also known as the strain constant, is extremely important because it describes how effectively the material will be able to convert mechanical energy into electrical energy, which is the chief purpose of piezoelectric materials.

Very similar to the “d” constants are the “g” constants. These constants relate the electric field to the applied mechanical stress instead of strain, and they have units of volts/meter per Newtons/square meter. The stress constants have the same subscripts as the strain constants, which signify the direction of stress and induced electric field. For both the “d” and “g” constants, a high value is desirable because it signifies that more power can be generated for a particular beam deflection.

Another constant that leads to better functionality of the piezoelectric material when it is of a high value is the electromechanical coupling factor, “k”. This constant indicates how efficiently the piezoelectric material converts mechanical energy into electrical energy and vice
versa. It is typically given as a percentage of the energy that it can convert from one form to the other. The “k” constant has the same subscripts as the “d” and “g” constants to describe the direction of the vibrations and electric field.

The last important constant needed to fully define a piezoelectric material is the relative permittivity. This is a measure of the amount of charge the material can store relative to the amount of charge that can be stored by the same electrodes in a vacuum. Typical notation for relative permittivity is $\varepsilon/\varepsilon_0$. Table 1 compares the piezoelectric properties of PVDF polymer with those of two popular piezoelectric ceramics, PZT and BaTiO$_3$. Full properties of the PVDF film used in the experiment can be found in table 3 in appendix A.

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>PVDF Film</th>
<th>PZT</th>
<th>BaTiO$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$10^2$ kg/m$^3$</td>
<td>1.78</td>
<td>7.5</td>
<td>5.7</td>
</tr>
<tr>
<td>Relative Permittivity</td>
<td>$\varepsilon/\varepsilon_0$</td>
<td>12</td>
<td>1,200</td>
<td>1,700</td>
</tr>
<tr>
<td>$d_{31}$ Constant</td>
<td>$(10^{15})$ C/N</td>
<td>23</td>
<td>110</td>
<td>78</td>
</tr>
<tr>
<td>$g_{31}$ Constant</td>
<td>$(10^3)$ Vm/N</td>
<td>216</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>$\kappa_{31}$ Constant</td>
<td>% at 1 KHz</td>
<td>12</td>
<td>30</td>
<td>21</td>
</tr>
</tbody>
</table>
Chapter 2

Experimental Setup

Many experiments have been conducted in the field of piezoelectric energy harvesting that have incorporated a wide range of variables in hopes to see higher output power. Some of these variables include the magnitude of the proof mass on the end of the cantilever, the length of the cantilever beam, and the size of the patch of piezoelectric material. For this experiment, all of the aforementioned values are held constant. The main purpose of this experiment is to demonstrate the effect that the gap width between the PVDF and the lid of the box that it is mounted to has on the output power and voltage when the PVDF is placed in cross-flow. Gap sizes of 0 mm, 2 mm, and 5 mm are examined, with wind speeds varying from 3.6 m/s to 9 m/s. The third variable of interest is the resistance that the leads of the PVDF are attached to, and those resistances are 1000 kΩ, 680 kΩ, and 470 kΩ.

Box Preparation

The first step in preparing the experiment was cutting the lid of the box in order to obtain the desired gap sizes for testing. Based on some preliminary analysis, it was decided that 0 mm, 2 mm, and 5 mm gaps would yield a wide range of useful results. Measurements were taken of the PVDF, and .dxf files were generated to be used by the laser cutter for precision cuts. The width of the PVDF cantilever is 16.5 mm, and the effective length is 32.5 mm. The total length of the PVDF is not used because some of the material will be mounted to the lid of the box and is
not free to move. The effective length refers only to the length of the material that is free to vibrate when placed in the wind tunnel. The PVDF beam and the associated measurements are seen in figure 5.

