Development of a Small Energy Scavenger

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ABSTRACT

This paper presents a compact energy-harvesting device. A mass is held with two tiny cantilever beams with piezoelectric materials on both surfaces. When the device moves, the inertia of the mass forces the beams to bend and as a result, the extensive deformation of the piezoelectric material generates electricity. The performance of the system is evaluated experimentally.

Keywords

Piezoelectricity, energy harvesting, vibration

1. INTRODUCTION

The rapid advancements in the electronics industry made it possible to reduce the size and the power requirements of most electronic devices. Although the devices become smaller, their batteries remain at the same size with limited lifetime.

The limited life of conventional batteries is a serious inconvenience in many wireless sensor applications. It is necessary either to connect them to an external power source or to change their batteries periodically. Wiring thousands of sensors attached on hard to reach locations of airplanes is impossible. Similarly, changing batteries of health monitoring systems on bridges, tracking devices attached to animals, and sealed underwater equipment is very inconvenient. Many researchers' efforts are concentrated on the development of energy harvesting devices to generate power from the mechanical vibrations of many systems. The use of inductive devices has been studied in the past. Wear, noise and generation of electromagnetic field are the main problems of this approach. The use of piezoelectric materials is attractive, since all the listed disadvantages of the previous approach are eliminated.

There is an increasing demand for energy harvesting or energy conversion from mechanical to electrical for power generation. For many energy-harvesting applications, the use of piezoelectric materials is feasible since they are affordable and they can be used with minimal design changes in most of the applications. Either the piezoelectric materials are attached to the locations where they will be subjected to strain, or the inertia of a mass is used to apply force to the piezoelectric elements when the device is subjected to mechanical vibrations. Piezoelectric materials convert mechanical energy into electricity and create an electrical charge when they are exposed to mechanical stress. This is called piezoelectric effect. When they are subjected to an electrical current they show mechanical strain and this is called inverse piezoelectric effect.

The main drawback of energy harvesting was the generation of very small amount of energy for the power hungry electronic components of the past. The new low power devices, effective noise suppression methods, and cheap wireless communication chips made the energy harvesting a feasible approach in many applications.

There are different approaches to harvest electrical energy from mechanically excited piezoelectric element. Most research has been focused on vibration-based energy harvesting [1-5]. Different design types for vibration-powered generators have been investigated and compared [6].

The studies started with implanting piezoceramic patches into a dog's body to harvest power from breathing using the elongation during the inspiration in 1984 [7]. As providing energy for devices that are placed at remote locations can be very difficult, piezoelectric materials are being used lately to transfer mechanical energy into electrical energy that can be stored. Sodano et al used piezoelectric materials (PZT) for powering wireless and micro-electro-mechanical-systems (MEMS) [8].

For piezoelectric devices, mathematical models have been constituted. A curved, thin unimorph bender piezoelectric device, which has piezoelectric material layers, has been used and the effects of its layer composition and geometry on energy harvesting have been investigated [9-10]. A thin film lead zirconate titanate, Pb (Zr, Ti) O-3 (PZT) cantilever device with a mass added to the end is designed to resonate at specific frequencies from an external vibrational energy source for power generation [11]. Experimental and analytical studies have been conducted using a clamped circular unimorph piezoelectric plate [12-13]. Clamped circular plate structures were modeled and energy was calculated with various thickness ratios.

An auxiliary structure, which consists of a mechanical fixture and PZT type piezoelectric element, was used for energy harvesting from vibrating systems for structural health monitoring purposes [14]. To improve the power output, strains in the attached PZTs can be maximized by adjusting different parameters.

