

Energy Harvesting Through Electromechanical Transducers

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NOMENCLATURE

A	Surface area of material	S_1	Axial mechanical strain
A_{CS}	Cross sectional area	s_{11}^E	Mechanical compliance under constant electric field
C	Capacitance	T_1	Applied axial stress
c	Damping coefficient	V, V_3	Voltage output by transducer
D_3	Electric displacement	w	Transducer width
d, d_{31}	Electromechanical coupling coefficient	Z_{m1}	Mechanical impedance
E	Elastic modulus	Z_{m2}	Viscoelastic mechanical impedance
E_3	Applied electric field	Z_p	Electrical Impedance
f	Generated force	ϵ_{33}^T	Permittivity under constant stress
h	Transducer thickness	η^T	Effective permittivity
i	Applied current	\dot{x}	Transducer velocity
k	Stiffness coefficient	x_b	Base displacement
L	Transducer length	\dot{x}_b	Base velocity
M	Mass	x_m	Free-end mass displacement
N	Electromechanical coupling ratio	\dot{x}_m	Free-end mass velocity
P	Power output	\ddot{x}_m	Free-end mass acceleration
R	Resistance		
R_{DC}	DC resistance		

ABSTRACT

As the use of low-power electronics has increased, it has led to the need for extended battery life. One possible solution to this problem is through the use of electromechanical transducers. These materials convert mechanical strain, such as ambient vibrations, into electrical power that can then be stored or immediately used. This study focuses on two active materials: the piezoelectric polymer polyvinylidene fluoride (PVDF) and the ionically conductive ionic polymer transducer (IPT). Analytical models are formed for both materials for axial dynamic loading, and simulation results are then compared to experimental results from tests. Each material's performance is then compared to examine the effectiveness of their mechanical to electrical energy conversion properties. The impedance of each sample is measured and used to calculate the power output of each material. Energy produced by the transducers is stored in a capacitor, confirming the feasibility for the use of these materials in energy harvesting applications.

1 INTRODUCTION

1.1 Motivation

A rise in the use and demand for low power electronic devices has lead to an increased interest in alternate energy sources. Traditional batteries are often heavy and must be recharged or replaced, increasing cost of the system over time. By harvesting ambient energy such as solar, thermal, or vibrations, enough electrical power

may be produced to run these low power systems. Electromechanical transducers, which convert dynamic strain energy into electrical energy, are one possible solution to this problem. Potential applications include small personal electronics powered with human movement and remote structural sensing units powered by structural vibrations. Utilizing these materials as a power source could decrease a system's implementation and operational costs by reducing the need for installation of permanent power sources and labor involved in changing batteries.

1.2 Background

Electromechanical transducers produce an electric field when mechanically strained or produce a mechanical deformation when subjected to an electric charge. These properties allow them to be used as producers of electrical energy or as mechanical actuators [1]. Two types of transducers are investigated in this study: the piezoelectric polymer polyvinylidene fluoride (PVDF), and the ionically conductive ionic polymer transducer (IPT). Both materials have a polymer base and are, therefore, much more compliant than the more common ceramic piezoelectric materials. This property allows for a new range of applications. For example, previous studies have been performed examining the piezoelectric polymer's ability to be used in a shoe being strained by the pressure between one's foot and the ground [2], and also in a backpack strap that experiences varying loads as one walks [3].

The PVDF transducer is fabricated by drawing the bulk PVDF material then heating the sample to its Curie temperature and exposing it to a strong electric field. This aligns the dipoles within the material which are originally randomly oriented [1]. As the material cools, the dipoles relax and a portion of their alignment is lost. When the material is strained, the dipoles realign, causing a fluctuation in the electric field within the material. The direction of the electric field applied during fabrication causes the material's electromechanical reaction to be different for strains in different directions. A thin metallic film is applied to both sides of the polymer strip to form the electrodes.

The ionic polymer transducer is similar to PVDF in that it is also made of a polymer with metal electrode layers, but it is much more compliant and also must remain hydrated. IPT is capable of producing larger currents at lower voltages than PVDF; however, the need to remain saturated introduces some difficulties in its application. IPTs consist of a thin polyelectrolyte membrane plated on both faces with a metal to allow surface conductivity. In this study Nafion is used as the membrane material, and is plated with an initial platinum layer which is then finished with a layer of gold to improve surface conductivity. With Nafion, a positively charged species of ion must be introduced to neutralize the negatively charged membrane backbone chains [4]. Applying a voltage to the electrodes causes these cations to transport toward one side of the membrane. As these ions accumulate on a face, they repel each other and cause that face of the membrane to elongate, which then causes the IPT to bend. Fluids previously used with IPTs have been water-based fluids, which tend to dry quickly. This effect subsequently changes the electromechanical coupling properties of the transducer with time, creating variability in results. Development of new ionic fluids have alleviated the need to remoisten the membranes, however this type of IPT was not able to be used successfully in this study.

1.3 Purpose

There are many methods to induce strain within an electromechanical transducer. Vibrations are a common phenomenon in structures, and could potentially provide power for small electrical systems. The goal of this study is to examine the effect of dynamic axial loading on both PVDF and IPT samples. Different input signals are used to simulate different operating conditions. Results of the tests for each material will be compared with theoretical models in order to validate these models for the design of future applications. The two materials will also be compared with each other to assess which may be better for a specific application. Finally, a circuit will be designed to capture the created energy in a capacitor to test its practical energy conversion and storage abilities for a prescribed base excitation.

2. MODELING

Using simplified models of the polymers, analytical models are developed for each material. Beginning with linear constitutive equations, relationships are derived relating the base excitation of each polymer to a voltage output of the material. These equations are then used to simulate a response for a given input, which are then compared to experimental results.

