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Comparison of Piezoelectric Energy Harvesting Devices for Recharging Batteries

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Abstract

Piezoelectric materials can be used as a means of transforming ambient vibrations into electrical energy that can be stored and used to power other devices. With the recent surge of micro scale devices, piezoelectric power generation can provide a convenient alternative to traditional power sources used to operate certain types of sensors/actuators, telemetry, and MEMS devices. However, the energy produced by these materials is in many cases far too small to directly power an electrical device. Therefore, much of the research into power harvesting has focused on methods of accumulating the energy until a sufficient amount is present, allowing the intended electronics to be powered. In a recent study by Sodano *et al*. (2004a) the ability to take the energy generated through the vibration of a piezoelectric material was shown to be capable of recharging a discharged nickel metal hydride battery. In the present study, three types of piezoelectric devices will be investigated and experimentally tested to determine each of their abilities to transform ambient vibration into electrical energy and their capability to recharge a discharged battery. The three types of piezoelectric devices tested are; the commonly used monolithic piezoceramic material lead-zirconate-titanate (PZT), the bimorph Quick Pack (QP) actuator and Macro Fiber Composite (MFC). The experimental results estimate the efficiency of the three devices tested and identify the feasibility of their use in real world applications. Various different capacity batteries are recharged using each device, to determine the charge time and maximum capacity battery that can be charged. The results presented in this paper show the potential of piezoelectric materials for use in power harvesting applications, provide a means of choosing the piezoelectric device to be used and estimating the amount of time required for it to recharge a specific capacity battery.

Keywords: Power harvesting, piezoelectric, Macro-Fiber Composite, MFC, self-powered.

Introduction

The increasing desire for completely self-powered electronics has caused the amount of research into power harvesting devices to become progressively larger over the last decade. With the advances being made in wireless technology and low power electronics, sensor are being developed that can be placed almost anywhere. However, because these sensors are wireless, they require their own power supply which in most cases is the conventional electrochemical battery. Once these finite power supplies are extinguished of their power, the sensor must be obtained and the battery replaced. The task of replacing the battery is tedious and can become very expensive when the sensor is placed in a remote location. These issues can be potentially alleviated through the use of power harvesting devices. The goal of a power harvesting device is to capture the normally lost energy surrounding a system and convert it into usable energy for the electrical device to consume. By utilizing these untapped energy sources electronics that do not depend on finite power supplies, such as the battery, can be developed. One source of typically lost energy is the ambient vibrations present around most machines and biological systems. This source of energy is ideal for the use of piezoelectric materials, which have the ability to convert mechanical strain energy into electrical energy and vice versa.

The concept of utilizing piezoelectric material for energy generation has been studied by many researchers over the past few decades. One early study into power harvesting by Hausler *et al.* (1984) investigated the ability to generate energy from the expansion and contraction of the rib cage during breathing. A prototype of the power harvesting system was constructed using polyvinylidene fluoride (PVDF) film and was implemented *in vivo* on a mongrel dog. The prototype was demonstrated to produce a peak voltage of 18V, which corresponded to a power of about 17μW. Another investigation into the ability to use piezoelectric materials for power harvesting from the motion of humans and animals, was performed by Ramsey and Clark (2001), who studied the ability to power an *in vivo* micro-electromechanical system (MEMS) application. The research used a thin square plate driven by blood pressure to provide power and was shown to be capable of powering the electronics if they were used intermittently. Another form of excitation commonly used is the ambient vibration of mechanical structures. Umeda et al (1996) quantified the amount of energy that could be produced when a steel ball impacted a piezoelectric plate. The authors used an equivalent circuit model to predict the energy while modifying numerous parameters in the system to find the best combination. It was determined that a significant amount of energy was returned to the steel ball in the form of kinetic energy as it bounced of the plate, making the system ineffective. Sodano et al. (2004b) formulated a model of a power harvesting system that consisted of a cantilever beam with piezoelectric patches attached. The model was developed such that any combination of boundary conditions and location of piezoelectric material could be accommodated, but was verified on a cantilever beam experiencing a base excitation from the clamped condition. The model was found to accurately estimate the energy generated and was also used to demonstrate the damping effect of power harvesting.

With the research into power harvesting devices growing it was determined that the amount of energy generated by piezoelectric materials was not sufficient to power most electronic devices. Thus, for power harvesting technology to make its way into the commercial market, methods of accumulating and storing the harvested energy until a sufficient amount can be recovered to power the portable electronics, are the key to a successful power harvesting system (Sodano *et al*. 2004c). One of the first researchers to realize the need for power storage circuitry was Starner (1996), who speculated the use of piezoelectric materials for harvesting numerous sources of energy around the body, including limb and finger motion. Additionally, the idea of using a capacitor and rechargeable battery for power harvesting was discussed with some advantages and disadvantages of each listed. This concept was taken a step farther by Umeda *et al.* (1997), who followed their earlier study up with an investigation into the use of a capacitor with piezoelectric materials. They theoretically and experimentally tested the circuit in various configurations to determine the optimal design. Shortly after the publication of this work, a power harvesting patent was issued to Kimura (1998) for a means of storing the rectified energy from a piezoelectric device in a capacitor. However, a circuit containing only a single capacitor is not sufficient to provide power to other electronic devices without additional circuitry. Therefore, Kymissis *et al.* (1998) developed a piezoelectric system that would harvest the energy lost during walking and used it to power a radio transmitter. Their circuit also used a capacitor as the storage medium, but the additional components allowed it to charge to a desired level before discharging. Once the capacitor had discharged to a pre-specified level, an electronic switch would be triggered to stop the flow of energy, thus allowing the capacitor to recharge. It was found that the two piezoelectric devices used produced sufficient energy to power a transmitter that could send a 12-bit radio frequency identification (RFID) code every 3-6 steps. The proof that power harvesting could supply sufficient energy to power a transmitter opened up many doors for research into wireless sensors. In a later study, Elvin *et al*. (2003) developed a self-powered damage detection unit that used PVDF for energy generation and a capacitor to store the energy. The circuit was capable of transmitting a signal that held information on the integrity of the structure.

