A Review of Energy Harvesting From Piezoelectric Materials

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ABSTRACT : *The field of power harvesting has experienced significant growth over the past few years due to the ever-increasing desire to produce portable and wireless electronics with extended lifespan. Current portable and wireless devices must be designed to include electrochemical batteries as the power source. The use of batteries can be troublesome due to their limited lifespan, thus necessitating their periodic replacement. In the case of wireless sensors that are to be placed in remote locations, the sensor must be easily accessible or of a disposable nature to allow the device to function over extended periods of time. Energy scavenging devices are designed to capture the ambient energy surrounding the electronics and convert it into usable electrical energy. The concept of power harvesting works towards developing self-powered devices that do not require replaceable power supplies. A number of sources of harvestable ambient energy exist, including waste heat, vibration, electromagnetic waves, wind, flowing water, and solar energy. While each of these sources of energy can be effectively used to power remote sensors, the structural and biological communities have placed an emphasis on scavenging vibration energy with piezoelectric materials. This article will review recent literature in the field of power harvesting and present the current state of power harvesting in its drive to create completely self-powered devices.*

Keywords - Energy Harvesting Review, Vibration Power, Self-Powered Systems, Power scavenging

I.   INTRODUCTION

1.1   Vibration Energy Harvesting

Vibration-based energy harvesting has received growing attention over the last decade. The research motivation in this field is due to the reduced power requirement of small electronic components, such as the wireless sensor networks used in structural health monitoring applications. The ultimate goal in this research field is to power such small electronic devices by using the vibration energy available in their environment. If this can be achieved, the requirement of an external power source as well as the maintenance requirement for periodic battery replacement can be minimized.

It appears from the literature that the idea of vibration-to-electricity conversion first appeared in a journal article by Williams and Yates in 1996. They described the basic transduction mechanisms that can be used for this purpose and provided a lumped-parameter base excitation model to simulate the electrical power output for electromagnetic energy harvesting. As stated by Williams and Yates, the three basic vibration-to-electric energy conversion mechanisms are the electromagnetic [1], electrostatic and piezoelectric transductions. Over the last decade, several articles have appeared on the use of these transduction mechanisms for low power generation from ambient vibrations. Two of the review articles covering mostly the experimental research on all transduction mechanisms are given by Beeby et. al. [2] .Comparing the number of publications appeared using each of these three transduction alternatives, it can be seen that the piezoelectric transduction has received the greatest attention especially in the last five years. Four review articles have appeared in four years [2004-2008] with an emphasis on piezoelectric transduction to generate electricity from vibrations.

The main advantages of piezoelectric materials in energy harvesting (compared to using the other two transduction mechanisms) are their large power densities and ease of application. When Vibration input is applied; usable voltage output can be obtained directly from the piezoelectric material itself based on the direct piezoelectric effect. In electrostatic energy harvesting, for instance, an input voltage is required so that it can be alternated due to the relative vibratory motion between the capacitor elements .The voltage output in piezoelectric energy harvesting emerges from the constitutive law of the material which eliminates the requirement of an external voltage input. In addition, unlike electromagnetic devices, piezoelectric devices can be fabricated both in macro-scale and micro-scale owing to the well-established thin-film and thick-film fabrication techniques .Typically, a piezoelectric energy harvester is a cantilevered beam with one or two piezoceramic layers. The harvester beam is located on a vibrating host structure and the dynamic strain induced in the piezoceramic layer(s) generates an alternating voltage output across the electrodes covering the piezoceramic layer(s).

