LA-UR-03-7148, JIMSS, 16(1), 67-75, 2005

# Generation and Storage of Electricity from Power Harvesting Devices

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## Abstract

The idea of capturing the energy surrounding an electronic system and converting it into usable electrical energy that could extend the lifetime of the power supply or provide an endless supply of energy has captivated many researchers and brought much attention to power harvesting. One method of obtaining the energy surrounding a system is to use piezoelectric materials. Piezoelectric materials have the unique ability to interchange electrical and mechanical energy. This property allows them to be uses to absorb the mechanical energy around a system, usually ambient vibration, and transform it into electrical energy that can be used to power other devices. However, the amount of energy generated by piezoelectric materials is far smaller than that needed by most electronic devices. Therefore, methods of accumulating and storing the energy generated until sufficient power is captured must be developed. This paper quantifies the amount of power generated by a piezoelectric plate and investigates two methods of accumulating the energy produced. The first uses a capacitor, which has been a common method of accumulating the energy produced and the second method is the use of nickel metal hydride batteries. The advantages of each method are discussed and the rechargeable battery is found to have more desirable qualities than the capacitor. It is shown that the power output of piezoelectric materials is compatible with that needed by a rechargeable battery and that a 40mAh battery can be charged in slightly under one hour.

## Introduction

Piezoelectric materials can be used as mechanisms to transform mechanical energy, usually ambient vibration into electrical energy that can be used to power other devices. The practice of harnessing the energy around a system and converting it into usable power is termed power harvesting. By implementing power harvesting devices, portable systems can be developed that do not depend on traditional methods for providing power, such as the battery, which has a limited operating life. However, the energy generated through the piezoelectric effect is not sufficient for directly powering most electronic devices. Therefore, a means of accumulating and storing the harvested energy so that it may be used to power portable electronics are an important aspect of a power harvesting system.

In recent studies and experiments, several researchers have found that if the energy provided by a piezoelectric device is to be of use, it must be accumulated in some way. One of the first researchers to realize the potential of power harvesting and speculate possible storage methods was Starner (1996). His research investigated the amount of power that could be generated through everyday human activity and proposed the use of capacitors and rechargeable batteries as storage devices for use with power harvesting systems. Umeda et al. (1997) went beyond the proposal of using a capacitor for energy storage, and tested the abilities of a circuit containing a rectifier and capacitor for storing the energy generated when a steel ball impacts a plate with piezoelectric material attached. 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 use 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 allowing it to recharge. It was found that the piezoelectric devices produced sufficient energy to power a transmitter that could send a 12-bit 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. Following this work, Elvin et al (2001) used a polyvinylidene fluoride (PVDF) piezofilm sensor attached to a simply supported Plexiglas beam to generate an electrical signal. The goal of the power harvesting experiment was to generate sufficient power from the strain induced on the piezofilm by a bending beam to provide the required energy to power a telemetry circuit. The circuitry used by Elvin et al functioned in much the same way as that of Kymissis et al; however the data transmitted was different. This circuit was used as a self-powered sensor that could transmit a signal 2m that contained information on the stain of the beam. Since these early studies in power harvesting, numerous other creative locations have been investigated for the placement of piezoelectric power harvesting devices.

While much of the research has been devoted to the search for efficient storage mediums compatible with piezoelectric devices, other researchers have investigated the use of circuitry to increase the amount of power generated by the piezoelectric material. One such study was performed by Ottman et al. (2002), who used a 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 required an open circuit voltage greater than ten volts for the power generated to be increased. The research that will be presented in this manuscript will concentrate on power storage methods that can be used for realistic vibration levels, whereas the study performed by Ottman et al. (2002) used a resonant signal at far greater excitation levels than available in most typical structures. The realistic signal used in this research was generated to be comparable with that found by placing an accelerometer on the compressor of a standard automobile and measuring the vibration levels at non-optimal locations.

This paper concentrates methods of storing electric energy generated by a monolithic lead ziconate titanite (PZT) piezoceramic. The amount of power that one particular PZT device can generate has first been estimated, and the feasibility of the device for recharging a battery has been studied. This research is motivated by the fact that the power generated by PZT is far smaller than required for the normal operation of most electronics in real field applications. However, when identifying the ideal storage method, the time required by PZT to charge power storage devices must be taken into account for the electronics intended to be powered. In addition, the low efficiency of both the PZT and the circuit has been identified as a critical issue in previous studies. In this study, the energy produced by the PZT is stored using two different methods. The first method tested will be the capacitor that allows for immediate access to the stored energy. This method has been commonly used by other researchers. The second method is to charge a nickel metal hydride battery. The battery charging method provides certain advantages over the capacitor method that will be outlined in the following sections. However, the use of energy generated from piezoelectric materials has not been previously shown to be compatible with rechargeable batteries. Therefore, the ability to use this energy to do so must first be shown before other studies into this technology can be performed.

