Articles

A Review of Power Harvesting from Vibration using Piezoelectric Materials

Henry A. Sodano, Daniel J. Inman and Gyuhae Park

ABSTRACT—The process of acquiring the energy surrounding a system and converting it into usable electrical energy is termed power harvesting. In the last few years, there has been a surge of research in the area of power harvesting. This increase in research has been brought on by the modern advances in wireless technology and low-power electronics such as microelectromechanical systems. The advances have allowed numerous doors to open for power harvesting systems in practical real-world applications. The use of piezoelectric materials to capitalize on the ambient vibrations surrounding a system is one method that has seen a dramatic rise in use for power harvesting. Piezoelectric materials have a crystalline structure that provides them with the ability to transform mechanical strain energy into electrical charge and, vice versa, to convert an applied electrical potential into mechanical strain. This property provides these materials with the ability to absorb mechanical energy from their surroundings, usually ambient vibration, and transform it into electrical energy that can be used to power other devices. While piezoelectric materials are the major method of harvesting energy, other methods do exist; for example, one of the conventional methods is the use of electromagnetic devices. In this paper we discuss the research that has been performed in the area of power harvesting and the future goals that must be achieved for power harvesting systems to find their way into everyday use.

KEYWORDS: power harvesting, energy scavenging, energy generation, piezoelectric.

1. Introduction

With the recent advances in wireless and microelectromechanical systems (MEMS) technology, the demand for portable electronics and wireless sensors is growing rapidly. Because these devices are portable, it becomes necessary that they carry their own power supply. In most cases this power supply is the conventional battery; however, problems can occur when using batteries because of their finite lifespan. For portable electronics, replacing the battery is problematic because the electronics could die at any time and replacement of the battery can become a tedious task. In the case of wireless sensors, these devices can be placed in very remote locations such as structural sensors on a bridge or global positioning system (GPS) tracking devices on animals in the wild. When the battery is extinguished of all its power, the sensor must be retrieved and the battery replaced. Because of the remote placement of these devices, obtaining the sensor simply to replace the battery can become a very expensive task or even impossible. For instance, in civil infrastructure applications it is often desirable to embed the sensor, making battery replacement unfeasible. If ambient energy in the surrounding medium could be obtained, then it could be used to replace or charge the battery. One method is to use piezoelectric materials to obtain energy lost due to vibrations of the host structure. This captured energy could then be used to prolong the life of the power supply or in the ideal case provide endless energy for the electronic devices lifespan. For these reasons, the amount of research devoted to power harvesting has been rapidly increasing. In this paper we review and detail some of the topics in power harvesting that have been receiving the most research, including energy harvesting from mechanical vibration, biological systems, and the effects of power harvesting on the vibration of a structure.

2. Fundamentals of Power Harvesting

The piezoelectric effect exists in two domains: the first is the direct piezoelectric effect that describes the material's ability to transform mechanical strain into electrical charge; the second form is the converse effect, which is the ability to convert an applied electrical potential into mechanical strain energy. The direct piezoelectric effect is responsible for the material's ability to function as a sensor and the converse piezoelectric effect is accountable for its ability to function as an actuator. A material is deemed piezoelectric when it has this ability to transform electrical energy into mechanical strain energy, and likewise to transform mechanical strain energy into electrical charge.

Piezoelectric materials belong to a larger class of materials called ferroelectrics. One of the defining traits of a ferroelectric material is that the molecular structure is oriented such that the material exhibits a local charge separation, know as an electric dipole. Throughout the material composition the electric dipoles are orientated randomly, but when the material is heated above a certain point, the Curie temperature, and a very strong electric field is applied, the electric dipoles

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reorient themselves relative to the electric field; this process is termed poling. Once the material is cooled, the dipoles maintain their orientation and the material is then said to be poled. After the poling process is completed the material will exhibit the piezoelectric effect.

The mechanical and electrical behavior of a piezoelectric material can be modeled by two linearized constitutive equations. These equations contain two mechanical and two electrical variables. The direct effect and the converse effect may be modeled by the following matrix equations (IEEE Standard on Piezoelectricity, ANSI Standard 176-1987):

direct piezoelectric effect: $\{D\} = [e]^T\{S\} + [\alpha^S]\{E\}$ (1)

converse piezoelectric effect: $\{T\} = [c^E]\{S\} - [e]\{E\}$ (2)

Here, $\{D\}$ is the electric displacement vector, $\{T\}$ is the stress vector, $[e]$ is the dielectric permittivity matrix, $[c^E]$ is the matrix of elastic coefficients at constant electric field strength, $\{S\}$ is the strain vector, $[\alpha^S]$ is the dielectric matrix at constant mechanical strain, and $\{E\}$ is the electric field vector.