2.1. PVDF Model

The first material to be modeled is the piezoelectric polymer PVDF. The material properties used in this model are based upon published specifications for Measurement Specialties, Inc. [5] piezofilm transducers, and the properties are listed in Table 1. The transducers are poled through the material thickness (the 3 direction) and are subject to a dynamic axial load along the 1 direction as illustrated in Figure 1. For modeling purposes the test fixture is modeled as a standard spring-mass-damper that is excited through a base excitation as shown in Figure 2. For piezoelectric materials, the electromechanical response is modeled through a system of linear constitutive equations,

$$\begin{aligned} S_1(t) &= s_{11}^E T_1(t) + d_{31} E_3(t) \\ D_3(t) &= d_{31} T_1(t) + \epsilon_{33}^T E_3(t) \end{aligned} \tag{1}$$

where s_{11}^E is the mechanical compliance under constant electric field ($E_3=0$), ϵ_{33}^T is the permittivity under constant stress ($T_1=0$), and d_{31} is the electromechanical coupling coefficient. The first expression governs the actuation response of the transducer, relating mechanical strain $S_1(t)$ to the applied mechanical stress $T_1(t)$ and electric field $E_3(t)$. Conversely, the sensing response is governed by the second equation, relating electric displacement $D_3(t)$ to the applied stress $T_1(t)$ and electric field $E_3(t)$.

For the energy harvesting application the focus will be on the power generated under mechanical loading, therefore the developed model will focus on the sensing relationship from Equation (1). Additionally, it can be seen that the transducer will not be subject to an applied electric field, reducing the governing equation to,

$$D_3(t) = d_{31} T_1(t) . \tag{2}$$

The dynamic model of the PVDF strap illustrated in Figure 2 begins by considering the base excitation problem discussed in many standard vibrations texts such as Inman [6]. In this case the dynamic equation can be written as,

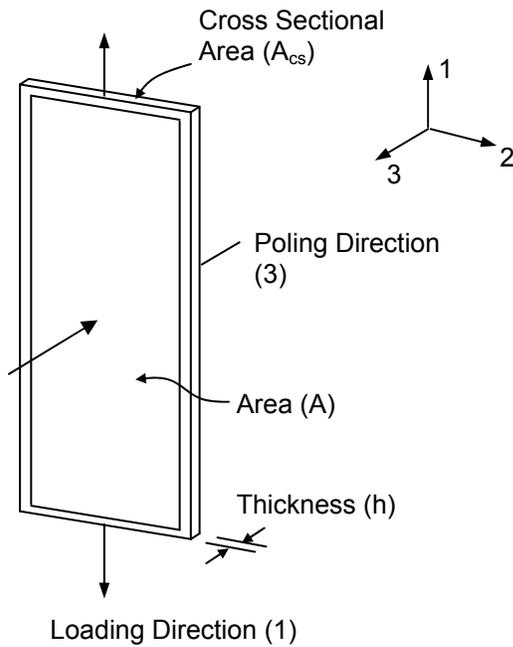


Figure 1. Polarization and loading directions for the PVDF transducer

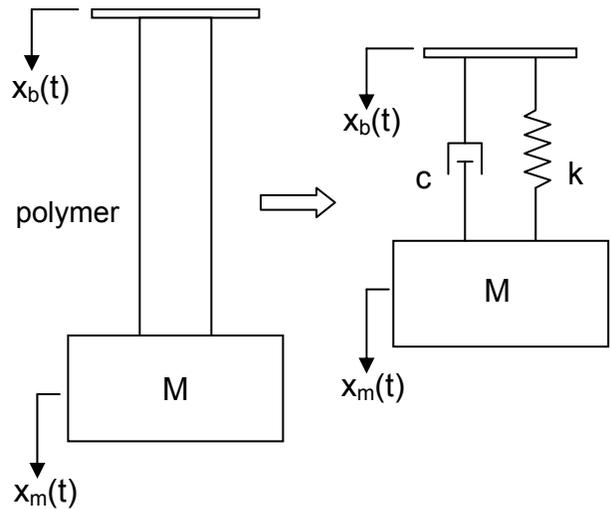


Figure 2. Simplified spring-mass-damper model of the loaded polymer transducer

Table 1. Listed Parameter Values for PVDF [5]

Parameter	Symbol	Value	Units
Thickness	h	28, 52	μm (micron, 10^{-6})
Piezo Strain Constant	d_{31}	23	$10^{-12} \frac{\text{C}/\text{m}^2}{\text{N}/\text{m}^2}$
Capacitance	C	380 for 100 μm	pF/cm^2 @ 1kHz
Young's Modulus	E	2 - 4	$10^9 \text{ N}/\text{m}^2$
Permittivity	ϵ	106 - 113	$10^{-12} \text{ F}/\text{m}$
Mass Density	ρ_m	1.78	$10^3 \text{ kg}/\text{m}^3$

$$M\ddot{x}_m(t) + c\dot{x}_m(t) + kx_m(t) = kx_b(t), \quad (3)$$

where the damping component of the base motion is assumed to be negligible with respect to the stiffness component. For validation purposes, a state-space representation of the dynamic system is generated in MATLAB to predict the mass displacement $x_m(t)$ for a prescribed base motion $x_b(t)$.