Figure 5: PVDF beam measurements

The aforementioned gap wraps around the three sides of the cantilever that are not fixed to the lid of the box. This results in a slot size of 26.5 mm x 37.5 mm for the 5 mm gap slot, a slot size of 20.5 mm x 34.5 mm for the 2 mm gap slot, and a slot size of 16.5 mm x 32.5 mm for the 0 mm gap slot. The laser cutter used to make these cuts could easily reach the necessary degree of precision, and was able to cut two slots of different sizes on both lids, as seen in figures 6 and 7.
The base of the PVDF is securely fastened to the lid of the box with Kapton tape to create a cantilever beam that is free to vibrate when placed in cross flow. While one slot size is being tested, the other slot on the lid is covered with the same tape so that the air flow passes through only the slot with the cantilever. The lids easily snap on and off of the box, which makes for fast and efficient testing in the wind tunnel.
Wind Tunnel Schematics

This experiment tests the response of the PVDF cantilever when placed directly in the cross flow of the wind tunnel. This means that the face that the cantilever is mounted on is perpendicular to the velocity of the air passing through it. The box is positioned at the center of the wind tunnel, with the open side of the box facing the upstream flow so that the air forces the tip of the cantilever to displace away from the box. The leads of the PVDF cantilever are able to pass through the bottom of the wind tunnel, and are attached to a resistance box that is connected to a data acquisition box that collects voltage data for a thirty second time interval. The Solidworks images generated to represent this experiment can be seen in figures 8 and 9, as well as an actual picture of the experiment in figure 10.

Figure 8: Isometric view of energy harvester in wind tunnel with sides and top removed
As seen in the above images, the bottom of the box is secured to a vertical sting that is fixed to the base of the wind tunnel, which allows the air to pass through the box without any disturbances. The main concern with having just a singular sting fixture was that the box might
be inclined to rotate about the sting axis, but this phenomenon did not occur even at the highest tested wind speeds. The small opening in the bottom of the wind tunnel allows for the leads of the PVDF to extend outside the constraints of the tunnel and attach to the data acquisition system (not shown in above schematics). Once the box is securely fastened in its proper position within the wind tunnel, it is necessary to calibrate the wind tunnel to achieve the proper wind velocities.

**Wind Tunnel Calibration**

The wind tunnel used in this experiment does not explicitly read out the wind velocity. Instead, it uses an electronic pressure transducer, which displays a voltage proportional to the pressure difference obtained by the pitot static probe in the wind tunnel. Typically, these transducers will be calibrated such that 1 Volt on the display is equivalent to 1 inch of water column pressure. Because the wind speeds we test are of relatively high speeds and create a high pressure difference, it is necessary to calibrate that transducer so that it reads 1 V for every 4 inches of water column pressure. This ensures that the voltage readings are not clipped by the limitations of the data acquisition system, which operates at a range from -5.0 V to 5 V.

The wind velocity can be obtained by manipulating Bernoulli’s equation to give velocity as a function of pressure difference. The derived expression for velocity is given below.

\[
v = \sqrt{\frac{2\Delta P}{\rho}}
\]

(1)

The transducer voltage multiplied by four gives the pressure difference in inches of water column, and simple unit conversions give velocity in terms of the desired m/s.
Chapter 3

Results and Conclusions

The data acquisition box that is used in the experiment collects voltage data from the piezoelectric energy harvester for thirty second intervals. Eight wind speeds are tested, with speeds ranging from 3.6 m/s to 9.0 m/s. All three gap size variations are tested at each wind speed and with resistances of 1000 kΩ, 680 kΩ, and 470 kΩ. The voltage vs. time data is converted into plots of voltage vs. frequency, power vs. time, and power vs. frequency using a fast Fourier transform (FFT) in MATLAB.

Natural Frequency Calculation

Before any experimentation took place, it was necessary to calculate the expected natural frequency of the piezoelectric unimorph cantilever. The equation used to calculate the natural frequency is given below [10].

\[
\omega_{nf} = \alpha_n^2 \sqrt{\frac{EI}{mL^4}}
\]

In the above equation, \( \alpha_n \) is a coefficient that corresponds to the mode shape of the vibrating unimorph. For this experiment, only the first mode of vibration is achievable, and the \( \alpha_n \) value that corresponds to the first mode shape is 1.875. The \( m \) value in the equation is mass-per-unit
length of the beam, \( L \) is the length of the beam, and \( EI \) is the bending stiffness of the beam.