After the material has been poled, an electric field can be applied in order to induce an expansion or contraction of the material. However, the electric field can be applied along any surface of the material, each resulting in a potentially different stress and strain generation. Therefore, the piezoelectric properties must contain a sign convention to facilitate this ability to apply electric potential in three directions. For the sake of keeping this discussion simple, the piezoelectric material can be generalized for two cases. The first is the stack configuration that operates in the –33 mode and the second is the bender, which operates in the –13 mode. The sign convention assumes that the poling direction is always in the "3" direction, with this point the two modes of operation can be understood. In the –33 mode, the electric field is applied in the "3" direction and the material is strained in the poling or "3" direction; in the –31 mode, the electric field is applied in the "3" direction and the material is strained in the "1" direction or perpendicular to the poling direction. These two modes of operation are particularly important when defining the electromechanical coupling coefficient that occurs in two forms: the first is the actuation term d, and the second is the sensor term g. Thus g_{13} refers to the sensing coefficient for a bending element poled in the "3" direction and strained along "1".

A full description of the piezoelectric effect and the methods used to model the behavior of these materials is beyond the scope of this paper. However, a significant number of journal papers and conference proceedings develop accurate models and discuss the fundamentals of these materials in great detail (Crawley and de Luis, 1987; Crawley and Anderson, 1990; Hagood et al., 1990; Smits and Choi, 1991; Smits et al., 1991; Near, 1996; Inman and Cudney, 2000; Niezrecki et al., 2001) as well as numerous books published on this topic (Gandhi and Thompson, 1992; Ikeda, 1996; Banks et al., 1996; Culshaw, 1996; Clark et al., 1998; Srinivasan and McFarland, 2001; Worden et al., 2003).

In the following sections of the paper we break the various works on power harvesting into the following groups: mechanical vibration, power harvesting efficiency, power storage and circuitry, implantable and wearable power supplies, and damping induced by power harvesting. In Section 3, we discuss one paper that investigates the amount of energy available from one power harvesting device subjected to a vibration environment. In Section 4 we look at research that was performed to classify the efficiency of certain methods of power harvesting. In Section 5 we look at research into various types of power storage mediums and different circuits developed to maximize the electric power generated. A large portion of work has been performed in the field of power harvesting from biological systems and, while the papers found in section 6 may deal with various subjects, they all have a major focus on the ability to obtain energy from human or animal activity. Section 7 will detail work into quantifying the effect of power harvesting on the dynamics of a vibrating structure.

3. Mechanical Vibration

One of the most effective methods of implementing a power harvesting system is to use mechanical vibration to apply strain energy to the piezoelectric material or displace an electromagnetic coil. Power generation from mechanical vibration usually uses ambient vibration around the power harvesting device as an energy source, and then converts it into useful electrical energy, in order to power other devices. The research in the following three sections has made use of mechanical vibration in order to quantify the efficiency and amount of power capable of being generated, as well as to power various electronic systems, ranging from digital electronics to wireless transmitters.

Williams and Yates (1996) proposed a device, which generated electricity when embedded in a vibrating environment. For their evaluation, an electromagnetic transducer was chosen. A harmonic analysis of the generator was performed in order to evaluate the viability of the device and to optimize the design. It was determined from the analysis that the amount of power generated was proportional to the cube of the vibration frequency. This illustrated that the generator was likely to perform poorly at low frequencies. It was also determined that a low damping factor was required to maximize power generation, therefore the design must allow for large deflections of the mass. For a typical device the predicted power generation was 1 μW at an excitation frequency of 70 Hz, and 0.1 mW at 330 Hz (assuming a deflection of 50 μm).

4. Power Harvesting Efficiency

The two papers in this section investigate the efficiency of a piezoelectric generator. The first paper looks at the efficiency of a piezoelectric vibrating in the –31 direction and the second paper tests a stack that operates in the –33 direction. It is important to quantify the efficiency of the power harvesting medium in order to allow the device to be designed to function optimally in its intended environment.

Umeda et al. (1996) carried out an investigation concerning the fundamentals of a generator, which transformed mechanical energy to electrical energy using a piezoelectric vibrator and a steel ball. They also investigated the effect of the various characteristics of the piezoelectric vibrator. To simulate the generation mechanism, they introduced an electrical equivalent model. The fundamental modes of bending vibration for two models were calculated: model A (the transducer with the steel ball) and model B (the transducer only). The admittance characteristics of each model were measured and they found that it was clear that the peak frequencies corresponded to the vibration modes. It was seen that the calculated waveforms of the output voltage were similar to the measured ones; therefore, the model provided an accurate simulation of the output voltage. An efficiency curve was drawn for various input mechanical energies, and they determined that as the potential energy of the ball increased the maximum efficiency decreased. A large part of the applied energy was returned to the steel ball in the form of kinetic energy causing it to bounce off the plate. It was concluded that the energy generated would be large if the steel ball did not bounce off after an impact but rather vibrated with the piezoelectric plate. This case was simulated and it was determined that a maximum efficiency of 52% could be obtained. The effects of the characteristics of the piezoelectric vibrator were investigated and it was determined that the efficiency increased if the mechanical quality factor increased, the electromechanical coupling coefficient increased and the dielectric loss decreased.