1.2   Need of Energy Harvesting
       Advanced technical developments have increased the efficiency of devices in capturing trace amounts of energy from the environment and transforming them into electrical energy. In addition, advancements in microprocessor technology have increased power efficiency, effectively reducing power consumption requirements. In combination, these developments have sparked interest in the engineering community to develop more and more applications that utilize energy harvesting for power.
       Energy harvesting from a natural source where a remote application is deployed, and where such natural energy source is essentially inexhaustible, is an increasingly attractive alternative to inconvenient wall plugs and costly batteries. This essentially free energy source, when designed and installed properly, is available maintenance-free and is now available throughout the lifetime of the application. Such systems can be more reliable than wall plugs or batteries. In addition, energy harvesting can be used as an alternative energy source to supplement a primary power source and to enhance the reliability of the overall system and prevent power interruptions.

II.   PIEZOELECTRIC ENERGY HARVESTING

2.1   Piezoelectric Effect
       The piezoelectric effect describes the relation between a mechanical stress and an electrical voltage in solids. It is reversible: an applied mechanical stress will generate a voltage and an applied voltage will change the shape of the solid by a small amount (up to a 4% change in volume).
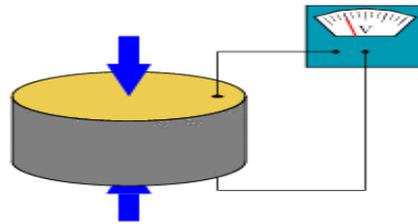

Fig. 1 Piezoelectric Effect

2.2   Piezoelectric Materials
       The piezoelectric effect occurs only in non-conductive materials. Piezoelectric materials can be divided in 2 main groups: crystals and ceramics as shown in Table1.

III.   PIEZOELECTRIC GENERATORS

3.1   Introduction
       Piezoelectric ceramics have been used for many years to convert mechanical energy into electrical energy. The following sections describe the range of piezoelectric generators described in the literature to date. For the purpose of this review, piezoelectric generators have been classified by methods of operation and applications and include both macro scale (>cm) and micro scale (μm to mm) devices. It begins with a brief description of piezoelectric theory in order to appreciate the different types of generator and the relevant piezoelectric material properties.

3.2   Human Powered Piezoelectric Generation
       The use of piezoelectric generators to power human-wearable systems has been extensively studied. Human motion is characterized by large amplitude movements at low frequencies and it is therefore difficult to design a miniature resonant generator to work on humans. Coupling by direct straining of, or impacting on, a piezoelectric element has been applied to human applications and these are detailed below. Studies have shown that an average get walking human of weight 68 kg, produces 67Wof energy at the heel of the shoe. Whilst harvesting this amount of energy would interfere with the gait, it is clear that extracting energy from a walking person presents a potential energy harvesting opportunity. The theoretical limits of piezoelectric energy harvesting on human applications based upon assumptions about conversion efficiencies have suggested that 1.27W could be obtained from walking. One of the earliest examples of a shoe-mounted generator incorporated a hydraulic system mounted in the heel and sole of a shoe coupled to cylindrical PZT stacks . The hydraulic system amplifies the force on the piezoelectric stack whilst reducing the stroke. Initial calculations were

performed in order to design a generator capable of developing 10 W. A 1/17th scale model was built and tested and was found to generate 5.7 ± 2.2 mW kg−1 whilst walking, which suggested that 6.2 W could be generated with the full size generator on a 75 kg subject. The generator design was relatively large in size and the intended power levels are likely to interfere with the gait of the user.