Much of the research into power harvesting has dealt with optimizing the power harvesting configuration or developing circuitry to store the energy, however, some researchers have looked into the ability to use circuitry for extracting more energy from the piezoelectric material. One such study was performed by Kasyap *et al*. (2002), who used the concept that the energy transfer from the piezoelectric to the load is maximized when the impedance of the two are matched, to developed a circuit whose impedance could be modified. The authors provide a description of the fly back converter circuit and the equations needed to set the circuit impedance to the desired value. Ottman *et al.* (2002) studied the use of an adaptive step down DC-DC converter to maximize the power output from a piezoelectric device. It was found that at very high levels of excitation the power output could be increased by as much as 400%. However, this study did have a drawback, the additional electronic components required to optimize the power output dissipated energy. This additional circuitry needed an open circuit voltage greater than ten volts for an increase in the generated power. To overcome this problem, Hofmann *et al*. (2002) modified the circuit by removing the adaptive circuitry and used a fixed switching frequency. However, the improvements made to the circuit now required more than 25 volts open circuit for increased power to be supplied to the load. Furthermore, the level of excitation necessary to produce greater than 25 volts open circuit is far greater than present in any typical vibrating machinery, making the circuitry unrealistic.

While significant headway has been made in the field of power harvesting, the amount of energy produced in most cases is still not sufficient to power the desired electronic systems. Sodano *et al*. (2004c) saw the use of the capacitor as a fundamental problem with the research that had been performed in power storage methods. Because of the poor energy storage characteristics of the capacitor, it could only be used to send out short pulses of energy, which severely limited the number of applications for power harvesting. Therefore, Sodano *et al*. (2004c) investigated the ability to use the energy from the piezoelectric material to recharge a discharged battery. Their study showed that a watch battery could be recharged from a completely discharged state, in less than one hour by vibrations consistent in amplitude with those found on a typical vibrating machine. Furthermore, the authors compared this new concept to the more traditional method of storing the energy in a capacitor and found the use of a battery provided more flexibility in the electronics to be powered, due to the capacitor's quick discharge time. In the present study, the efficiency of three different piezoelectric materials will be studied and the energy from the excitation of a piezoelectric patch will be used to recharge various capacity nickel metal hydride batteries. The three actuators are the traditionally used PZT material, the Quick Pack actuator and the macro-fiber composite (MFC) that was recently developed at the NASA Langley Research Center.

The MFC actuator is constructed using piezofibers surrounded in an epoxy matrix and covered with a Kapton shell (Williams, 2002). The Construction of this actuator allows it to be extremely flexible, as well as robust to damage and environmental conditions. These are two desirable properties for power harvesting applications. Additionally, the MFC uses an interdigitated electrode pattern that capitalizes on the higher d_{33} piezoelectric coupling coefficient, which means the device is more efficient in converting energy between the mechanical and electrical domains. For these reasons the MFC could be an ideal candidate for use as a power harvesting device. The Quick Pack actuator is a bimorph piezoelectric device that uses monolithic piezoceramic material embedded in an epoxy matrix. The use of monolithic material causes the device to be far less flexible than the MFC but the epoxy shell does make it more robust than raw monolithic material. Lastly, the traditionally used monolithic piezoceramic material PZT is tested. The PZT material is effective but extremely brittle and susceptible to accidental breakage, making it the least robust of the three piezoelectric devices tested. In the following sections the efficiency of each device will be first identified to allow the work to be scaled to other sized actuators and piezoelectric materials. Next the study will provide the time required by each piezoelectric device to charge batteries ranging from 40mAh to 1000mAh, followed by a discussion of each actuators performance.

Experimental Setup

Each of the three actuators was mounted with cantilever boundary conditions to allow the excitation to be applied using base motion of the clamped edge. Due to the brittle nature of the PZT material and the extreme flexibility of the MFC, these two devices were bonded to a 0.0025 inch aluminum plate. The plate was so thin that is added little stiffness but allowed the MFC to support its own weight and provided the PZT with added durability. The PZT material was PSI-5H4E piezoceramic (PZT) from Piezo Systems Inc. and had dimensions shown in Firgure1. The dimensions of the MFC are shown in Figure 2. The Quick Pack actuator was not required to be bonded to an aluminum plate because it was not too stiff like the PZT or too flexible like the MFC; however, due to the aspect ratio it required a support on the top and bottom of the actuator. The dimensions of the Quick Pack are shown in Figure 3.