The mechanical stress can then be written as,

$$T_1(t) = E \frac{x_m(t) - x_b(t)}{L}, \quad (4)$$

where E represents to the Young's modulus of the material. To analyze the power generation within these materials, it is useful to express the output in terms of the electrical charge or voltage rather than electric displacement. This conversion is accomplished by imposing general electrical relationships, generating the voltage $V_3(t)$ to mechanical stress relationship,

$$V_3(t) = \frac{d_{31}EA_{cs}}{Ch} (x_m - x_b). \quad (5)$$

From this the estimated power output can be expressed as V^2/R ,

$$P(t) = \frac{1}{R} \left(\frac{d_{31}EA_{cs}}{Ch} (x_m - x_b) \right)^2. \quad (6)$$

2.2. IPT Model

The ionic polymer transducer is tested under similar conditions to the PVDF samples discussed in the previous section. Thus the dynamic portion of the IPT model follows the same development as the PVDF. The fundamental difference between the materials arises in the electromechanical model. Newbury and Leo [7-8] proposed the system of linear constitutive equations for the ionic polymer transducer,

$$\begin{Bmatrix} V \\ f \end{Bmatrix} = \begin{bmatrix} \frac{Z_p}{1 + Z_p/R_{dc}} & N \frac{Z_{m1}}{1 + Z_p/R_{dc}} \\ N \frac{Z_m}{1 + Z_p/R_{dc}} & Z_{m1} + Z_{m2} \end{bmatrix} \begin{Bmatrix} i \\ \dot{x} \end{Bmatrix}, \quad (7)$$

where Z_p is the electrical impedance of the IPT, Z_{m1} is the mechanical impedance, Z_{m2} is the viscoelastic impedance, N is the electromechanical coupling ratio, V is the voltage, f is the generated force, i is the applied current and \dot{x} is the polymer velocity. The sensing term of this expression is again of interest for the power generation application, as it relates the developed voltage to an applied current and velocity. For the present test configuration there is not any applied electrical current, resulting in the sensing equation,

$$V = N \frac{Z_{m1}}{1 + Z_p/R_{dc}} \dot{x} . \quad (8)$$

For frequencies above $\sim 0.5\text{Hz}$, the polymer's impedance rapidly decreases as Z_p becomes much less than R_{dc} , causing the ratio Z_p/R_{dc} to become negligible, simplifying the sensing equation to,

$$V = NZ_{m1} \dot{x} . \quad (9)$$

Following Newbury and Leo's [7] development of the coupling ratio N and the mechanical impedance Z_{m1} it is possible to derive the relationship between voltage and velocity for the case of axial loading,

$$V = \frac{d}{\eta^T w} \frac{EA_{cs}}{L} (\dot{x}_m - \dot{x}_b) , \quad (10)$$

where E is the material modulus, A_{cs} the cross-sectional area, L the clamped length, w the material width, η^T the effective permittivity, and d the coupling coefficient. Because of the difficulty in obtaining the coupling coefficient d and the permittivity η^T with the available equipment, the ratio d/η^T is treated as a tuning parameter when comparing the model to experimental results. Comments will be made regarding the comparable magnitude of d/η^T for the ionic polymer and d_{31}/ϵ_{33}^T for the piezoelectric polymer PVDF since this ratio relates to each material's ability to convert energy between the mechanical and electrical domains with the material's ability to store electrical energy. The results of each of these models are compared to experimental data in the Results section of this investigation.

3. EXPERIMENT

In this study, the energy harvesting capabilities of two active materials are inspected. PVDF and IPT have been tested and their capabilities for energy generation and storage are compared. The mechanical natural frequencies are found for each material. Specific excitations are then imposed near the natural frequencies to obtain the largest power output. An impedance analyzer was utilized to measure the electrical impedance of the test materials as a function of frequency. Finally, a rectifying circuit was used to harvest the energy produced by each of these materials in a capacitor.

3.1 Apparatus

The test assembly consists of a rigid platform, Labworks Inc. Electrodynamic Shaker model ET-132 and Power Amplifier model pa-138, National Instruments (NI) Embedded Controller model NI PXI-1042Q, PCB signal conditioner model 482A16 and PCB Piezotronics Shear Accelerometers model 352A24, PCB 208A force transducer, Keyence LC-2400A / 2450 laser vibrometer, weights, and clamps at each end of the test sample. The shaker is bolted to the platform structure with the mounting surface facing downwards. The force transducer is connected to the shaker mount. A plastic clamp attaches the top of the test material to the force transducer. Another clamp is connected at the bottom of the test material to allow attachment of the aluminum weights. The amount of weight and configuration of the masses can be adjusted in order to improve the stability of the test material during excitation. Accelerometers are placed above the top clamp and directly below the weights, while the laser vibrometer is used to measure the displacement of the top clamp. The test assembly can be seen in Figures 3 and 4. The NI controller outputs a voltage signal that Matlab generates. The signal passes through the power amplifier before activating the shaker. The NI controller then collects the output signals from the force transducer, accelerometers, and test material, which can then be analyzed and visualized with Matlab.

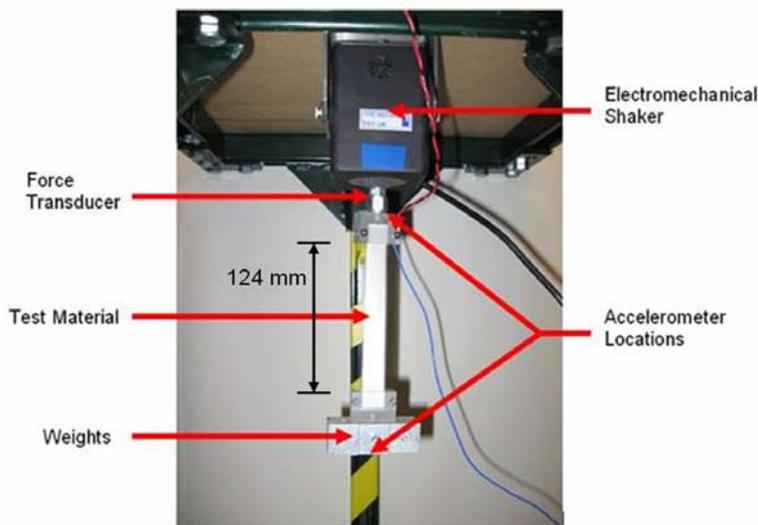


Figure 3. Test assembly with PVDF sample



Figure 4. Test setup in support frame

3.2 Procedure

In testing these polymeric transducers, each sample is subjected to time varying axial loads. The samples used are 0.75 inches (19.1mm) wide by 6.00 inches (152.4mm) long for the PVDF and 0.40 inches (10.2mm) wide by 3.15 inches (80.0mm) long for the IPT. Two different PDVF samples are also used, with thicknesses of 0.040 and 0.064mm. The leads from the polymer are attached to the top of the test bench in order to prevent interference with the test sample. The gain on the amplifier and distribution of weight is adjusted as needed to obtain consistently coherent results when performing each of the following tests. The following procedures are applied to both PVDF and the IPT samples.