Because the unimorph consists of two layers of material, a 125 µm thick layer of Mylar and a 28 µm thick layer of PVDF, equations 3 through 8 must be used to calculate \( EI \).

\[
EI = b \left[ \frac{E_s (h_b^3 - h_a^3) + E_p (h_s^3 - h_p^3)}{3} \right]
\]  

(3)

\[
h_{pa} = \frac{h_p^2 + 2nh_p h_s + nh_s^2}{2(h_p + nh_s)} \quad \quad h_{sa} = \frac{h_p^2 + 2h_p h_s + nh_s^2}{2(h_p + nh_s)}
\]  

(4)  

(5)

\[
h_a = -h_{sa} \quad \quad h_b = h_{pa} - h_p \quad \quad h_c = h_{pa}
\]  

(6)  

(7)  

(8)

Table 2: Material properties of unimorph used for natural frequency calculation

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of Mylar (h_s)</td>
<td>125</td>
<td>µm</td>
</tr>
<tr>
<td>Thickness of PVDF (h_p)</td>
<td>28</td>
<td>µm</td>
</tr>
<tr>
<td>Young's modulus of Mylar (E_s)</td>
<td>5</td>
<td>GPa</td>
</tr>
<tr>
<td>Young's modulus of PVDF (E_p)</td>
<td>3</td>
<td>GPa</td>
</tr>
<tr>
<td>Beam width (b)</td>
<td>16.5</td>
<td>mm</td>
</tr>
<tr>
<td>Young's moduli ratio (n)</td>
<td>1.67</td>
<td>-</td>
</tr>
<tr>
<td>( h_{pa} )</td>
<td>0.00008144</td>
<td>m</td>
</tr>
<tr>
<td>( h_{sa} )</td>
<td>0.00007156</td>
<td>m</td>
</tr>
<tr>
<td>( h_a )</td>
<td>-0.0000715</td>
<td>m</td>
</tr>
<tr>
<td>( h_b )</td>
<td>0.0000534</td>
<td>m</td>
</tr>
<tr>
<td>( h_c )</td>
<td>0.0000814</td>
<td>m</td>
</tr>
<tr>
<td>Bending stiffness of beam (EI)</td>
<td>0.0000207</td>
<td>N*m^2</td>
</tr>
<tr>
<td>Mass per unit length of beam (m)</td>
<td>0.003689</td>
<td>kg/m</td>
</tr>
<tr>
<td>Frontal area of beam (A)</td>
<td>0.000536</td>
<td>m^2</td>
</tr>
<tr>
<td>Length of beam (L)</td>
<td>32.5</td>
<td>mm</td>
</tr>
<tr>
<td>Natural Frequency (w_{nf})</td>
<td>46.53</td>
<td>Hz</td>
</tr>
</tbody>
</table>

Using the values from table 2 with equations 2-8, it is calculated that the natural frequency of the energy harvester is 46.53 Hz. This is the resonant frequency that the energy harvester should vibrate at in the wind tunnel. An FFT of the voltage vs. time data taken by the
data acquisition system gives voltage as a function of frequency, and the peak voltage should occur at the natural frequency. As seen in figures 11 and 12, the experimental natural frequency matches very closely with the theoretical value.

![Figure 11: Voltage vs. frequency plot for 5 mm gap with 1000 kΩ resistance and 5.7 m/s wind speed](image1)

![Figure 12: Voltage vs. frequency plot for 2 mm gap with 470 kΩ resistance and 4.9 m/s wind speed](image2)
These two figures also validate that a change in gap size, resistance, or wind speed does not affect the natural frequency of the unimorph. It always vibrates at approximately 50 Hz, which is very close to the 46.53 Hz predicted by equations 2-8.