## Experimental Setup

The piezoelectric device used for this portion of the study consisted of an aluminum plate with a PSI-5H4E piezoceramic (PZT) from Piezo Systems Inc. bonded to its surface. The piezoelectric material was bonding using superglue and the plate and piezoelectric patch had dimensions as shown in Figure 1. The thickness of the aluminum plate and the PZT were 0.04 in. and 0.0105 inches respectively. The relatively thick aluminum plate was used because the piezoceramic material is extremely brittle and is susceptible to accidental breakage, when bonded to a thick substrate the likelihood of damaging the piezoelectric is greatly reduced.

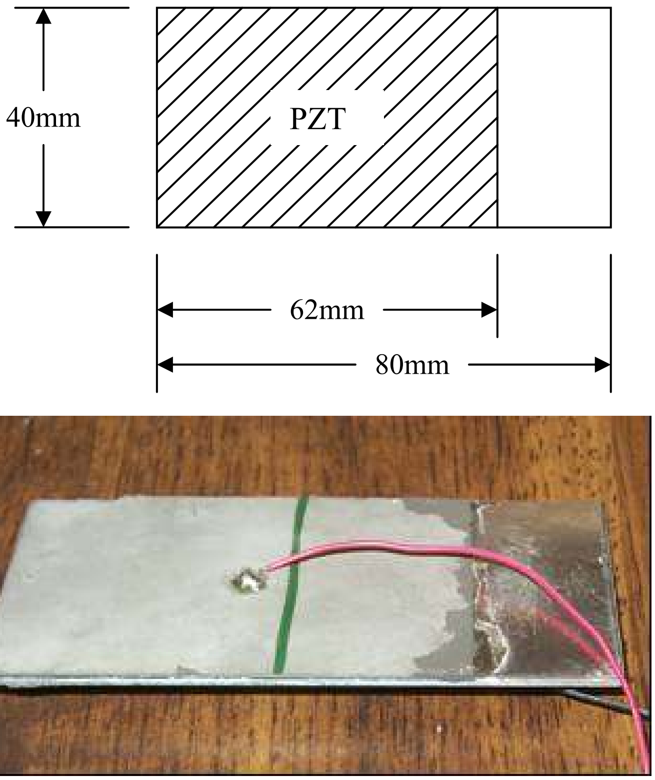

Figure 1: Dimensions and layout of the piezoelectric on the aluminum substrate.

An example of a random vibration environment that is easily accessible for study is the automobile engine. Other applications might be a highway bridge, tall buildings or an aircraft wing. Each provides ample ambient vibration. However, an automobile compressor was chosen because it is easily accessible and a random nature. Therefore, the following experiments investigate the possibility of obtaining power from the vibration of a typical mechanical system such as an automobile compressor. In order to simulate the vibration of an automobile compressor, a PCB accelerometer, model 352C22, was attached at a random location on the compressor. 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 while the accelerometer measured the compressor's response. The signal measured from the compressor of a Mitsubishi Eclipse had the appearance of random vibration from 0 to 1000 Hz. A typical response showing the magnitude of vibration measured at a random location on the automobile compressor is shown in Figure 2, along with the input signal used for the experiment, shown in Figure 3. The aluminum plate was attached to a ridged structure with cantilever boundary conditions (fixed-free), while a shaker applied an excitation force, as shown in Figure 4. The excitation signal used in the experiments was found by placing the same accelerometer on the piezoelectric plate and adjusting the signal supplied to the shaker until it was comparable with that of the compressor. The disturbance used in the experiments had a magnitude that was 9.5% less than that of the automobile compressor, indicating that the excitation signal used was conservative in representing the vibration of an automobile compressor. The energy produced by the PZT was stored using two different methods. The first was in a capacitor that allows for immediate access to the stored energy and the second method charged a nickel metal hydride battery.