3.2.1 Material Modal Parameter Determination

The first step in testing is to determine the modal parameters of each material. Each sample is excited with a sine chirp signal in order to inspect the effect of a wide range of frequencies. After analyzing the response for a broadband chirp signal up to 500Hz for both materials, a more narrow frequency range of interest was selected for each. The range of frequencies tested in the sine chirp is from 50 to 250Hz for the PVDF samples. The IPT material is more compliant, and is tested from 0 to 100Hz. Two frequency responses were measured in this configuration, one relating the acceleration of the lower mass to the acceleration of the top clamp, and another relating the output voltage from the sample to the voltage input to the Labworks shaker. The first frequency response corresponds to the mechanical frequency response for the material, whereas the second corresponds to a FRF for the electromechanical response of each material. Analyzing the mechanical frequency response allows for determination of the mechanical resonance frequencies of the material, as well as allowing for extraction of modal damping coefficients through a least-square curve fitting method. The damping values are then used in the analytical models to better reflect the characteristics of the materials tested and provide for more accurate simulation predictions.

3.2.2 Maximum Voltage Output

In order to determine the power output capability of each polymer, tests are performed to determine the maximum voltage that each material can output. It is assumed that the maximum output voltage will occur at the natural frequency of the electromechanical frequency response determined in the previous step. Since it was not practical to directly control the input displacement, this transfer function relates the voltage out to the excitation signal into the electromechanical shaker. Single harmonics at this resonance frequency are input to the shaker. Mass is added and the amplitude of the signal is gradually increased in order to increase the stress level in the polymers, causing the output voltage to increase. Masses are selected for each material to produce similar static stresses in the PVDF and IPT sample so that the output voltages can be compared.

3.2.3 Impedance Testing

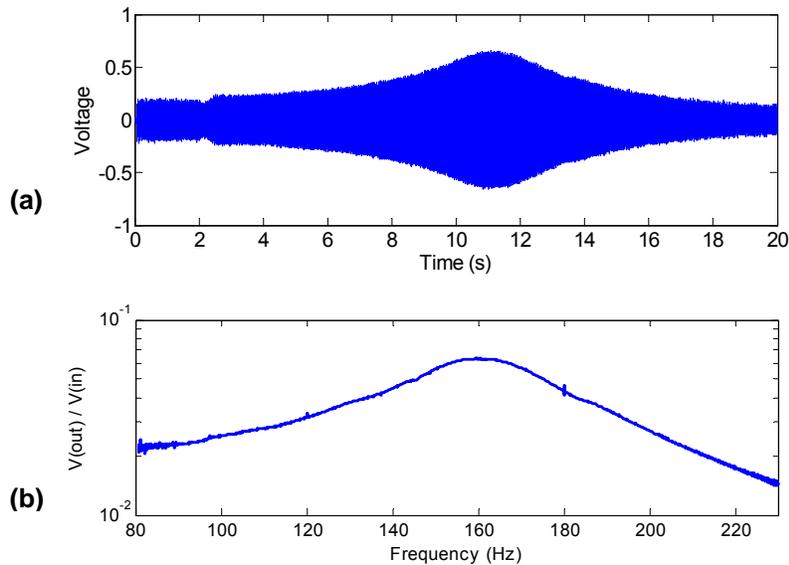


Figure 5. PVDF response to sine chirp (a) Time history of output voltage, (b) FRF of V_{out}/V_{in} .

The impedance of the materials is required in order to calculate the power output for each material. An impedance analyzer is used to find the real and imaginary parts of impedance from 40 – 500Hz for both PVDF samples and the IPT sample. The power output is calculated as V^2/Z_p , where the impedance used is the absolute value of the impedance at the frequency of interest, particularly the natural frequency determined in the first step.

3.2.4 Energy Storage

In order to use piezoelectric polymers as energy harvesters, a storage device needs to be connected to the output of transducers. A capacitor is selected because of its ease of charging directly. The output from the transducers is connected to a capacitor through a full-wave rectifier circuit. The test materials are again excited at their respective natural frequency as determined from the first step. The charging profile is obtained by recording the voltage across the capacitor as the test materials are excited by the shaker. Using capacitor circuit relationships, the charge and power can be determined from the voltage measurements. Multiple capacitance values are used to match the impedance of the materials in order to maximize energy storage. As a final test, white noise is used as an input, and the energy storage capability of the materials for real applications is examined.

4. RESULTS

Tests were performed on both thicknesses of PVDF and the IPT sample. Sine chirp signals were used to determine the modal characteristics of the materials. Tests were conducted on both thicknesses of PVDF and the water-based ionic polymer. The samples were excited with the shaker at the determined electromechanical frequencies at increasing stress levels, and the test materials' maximum voltage output was recorded. The experimental results from the single harmonic inputs are used as an input to the developed model simulations. The simulation results are compared to the measured test outputs to determine the accuracy of the analytical models for predicting the material's behavior. Finally, the test samples are used to charge a capacitor, and the voltage stored across the capacitor is measured.