Goldfarb and Jones (1999) have analyzed the efficiency of the piezoelectric material in a stack configuration for the purpose of electric energy generation. An analytical model is presented and suggests that the fundamental problem in generating electrical power from the piezoelectric material is that it stores the majority of the energy produced and returns it to the excitation source that initially caused the charge to be generated. They state that this occurrence is particularly problematic when the piezoceramic is placed in parallel with a capacitor that is in series with the load. Therefore, it is suggested that the maximum efficiency of power generation can be achieved by minimizing the amount of energy stored inside the piezoelectric material. The efficiency of the model was determined across a spectrum of frequencies and resistive values. It was found that, at frequencies above 100 Hz, the efficiency of the stack actuator was negligible and that the highest efficiency was obtained at 5 Hz. This frequency is far lower than the first mechanical and electromechanical resonances of the stack, which occur at approximately 40 and 60 kHz, respectively. The authors state that the frequency of maximum efficiency occurs so low because of the energetic structure of the stack. In addition, it is found that the efficiency of the stack is most strongly dependent on the frequency of excitation, with the load resistance providing a lower effect on it.

5. Power Storage and Circuitry

When using piezoelectric materials as a means of gathering energy from the surroundings, in most cases it is a necessity that a means of storing the energy generated be used. Without accumulating a significant amount of energy, the power harvesting system will not be a feasible power source for most electronics. The following research has made use of circuitry to either store the energy generated by the piezoelectric material or to develop circuits that allow the energy to be removed from the piezoelectric in a more efficient way allowing more power to be generated.

Umeda et al. (1997) continued their investigation with a study into the characteristics of energy storage by a piezo-generator with a bridge rectifier and capacitor. As in their previous research, the piezo-generator consisted of a steel ball and a piezoelectric vibrator, and with the introduction of a bridge rectifier and capacitor they were able to determine the energy storage characteristics both theoretically and experimentally. To simulate the generation and storage mechanism they employed an equivalent circuit model, where the input mechanical energy was translated into an initial electrical energy. Changing the parameters of the circuit simulated the separation of the vibrator and the ball. After examining the storage characteristics for the first impact they determined that as the capacitance increased the electrical charge increased due to an increased duration of oscillation. They also determined that for each value of capacitance as the initial voltage increased the stored electric charge decreased, and the efficiency increased. When considering the overall storage characteristics for multiple impacts they determined that, for each value of capacitance, the first impact gave the largest electric charge. The overall storage characteristics were observed when the initial voltage was changed; as the initial voltage increased, the electric charge decreased for each value of capacitance, while the efficiency increased. Their prototype achieved a maximum efficiency of 35%, over three times that of a solar cell.

Elvin et al. (2001) used a polyvinylidene fluoride (PVDF) piezofilm sensor attached to a simply-supported Plexiglas beam with an aspect ratio of 0.11 to generate an electrical signal. The goal of this power harvesting experiment was to generate sufficient energy from the strain induced on the piezofilm by the bending beam to power a telemetry circuit. The energy generated from the PVDF patch was accumulated in a capacitor. A switch was added to the circuitry to allow the capacitor to charge to a predetermined value of 1.1 V, at which point the switch would open and the capacitor would discharge through the transmitter. Once the capacitor had discharged to a value of 0.8 V, the switch would close and the capacitor would be allowed to recharge and repeat the process. The operation of the power harvesting system was found to provide the required energy to power the circuitry and transmit a signal containing information regarding the strain of the beam a distance of 2 m.

Kasyap et al. (2002) developed a lumped element model (LEM) using an equivalent circuit model to describe the power generated from the forced vibration of a cantilever beam with a piezoelectric element attached. It was found that the LEM provided results consistent with those generated using a finite element model from excitation frequencies ranging from DC through the first resonance of the beam. A similar result was found during a second model validation using experimental results. The goal of the study was to use a flyback converter to increase the efficiency of the power transfer from the piezoelectric patch to a power storage medium. The use of a flyback converter allows the circuit impedance to be matched with the impedance of the piezoelectric device. It was found that when using the flyback converter a peak power efficiency of 20% was achieved.