**Experimental Results**

By compiling the peak voltage and peak power results from the FFT into plots with respect to wind velocity, some obvious trends become apparent. Gap size, resistance, and wind velocity all have a significant effect on the magnitude of voltage and power that are generated. Voltage trends are illustrated in figure 13.
Figure 13: Peak voltage vs. wind velocity with applied resistances of (a) 1000 kΩ, (b) 680 kΩ, and (c) 470 kΩ
The most obvious trend that can be observed is the overall rise in peak voltage as wind speed is increased. Regardless of the gap size or resistance, voltage is going to increase as wind speed increases. This is a result that is fairly intuitive, as higher wind speeds always lead to greater deflection of the unimorph. Every gap size tested sees an increase of at least 5 mV at every resistance, with the largest increase occurring with the 1000 kΩ case, where the peak voltage for each gap size increases by approximately 10 mV over the span of wind speeds tested.

Figure 13 also demonstrates that gap size has a clear effect on output voltage. For wind velocities between 4 m/s and 7 m/s, the trend is consistent at all three resistances. The energy harvester with the 5 mm gap produces the highest peak voltage at every tested wind speed, followed by the energy harvester with the 2 mm gap and 0 mm gap. This trend may seem to suggest that voltage will continue to increase with increasing gap size, but some preliminary analysis showed that the 5 mm gap would produce optimal results. Any gap size larger than 5 mm would likely produce inferior results.

The last trend that can be taken away from figure 13 is the effect that resistance has on the magnitude of the peak voltage. Based on the figure, peak voltage is directly related to the applied resistance. The output voltages from the experiment with the 1000 kΩ resistor are higher than the output voltages at both other resistances at every single wind speed tested. Similar trends were observed for peak power, which can be seen in figure 14.
Figure 14: Peak power vs. wind velocity with applied resistances of (a) 1000 kΩ, (b) 680 kΩ, and (c) 470 kΩ
Comparable to the trend observed in the voltage domain, peak power also increases as wind speed increases. This is not a surprise, as both power and voltage depend on the extent to which the piezoelectric material is deflected.

The gap size also has a definite impact on the peak power. Between wind velocities of 4 m/s and 7 m/s, it is clear that the energy harvester with the 5 mm gap yields the best power results, followed by the energy harvesters with the 2 mm gap and 0 mm gap sizes, respectively. Interesting results are seen when the wind speed surpasses 7 m/s. The power output for the energy harvester with the 0 mm gap drastically increases after 7 m/s and actually surpasses the power output by the harvester with the 2 mm gap width. This is most apparent in figure 14c, where the 0 mm gap energy harvester has the lowest peak power at 7 m/s, but has close to the highest peak power at the highest tested wind speed of 9 m/s. This breaks the previously observed trend, but suggests that harvesters with smaller gap sizes should be considered for use in applications where wind speeds are high.

Resistance has a similar effect on peak power as it has on peak voltage. Higher power outputs are achieved when the resistance box is set to 1000 k\(\Omega\) than when it is set to 680 k\(\Omega\) or 470 k\(\Omega\). For example, looking at the data for the 5 mm gap at 7 m/s, it is observed that the peak power goes from 1.8 nW with the 1000 k\(\Omega\) resistor, to 1.4 nW with the 680 k\(\Omega\) resistor, to 1 nW with the 470 k\(\Omega\) resistor.

**Conclusions and Future Research**

The results from the wind tunnel tests demonstrate that slight changes in the input variables, namely gap width, wind speed and resistance, have a significant impact on the output
power and voltage. However, regardless of the combination of these variables, the output power is always fairly underwhelming. The highest power is achieved on the 5 mm gap width model at a wind speed of 9 m/s and applied resistance of 1000 kΩ. This peak power is only 3.2 nW, which is too low to power even very small devices. This underwhelming amount of power is most likely due to the fact that PVDF has a relatively low $d_{31}$ constant compared to piezoelectric ceramics such as PZT. PVDF would have seen better results in an experiment where it experienced higher levels of stress instead of strain because its $g_{31}$ constant is much higher than its $d_{31}$ constant.