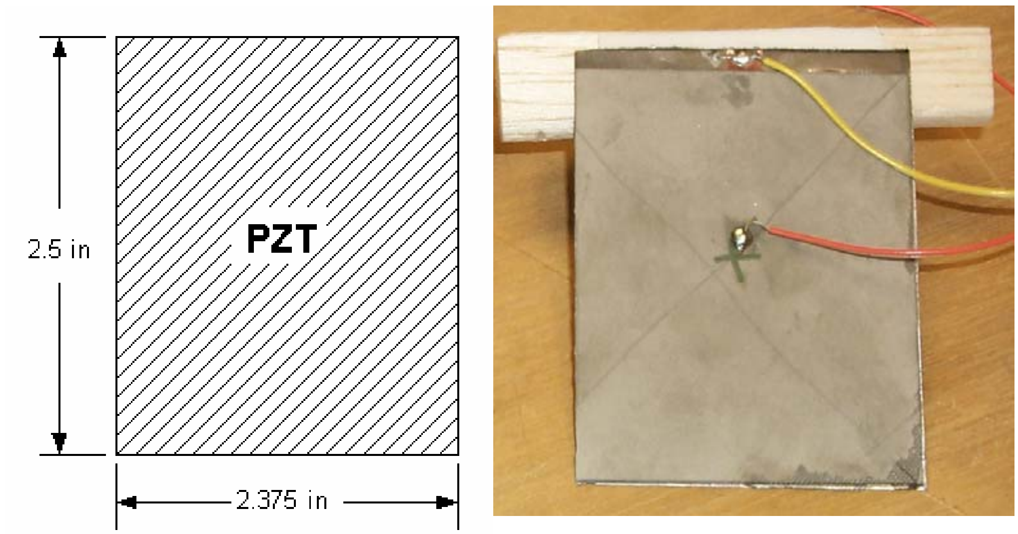

Figure 1: Size and layout of the PZT plate.

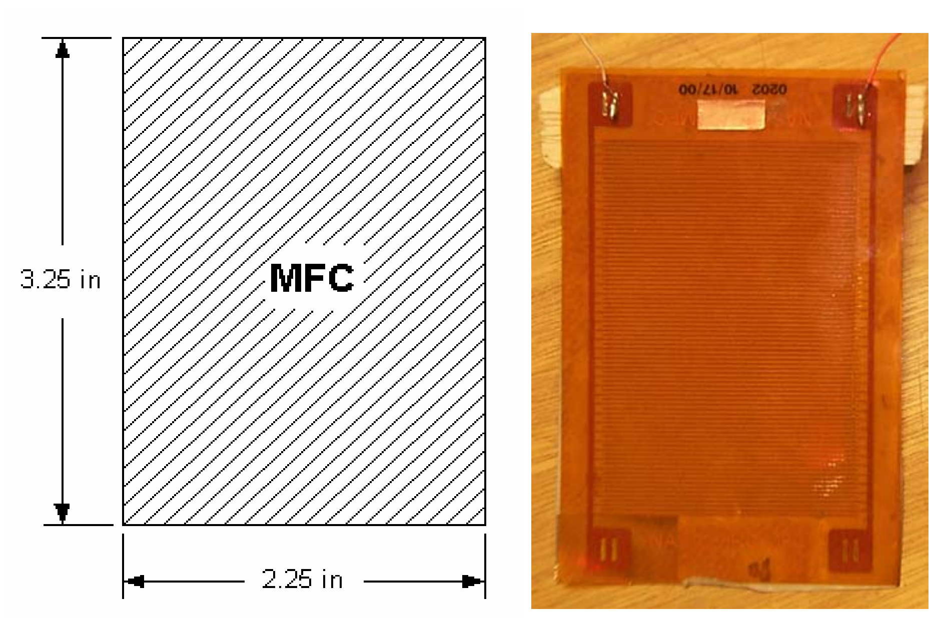

Figure 2: Size and layout of the MFC plate.

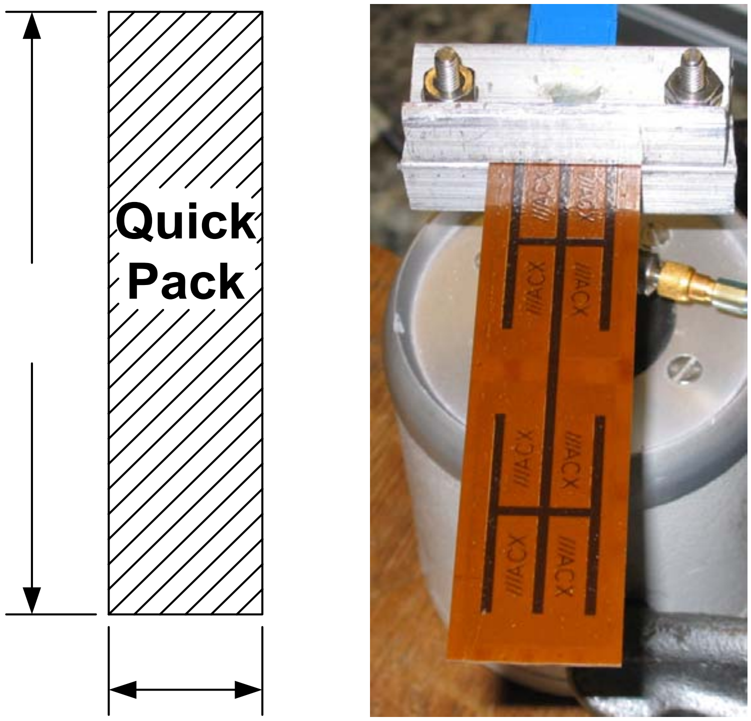

Figure 3: Size and Layout of the Quick Pack actuator.

One of the goals of this research was to identify the time required to charge various capacity batteries when subjected to a realistic ambient vibration source. Thus, the vibration of a typical vibrating machine was measured, and then a signal similar in frequency content and amplitude was used to excite the three piezoelectric devices. An example of a few mechanical systems that experience ambient vibration would be ships, bridges, railroad cars and aircraft. However, for the tests performed in this study the engine compartment of an automobile was chosen because the system was readily available and easy to test. To measure the vibration signature of the automobile, a PCB accelerometer, model 352C22, was randomly placed on the air compressor of a Mitsubishi eclipse. The term 'random location' is used because no effort was made in optimizing the placement of the accelerometer to produce the maximum magnitude of vibration, nor is the compressor the optimal location in the engine compartment for obtaining vibration energy. The engine was run at various speeds and the response was measured. The signal measured from the compressor had the appearance of random vibration from 0 to 1000 Hz, a typical response is shown in Figure 4. Using the measured data a function generator was used to excite a LDS V203 shaker with the same PCB accelerometer attached to it. The excitation was then adjusted until the function generator supplied a signal of similar amplitude and frequency content as identified from the compressor.