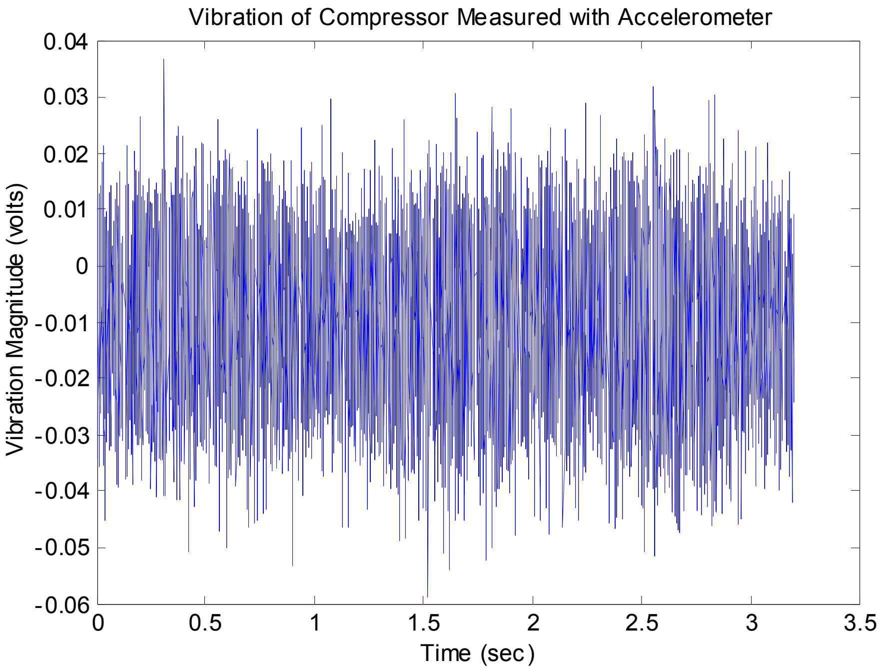

Figure 2: Vibration of an automobile compressor measured by an accelerometer.

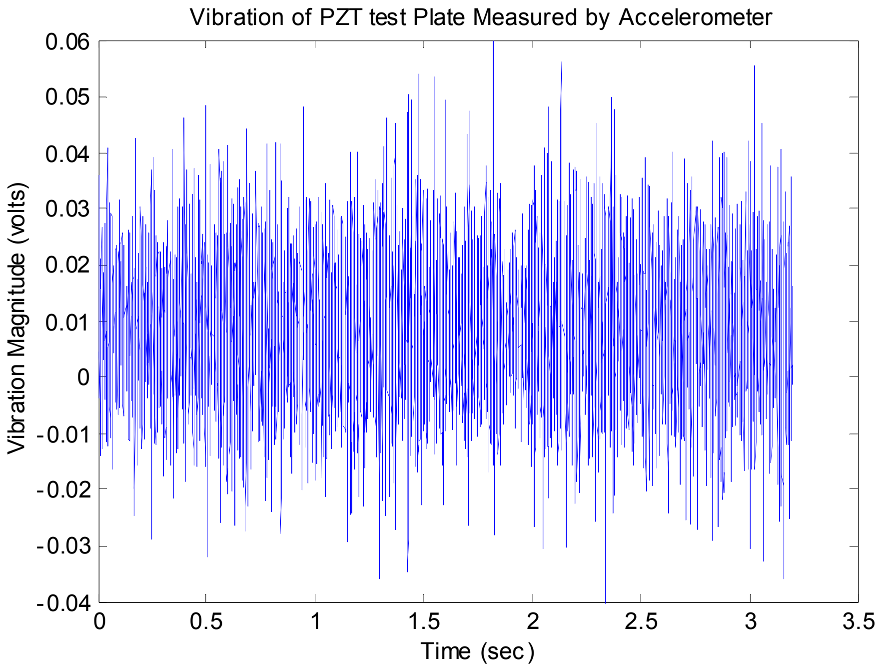

Figure 3: Random signal applied to the shaker as the disturbance force, with matched amplitude to the automobile compressor.

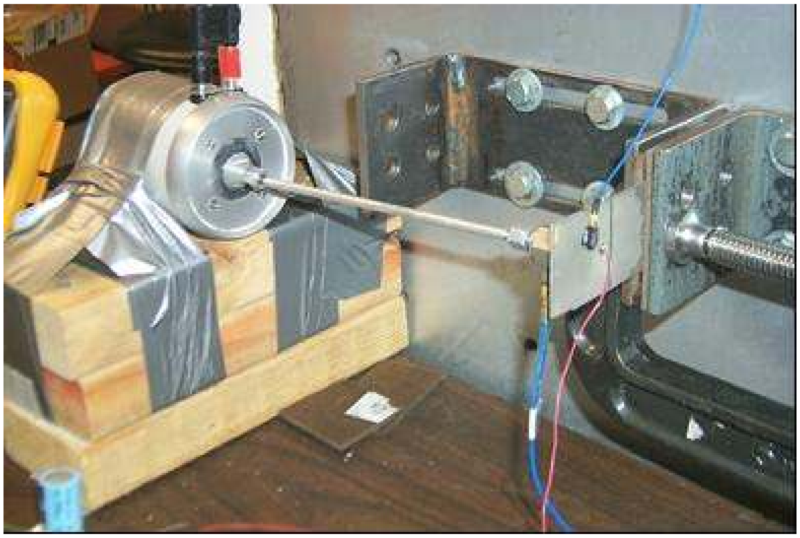

Figure 4: Experimental Setup used to both excite the plate and measure the vibration.