4.1 Material Characteristics Determination

The first step of this study was to find the mechanical and electromechanical resonance frequencies of each PVDF sample with each mass configuration. To achieve this, sine chirps were run for each material as previously described, and frequency response plots were created. Figure 5 shows one plot of an averaged frequency response from the output voltage to the input voltage that is typical of the materials. From each of these response plots, the peaks were selected as the excitation frequencies. The combinations tested and their resonance frequencies are shown in Table 2. Response plots from the free end acceleration to the base acceleration were

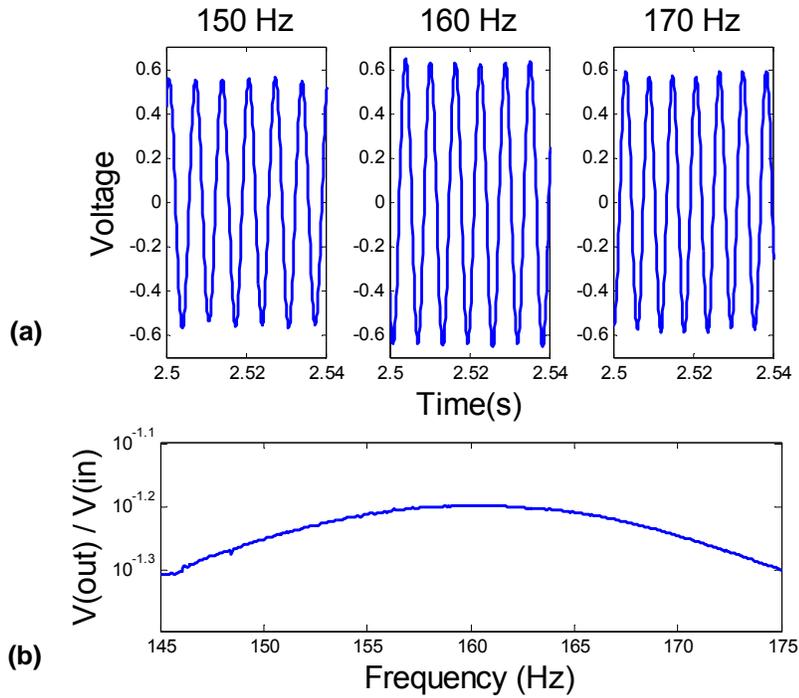


Figure 6. (a) Response of 0.064mm thick PVDF with 892g weight excited with sine waves of varying frequency and (b) its corresponding FRF for a sine chirp.

also created, and damping coefficients for each test configuration were extracted by using a least-squares curve fitting technique. These damping coefficients are used in the damping terms in the models to more accurately model the materials tested.

From these results, it was seen that certain configurations exhibit multiple peaks in the response. At lower loading conditions it was observed that non-axial modes were present, causing a bending or twisting mode to appear near the first longitudinal resonant frequency. As mass is added, the influence of these non-axial modes was diminished and the longitudinal mode became dominant, resulting in a single natural frequency. Single harmonic sine waves were then used to excite the polymers. First, the polymers were tested at the frequencies around the identified natural frequencies to confirm the results from the sine chirp tests, and an example can be seen in Figure 6.

Table 2. PVDF Sample Configurations and Natural Frequencies

PVDF Sample Thickness [mm]	Mass [g]	Natural Frequency [Hz]
0.040	128	146, 160
0.040	192	143
0.040	324	142
0.064	206	142, 152, 214
0.064	312	137, 176
0.064	518	158
0.064	892	160
0.064	1208	138

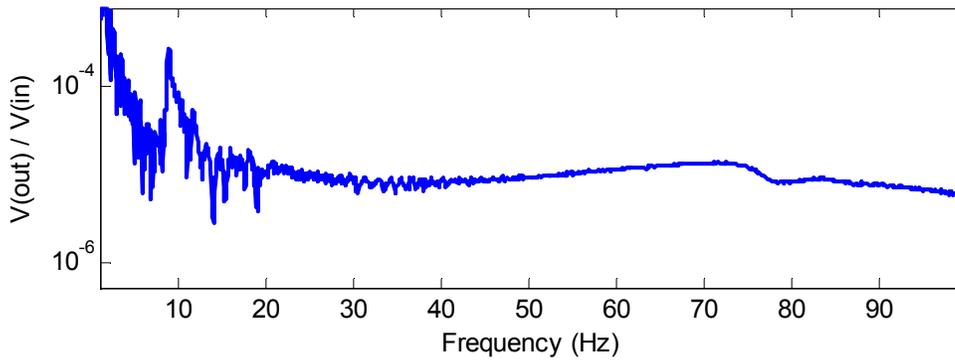


Figure 7. Frequency response for the ionic polymer transducer.

Steps taken in testing the ionic transducer are nearly identical to those for the PVDF. Sine chirps are used to determine the resonant frequencies. As figure 7 shows the ionic polymer exhibits much more noise in the low frequency region as compared to the PVDF samples when driven by a chirp excitation.. The first peak appears to be at approximately 8 Hz, and was found to correspond to a bending mode within the sample. To avoid this transverse deflection in the IPT, samples were excited at the second peak near 75Hz, corresponding to the first longitudinal mode of the test sample.

After performing the sine chirps, single harmonics were used to excite the polymer at resonance. Once again, three sample masses are used. Initially, calculations were performed to determine the weight needed to normalize the stress, but more weight was needed to help reduce bouncing and twisting of the sample.