The previous papers in this section concentrated their efforts on the use of a capacitor as the storage medium. However, in most cases the capacitor is not an efficient method of storing energy. Sodano et al. (2002) performed a study to investigate the amount of power generated through the vibration of a piezoelectric plate, as well as two methods of power storage. The plate was excited using an electromagnetic shaker with both resonant and random excitation signals. It was found that the piezoelectric could generate a maximum power of 2 mW when excited at the resonant frequency of the clamped-free plate. In addition, the ability of the piezoelectric plate to store its power in both a capacitor circuit and a rechargeable battery was tested. This paper was the first to demonstrate that the power output of piezoelectric material was able to recharge a fully discharged battery without the use of external energy sources. It was also shown that both methods of power storage could be used; however, the use of rechargeable batteries was found to possess power storage qualities that would allow a far larger range of electronic devices to be powered than the capacitor. This is because of the capacitor's poor ability to store large amounts of power and its fast discharge rate, which caused the output of the circuit to switch on and off making a periodic power supply.

Following the work of Sodano et al. (2002), a second paper was published (Sodano et al., 2003) to further investigate the ability of piezoelectric materials to recharge batteries. This study compared the macro-fiber composite (MFC) actuator with the monolithic piezoceramic material PZT for recharging batteries. The MFC is an actuator that uses piezofibers and interdigitated electrodes to capitalize on the higher g_{33} piezoelectric coupling coefficient, allowing it to produce higher strain and force than typical monolithic PZT (Sodano et al., 2004a). This property of the actuator makes it attractive for power harvesting applications. First, the efficiency of both the MFC and PZT was determined in order to compare their ability to generate electrical energy. It was determined that the MFC was less effective for power harvesting than the PZT because of a very low current generation by the MFC. Reasons for the low current generation were proposed. Furthermore, because of the poor current output of the MFC it was found to be ineffective at charging the batteries due to their requirement for fairly significant current. However, the PZT was used to charge a variety of different capacity nickel metal hydride batteries; a typical charge cycle of one battery is shown in Figure 1. The charge time for each was supplied and the maximum capacity battery capable of efficiently being charged was determined.

Another investigation into the ability to store and use the energy generated from a power harvesting device was performed by Amirtharajah and Chandrakasan (1998). They designed and tested a chip which integrated a finite impulse response (FIR) filter, power field-effect transistors (FETs) and pulse width modulation (PWM) control circuitry, in order to demonstrate the possibility of running a digital system from the power generated by vibrations in its environment. They proposed a self-powered system consisting of a load circuit, a generator to create voltage that could vary depending on the environment, a voltage regulator to set the voltage to a desired level, and a backup power source. The implementation of a backup power source was required at circuit startup because of the need for the voltage regulator to obtain its power from a source other than the generator, whose output was too uncontrolled to be utilized. An inertial electromechanical generator and acoustic generator were proposed as the power supply and a prototype of each was built to test its ability to power the digital circuitry. It was found that the electromagnetic generator was capable of supplying 400 μW of power during a typical excitation that was intended to represent that of a human walking. The electromagnetic prototype was tested and it was shown that the portable digital system could be powered entirely from ambient environmental vibrations for a period of 23 ms. A second investigation into the use of incident sound as a form of excitation energy was also tested and it was found that it could generate power sufficient to run the system; however, the acoustic energy source was limited to very high noise environments (about 114 dB).

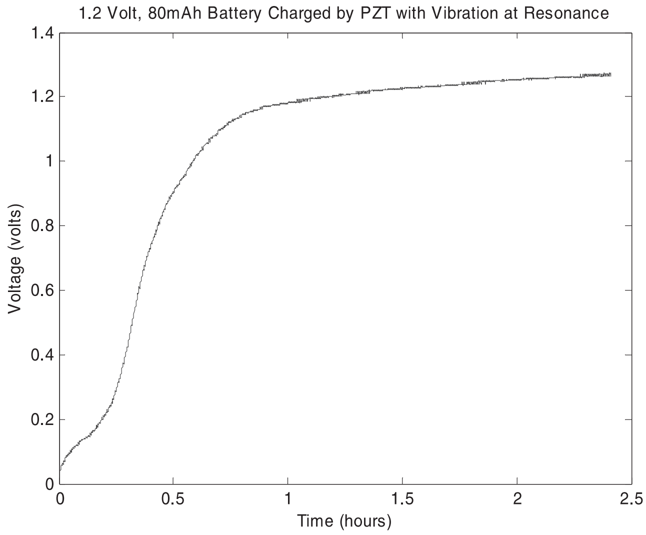

Figure 1. Typical charge cycle of a nickel metal hydride battery; in this case an 80 mAh battery was charged (Sodano et al., 2003)

Rather than developing methods of accumulating the energy developed by piezoelectric materials, Ottman et al. (2002) worked to develop a circuit that would maximize the power flow from the piezoelectric device. A DC–DC step-down converter was implemented in coordination with a wave rectifier, capacitor, and electrochemical battery. In addition to the circuitry, an adaptive control technique was developed to continuously implement optimal power transfer theory and to maximize the power flow into the battery. This active controller varied the switching frequency of the step-down converter to maximize to the power flow from the piezoelectric elements and to raise the current to levels more acceptable for maintaining the charge on batteries. The circuit and controller were built and tested on a bimorph piezoelectric cantilever plate excited at resonance. It was found that when using the circuit, over four times the energy was transferred to the battery than with direct charging alone. However, if the power harvesting medium produced less than 10 V, then power flow into the battery was reduced because of losses in the additional circuit components.