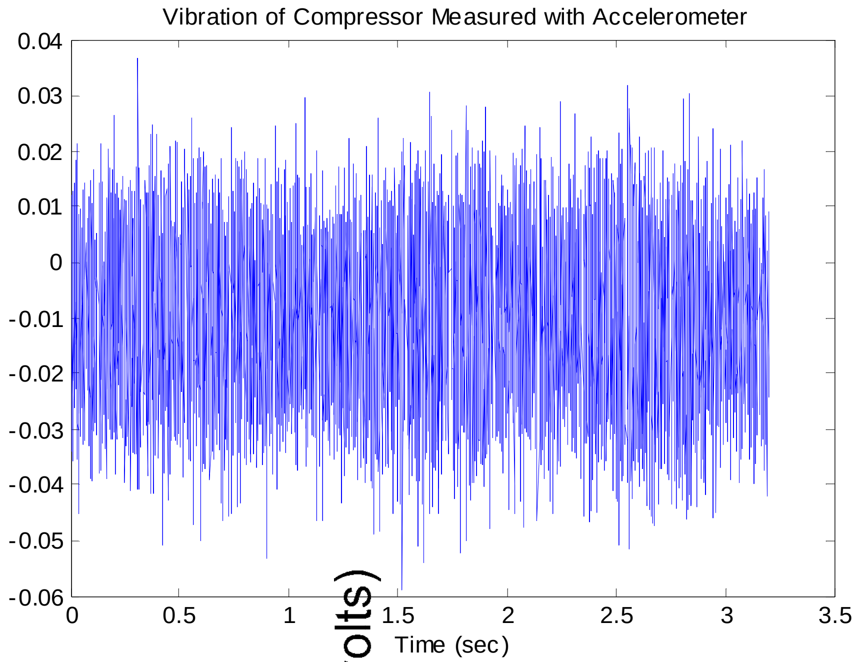

Figure 4: Vibration of an automobile compressor measured by an accelerometer.

The excitation of the piezoelectric devices was accomplished by mounting the clamped end of each to the shaker, thus exciting the system using base motion as shown in Figure 5. Using this setup, the efficiency of each piezoelectric device was measured with a Polytec laser vibrometer that determined the displacement of the clamped boundary condition and a PCB force transducer (model 208) was used to measure the applied force. These two pieces of information allowed the power into the system to be determined, while the power output from the system was found by measuring the voltage drop across a load resistor that was matched to the impedance of each particular piezoelectric at its first resonant frequency. With the resistance and voltage drop known the power output can be determined using Ohm's law.

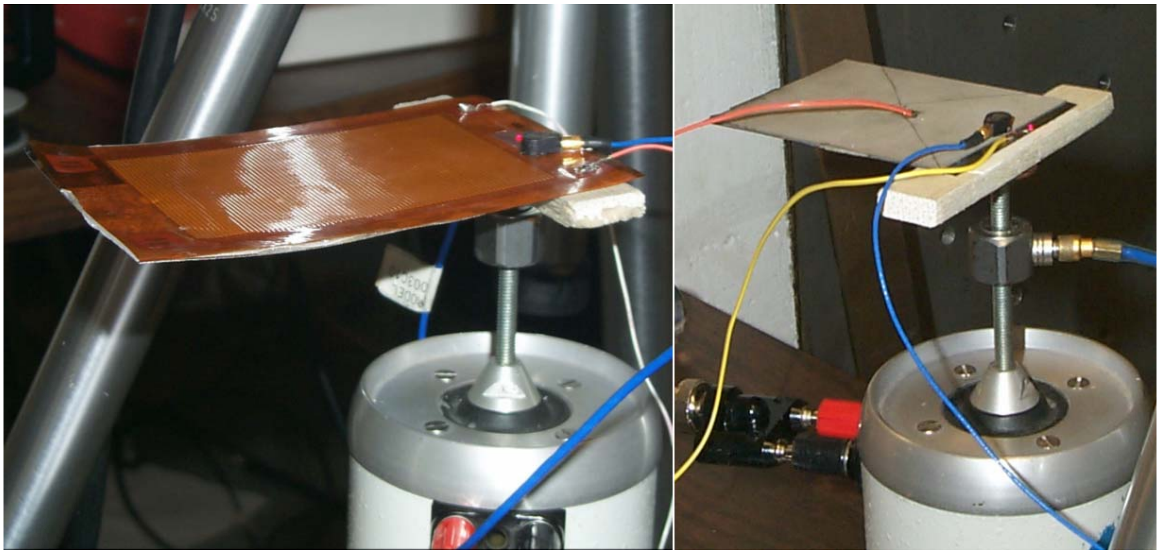

Figure 5: Experimental setup with the MFC plate and PZT Plate in a cantilever configuration.

For the battery charging experiments nickel metal hydride batteries were chosen because they have a high charge density and unlike lithium ion batteries they do not require any type of charge controller or voltage regulator to be incorporated into the circuitry. The circuit constructed to charge the battery consisted of a full wave rectifier, capacitor and the battery intended to be charged, as shown in Figure 6. The voltage produced by the PZT was first full wave rectified then accumulated in a large capacitor, typically greater than 1000μF, followed by the battery intended to be charged, which was placed in parallel with the capacitor. The simplicity of this circuit allows it to be constructed very compactly and without additional components that would result in additional power dissipation, the circuit used is shown in Figure 7.