## Layout of Capacitor Charging Circuit

The first method of storage used a capacitor to accumulate the energy output of the piezoelectric patch, a schematic of the complete circuit used is shown in Figure 5, and the circuit build on a breadboard is shown in Figure 6. The circuit design was modified from one used for a self-powered RF tag (Kymissis et al, 1998). The principle of operation of this circuit is as follows; first the signal from the PZT is full wave rectified and accumulated in capacitor C1. Once C1 is charged past the zener diode voltage, in this case 6.5 volts, the capacitor releases it charge, switching the BJT, Q1, to the on position, and triggering the MOSFET, Q2, to pull the ground line down allowing C1 to discharge through the circuit. The MAX666 chip is a low-power series regulator that produces a +5 volt DC signal as C1 discharges. Once C1 has discharged beyond 4.5 volts, the MAX666 sends out a negative pulse that turns the Q1, off, allowing C1 to begin the process over and recharge. In the "off" state, the circuit has a high impedance allowing C1 to charge fast.

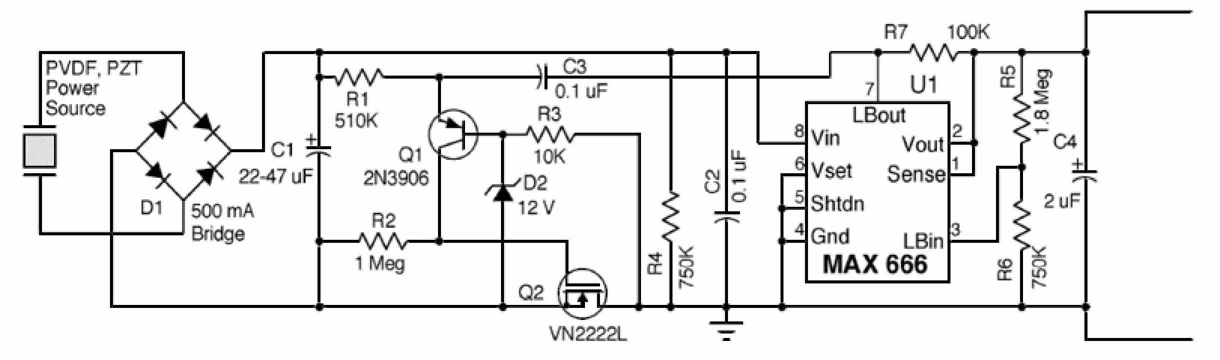

Figure 5: Schematic of the capacitor circuit layout (Kymissis 1998).

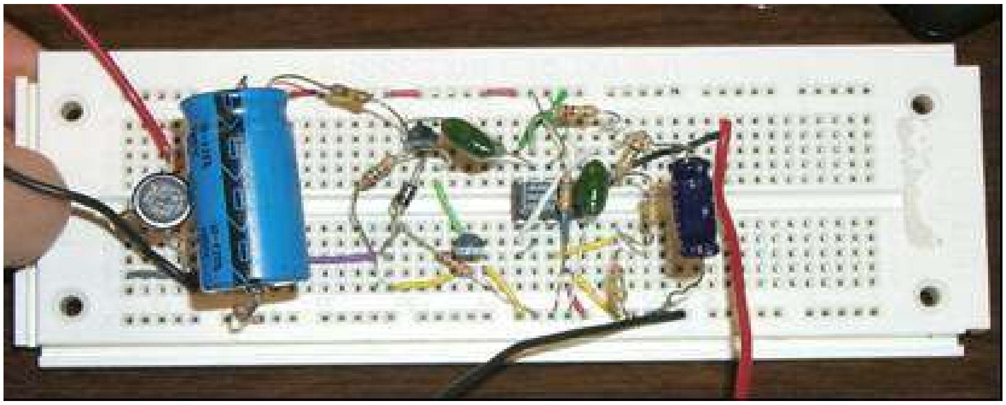

Figure 6:  Schematic of Power Harvesting Circuit.

## Layout of Battery Charging Circuit

The second method of power storage used was a circuit that charged a nickel metal hydride button cell battery. Nickel Metal Hydride batteries were used because they have a very high charge density and unlike a lithium ion battery 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 was very simple, it consisted of a full wave rectifier, capacitor and the battery intended to be charged, as shown in Figure 7. The voltage produced by the PZT was first full wave rectified then accumulated in a large capacitor, typically greater than 1000µF, then the battery intended to be charged 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, as shown in Figure 8

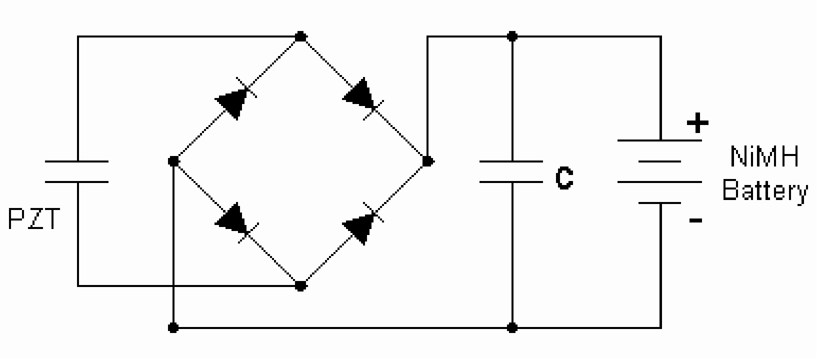

Figure 7: Schematic of the battery charging circuit.