4.2 Comparison of Experimental Results to Model

Experimental results are used to assess the accuracy of the models developed in Section 2 of this paper. The Keyence laser vibrometer was used to measure the displacement at the base of the material during tests. This data was used as input into the simulations. The comparison of the model prediction and experimentally collected data for the PVDF and IPT are shown in Figures 7 and 8, respectively. Each model performs well when compared to the experimental model. The PVDF prediction shown in Figure 7 relies on published data from the

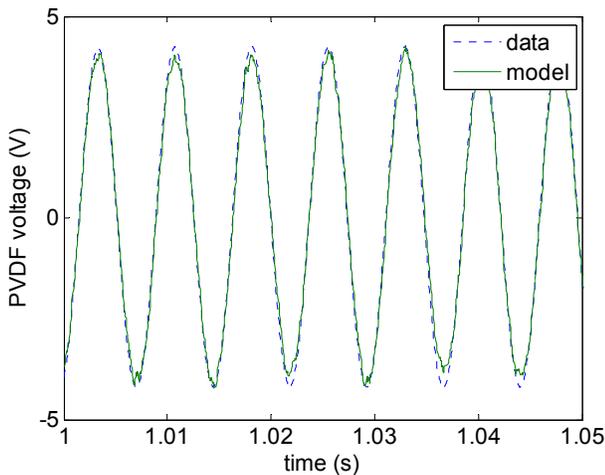


Figure 7. PVDF comparison

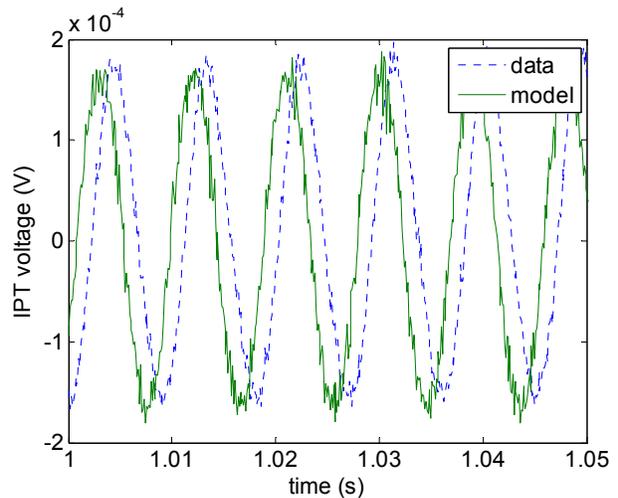


Figure 8. IPT comparison

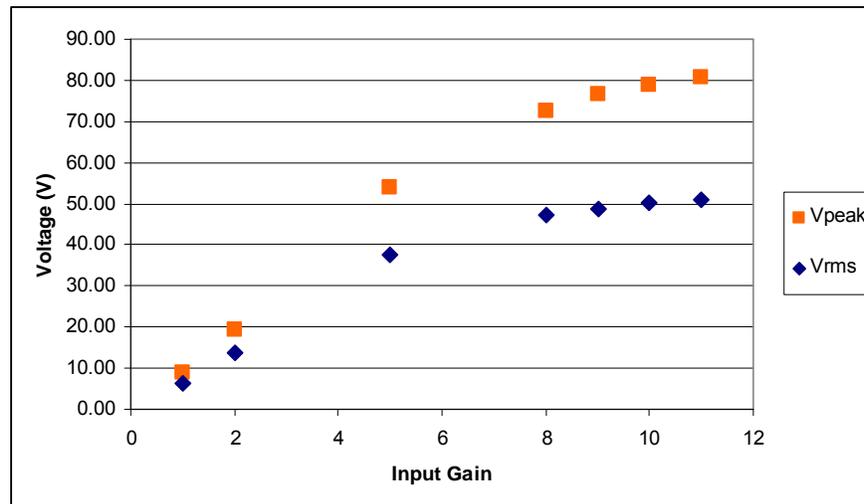


Figure 9. Affect of input excitation on voltage output for 64 μm PVDF

manufacturer and from experimental characterizations of the material's mechanical damping coefficient. The ionic polymer model also matches the experimental results relatively well. There does exist a phase lag between the experimental data and the model prediction as seen in Figure 8. This time delay is approximately 1.5ms, and is attributed to ion motion within the IPT. The model from Section 2 assumes that the ion motion is nearly instantaneous, and thus it does not account for any delays due to ion transport within the ionic polymer.

The magnitude of the IPT model is tuned through the ratio of the coupling coefficient to the frequency dependent permittivity, d/η^T . For modeling purposes, the permittivity was prescribed to be 2×10^{-4} F/m at 75Hz based upon the experimental results of Buechler and Leo [9]. With this value for η^T , the IPT coupling coefficient d is estimated to be 4.4×10^{-13} (C/m²)/(N/m²) to properly predict the magnitude of the IPT response. When compared to the properties of the PVDF transducer in Table 1, it is seen that the coupling coefficient for the IPT is approximately 2 orders of magnitude smaller, whereas the permittivity is approximately 6 orders of magnitude larger. This indicates that the ionic polymer is efficient at storing charge, but less capable of transforming mechanical stress into harvestable voltage [10-11].

4.3 Maximum Voltage Output

The active materials were next driven with higher mass loading as well as an increased excitation through the Labworks shaker. This is done to investigate the maximum voltage that the materials are able to output with the given test setup. Table 3 shows the results of the thick PVDF transducer with the largest weight attached to it, and the voltage output during each test.

Both the thinner PVDF sample and the IPT sample were not tested to the extent of the thick PVDF sample. The IPT sample could not support the load of larger masses without failing, and there was a concern that the thin PVDF sample could also fail during testing. The maximum voltages obtained for each material and the testing configurations are shown in Figure 9.

4.4 Impedance Measurements

After experimentation with single harmonics it was desirable to look at the maximum power obtainable from the samples. To do this, the impedance of the transducer was measured. Using an impedance analyzer the sample was subject to a sweep from 40 to 500 Hz. The start frequency of 40 Hz was used because it is the machine's lower bound. The magnitude of the electrical impedance for the 64 μm sample of PVDF is shown in Figure 10. This is composed of a real component of the impedance that decreases with frequency and an imaginary component that increases with frequency. For the piezoelectric material the real component is conventionally

related to the resistive properties of the material, whereas the imaginary component is often related to the material's capacitance. The ionic polymer exhibits a similar response in the overall impedance, however the real and imaginary components cannot be related as easily to the resistance and capacitance due to a more involved electrical equivalent model [12]. Following the work of Han et al. [13] the impedance was used to determine what circuit components were needed to match the complex impedance in order to obtain maximum power transfer. This process was repeated for each specimen.