TABLE 1 Summary of Several Piezoelectric Materials Investigated

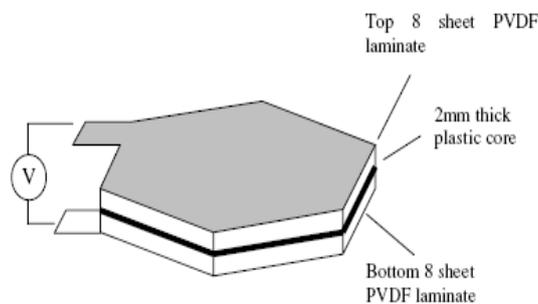| Summary Of Several Piezoelectric Materials Investigated.			
Author	Type Of Material	Advantages/Disadvantages	Power Harvesting Capabilities
Lee *et al* (2005)	Monolithic PZT	Most common type of device. Not flexible. Susceptible to fatigue crack growth during cyclic loading	N/A
Lee *et al* (2004, 2005	PVDF film coated with PEDOT/PSS electrodes	Resistance to fatigue crack damage to electrodes	N/A
Mohammadi *et al* (2003)	Piezofiber composite	Increased flexibility	120 mW from 34 × 11mm plate of 5.85 mm thickness
Churchill *et al* (2003)	Piezofiber composite	Increased flexibility	7.5 mW from 130 × 13 mm patch of 0.38 mm thickness
Sodano *et al* (2004a)	MFC composite quick pack IDE quick pack	MFC–flexibility, MFC and quick pack IDE—low-capacitance devices quick pack—energy harvesting capability	Quick pack proved to harvest the most energy
Sodano *et al* (2005a)	Monolithic PZT, quick pack, MFC	MFC—flexibility quick pack and monolithic PZT—energy harvesting capability	PZT proved to be most efficient (6.8% for random vibration excitation)

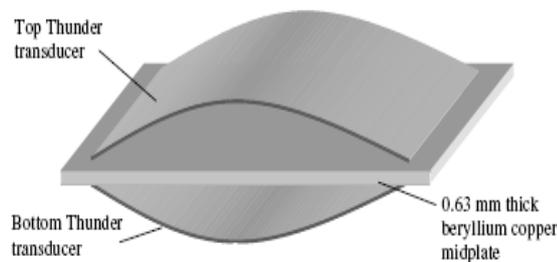Fig.2. PVDF shoe insole (After Kymiss)

Fig. 3. Schematic of the piezoelectric dimorph (After Shenck)

A subsequent device has been developed at the Massachusetts Institution of Technology (MIT) in the 1990s. Researchers first mounted an 8 layer stack of PVDF laminated with electrodes either side of a 2 mm thick plastic sheet (see figure 4). This stave was used as an insole in a sports training shoe where the bending movement of the sole strains both PVDF stacks producing a charge from the $d31$ mode. At a frequency of a footfall of 0.9 Hz, this arrangement produced an average power of 1.3 mW into a 250 kΩ load. A second approach involved the use of a compressible dimorph (see figure 5) located in the heel of a Navywork boot that generated energy from the heel strike .The dimorph incorporated two Thunder TH-6R piezoelectric transducers manufactured by Face International Corporation. The Thunder transducers are pre-stressed assemblies of stainless steel, PZT and aluminium which are bonded together at elevated temperature using a NASA patented polyimide adhesive LaRCTM-SI. The differential thermal expansion coefficients of the materials result in a characteristic curved structure with the PZT layer being compressively stressed enabling it to deform to a far greater extent than standard PZT structures. As the heel of the shoe hits, the transducers are forced to deform and, as the heel is lifted, the transducers spring back into their original shape. Each event results in a voltage being generated and with an excitation of 0.9 Hz the dimorph produces an average of 8.4 mW power into a 500 kΩ load.

3.3 Cantilever-Based Piezoelectric Generators

A cantilever structure with piezoelectric material attached to the top and bottom surfaces is an attractive geometry for harvesting energy from vibrations. The structure is designed to operate in a bending mode thereby straining the piezoelectric films and generating a charge from the $d31$ effect. A cantilever provides low resonant frequencies, reduced further by the addition of a mass on the end of the beam, in a low volume structure and high levels of strain in the piezoelectric layers.
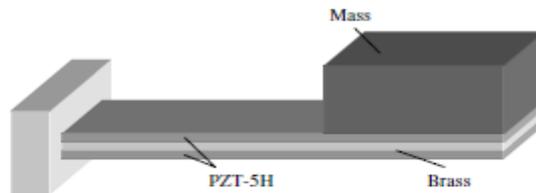

Fig. 4 Schematic of cantilever piezoelectric generator developed by Roundy [4]