Hofmann et al. (2002) have continued the work of Ottman et al. (2002) by implementing circuitry to maximize the power flow from the piezoelectric device. This study uses a similar circuit as before, but realizes that one of the drawbacks of their previous work was that the PWM control circuitry required more power than was produced at low levels of excitation. In order to correct this problem, the authors realized that the optimal duty cycle changes very little at higher levels of energy generation when excited with a sinusoidal signal. Therefore, the control circuitry was removed and a constant duty cycle was used. Furthermore, at low levels of power generation the optimal duty cycle varies greatly, causing the PWM generation circuitry to be ineffective; thus, this circuitry is bypassed at a certain threshold and a pulse-charging circuit is used. The optimal value of the duty cycle was investigated both analytically and experimentally, resulting in a value of 2.8%. With this circuit, the power flow was increased by over a factor of 3 at a peak resonant excitation level of 70 V open circuit. Additionally, their circuitry was found to reach values as high as 70% efficiency at an optimal value of excitation.

Lesieutre et al. (2002) discuss two topics: the first is an energy harvesting circuit and the second a measure of the damping induced in a structure due to energy harvesting, which will be discussed in a section 7. The goal of the first portion of this research was to further improve upon a circuit that would maximize the energy output of the piezoelectric material through the use of a DC–DC step-down converter. The energy harvesting circuit was developed to improve on two previously constructed circuits in Ottman et al. (2002) and Hoffman et al. (2002). The first circuit used a controller to modify the PWM of a DC–DC step-down converter, which consumed a significant amount of power. Additionally, their circuit used the controller at all times, which means that when the piezoelectric produces a very small amount of energy the controller would be drawing more energy than available. To correct this problem, a second circuit was developed using a constant near-optimal duty cycle and the control circuitry was removed. However, the circuit was still inefficient when less than 25 V open circuit was generated. Therefore, to further correct this issue the pulse-charging circuitry that turned on below 25 V open circuit was done away with and only direct charging was used in this range. This circuit was found to provide a 324% increase in power when excited at a level sufficient to produce 68 V open circuit and it alleviated many of the shortcomings of the previously used circuits.

6. Implantable and Wearable Power Supplies

In an effort to incorporate computers and digital systems into our everyday lives, research has been carried out to investigate the possibility and practicality of imbedding them into our clothing, or inside biological systems such as the human body. The use of power harvesting devices to capture the energy lost during everyday human life is a captivating idea and has been one of the main topics facilitating the rapid growth of the power harvesting field. The following research presented here has investigated numerous ideas of obtaining energy from both human and animal activity.

Possibly the first investigation of power scavenging systems incorporated into a biological environment was performed in 1984 by Hausler and Stein, who published a paper proposing the use of an implantable physiological power supply using PVDF films (Hausler and Stein, 1984). Based on the concept that the energy expended for respiration could be converted into electric power, Hausler and Stein used the relative motion of the ribs to periodically stretch a converter. A miniaturized prototype was designed and used to conduct an animal experiment. The converter was fixed to the ribs of a mongrel dog and spontaneous breathing led to a peak voltage of 18 V, which corresponded to a power of about 17 μW. However, the power generated was insufficient to power the desired electronics, making it ineffective for use as an implanted power supply. It is speculated that optimization of the PVDF film properties, as well as a more suitable converter attachment at the ribs would make it possible to develop power converters with an output of 1 mW, yielding a mechanical power load of 20 mW. In addition, this study was performed at an early stage in low-power electronic and computer technology, suggesting that the use of more efficient electronics, now available, would have resulted in significantly more promising results.