Systems, which harvest energy from the environment, are generally used in remote locations and they need to store energy. A vibrating piezoelectric device is different from the typical power source and does not give optimal power flow because it may be driven by mechanical vibrations at various amplitudes. Ottman et al [15] worked on implementing the optimal power transfer to store the energy and used a dc-dc converter. They proposed an energy harvesting circuit, which consists of an ac-dc rectifier with an output capacitor, an electrochemical battery, and a dc-dc converter that controls the energy flow into the battery. Using this converter, power transfer was increased over 400%. Then an optimized method, which utilizes a piezoelectric element that used a step-down dc-dc converter was, used [16-17]. The dc-dc converter regulates the power flow from the piezoelectric device to the electric load. Experimental results have also verified the increase of harvested power. Another technique, which is called synchronized switch harvesting (SSH), was developed [18-19]. This technique is derived from a nonlinear technique to define problem of vibration damping on mechanical structures and has been applied to the structures, which are excited at their resonance frequency. The SSH approach has also been used to optimize the power flow of vibration-based piezoelectric energy-harvesting devices [20].

2. THEORETICAL BACKGROUND

Piezoelectric materials have been used to convert mechanical energy to electrical energy or electrical energy to mechanical energy. The piezo term comes from a Greek word piezein for pressure.

Jacques and Pierre Curie brothers discovered piezoelectric effect when they subjected quartz crystals to mechanical stress and got electrical charge in the 1880's. They also discovered inverse piezoelectric effect applying voltage in 1881 [21-22]. When Curie brothers apply voltage to the materials, mechanical strain or deformation was observed in the crystals. The piezoelectric effect is commonly used in sensors, such as displacement and force sensors. The linear actuators of many position control devices and ultrasonic cleaning devices use inverse piezoelectric effect [23]. Many crystalline materials, like tourmaline, quartz, topaz, cane sugar, and Rochelle salt (sodium potassium tartrate tetrahydrate) have piezoelectric effects. There are also other materials like lead zirconate titanate ceramics (e.g. PZT-4, PZT-5A, etc.), barium titanate, or polyvinylidene flouride (a polymer film) [24]. In our study, PZTs, which are the most common materials, have been used.

According to Hooke's Law [24]:

$$S = s\,T \tag{1}$$

Where S is mechanical strain, which is the deformation of materials that is caused by stress on a body, s is compliance or the inverse of strain and T is stress [24].

As piezoelectricity is related to both electrical and mechanical properties, the volumetric charge density can be calculated by considering the electric field and permittivity [24]:

$$D = \varepsilon\,E \tag{2}$$

Where D is volumetric charge density, ε is permittivity, and E is electric field.

Piezoelectricity is the combined effect of the electrical and mechanical behavior of the material and we can add these two equations together in matrix form for a linear piezoelectric material [25]:

$$\{S\} = \left[s^E\right]\{T\} + \left[d_t\right]\{E\} \tag{3}$$

Where {S} is strain vector, $[\,s^E\,]$ is the compliance matrix evaluated at constant electric field, {T} is the vector of stresses, $[\,d_t\,]$ contains piezoelectric strain coefficients in the matrix form, and {E} is the electric field vector. We can also write the electric displacement vector below:

$$\{D\} = [d]\{T\} + \left[\varepsilon^T\right]\{E\} \tag{4}$$

Where {D} is the electric displacement vector, [d] stands for piezoelectric coupling terms in the matrix form, {T} is the stress vector, $[\,\varepsilon^T\,]$ is the dielectric constant matrix evaluated at constant stress [25].

The equations may also be written in different forms [25]:

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & & & \\ s_{12}^E & s_{11}^E & s_{13}^E & & & \\ s_{13}^E & s_{13}^E & s_{33}^E & & & \\ & & & s_{44}^E & & \\ & & & & s_{44}^E & \\ & & & & & s_{66}^E = 2(s_{11}^E - s_{12}^E) \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{31} \\ 0 & 0 & d_{33} \\ 0 & d_{15} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{13} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{11} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \tag{6}$$

PZTs are a mixture of lead zirconades and lead titanates. After mixing at 800-1000 degrees C, a powder is formed and mixed with a binding agent [21]. Then it is sintered into the shape we want to have. The PZT takes on a tetragonal structure with electrical and mechanical asymmetry after cooling process [26].