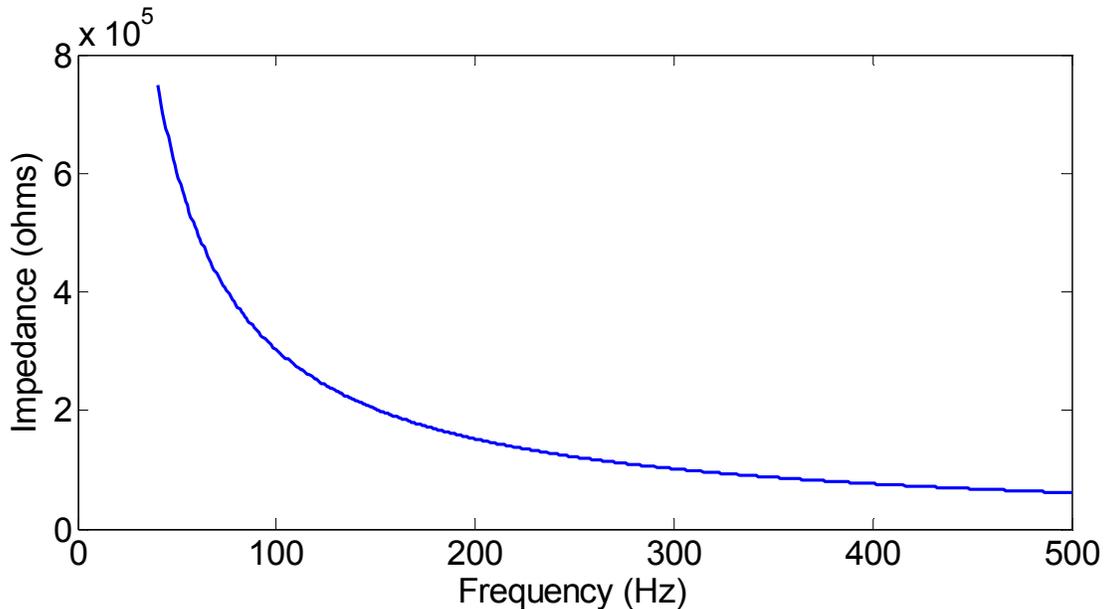


Figure 10. Impedance measurements for 64 μm PVDF

4.5 Power Calculations

After taking impedance measurements, they can then be combined with the voltage measurements to obtain power outputs for each material. For the thick PVDF specimen we used its maximum power output measurements for this analysis. The impedance was taken at the resonant frequency for each test and material. The maximum power output of 11.85 mW was calculated for the 64 μm PVDF sample. Since the IPT was not capable of withstanding higher mass loads, comparisons are made with the 40 μm PVDF sample when loaded with similar input forces as measured by the force transducer. The results of this comparison can be seen in Table 3.

4.6 Power Storage

The final step in testing the PVDF samples was to charge a capacitor. A full wave rectifier circuit is used to obtain a larger amount of power from the excited sample with a 33 μF capacitor. A diagram of the circuit configuration can be seen in figure 11.

Table 3. Comparison Between PVDF and IPT Power Outputs

	PVDF (64 μm)	IPT
Mass (g)	1208	346
Natural Frequency (Hz)	138	70
Impedance (ohms)	2.19E+05	4.664
V _{rms} (V)	0.314	1.21E-04
Power (mW)	4.494E-04	3.15E-06

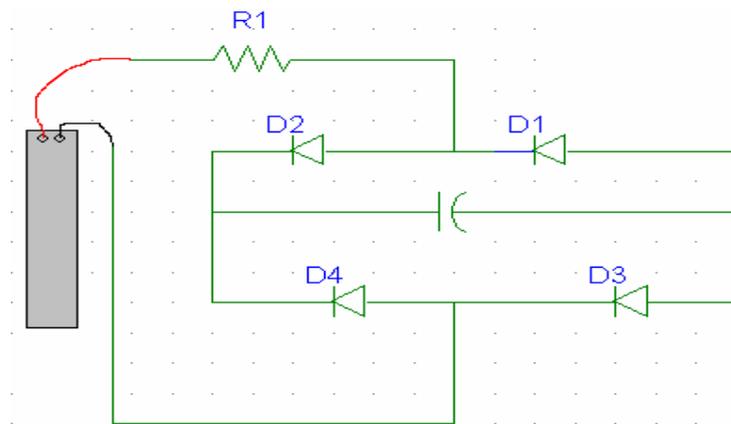


Figure 11. Full wave rectifier circuit

A single harmonic at resonance is input to the transducer with the output going directly into the circuit. Figure 12 shows a plot of the voltage across the capacitor with respect to time. The profile is a typical charging profile and subsequent tests yielded very similar results. Figure 13 shows the results of charging a capacitor with IPT using 2 different input amplitudes. The variation in the signal is likely due to dehydration of the ionic polymer during testing.

5 CONCLUSIONS

Testing accomplished the goals originally set for this research project. The proof of concept portion was shown very well through the charging of a $33\mu\text{F}$ capacitor with both the PVDF and IPT materials. Clean data from each transducer was obtained and analyzed. It was shown that both materials could successfully produce coherent results in our testing. Further, each material was able to successfully charge a capacitor. This is a very important step because just producing energy isn't very useful without the ability to store the energy for later use. While it would be difficult to charge batteries with the amount of power produced in these tests, it was shown that with larger samples or higher excitation batteries could likely be charged.

One observation that was made during this testing was that the ionic polymer transducers were more difficult to work with. While these materials show promise in their strength and storage capabilities, there are problems that need to be addressed. The electrodes on the ionic polymers need to be more robust. The ionic fluid sample broke in the initial tests and there was considerable cracking in the surface electrodes. Two water based samples also broken during testing with relatively light loads. More robust electrodes would allow for a greater range of test inputs and make the polymers more useful. A second problematic area comes in the hydration of the material.