Throughout our daily activity, a significant amount of energy is expended in various forms, some of which make for attractive power harvesting locations. Starner (1996) has performed an investigation into the amount of power expended for a vast range of human activities. His paper explores the possibility of eliminating bulky and inconvenient power systems by harnessing the energy expended in everyday activity and using it to generate power for a computer. The paper contains a survey of various power generation methods ranging from body heat and breath to finger and upper limb motion. An analysis of the power available from each of the different locations is presented. He calculates that approximately 67 W of power is lost during walking and that a piezoelectric device mounted inside a shoe with a conversion efficiency of 12.5% could achieve 8.4 W of power. Two methods of power generation during walking are identified, piezoelectric and rotary generator, with the advantages and weaknesses of each outlined. One idea he explains is to place piezofilm patches in the joints of clothing to harvest the energy lost during bending and he states that about 0.33 W could be obtained. In addition to investigating the possible location and power converters to be used, he realizes that the energy generated will never be constant and, at times, energy may not be produced at all, making the use of a power storage medium a must. Power would be accumulated when the energy is plentiful and would be used when insufficient energy is produced. The paper investigates two methods of power storage: the capacitor and rechargeable batteries. He states that energy storage in a capacitor would be sufficient for low-power areas such as blood pressure and body heat, but rechargeable batteries are a necessity for higher power areas, such as limb motion and walking.

The work of Starner (1996) brought the possibility of power harvesting locations around the human body to the attention of many researchers and the work in wearable power supplies began to grow. Post and Orth (1997) investigated the concept of “smart fabric” for wearable clothing. Their research described techniques used in building circuits from commercially available fabrics, fasteners, etc. Multiple different conductive fabrics were explored, including silk organza, constructed of silk thread wrapped in thin copper foil running in one direction and plain silk in the other. This material was highly conductive, had a high tensile strength, and could withstand high temperatures, allowing it to be sewn using industrial machines. A second type of conductive yarn is manufactured with both conductive and cloth fiber interspersed throughout the material. Post and Orth (1997) state that by varying the amount of conductive material the resistance of the fiber can be adjusted and other components, such as capacitors and coils, can be sewn directly into the fabric.

The use of this type of material has led to the development of several devices constructed of fabric, including a type of fabric keyboard that can be crumpled up, thrown in the wash and even used as a potholder without losing its ability to function. These materials would be very effective for transmitting the energy generated around the body to the storage medium in a convenient and unnoticeable way.

Kymissis et al. (1998) studied the use of piezoelectric actuators located inside the sole of a shoe for power harvesting. Their research examined three different devices that could be built into a shoe to harvest excess energy and generate electrical power parasitically while walking. The devices that were considered included a "Thunder" actuator constructed of piezoceramic composite material located in the heel, a rotary magnetic generator also located under the heel, and a multilayer PVDF foil laminate patch located in the sole of the shoe. The Thunder actuator was developed by the National Aeronautics and Space Administration (NASA) and has a rainbow (arch) configuration that allows the high impact vertical energy of the heel to be translated into bending strain for electrical power generation. The electromagnetic generator used the pressure of the heel to spin a flywheel and rotary generator, to extract the power from the pressure of the heel during walking. The last device used was the laminate of piezofilm, or "stave", which was used to harness the energy lost during the bending of the sole. In order to compare the performance of the three methods, a working prototype was constructed for each and its performance was measured. The peak powers were observed to approach 20 mW for the PVDF stave and 80 mW for the PZT unimorph. However, because of slow excitation, the average power generated from both the PVDF stave and the Thunder actuator was significantly lower, approximately 1 and 2 mW, respectively. The shoe mounted rotary generator resulted in a peak power of about 1 W and averaged to about 0.25 W over a 5 s sample period. However, the rotary generator was not easily integrated into the shoe and significantly interfered with the user's gait, unlike the PVDF stave and PZT Thunder actuator. Because of these two limitations of the rotary generator, it was determined that it was an unrealistic method of generating energy during walking. After examining the performance of the piezoelectric generators, their ability to power a battery-less active radio-frequency (RF) tag was tested. The authors developed a circuit that used a capacitor to accumulate the electrical energy along with various other components to regulate the charging and discharging cycle of the capacitor. The discharge of the capacitor was limited at 5 V to accommodate an encoder and transmitter used to transmit the RF tag. The circuit was found to be compatible with both the shoe mounted piezoelectric generator systems and was able to transmit five to six 12-bit signals every few steps. The circuitry developed in this study has also found use in the work of several other researchers. The research presented in this paper demonstrated the potential of piezoelectric power harvesting devices for use as a power supply of self-powered electronics. Further, the ability to use energy from power harvesting for transmitting data was shown and gained the attention of many researchers in the area of self-powered wireless sensors.