To give the materials piezoelectric properties, poling is necessary. It means heating the materials over the Curie temperature that allows the molecules inside the material to move freely. When a large electric field is applied to the material, the crystals inside them align themselves in one direction and it continues after the electric field is taken off [21].

The PZTs can be modeled in different ways. Voltage and power can be calculated. If we consider a PZT bender sensor, which is a thin wafer material, we can say that PZT benders can produce voltage in one direction when bending force strains occurred in three directions [21]. A cantilever beam is shown in Figure 1 for bending.

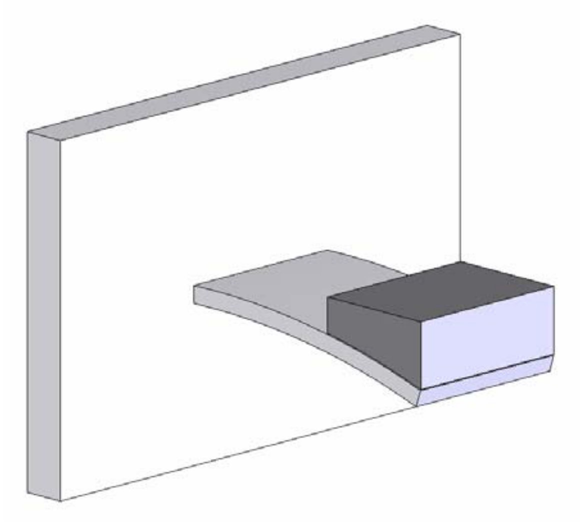


Figure 1. Cantilever beam configuration for the piezoelectric element

If we derive the equations for the piezoelectric bender, the equations can be shown below [21]:

$$\varepsilon_1 = s_{11}^E \sigma_1 + d_{13}E_3 \qquad (7)$$

Where ε is mechanical strain [m/m], s, is elastic compliance [m^2/N], σ is stress [N/m^2], d is piezoelectric strain coefficient [m/V] and E is electrical field [V/m].

$$D_3 = d_{13}\sigma_1 + e_{33}^T E_3 \qquad (8)$$

Where D is electrical density [C/m^2], d stands for piezoelectric strain coefficient [m/V] σ is stress [N/m^2], e is electric permittivity [F/m] and E is electrical field [21].

3. PROPOSED METHOD

The piezoelectric materials should be subjected to maximum possible strain without exceeding the materials capabilities to generate the desired energy. One of the common designs is to attach the piezoelectric materials to two opposite sides of a cantilever beam. In this way, one of the piezoelectric materials will be subjected to compression while the other one is subjected to stress. In this way, a generator is created. Since, the stiffness of the cantilever beam is very small, it consumes a small portion of the energy. The strains on the very thin piezoelectric materials are large and they generate considerable electricity [27].

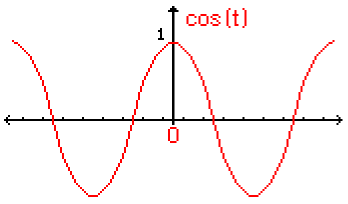
In this study, a mass was supported by two miniature beams made of thin sheet metal. The beams had two extremely thin (0.0019 mm or 7.5×10^{-5} in) piezoelectric material layers at the two opposite surfaces. Since each piezoelectric beam would generate certain voltage, the generated energy increases with the number of beams. The number of the beams and the size of the mass should be selected carefully to tune the device to have the resonance at the dominant frequencies of the environment the device will be installed.

We measured the voltage of a sinusoidal wave signal by considering RMS value.

To measure the value of an alternating current signal, it is often necessary to convert the signal into a direct current signal of equivalent RMS (Root Mean Square) value.