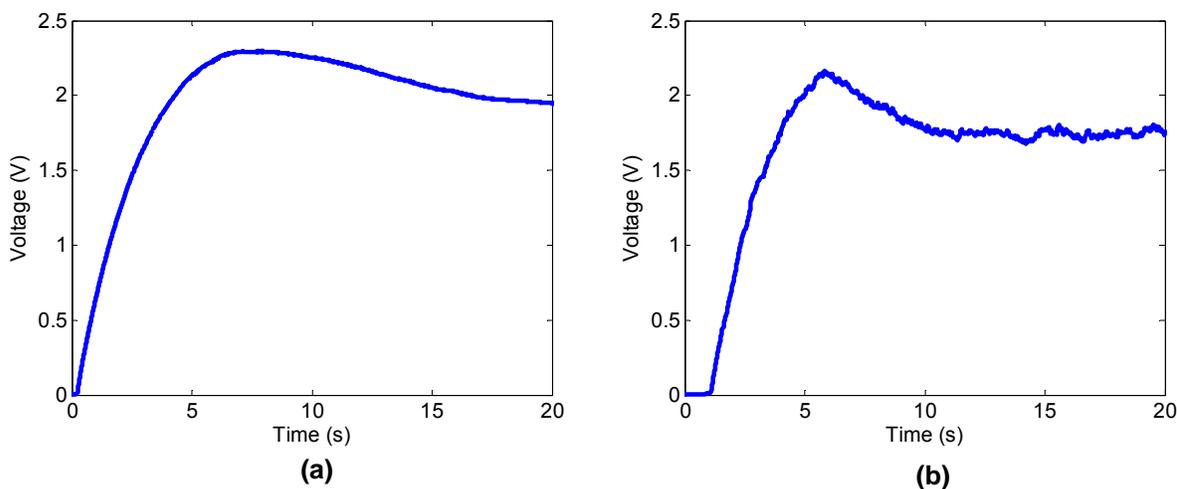


Figure 12. Charging a $33\mu\text{F}$ capacitor with $64\mu\text{m}$ thick PVDF with a (a) sinusoidal input and (b) random signal input.

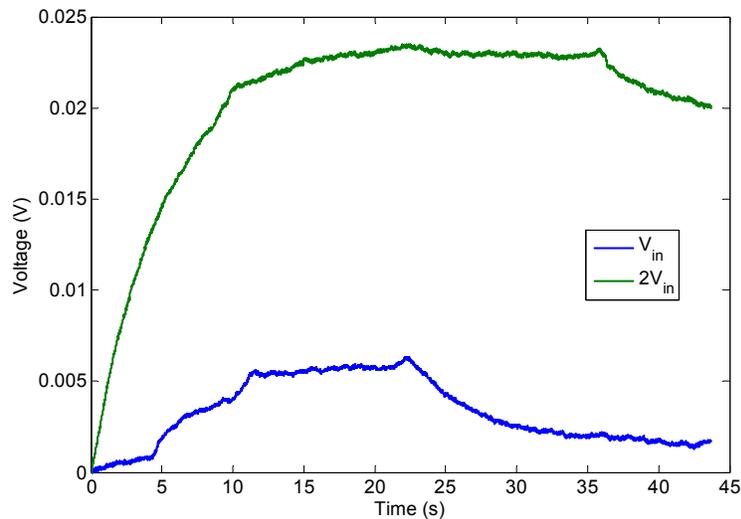


Figure 13. Charging of a capacitor with IPT

Keeping the water based samples hydrated was very difficult. The performance was seen to degrade as the material dried out, and it began to dry out immediately upon removing it from the water. More work should be invested in studying materials with various ionic liquids as solvents, as with the work of Bennett and Leo [17]. A better ionic liquid could enhance the IPT performance and improve its electromechanical response when operating in open air.

Next, it was shown that in the material comparison, PVDF was a much better material for energy harvesting in this test configuration. It was able to charge the capacitor to a much higher voltage than the ionic polymers. Its power output was also considerably higher. However, the testing set-up was skewed toward the PVDF. PVDF naturally strains axially whereas the ionic polymer's natural strain state is in bending. An inspection of the ionic polymer's energy harvesting capabilities under large bending strains would likely yield much more promising results.

Finally, it was found that the ionic polymer favors storing the produced energy. The dielectric permittivity is much larger for the ionic polymer, while the coupling coefficient is much smaller relative to the permittivity when compared to the PVDF samples. This result supports Roundy's [15] conclusions that the coupling coefficient governs an electromechanical transducer's ability to harvest energy. From the experimental results in this study, it is evident that the ionic polymer is less efficient at harvesting energy from axial vibrations than the PVDF transducer. This could be partly a result of the fact that ionic polymers are inherent benders, and that their coupling would be lower when subject to axial strain in the polymer, as opposed to exciting the sample in bending. The coupling coefficient is directly related to how well the material converts energy from the mechanical domain to the electrical energy and vice versa, whereas the permittivity is related to how capacitive the material is or how well it will store the electrical energy. With a high permittivity and low coupling coefficient the ionic polymer can be considered a good storage medium as opposed to a energy harvester for axial loading.

While the ionic polymer was found to be less suitable for energy harvesting in this application, it is important to note that the material was capable of generating a coherent voltage signal when axially loaded, and was able to charge a $33\mu\text{F}$ capacitor to 20 mV. This supports many of the conclusions made by Dogruer et al. [16] who recently published a study looking into the effectiveness of these materials as energy harvesters. Further refinement of the base polymer, coupled with improvements in the solvent and electrode robustness may enable these materials to operate as an effective method for generating and storing electrical energy. By taking advantage of the ionic polymer's inherent nature to operate as a bender, it may also be possible to identify applications where these materials would be more suited for energy harvesting than piezoelectric materials such as PVDF.

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