Similar to the work of Kymissis et al. (1998), Shenck (1999) demonstrated electrical energy generation from piezoelectric patches located in a shoe. He evaluated different regulation systems for conditioning the electrical energy harnessed by the piezoceramic source imbedded in the sole of a shoe. A rigid bimorph piezoceramic transducer was developed and integrated into a mass produced shoe insert. The use of a bimorph piezoelectric device posed several advantages over the previously used actuator. Since the vertical displacement of the transducer was required to be very small, so the use of a second piezoelectric patch allowed more energy to be generated. Additionally, with two piezoelectric patches present the electrical leads could be configured as parallel energy sources, improving the lumped impedance characteristics of the sources. Furthermore, it was determined that a bimorph transducer was stronger and less intrusive to the user, because it was capable of better adapting to various distributions of body weight and footfall velocity. The piezoelectric patch was configured similarly to the Thunder actuator previously mentioned, allowing it to absorb the energy of a heel strike and lift during walking, thus inducing a charge across the capacitive PZT. The energy stored was removed at its peak and converted into a useful form using a high-frequency switching technique.

A design study was conducted by Ramsey and Clark (2001), which investigated the feasibility of using a piezoelectric transducer as a power supply for an *in vivo* MEMS application. The 33- and 31- modes of operation for a piezoelectric generator were analyzed and compared, and it was determined that when using the 31- mode, or thin plate configuration, there existed a strong mechanical advantage in converting applied pressure to working stress. For very low-pressure sources, the 31- mode had a greater advantage in energy conversion, which became important when attempting to implement this technology in a biological microsystem application. A design study was used to investigate whether or not the 31- mode was well suited for the *in vivo* environment, and it was carried out using a square thin plate driven by blood pressure. It was shown that ample power existed from various sources in the body to meet the requirements of their investigation, and additional calculations illustrated the feasibility of providing intermittent power instead of continuous power.

7. Damping Effect of Power Harvesting

When a power harvesting system is integrated into a structure, energy is removed in the form of electricity. Because energy is removed from the structure, it must see some effect on its dynamics. The subsequent papers have looked to quantify this damping effect.

Lesieutre et al. (2002) investigated the damping added to a structure due to the removal of electrical energy from the system during power harvesting. The damping was first estimated using analytical methods and later verified through experimental results. It is stated that optimal power transfer is achieved when the operating rectifier output voltage is half the open circuit voltage; this assumption allows the effective loss factor of the system to be dependent only on the coupling coefficient. Using this simplification the study analytically predicted the damping loss factor from power harvesting to be 2.3% in the fundamental mode of vibration of a cantilever beam. The prediction was then verified to be 2.2% through experimental results, showing excellent agreement between theory and their experimental work. This result was found

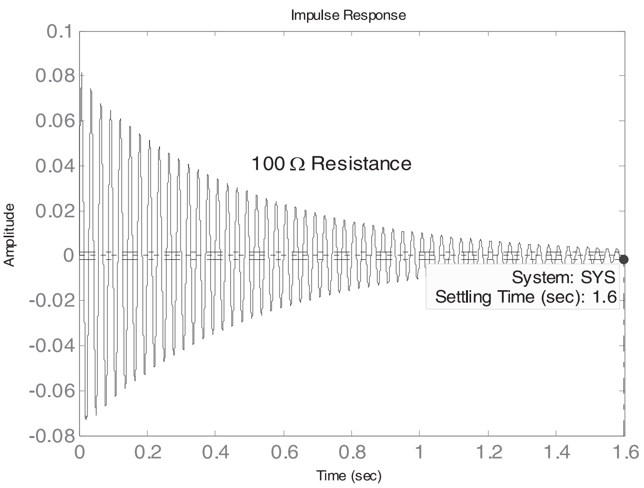

Figure 2. Impulse response with a 100Ω resistive load (Sodano et al., 2004a)

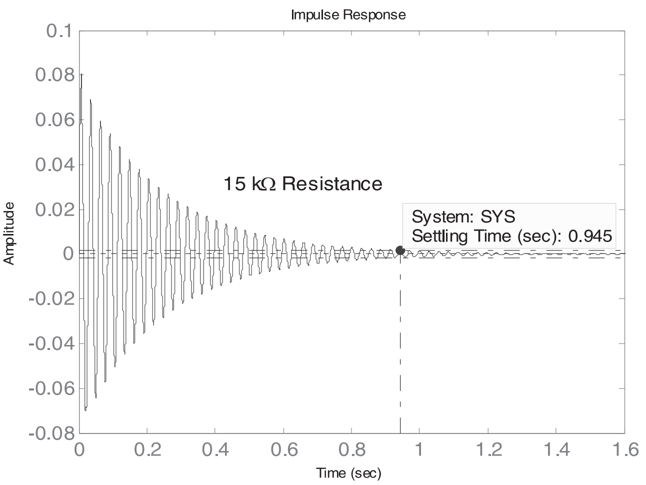

Figure 3. Impulse response with a 15 kΩ resistive load (Sodano et al., 2004a)

to be comparable to that of resistive shunting while not having the frequency dependency that shunting does.