The concept of VRMS may be examined graphically. Let s(t) be a cosine waveform.

s (t) =



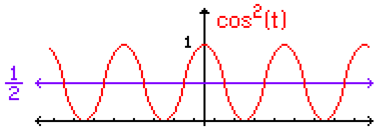
The average value of cos(t) is zero. The peak value (amplitude) of the cosine is 1. The peak-to-peak value is 2. Using the trigonometric identity below,

$$2\cos A\cos B = \cos(A-B) + \cos(A+B) \qquad (9)$$

The function becomes,

$$s^2(t) = \cos^2(t) = (1/2)(1+\cos(2t)) \qquad (10)$$

s^2 (t) =



This is the squared version of the signal, and its mean value is 1/2, as shown above. Therefore, the "mean squared" value is 1/2. By inspection, the "root mean squared" value is the square root of 1/2 (approximately 0.707).

If this were an electrical waveform, cos(t) would be called a 0.707 VAC signal.

4. EXPERIMENTAL SETUP AND DATA COLLECTION

The objective of this study is to reduce the size of the first generation piezoelectric battery we developed. The picture of the first generation design is presented in Figure 2. A mass was supported by two cantilever beams at the two ends of the beam. Instead of shaking the structure, an electric motor with an unbalanced weight was installed on the mass in the experimental studies. When the electric motor rotated, the unbalanced mass created a periodic force and vibrated the small beams on both edges (Figure 2).

In the new design, two beams with piezoelectric material layers at their two opposite sides supported a mass in a small box (3in x 3in x 1-1/4in), in a cantilever configuration, leaving enough space for the oscillation of elements (Figure 3).

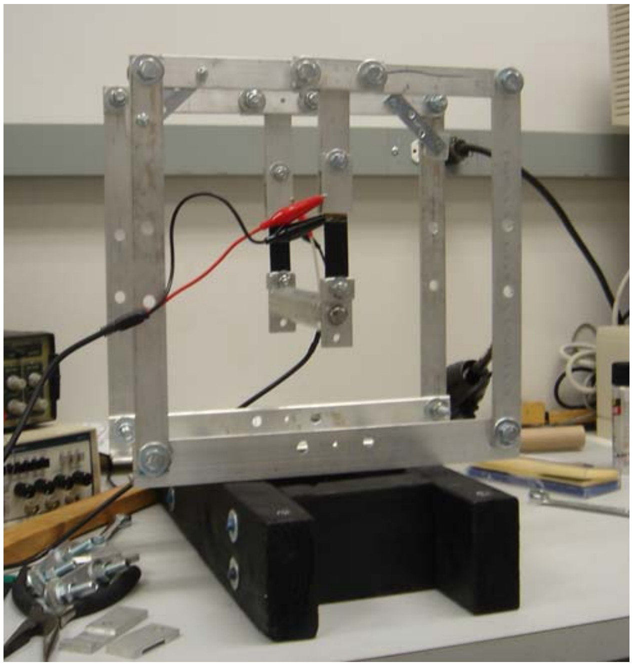


Figure 2. Previous Piezoelectric Battery

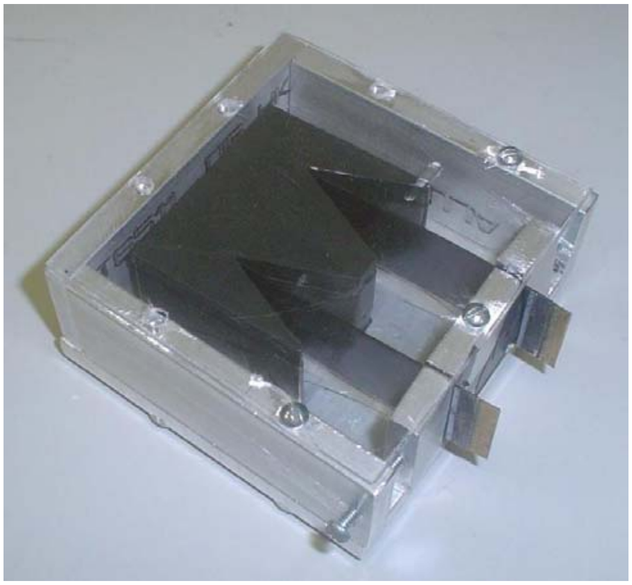


Figure 3. Small Piezoelectric Battery

Both elements were connected together with one weight, providing the mass at the end of the cantilever configuration.