Composite piezoelectric cantilever beam generator has been developed by Roundy and Wright .The cantilever used was of constant width which simplifies the analytical model and beam fabrication but results in an unequal distribution of strain along its length. A prototype generator was fabricated by attaching a PZT-5A shim to each side of a steel centre beam. A cubic mass made from an alloy of tin and bismuth was attached to the end and the generator tuned to resonate at 120 Hz. The prototype produced a maximum power output of nearly 80 μW into a 250 k load resistance with 2.5 m s−2 input acceleration and the results showed a reasonable level of agreement with the analytical models. These models were then used to optimize the generator design within an overall size constraint of 1 cm^3. Two designs were adopted, each using PZT-5H attached to a 0.1 mm thick central brass shim .Design 2 using a PZT thickness of 0.28 mm, possessing a beam length of 11 mm and a tungsten proof mass of $17 \times 7.7 \times 3.6$ mm, produced 375 μW with an input acceleration of 2.5 m s−2 at 120 Hz. This generator was demonstrated powering a radio transceiver with a capacitor used for energy storage and achieved a duty cycle of 1.6%.This work concluded that the generator output at resonance is proportional to the mass attached to the cantilever and this should be maximized provided size and strain constraints are not exceeded. Another composite piezoelectric cantilever beam generator has been developed by Roundy and Wright [4, 11].The cantilever used was of constant width which simplifies the analytical model and beam fabrication but results in an unequal distribution of strain along its length. A prototype generator was fabricated by attaching a PZT-5A shim to each side of a steel centre beam. A cubic mass made from an alloy of tin and bismuth was attached to the end and the generator tuned to resonate at 120 Hz. The prototype produced a maximum power output of nearly 80 μW into a 250 k_ load resistance with 2.5 m s−2 input acceleration and the results showed a reasonable level of agreement with the analytical models. These models were then used to optimize the generator design within an overall size constraint of 1 cm3. Two designs were adopted, each using PZT-5H attached to a 0.1 mm thick central brass shim (see figure above). Design 2 using a PZT thickness of 0.28 mm, possessing a beam length of 11 mm and a tungsten proof mass of $17 \times 7.7 \times 3.6$ mm, produced 375 μW with an input acceleration of 2.5 m s−2 at 120 Hz. This generator was demonstrated powering a radio transceiver with a capacitor used for energy storage and achieved a duty cycle of 1.6%.This work concluded that the generator output at resonance is proportional to the mass attached to the cantilever and this should be

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maximized provided size and strain constraints are not exceeded. Piezoelectric cantilever generators have also been investigated by Sodano *et al* .An alternative mathematical analysis uses energy methods to arrive at the constitutive equations of a cantilever PZT bimorph similar to that shown in figure above but with no mass and the PZT not extending to the end of the beam. Models were validated by evaluating a Quick Pack QP40 N (Mide Technology Corporation) piezoelectric actuator clamped at one end and placed on a shaker. The transducer is a composite formed from four piezoceramic elements embedded in a Kapton and epoxy matrix. The model is able to predict the current output for a given excitation frequency and amplitude and the results were within 4.61% of the experimental values. The efficiency of the conversion and the degree of damping is not only dependent upon the transducer but also the associated circuitry. The influence of the input impedance on system damping was evaluated and optimum efficiency and therefore maximum damping was found to occur at 15 k_. This value will be particular to the transducer and is matched to the impedance of the device. The Mide Technology Corporation has since marketed a vibration energy harvesting device based upon a cantilevered Quick Pack transducer with an inertial mass clamped to the free end .The device is $3.6 \times 1.7 \times 0.39$ inches in size and generates 500 μW at 113 Hz and 1g acceleration.