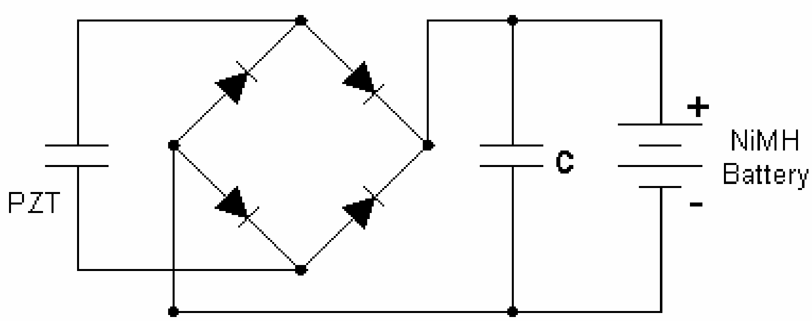

Figure 6: Schematic of the battery charging circuit.

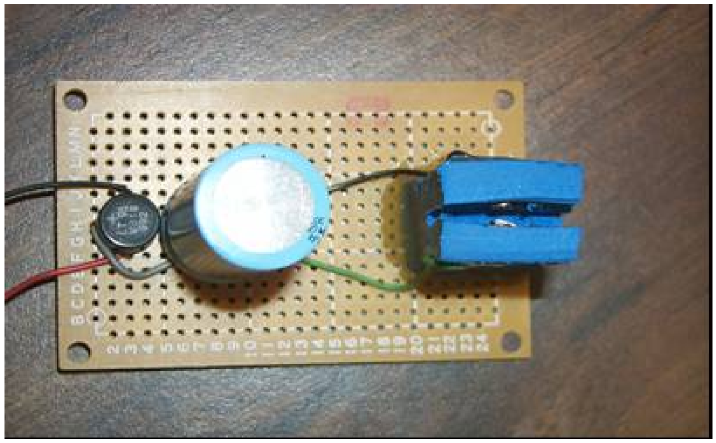

Figure 7: Layout of the Battery charging circuit built on a breadboard.

Efficiency Calculation of PZT and MFC

The first goal of this work was to compare the effectiveness of the MFC, Quick Pack and PZT for use as power harvesting devices. This was done by determining the efficiency of each device used in the experiments. With this data obtained from the laser vibrometer, force transducer and voltage output from the piezoelectric, equation 1 was numerically calculated to determine the average efficiency:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{\displaystyle\sum_{n=2}^{m} \frac{\left(V_n - V_{n-1}\right)^2 / R}{\left(\left(F_n - F_{n-1}\right) \cdot \left(d_n - d_{n-1}\right)\right) / \left(t_n - t_{n-1}\right)}}{m} \times 100\% \qquad (1)$$

where η is the efficiency, V is the voltage drop across load resistance R, F is the force applied to the base of the plate, d is the displacement of the plate, t is the time increment between data points, n is the data point index and m is the total number of data point measured. The efficiency of each piezoelectric device was calculated when excited at the first resonant frequency, with a chirp from 0-500 Hz and with a random signal form 0-500 Hz. As mentioned before, the automobile compressor vibrated randomly; therefore this efficiency most likely represents the piezoelectric device being subjected to ambient vibration. The resulting efficiencies are shown in Table 1. It must be noted that the efficiencies do not represent that of the actuator itself, because the experimental configuration and other factors may vary. However, these efficiencies do provide a comparison between the three actuators tested. For each signal, three measurements were made to show consistency. The efficiency of the PZT plate is low at resonance because the resonance frequency used was that of the largest voltage output, not the frequency with the best force in and voltage out characteristics. This lower efficiency is shown because that is the resonance frequency used to charge the battery. Additionally, it can be seen that the Quick Pack has a very high efficiency at resonance but not when excited at other frequencies. However, all of the efficiencies are fairly low because of the excitation method used.

Table 1: Efficiency of PZT and MFC with three different inputs.

Signal	**PZT Efficiency (%)**	**MFC Efficiency (%)**	**QP Efficiency (%)**
Resonant	1.1675	0.9442	8.8499
	2.0777	1.0727	9.0237
	1.1796	0.8782	8.9302
Chirp 0-500 Hz	3.927	2.7421	0.5238
	3.9388	2.5476	0.4133
	3.8948	2.6285	0.4610
Random 0-500 Hz	3.9369	0.7636	0.5364
	3.6825	0.828	0.2911
	4.2174	0.7366	0.4083

From Table 1 it can be seen that the MFC performed poorly for both the resonant and the random excitation signals. Through these tests it was found that the MFC performed inadequately as a power harvesting medium. The electrical output from the MFC contained a very large voltage component but an extremely low current. It may be thought that the power would still be the same even if the voltage was large and the current was low, but for the case of the MFC the power generated is about a factor of ten smaller. It is believed that the performance of the MFC is degraded due to increased impedance caused by the use of interdigitated electrodes. Another way to think of this situation is to consider each segment of piezoelectric fiber between the interdigitated electrodes as a small power supply (when used for power harvesting this is essentially what happens); this is shown by the schematic in Figure 8. Along the fiber there are numerous sections of electrodes that cause the majority of these small power sources to be electrically connected to one another in series. When two power sources are connected in series, the voltages add but the current does not. This concept of series connections can be used to describe the reason for the low power generated by the MFC. Due to the series connection, the MFC produces a much higher voltage while the current remains far smaller than that of the PZT. The low current also causes much of the power generated to be dissipated by electronic devices, such as diodes, resulting in a lower efficiency. However, because the MFC was constructed for actuator purposes, a definitive and full understanding of the electrical properties of the MFC when used for power harvesting is not completely understood yet, and is currently being investigated by the authors. Additional effects of resulting from the low current generation of the MFC will be detailed in the following section.