Future research into energy harvesters of this type will most likely continue to use piezoelectric ceramics instead of polymers because of their better energy harvesting abilities in response to wind induced strain. It would be interesting to run this same experiment again but with several different ceramics to see if the same trends are apparent. For those tests, it would be important to include a couple gap widths greater than 5 mm to see if the power outputs continue to rise with increasing gap width or if an optimal value becomes obvious. One other change that should be incorporated if this experiment is performed again is to take data when there is no applied resistance. No additional wind speeds would be needed for future tests, as 9 m/s is already very high and there are not many practical applications that would see wind speeds higher than that. With these changes to the experiment, improved results would be expected.
## Appendix A: Tables Used for Calculations

### Table 3: Material properties and geometry of PVDF film

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>PVDF</th>
<th>Copolymer</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>t</td>
<td>Thickness</td>
<td>9, 28, 52, 110</td>
<td>&lt;1 to 1200</td>
<td>μm (micron, (10^{4}))</td>
</tr>
<tr>
<td>(d_{31})</td>
<td>Piezo Strain Constant</td>
<td>23</td>
<td>11</td>
<td>(10^{12}) (\text{m} / \text{m} ) or (\text{C} / \text{m}^{2} )</td>
</tr>
<tr>
<td>(d_{33})</td>
<td>Piezo Stress constant</td>
<td>-33</td>
<td>-38</td>
<td>(10^{9}) (\text{N} / \text{m}^{2} ) or (\text{m} / \text{m} )</td>
</tr>
<tr>
<td>(e_{33})</td>
<td>Electromechanical</td>
<td>216</td>
<td>162</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coupling Factor</td>
<td></td>
<td>12%</td>
<td>20%</td>
</tr>
<tr>
<td>(k_{t})</td>
<td></td>
<td>14%</td>
<td>25-29%</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Capacitance</td>
<td>380 for 28μm</td>
<td>68 for 100μm</td>
<td>pF/cm² @ 1KHz</td>
</tr>
<tr>
<td>Y</td>
<td>Young's Modulus</td>
<td>2.4</td>
<td>3.5</td>
<td>(10^{9}) (\text{N} / \text{m}^{2} )</td>
</tr>
<tr>
<td>V (s)</td>
<td>Speed of Sound</td>
<td>1.5</td>
<td>2.3</td>
<td>(10^{5}) (\text{m} / \text{s} )</td>
</tr>
<tr>
<td>p</td>
<td>Pyroelectric Coefficient</td>
<td>30</td>
<td>40</td>
<td>(10^{4}) (\text{C} / \text{m}^{2} \cdot \text{K} )</td>
</tr>
<tr>
<td>ε</td>
<td>Permittivity</td>
<td>106-113</td>
<td>65-75</td>
<td>(10^{12}) (\text{F} / \text{m} )</td>
</tr>
<tr>
<td>ε/ε₀</td>
<td>Relative Permittivity</td>
<td>12-13</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td>ρₘ</td>
<td>Mass Density</td>
<td>1.78</td>
<td>1.82</td>
<td>(10^{3}) (\text{kg} / \text{m}^{3} )</td>
</tr>
<tr>
<td>ρₑ</td>
<td>Volume Resistivity</td>
<td>&gt;10¹³</td>
<td>&gt;10¹⁴</td>
<td>(\text{Ohm} \cdot \text{meters} )</td>
</tr>
<tr>
<td>R₀</td>
<td>Surface Metallization</td>
<td>&lt;3.0</td>
<td>&lt;3.0</td>
<td>(\text{Ohms/square} ) for (\text{NiAl} )</td>
</tr>
<tr>
<td>Rₘ</td>
<td>Resistivity</td>
<td>0.1</td>
<td>0.1</td>
<td>(\text{Ohms/square} ) for (\text{Ag Ink} )</td>
</tr>
<tr>
<td>tan δₑ</td>
<td>Loss Tangent</td>
<td>0.02</td>
<td>0.015</td>
<td>@ 1KHz</td>
</tr>
<tr>
<td>Yield Strength</td>
<td></td>
<td>45-55</td>
<td>20-30</td>
<td>(10^{6}) (\text{N} / \text{m}^{2} ) (stretch axis)</td>
</tr>
<tr>
<td>Temperature Range</td>
<td></td>
<td>-40 to 80...100</td>
<td>-40 to 115...145</td>
<td>°C</td>
</tr>
<tr>
<td>Water Absorption</td>
<td></td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
<td>(% \text{H₂O} )</td>
</tr>
<tr>
<td>Maximum Operating Voltage</td>
<td></td>
<td>750 (30)</td>
<td>750 (30)</td>
<td>V/(\text{mil}(\text{V} / \mu\text{m})), (\text{DC, @ 25°C} )</td>
</tr>
<tr>
<td>Breakdown Voltage</td>
<td></td>
<td>2000 (80)</td>
<td>2000 (80)</td>
<td>V/(\text{mil}(\text{V} / \mu\text{m})), (\text{DC, @ 25°C} )</td>
</tr>
</tbody>
</table>
### Table 4: Voltage and power outputs with 1000 kΩ resistor