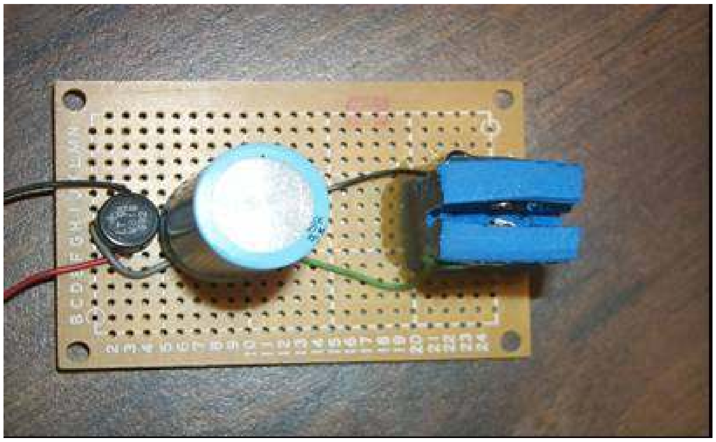

Figure 8: Layout of the Battery charging circuit built on a breadboard.

## Power Generation

Before the previously mentioned circuits were used to accumulate the generated energy, the amount of power this particular device could produce was measured. The results are specific to this particular piezoelectric device because there are many factors that affect the power generated, such as the substrate thickness, material used, excitation strength, and load resistance used. In general, the maximum power output occurs when the impedance of the piezoelectric element and the load resistance are matched. However, this cannot always be achieved during testing because the piezoelectric is a capacitive device, which means that the impedance varies with frequency, and therefore, the optimal load resistance varies. For the following power generation results, the load resistance was set to be the impedance of the PZT at the resonant frequency of the cantilever plate.

The power generated by the PZT was obtained using the voltage drop across a 10kΩ resistor. The power is calculated using the following relation obtained using Ohm's law:

$$P = \frac{V^2}{R} \tag{5.1}$$

where $P$ is the power and $V$ is the voltage drop across the load resistance $R$. The resulting power (with a chirp input from 0-250Hz) is shown in Figure 9 and the voltage and current found are shown in Figure 10. The data presented uses a chirp signal rather than the random signal shown previously because a chirp signal allows the voltage produced at different frequencies to be visualized more easily. As can be seen in the Figure, the maximum instantaneous power is identified as 2mW, which occurs at the resonance of the test plate. Three PZT plates were tested with the same configuration, and all produce a maximum power in the range of 1.5-2mW, and an average power of 0.14-0.2mW. These measurements were made with the magnitude of the chirp signal matching that of the signal measured from the automobile compressor. In addition, these measurements were made without a capacitor, which points out that this power would be immediately available for powering other devices. This estimation however does not account for the efficiencies of circuit components, such as a capacitor, diode, and voltage regulator. This estimated power certainly would not be sufficient to operate commonly available sensors, actuators or telemetry devices in many field applications, not to mention that it would require a certain period of time to charge the circuit, if a capacitor or battery is used.

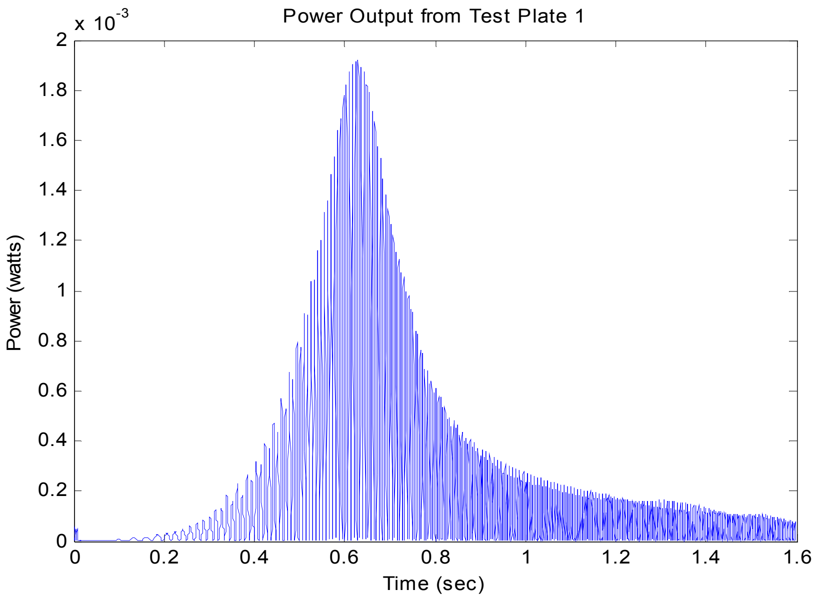

Figure 9:  Power output from test plate with a chirp input signal.