Sodano *et al* have also investigated the amount of power generated through the vibration of a composite piezoelectric aluminium plate and have compared two methods of power storage. A Piezo Systems PSI-5H4E plate ($62 \times 40 \times 0.27$ mm) was bonded to an aluminium plate ($80 \times 40 \times 1$ mm) and excited using an electromagnetic shaker with both resonant and random excitation signals. It was found that the plate could generate a maximum power of 2 mW when excited at its resonant frequency. This paper demonstrated that the power output of a piezoelectric material was able to recharge a fully discharged battery and suggests that batteries are the superior option for storing electrical energy for continuous power supply applications. Capacitors, it is suggested, are better suited to duty cycled applications that only require a periodic power supply.

IV.   PIEZOELECTRIC GEOMETRIES

The most commonly used geometrical configuration in piezoelectric power harvesting is the rectangular cantilever beam. The cantilever beam harvester has been well developed and has proven to be easy to implement and effective for harvesting energy from ambient vibrations. A summary of the various piezoelectric geometries reviewed is presented in TABLE 2.

V.   MATHEMATICAL MODELING OF PIEZOELECTRIC ENERGY HARVESTING

The following section describes the development of the PZT models and the analytical estimations of power generation. It is presented a model of a beam with a single wafer mounted on its surface. The linear constitutive equations for a piezoelectric material [13] have been employed in terms of the piezoelectric coefficient e_{31}, the dielectric constant ε_{33} and the electric field applied across the thickness of the layer *Ez*.

$$D_z = e_{31}\varepsilon_x + \in_{33} E_z \qquad (1)$$

The stress σ in z-direction is assumed zero. This occurs when piezoelectric layer thickness in comparison to the length of the beam can be considered very thin.

5.1   The Cantilever Beam Model

Figure 5 shows the setup for the cantilever beam model. The PZT patch is attached to the beam near the clamped edge for maximum strain. For the estimated power that a PZT can produce from beam vibrations to be calculated, the moment that the PZT experiences must first be determined.
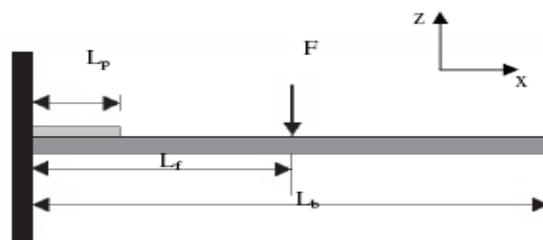
Fig. 5 Cantilever Beam with attached PZT sensor

TABLE 2 Piezoelectric Geometries

Author	Piezoelectric Configuration	Advantages/Disadvantages
Mated and Moll (2005)	Rectangular cantilever and triangular cantilever	Triangular configuration capable of higher strains and higher power generation
Roundy et al (2005)	Trapezoidal cantilever	Trapezoidal configuration allows strain to be evenly distributed increasing efficiency
Baker et al (2005)	Rectangular cantilever and trapezoidal cantilever	Trapezoidal beam produced 30% more energy than rectangular
Mossi et al (2005)	Unimorph prestressed bender	Initially curved shape can help improve harvesting capability
Danak et al (2003)	Initially curved PZT unimorph	Initially curved shape can help improve harvesting capability
Yoon et al (2005)	Initially curved PZT unimorph	Initially curved shape can help improve harvesting capability
Baker et al (2005)	'Bi-stable' pin–pin connected initially compressed beam	'Bi-stable' device has wider range of performance versus excitation frequency
Ericka et al (2005)	Unimorph circular membrane	Capable of harvesting energy from high accelerations
Kim et al (2005a, 2005b)	Clamped circular plates	Capable of harvesting energy from fluctuating pressure sources
Kim et al (2004)	Piezoelectric 'cymbal'	Improved efficiency through load distribution. Capable of withstanding high loads