<table>
<thead>
<tr>
<th>Wind Velocity</th>
<th>0 mm Gap</th>
<th>2 mm Gap</th>
<th>5 mm Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak Voltage (V)</td>
<td>Peak Power (µW)</td>
<td>Peak Voltage (V)</td>
</tr>
<tr>
<td>3.607448078</td>
<td>0.0017</td>
<td>0.0001011</td>
<td>0.002374</td>
</tr>
<tr>
<td>4.033249563</td>
<td>0.00276</td>
<td>0.000153</td>
<td>0.00389</td>
</tr>
<tr>
<td>4.598612036</td>
<td>0.00269</td>
<td>0.000162</td>
<td>0.005844</td>
</tr>
<tr>
<td>4.939701718</td>
<td>0.00360</td>
<td>0.000186</td>
<td>0.006026</td>
</tr>
<tr>
<td>5.703876233</td>
<td>0.005373</td>
<td>0.000471</td>
<td>0.007235</td>
</tr>
<tr>
<td>6.985793163</td>
<td>0.006714</td>
<td>0.0008479</td>
<td>0.00896</td>
</tr>
<tr>
<td>8.066499127</td>
<td>0.009722</td>
<td>0.001614</td>
<td>0.007603</td>
</tr>
<tr>
<td>9.018620194</td>
<td>0.01189</td>
<td>0.002926</td>
<td>0.01261</td>
</tr>
</tbody>
</table>

### Table 5: Voltage and power outputs with 680 kΩ resistor

<table>
<thead>
<tr>
<th>Wind Velocity</th>
<th>0 mm Gap</th>
<th>2 mm Gap</th>
<th>5 mm Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak Voltage (V)</td>
<td>Peak Power (µW)</td>
<td>Peak Voltage (V)</td>
</tr>
<tr>
<td>3.607448078</td>
<td>0.001241</td>
<td>0.00006803</td>
<td>0.002144</td>
</tr>
<tr>
<td>4.033249563</td>
<td>0.001899</td>
<td>0.00009622</td>
<td>0.00293</td>
</tr>
<tr>
<td>4.598612036</td>
<td>0.002227</td>
<td>0.0001179</td>
<td>0.00393</td>
</tr>
<tr>
<td>4.939701718</td>
<td>0.002762</td>
<td>0.000172</td>
<td>0.004934</td>
</tr>
<tr>
<td>5.703876233</td>
<td>0.004122</td>
<td>0.0003875</td>
<td>0.006302</td>
</tr>
<tr>
<td>6.985793163</td>
<td>0.005525</td>
<td>0.0006901</td>
<td>0.007863</td>
</tr>
<tr>
<td>8.066499127</td>
<td>0.007208</td>
<td>0.001141</td>
<td>0.00827</td>
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<tr>
<td>9.018620194</td>
<td>0.00994</td>
<td>0.002073</td>
<td>0.009075</td>
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</table>