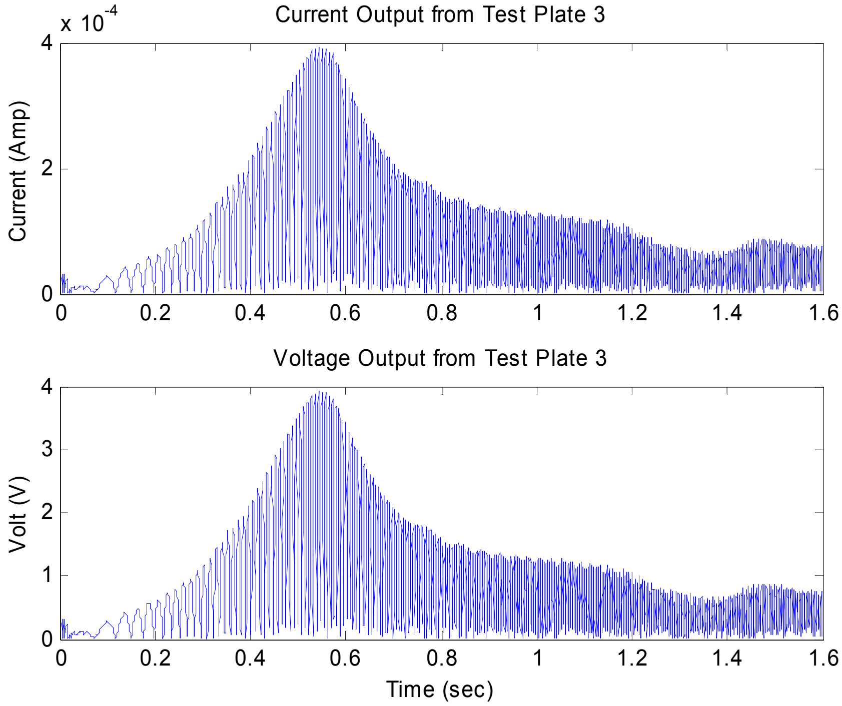

Figure 10:  Voltage and current output from the piezoceramic test pate.

## Results of the Capacitor Circuit

The random excitation of the plate with piezoceramic attached was able to successfully charge the capacitor and operate the circuit as expected. However, when using the high frequency excitation found on the compressor, once the capacitor reaches the charged level it discharges and charges so fast that the circuit outputs high frequency pulses corresponding to the charging and discharging of the circuit. To better show the performance of the capacitor circuit, the system was slowed down to allow the capacitor to visually discharge and recharge. Figure 11 shows the voltage on the capacitor and the output of the circuit with respect to time. The Figure shows that as the capacitor charges up to 6 volts, the circuitry allows it to discharge and the voltage output goes up to the regulated 5 volts. During the discharge of the capacitor, the output of the circuit stays at 5 volts until the capacitor reaches 4.5 volts, when the circuit begins to shut off, seen by the bump in the discharge of the capacitor. The process then repeats itself and the capacitor recharges. This method of collecting the energy generated by the piezoelectric allows the energy to be attained almost instantaneously. However, the circuit can only output energy for a very limited amount of time, making this method of storage impractical for powering many electronic devices, although it is effective for transmitting a short signal as done in the work by Kymissis et al. (1998).

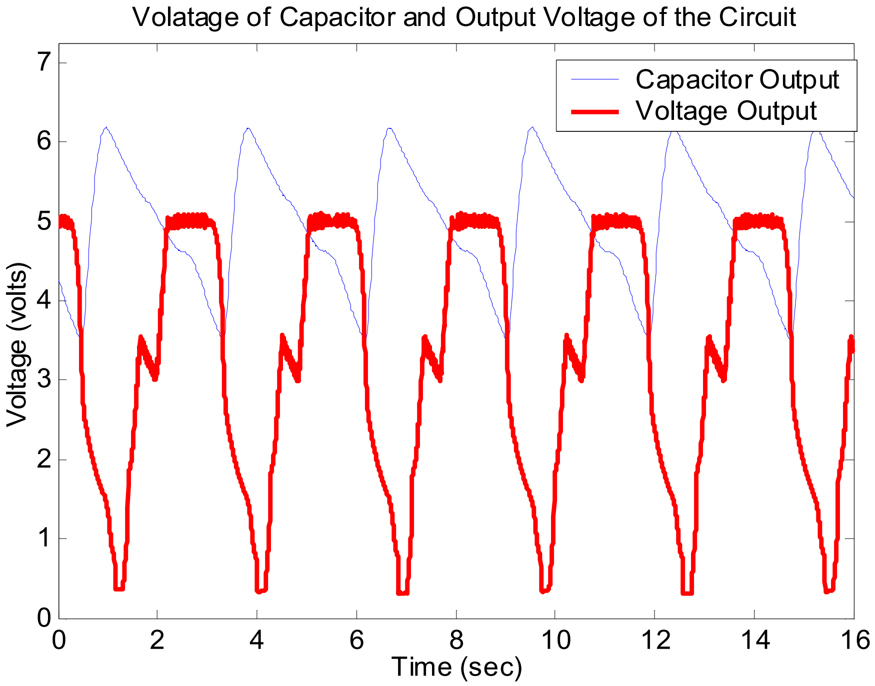

Figure 11: Plot of the time history of the Capacitor charging and discharging.