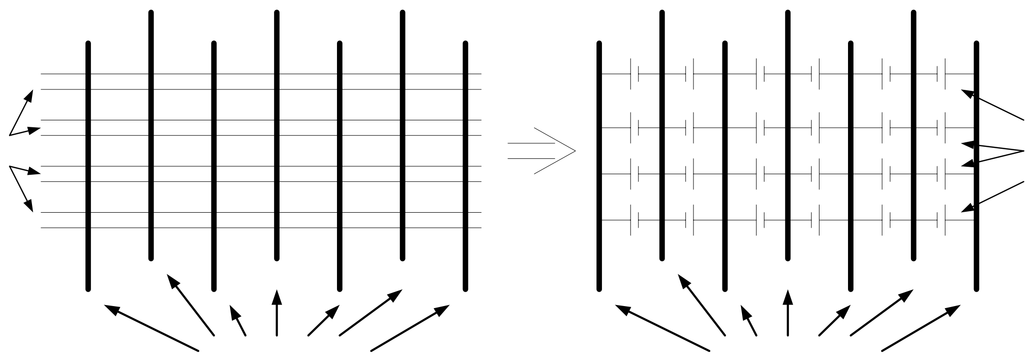

Figure 8: Layout of a MFC patch and the equivalent circuit layout.

Battery Charging Results

The tests presented in this section, investigate the ability of the three piezoelectric devices to recharge batteries ranging in size from 40mAh up to 1000mAh (the unit "mAh" stands for milli-amp-hour and is a measure of the battery's capacity, a 40mAh capacity means that the batteries will last for one hour if subjected to a 40mA discharge current), the charge time required is also provided to demonstrate the relative effectiveness of each device. The charge time was recorded using a dSpace real time control board over a period ranging from 1 to 50 hours, depending on the size of the battery. It was determine through testing the MFC that it was unable to recharge even the lowest capacity battery tested; unless the excitation signal provided by the shaker was unrealistically large (the goal of this work is to show that piezoelectric devices can charge batteries when experiencing typical levels of ambient vibration). The MFC's inability to charge batteries can be attributed to the issue of low current generation, as discussed in the previous section. When charging a battery, the most important electrical factor of the power supply is that it be able to provide a fairly significant amount of current. The charge time of a rechargeable battery is directly dependent on the amount of current supplied to it. Since the MFC generates such a low current and the battery requires a fairly high current (usually one-tenth the battery's capacity or higher), the MFC actuator is not compatible with rechargeable batteries. With this point in mind the results from tests using the MFC to charge batteries will not be presented.

Working with the two piezoelectric devices left, the PZT and Quick Pack, two signals were applied to the shaker in order to excite each device for charging batteries; the first bending resonance (50Hz for the PZT and 32Hz for the Quick Pack) and a random signal ranging from 0-500Hz. As indicated in the experimental setup section, the magnitude of the signals applied to the shaker caused the excitation of the piezoelectric devices to closely resemble the vibration that would be experienced in the engine compartment of an automobile. During the experiments the time required for the battery to charge past the cell voltage of 1.2 volts was measured in each case. This is not a complete charge but is approximately 90% full, and provides an easy method of comparing the time needed by PZT and Quick Pack to charge the battery. In order to finish charging the battery a charge controller is needed to detect the either a temperature change inside the battery cell or a slope change in the charge cycle. The electronics required to do this would complicate the system and dissipate a significant amount of the energy generated, potentially negating the ability of the piezoelectric to recharge the battery. For this reason and the inability to detect a full charge due to the absence of a charge controller compatible with the power output from the PZT, 90% was considered a full charge. To give an idea of the amount of energy that can be stored in the batteries being tested a 40mAh battery contains enough energy to power a Casio LW22H watch for two years (Casio Inc.), and a 750mAh battery is equivalent to a typical AAA battery.

Using the methods outlined, each battery was charged while the voltage on the battery was measured. The resulting charge time for each battery is shown in Table 2 and plots of the typical battery charging cycle are shown in Figures 7 and 8, for the PZT and in Figures 9 and 10, for the Quick Pack, charging of the 300mAh battery is shown in all four figures, to demonstrate how each excitation and device performs. Although the larger batteries will reach a charge level of 1.2 volts it is unknown without a charge controller how long the piezoelectric material would take to supply sufficient current for a full charge of these batteries to be achieved. From Table 2 it is apparent that both the PZT and Quick Pack are capable of recharging a discharged battery.

However, it can be seen that as the capacity of the battery increases the Quick Pack begins to become less effective than the PZT. Additionally, it is noted that during the efficiency testing, it was found that the Quick Pack performed very well at resonance but was less effective when excited with a range of frequencies. This point is further demonstrated by looking at the difference between the charge times of the Quick Pack when excited at resonance and randomly, for instance the charge time for a 750mAh battery at resonant excitation is 8.5 hours and is increased to 25 hours with random excitation. In contrast to this issue with the Quick Pack, the PZT does not experience this issue, from the efficiency tests, the PZT was shown to perform well when excited at a range of frequencies. This is demonstrated by the when charging the batteries also, for example the charge time for a 750mAh battery at resonant excitation is 7 hours and is only increased by approximately 20% up to 8.6 hours with random excitation.

Table 2: Time required charging different sized batteries using a piezoelectric.