### Table 6: Voltage and power outputs with 470 kΩ resistor

<table>
<thead>
<tr>
<th>Wind Velocity</th>
<th>0 mm Gap</th>
<th>2 mm Gap</th>
<th>5 mm Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak Voltage (V)</td>
<td>Peak Power (µW)</td>
<td>Peak Voltage (V)</td>
</tr>
<tr>
<td>3.607448078</td>
<td>0.0008661</td>
<td>0.00005976</td>
<td>0.001412</td>
</tr>
<tr>
<td>4.033249563</td>
<td>0.00112</td>
<td>0.00006102</td>
<td>0.002535</td>
</tr>
<tr>
<td>4.598612036</td>
<td>0.00204</td>
<td>0.0001077</td>
<td>0.003214</td>
</tr>
<tr>
<td>4.939701718</td>
<td>0.002023</td>
<td>0.0001445</td>
<td>0.004001</td>
</tr>
<tr>
<td>5.703876233</td>
<td>0.003152</td>
<td>0.0002681</td>
<td>0.004554</td>
</tr>
<tr>
<td>6.985793163</td>
<td>0.00382</td>
<td>0.000506</td>
<td>0.005039</td>
</tr>
<tr>
<td>8.066499127</td>
<td>0.006036</td>
<td>0.001259</td>
<td>0.0061</td>
</tr>
<tr>
<td>9.018620194</td>
<td>0.006565</td>
<td>0.001655</td>
<td>0.007062</td>
</tr>
</tbody>
</table>
Appendix B: Voltage vs. Frequency FFTs

Figure 15: 0 mm gap. 1000 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Figure 16: 0 mm gap. 680 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Figure 17: 0 mm gap. 470 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Figure 18: 2 mm gap. 1000 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Figure 19: 2 mm gap. 680 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Figure 20: 2 mm gap. 470 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Figure 21: 5 mm gap, 1000 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Figure 22: 5 mm gap. 680 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Figure 23: 5 mm gap, 1000 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Appendix C: Power vs. Frequency FFTs

Figure 24: 0 mm gap. 1000 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Figure 25: 0 mm gap. 680 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Figure 26: 0 mm gap. 470 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Figure 27: 2 mm gap. 1000 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Figure 28: 2 mm gap. 680 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Figure 29: 2 mm gap. 470 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Figure 30: 5 mm gap, 1000 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Figure 31: 5 mm gap. 680 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s
Figure 32: 5 mm gap. 470 kΩ. (a) 3.6 m/s (b) 4 m/s (c) 4.6 m/s (d) 4.9 m/s (e) 5.7 m/s (f) 7 m/s (g) 8 m/s (h) 9 m/s


ACADEMIC VITA

Greg Fobben
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Education
Bachelor of Science in Mechanical Engineering
The Pennsylvania State University, Spring 2015
Schreyer Honors College

Relevant Work Experience
Advanced Technology Intern (6/2014 – 8/2014)
Raytheon Integrated Defense Systems, Sudbury, MA
  • Designed an insulating shutter using Pro Engineer to be used with the Hybrid
    Dish/Engine Expeditionary Generator (HyDE-2G) program
  • Performed heat transfer analysis to ensure that no part of the shutter or dish would exceed
    450 degrees Celsius
  • Calculated how much solar power would be wasted with certain limitations to the dish’s
    range of motion at various times of the year

3D Printing Lab Assistant (1/2012 – 4/2012)
Dr. Richard F. Devon’s Engineering Design Laboratory, University Park, PA
  • Collaborated with a team of three to construct a fully functional 3-D printer through a
    reverse engineering process
  • Presented and explained the 3-D printing process to several engineering design classes
    throughout the semester
  • Improved skills in CAD programs such as Solidworks by designing parts to be used on 3-
    D printers

Leadership Experience
Penn State Club Soccer, University Park, PA
President (1/2014 – 1/2015)
Vice President (1/2013 – 1/2014)
  • Delegate responsibilities amongst the other club officers
  • Schedule 15 games per season, make travel arrangements for away games, locate
    referees, and organize home tournaments
  • Organize and run practice 4 times a week for a team of 31 players
  • Assist the team treasurer with finances

Schreyer Honors College Orientation, University Park, PA
Mentor (5/2012 – 9/2012)
Acted as a resource for 12 incoming freshman’s transition to college by providing them with necessary information and corresponding with them regularly throughout the summer

Led and supported the group throughout a three day orientation and throughout the academic year.

**Skills/Activities**
- Member of the Pi Kappa Alpha fraternity
- Proficient in MS-Word, MS-Powerpoint, MS-Excel, Pro Engineer, Solidworks, and MATLAB
- Interests include playing the piano, fishing, soccer, and golf.