This configuration allowed us to attach the second-generation piezoelectric battery to a vibrating structure and to generate electricity. In this study, the generated voltage was monitored using Nicolet Integra 10 digital oscilloscope.

This generated voltage has a relation with the vibration force. For this reason, we attached an accelerometer to the second-generation piezoelectric battery to be able to measure the G force generated during the vibration.

To collect the data, the piezoelectric elements of the first generation kinetic battery were replaced with two aluminum strips. The second-generation kinetic battery was installed on the central beam. An electric motor with an unbalanced beam was also attached on the beam of the first generation kinetic battery and the figures for the piezoelectric battery, which is attached to the vibrating element, are shown in Figures 4-5.

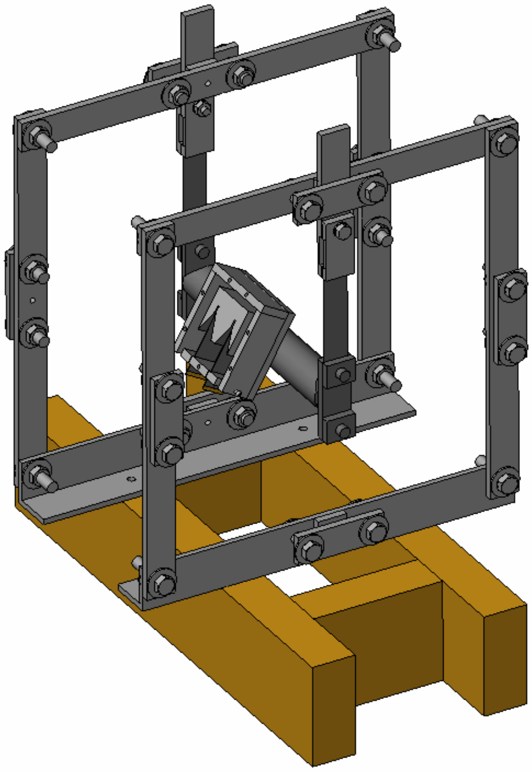


Figure 4. Drawing illustrating the new configuration

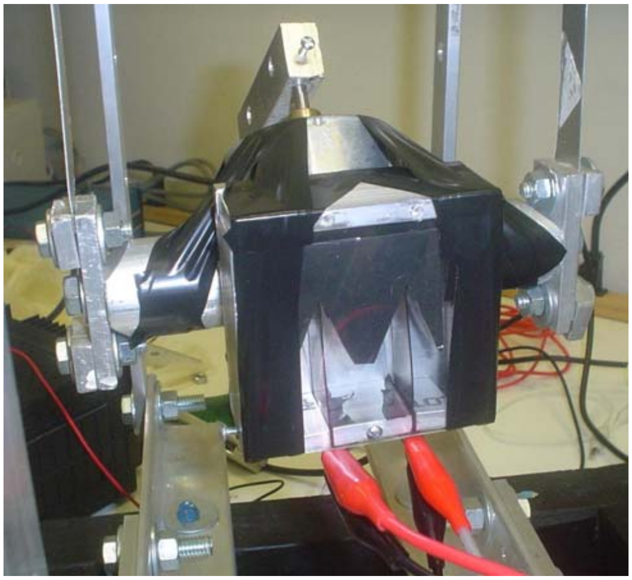


Figure 5. Piezoelectric Battery attached to the vibrating element

5. RESULTS AND DISCUSSION

In the experiments, initially the second-generation battery was vibrated by hand and the characteristics of the signal were visually evaluated. Later, the beam of the first generation battery was excited at a known frequency using the electric motor. The second-generation battery was also excited since it was attached to the same beam.