	Resonant Charge Time (hours)		**Random Signal Charge Time (hours)**	
Battery Size (mAh)	**PZT**	**Quick Pack**	**PZT**	**Quick Pack**
40	1.62	0.75	1.6	7
80	1.2	2.9	2	12.5
200	4	3	1.2	20
300	6	10.8	9.8	22
750	7	8.7	8.6	25
1000	22	>50	32	>50

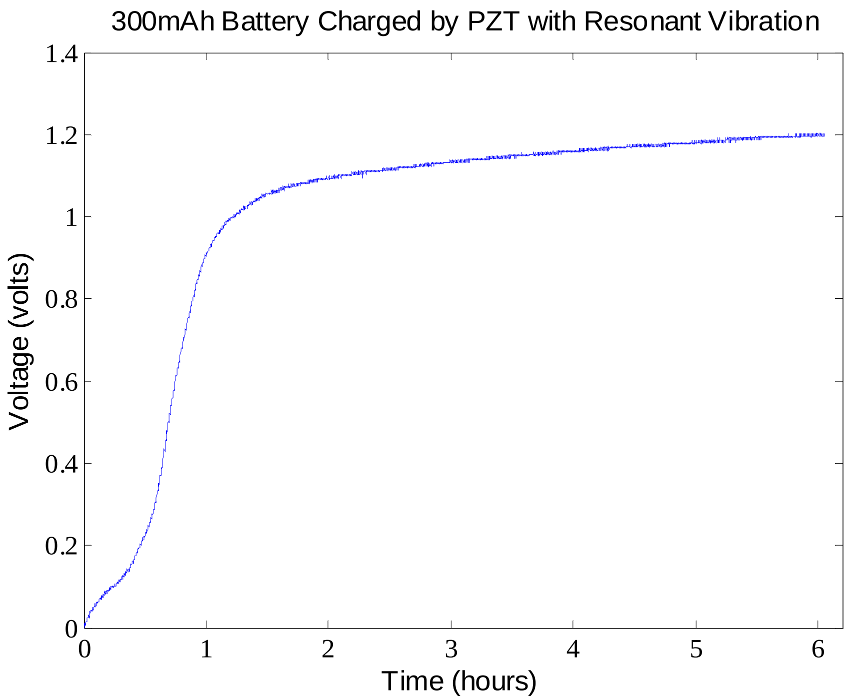

Figure 7: Charge history of a 300mAh battery with resonant excitation of the PZT material.

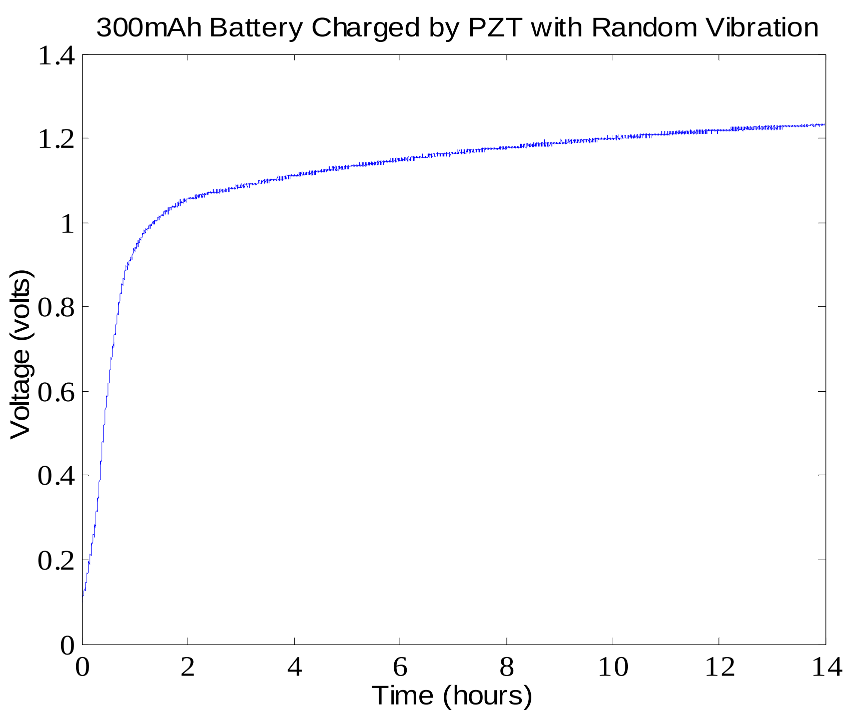

Figure 8: Charge history of a 300mAh battery with resonant excitation of the PZT material.

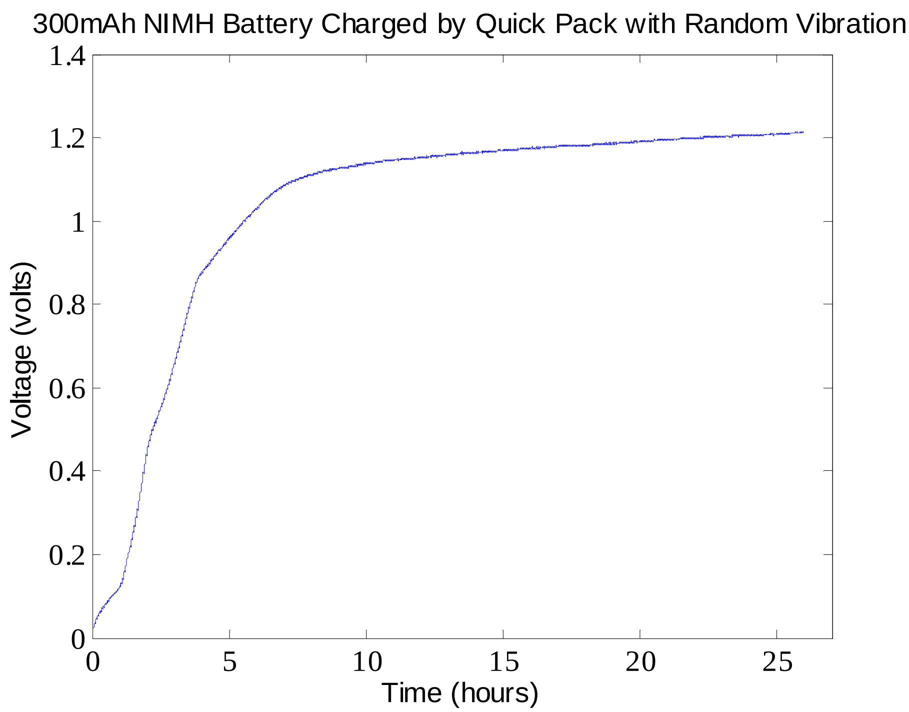

Figure 9: Charge history of a 300mAh battery with resonant excitation of the Quick Pack.