The Euler-Bernoulli method is used to model the cantilever beam. The governing un-damped equation of motion for the beam for forced motion under zero initial conditions can be written as:

$$\rho A \frac{\partial^2 w(x,t)}{\partial t^2} + E_b I_b \frac{\partial^4 w(x,t)}{\partial x^4} = F(t) \qquad (2)$$

where w is the displacement of the beam, ρ is the density of the steel beam, A is the cross-sectional area, and $F(t)$ is the external force applied to the beam. The boundary conditions are:

$$w(0,t) = 0,$$
$$w_x(0,t) = 0,$$
$$w_{xx}(L_b,t) = 0,$$
$$w_{xxx}(L_b,t) = 0$$

Considering a harmonic forcing function applied to a single point on the beam, according to Fig. 1, we can write:

$$\frac{\partial^2 w(x,t)}{\partial t^2} + c^2 \frac{\partial^4 w(x,t)}{\partial x^4} = \frac{F_0}{\rho A} sen(\omega x) \delta(x - L_f) \qquad (4)$$

where ω is the frequency, L_f is the position of the applied force and c2 can be written as:

$$c^2 = \frac{E_b I_b}{\rho A} \qquad (5)$$

The frequency will be equal to the beam's first natural frequency because the largest deflections occur at the first natural frequency. A general solution for this equation is given by:

$$w(x,t) = \sum_{i=1}^{3} q_i(t) X_i(x) \tag{6}$$

where qi is the *i-th* modal coordinate equation of the beam and Xi is the *i-th* mode shape of the beam. For consistency, only the first three mode shapes will be used in the summation process described by Eq. 6.Therefore, considering the free un-damped vibration,

$$X_i(x) \frac{\partial^2 q_i(t)}{\partial t^2} = -c^2 \frac{\partial^4 X_i(x)}{\partial x^4} q(t) \tag{7}$$

Using the standard method of separation of variables in the solution of Eq. 7, we have the equations:

$$-\frac{\frac{\partial^2 q_i(t)}{\partial t^2}}{q(t)} = \frac{c^2 \frac{\partial^4 X_i(x)}{\partial x^4}}{X_i(x)} = \omega_n^2 \tag{8}$$

Here, we can write the Eq. (8) as:

$$\begin{cases} \frac{\partial^2 q_i(t)}{\partial t^2} + \omega_n^2 q_i(t) = 0 \\ \frac{\partial^4 X_i x}{\partial x^4} - \frac{\omega_n^2}{c^2} X_i(x) = 0 \end{cases} \tag{9}$$

The solution of the second equation in Eq. (9) is:

$$X_i(x) = A_1 \cos(\beta_i x) + A_2 \sin(\beta_i x) + \\ + A_3 \cosh(\beta_i x) + A_4 \sinh(\beta_i x) \tag{10}$$

Applying the boundary conditions is found the general mode shape equation for a cantilever beam

$$\beta_i = \sqrt{\frac{\omega_{ni}^2}{c^2}} \tag{12}$$

where Lb is the beam length. In the Eq. (11), $i\_$ can be written as:

$$\cos(\beta_i L_b)\cosh(\beta_i L_b) = -1 \tag{13}$$

More details regarding the solution process can be found in Inman [14].
For the first equation in (9), we have the solution:

$$q_i(t) = \frac{1}{\omega_{di}} e^{-\varsigma \omega_n t} \int_0^t F_i(\tau) e^{\varsigma \omega_n t} sen(\omega_{di}(t-\tau)) d\tau \tag{14}$$

where ω_{ni} is the damped natural frequency and ζ is the damping ratio. Now the equation (6) already can be evaluated.

VI.   CONCLUSION
- Vibrations represent one of the most promising renewable and reliable solutions for mobile electronics powering.
- 90% of WSNs cannot be enabled without Energy Harvesting technologies.
- Most of vibration energy sources are inconsistent and have relative low frequency.
- The analysis indicates that piezoelectric converters will be capable of converting more power per unit volume than capacitive converters.
- Piezoelectric converters are also favorable because they require no separate voltage source, and because the output voltage for the vibration sources is in the range of 3-10 V.

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