In the experiments, the output of single piezoelectric component was monitored. Since the system has four piezoelectric elements, total power is about the four times of the observed power in this study as long as the circuits use the generated voltage efficiently.

The heavy shaking gave us a reading of 43V peak to peak for one layer. The peak-to-peak acceleration was 19.6 m/s^2 and it is shown in Table 1 and Figure 6. The power was calculated using the following equation:

$$P = V_{rms}^2 / R \qquad (9)$$

Table 1. Values obtained for a heavy shaking from single piezoelectric layer

Total System Voltage	VRMS	Power (Watts)
43	30.40	1.85e-3

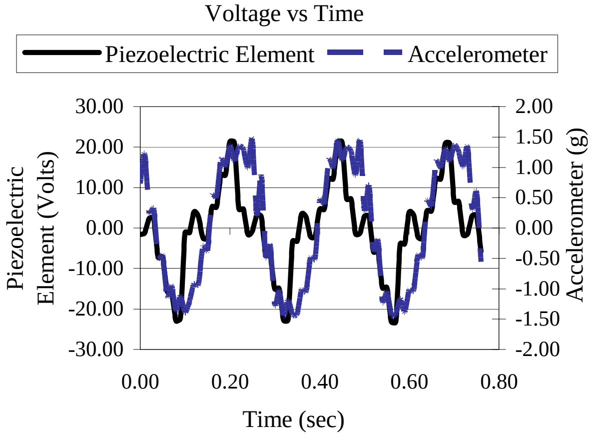


Figure 6. Reading from oscilloscope for heavy shaking

For the next trial, we applied 5 volts to the electric motor when the maximum current was set to 3A. Single piezoelectric layer gave 38V peak to peak. The observed peak-to-peak acceleration was 19.6 m/s^2 and it is shown in Table 2 and Figure 7. The power generated by the single piezoelectric layer (it had total four) of first generation battery is also shown in Table 3.

Table 2. Values obtained for a vibration motor

Total System Voltage	VRMS	Power (Watts)
38	26.87	1.445e-3

Table 3. The power generated by the single piezoelectric layer (it had total four) of first generation battery

Power in Watts
4.67E-03
2.59E-03
2.71E-03

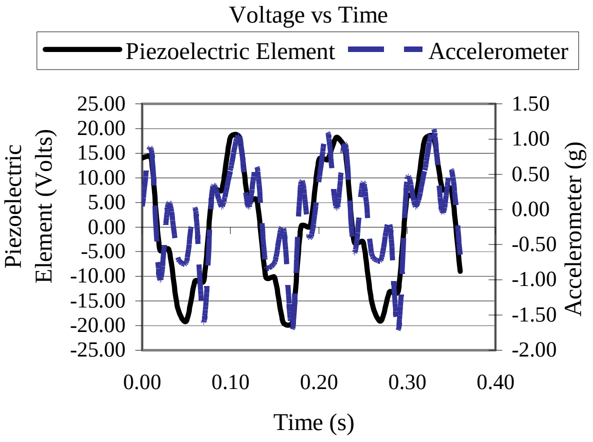


Figure 7. Reading from oscilloscope for a vibration motor

6. CONCLUSIONS

The volume of the first generation piezoelectric battery was reduced about 90% without significant loss in performance. The observed power of one of the four piezoelectric layers of the recently designed kinetic battery was between 1.445 and 1.85 mW.

The generated voltage over volume ratio of the piezoelectric battery was a very impressive 3.5 Volts/in^3. The same figure for an AA battery is 3.19Volts/in^3. However, single piezoelectric element of the proposed battery would generate the energy of a 2,000 mAh in 2,000 hours.

7. ACKNOWLEDGEMENT

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