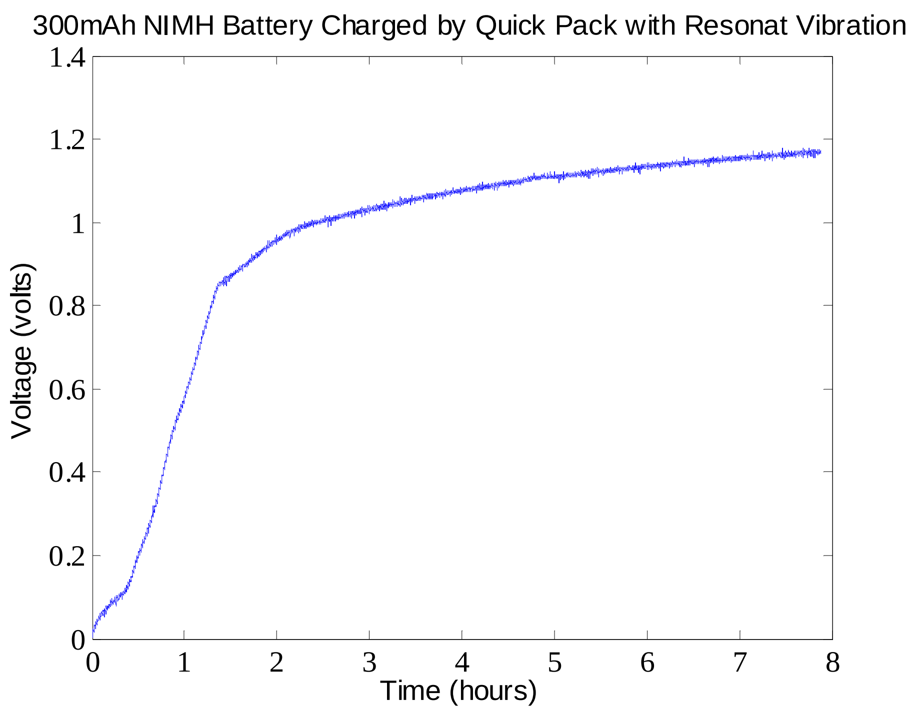

Figure 10: Charge history of a 300mAh battery with resonant excitation of the Quick Pack.

The results presented provide a platform to build off when using piezoelectric materials to charge batteries. Using the information from Tables 1 and 2, the type of piezoelectric device for recharging batteries and the capacity that can be charged in a required time can be determine, thus allowing the ideal power harvesting components can be found for a specific application. Sodano *et al*. (2004) stated, the finding that piezoelectric materials can be utilized for recharging batteries brings power harvesting significantly closer to the commercial market and opens up many doors for its application. The rational for this comment revolves around the severe limitations that are brought on an electrical system when energy is stored in a capacitor. The major factor that really limits the electronics is the quick charge and discharge time of the capacitor; it can only be used to provide short bursts of power. This makes the use of computational electronics or data processing impossible. Additionally, the capacitor does not have a cell voltage that it maintains a constant voltage, but rather charges up to a high voltage then releases a quickly changing output, making the use of a voltage regulator, which dissipates energy, a necessity. Furthermore, portable electronics that are commercially available utilize batteries, allowing power harvesting systems that use rechargeable batteries to be easily adapted to current electronics. Power harvesting systems that utilize rechargeable batteries are the key to developing commercially viable self-powered electronic systems.

Conclusions

The idea of power harvesting has become increasingly popular over the past few decades. With the advances in wireless technology and low power electronics, portable electronics and remote sensors are now part of our everyday lives. The key to replacing the finite power supplies used for these applications is the ability to capture the ambient energy surrounding the electronics. Piezoelectric materials form a convenient method of capturing the vibration energy that is typically lost and converting it into usable electrical energy. This material has been used in the power harvesting field for some time; however, the energy generated by these materials is far too small for directly powering most electronic systems. This problem has been found by most all researchers that have investigated this field, thus showing the need for methods to accumulate the generated energy until a sufficient amount is present. Typically the storage medium used has been the capacitor, but the capacitor is not a good candidate because it can only provide short busts of power. Realizing this issue Sodano *et al*. (2004a) showed that the rechargeable battery could be used with piezoelectric materials as an alternative to the capacitor. Using this idea, the present study has investigated the ability of three different piezoelectric devices to recharge various capacity nickel metal hydride batteries. First the efficiency of each power harvesting device was tested under different excitation conditions to show the relative performance and allow the work to be compared to other studies. The results of the study found that both the Quick Pack and the monolithic piezoceramic material PZT were capable of recharging the batteries in question. However, the PZT was shown to be more effective in the random vibration environment that is usually encountered when dealing with ambient vibrations. Furthermore it was shown that the Macro-fiber composite was not well suited for power harvesting. Reasons for the poor performance were discuss, but the electrical characteristic of the MFC are unknown for power harvesting and are currently being investigated by the authors. The work presented provides a means for determining the ideal piezoelectric device and capacity rechargeable battery for a specific power harvesting application. Without a method of storing energy more effective than the capacitor, power harvesting will never become a viable power supply in commercial applications.

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