Sodano et al. (2004b) presented a paper that developed a model of a power harvesting system. The model was derived from variational principles and was used to predict the amount of electrical energy that could be generated through the vibration of piezoelectric patches on a beam structure. To validate the accuracy of the model, a composite beam with a complex layout of four piezoelectric patches was experimentally tested and compared to the results of the simulation. It was shown that the model provided a very accurate estimate of the power generated independent of the excitation frequency and load resistance. Following the validation of the model, it was used to show the effects of power harvesting on the damping of a structure that has energy being generated from it. The impulse response of a cantilever beam was shown for a power harvesting system that had three different load resistances; the effect of power harvesting on each of these

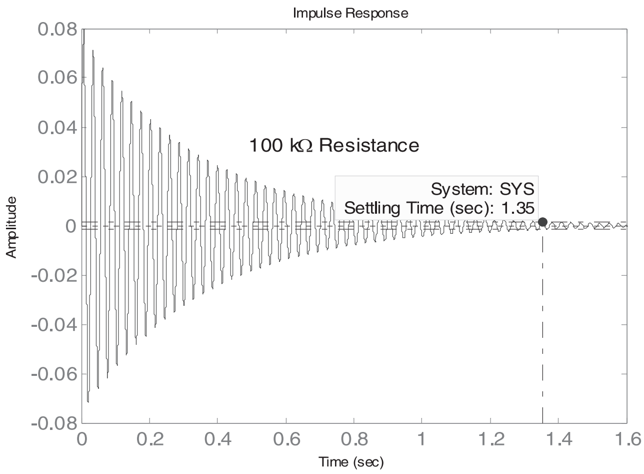

Figure 4. Impulse response with a 100 kΩ resistive load (Sodano et al., 2004a)

three cases is shown in Figures 2, 3 and 4. It was shown that for a small load resistance, the damping did not become much larger than the mechanical damping of the structure, because only a slight amount of energy was being removed from the system. As the resistance increases, more energy is removed from the system and the damping increases, as shown in Figure 3. At the optimal load resistance the maximum energy is removed from the system and the damping becomes far larger than that of the structure. As the load resistance moves past the optimal value the damping begins to decrease again, as shown in Figure 4. The damping begins to decrease at higher load resistances because as the load increases in impedance the circuit begins to look like an open circuit, thus interfering with the ability of the generated electricity to efficiently flow out of the piezoelectric material. This simulation showed that power harvesting works very much like a shunt damping system with the major difference being that the energy is stored rather than dissipated.

8. Future of Power Harvesting

The idea of carrying electronic devices such as a portable radio and never worrying about when the batteries will need to be replaced could be far closer than one would think. This thought has caused the desire for self-powered electronics to grow quickly, leaving only one limitation before these devices can become a reality. The one issue that still needs to be resolved is a method to generate sufficient energy to power the necessary electronics. However, with the advances in power harvesting that have been outlined in this paper the ability to obtain and accumulate the necessary amount of energy to power such devices is clearly possible.

The major limitations facing researchers in the field of power harvesting revolve around the fact that the power generated by piezoelectric materials is far too small to power most electronics. Therefore, methods of increasing the amount of energy generated by the power harvesting device or developing new and innovative methods of accumulating the energy are the key technologies that will allow power harvesting to become a source of power for portable electronics and wireless sensors. One recent advance that shows great promise for power harvesting is the use of rechargeable batteries as a means of accumulating the energy generated during power harvesting. Much of the early research into power harvesting looked to the capacitor as a method of storing energy and powering electronics. However, the capacitor has poor power storage characteristics because of its quick discharge time, causing the electrical output of such circuitry to switch on and off as the capacitor charges and discharges. This aspect of the capacitor is not suitable for powering computational electronics. However, the rechargeable battery can be charged and then used to run any number of electronic devices for an extended period of time while being continuously charged by ambient motion. Innovations in power storage such as the use of rechargeable batteries with piezoelectric materials must be discovered before power harvesting technology will see widespread use.

Furthermore, the efficiency of the power harvesting circuitry must be maximized to allow the full amount of energy generated to be transferred to the storage medium. The continuous advances that are being made in low-power electronics must be studied and utilized both to optimize power flow from the piezoelectric and to minimize circuit losses. Gains in this area are a necessity for the successful use of piezoelectric materials as power harvesting devices. Additionally, the intended location of the power harvesting system must be identified so that its placement can be optimized and the excitation range realized to allow for tuning of the power harvesting device. By tuning the power harvesting medium with the structure, the excitation can be made to maximize the strain of the piezoelectric material using the concept of resonance.

Finally, practical applications for power harvesting systems such as wireless sensors and self-powered damage detection units must be clearly identified to encourage growth in this area of research, thus allowing the contributions and in flow of ideas to increase. With the advances in wireless technology and low-power electronics, power harvesting is the missing link for completely self-powered systems.

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