## Results of the Battery Charging Circuit

Next the ability of a monolythic piezoceramic and macro-fiber composite (MFC) actuator to be used as power harvesting devices for recharging batteries is compared. The ability to use the energy generated during vibration of piezoelectric materials to charge a battery has not previously been performed. Therefore, the ability to use these devices for this purpose must first be shown. For this investigation into recharging batteries with piezoelectric materials, two different types of excitation signals were used to charge a 40mAh battery (the unit "mAh" stands for mille-amp-hour and is a measure of the battery's capacity, a 40mAh capacity means that the batteries will last for 1 hour if subjected to a 40mA discharge current). The first excitation signal used was a sinusoidal input at the resonant frequency of the plate, in this case 63 Hz, while the second excitation was similar to the random signal from 0-1000 Hz, corresponding to the vibration of an automobile's compressor, shown in Figure 3. The resonant signal was used first because compatibility of the piezoelectric output power and the charging requirements of the battery needed to be shown before other tests could be performed. Furthermore, the resonant signal had a higher probability of charging the battery due to the larger power output obtained at this frequency. Once the compatibility of the piezoelectric device and battery was shown, the random excitation could be used to demonstrate that the vibration available from an automobile vibration was capable of recharging the battery.

The first tests performed used the resonant signal to excite the plate. The time required for the battery to charge up to its cell voltage of 1.2 volts was recorded. Although the batteries charge up to values higher than 1.2 volts, this value is used for consistency. A typical time history of the battery charging at random vibration is shown in Figure 12. Looking at the Figure it can be seen that the battery charges up to it cell voltage in slightly over 20 minutes. This Figure shows that the piezoelectric device is capable of charging a nickel metal hydride battery rather quickly. Once this previously unexploited method of storing energy generated through the piezoelectric effect was verified, the ability to use the random excitation of a typical automobile's compressor was be tested.

The random signal was applied to the piezoelectric plate and the charge time was recorded as was done with the resonant signal. The results of a typical charging test are shown in Figure 13. When using a random signal from 0-1000Hz the piezoelectric patch generates far less energy because of the low strain mode shapes at these higher frequencies. However, looking at the Figure, it can be seen that even with the use of a random signal, the piezoelectric can still charge a battery in a few hours.

Numerous advantages arise when the power harvested from the vibration of a piezoelectric device is stored in batteries. First, the capacitor method requires the piezoelectric to constantly produce electrical energy the entire time the application consumes power. This is because the capacitor does not possess the power storage properties that batteries have. The power stored in batteries can be accumulated and saved for use when no vibration is present. Also the time required for a capacitor to discharge is much smaller than that of the battery, this causes the capacitor circuit to switch on and off as the capacitor charges and discharges. For applications that require a constant power supply the capacitor is not suitable, however, when using batteries, two batteries can be installed allowing one battery to be in the charging stage while the other is used to supply power. In addition, the power directly generated by piezoelectric materials would suffice to operate some micro-scale devices, but it is slightly insufficient for running typical sensors, actuators, or computing devices desired in many applications. For instance, a PIC 16C71 processor from Microchip Technology requires 18mW at 4MHz (microchip Technologies Inc.), and a functional wearable computer (without communication device) can operate with a continuous power consumption of 0.5mW (Starner, 1996). By using the power generated from a PZT to charge a battery the number of applications increases significantly. The 40mAh battery that was charged in less than half an hour, contains enough energy to power a Casio LW22H watch for two years (Casio Inc.). This shows that if vibration was only present for a small amount of time when using rechargeable batteries to store the power generated by piezoelectric materials that the electronics could still receive the power needed to run for a significant amount of time.

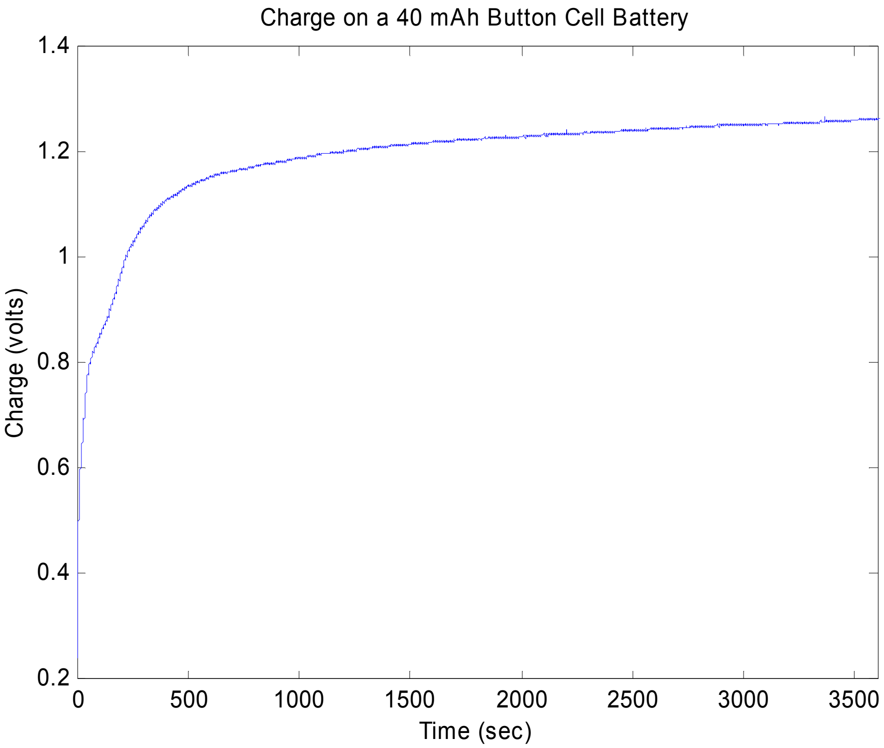

Figure 12: Plot showing the charge from a PZT on the battery (resonance input).

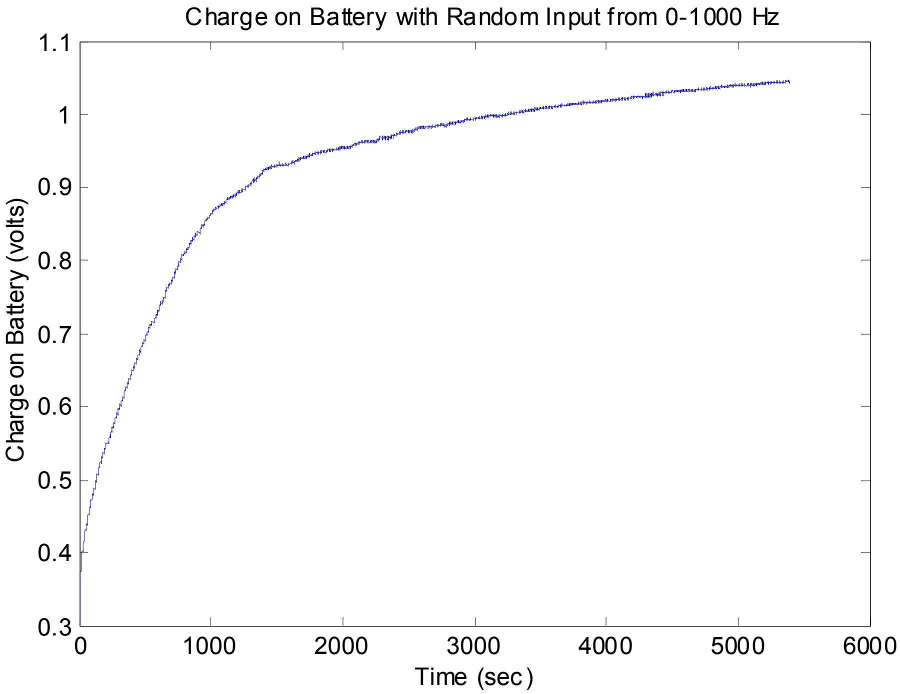

Figure 13: Plot showing the charge from a PZT on the battery (random input).

## Conclusions

This Paper has investigated two methods of storing power generated from piezoelectric materials. First, the amount of power capable of being generated from the particular piezoelectric power harvesting plate used was determined. This was done to both determine the maximum power generated and to provide a means of scaling this work to other devices. The first storage method tested was the use of a capacitor circuit and the second was a nickel metal hydride rechargeable battery. It was found the capacitor method worked well, but the high discharge rate of capacitors do not allow them to output a continuous signal, which is needed for many electronic applications. The second method of power storage tested, was to use rechargeable batteries, however, the concept of using piezoelectric materials to recharge a battery had not previously been shown. Therefore, tests were performed to demonstrate that the power output of a piezoelectric device is compatible with that required by the battery. To do this both random and resonant excitation signals were used. The amplitude of each signal corresponded to the vibration of a typical automobile compressor. Using these signals, it was found that when excited at resonance, the plate could charge the battery to its cell voltage in approximately 20 minutes and the random signal could charge the battery in only a few hours. A comparison of these two methods of power storage was also given.

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