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Study of Piezoelectric Cantilever Energy Harvesters

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Abstract:
Over the last decade there has been a growing increase in research in the field of vibrational energy harvesting devices which convert ambient vibrational energy into electrical energy. The major application area for such devices is as power sources for wireless sensors, thereby replacing currently used batteries which suffer from a finite lifespan and pose environmental issues during disposal. This growing problem has motivated the development of new technologies for harvesting energy from the ambient environment. Piezoelectric energy harvesters (PEH) are under consideration as a means for converting mechanical energy, specifically vibration energy, to electrical energy, with the goal of realizing completely self-powered sensor systems. This paper presents a brief introduction to the piezoelectric cantliver beam energy harvester.

1. Introduction

Energy harvesting is used for capturing minute energy from surrounding sources, accumulating them and storing them. With recent advancements in wireless technology, energy harvesting is highlighted as alternative for conventional battery. While there are different ways through which energy is harvested, piezoelectric devices shows a great promise. Piezoelectric materials have the property of producing electrical charge when strained. This is called direct piezoelectric effect. On the other hand, these materials undergo deformation when an electric field is applied. This is called converse piezoelectric effect. This property of piezoelectric materials is used in converting vibrational energy to electrical energy which may be stored and used as an alternative power source for portable electronics. In recent advancements, energy harvesting have attracted considerable attention as an energy source for wireless sensor networks because batteries cause a series of inconviences like limited operating life, size and contamination issues. Solar energy provides some solutions but it is limited in dark conditions. Piezoelectric devices are proved to be the potential source for power generation. Therefore they serve as a good alternative for conventional batteries.

2. Theoretical Foundation

Piezoelectric ceramics has been used to convert mechanical energy into electricity for many years. A brief introduction about piezoelectricity will help to understand the theoretical background of piezoelectric power harvesting. Piezoelectric materials can become electrically polarized or undergo a change in polarization when subjected to a stress because the slight change in the dimension of a piezoelectric material results in the variation in bond lengths between cations and anionscaused by stress. This phenomenon was discovered on many crystals, for instance, tourmaline, topaz, quartz, Rochelle salt, and cane sugar, by Jacques and Pierre Curie brothers in 1880, and named as piezoelectricity or piezoelectric effect, which describes a relationship between stress and voltage. Conversely, a piezoelectric material will have a change in dimension when it is exposed in an electric field. This inverse mechanism is called electrostriction. Those devices utilizing the piezoelectric effect to convert mechanical strain into electricity are called transducers, which can be used in sensing applications, such as sensors, microphones, strain gages, etc.; while those devices utilizing the inverse piezoelectric effect to generate a dimension change by adding an electric field are called actuators and used in actuation application, such as positioning control devices, frequency selective device, etc.

The constitutive equations for a linear piezoelectric material are given in Equations 2.1 and 2.2 (ANSI / IEEE, 1988, 176-1987)

$T= cS - dE;$ (2.1)
$D= dS + \varepsilon E;$ (2.2)

Where T = mechanical stress (N/m^2)
S = mechanical strain (m/m)
c= elastic stiffness or Youngs modulus (N/m^2)
d= piezoelectric strain constant (m/V) E=electric field (V/m)
D= electrical displacement or the
Charge density(C/ m^2)
ε= piezoelectric dielectric constant(C/ m^2)

The second term of dE in the right side of Equation 2.1 represents the piezoelectric coupling term, which provides the mechanism for energy conversion. As shown in Equations 2.1 and 2.2, the electric field across the material affects its mechanical behavior and vice versa.

The above piezoelectric constants are usually denoted as x_{ij} , where x represents the property variable, such as material elastic modulus c or strain coefficient d , and i and j represent the polarization and stress directions, respectively. The polarization direction is usually assigned 3, while other properties are assigned based on an orthogonal coordinate system, as shown in Figure 1. In this figure, the poling direction (in which the external voltage is exerted to polarize the piezoelectric material) is 3 and the strain direction is 1; as a result, the piezoelectric strain coefficient will be expressed as d31. The three principle axes (Figure 1) are named 1, 2, and 3 respectively, while the shear affects around the principle axes are named 4, 5, and 6 respectively. Due to the difference between the poling direction and the strain direction, piezoelectric materials can be configured in many different ways that may prove useful in energy harvesting applications.

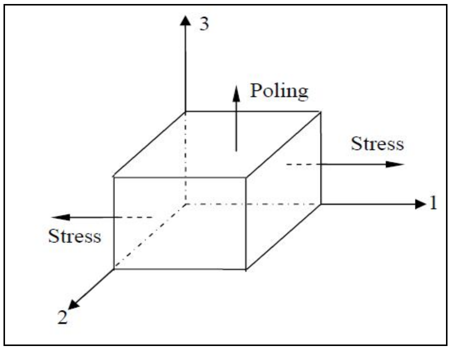

Figure 1: Orthogonal Coordinate System and Poling-Stress Direction

3. Piezoelectric Bender Converter

A piezoelectric bender converter is typically a cantilevered multi-layer beam structure, with one or more layers bonded to an elastic metal layer in order to increase the overall elasticity of the structure and overcome the brittleness of piezoelectric materials. Usually, one cantilevered beam with one piezoelectric layer bonded to a metal layer (such as brass or aluminum) is called unimorph, while a beam composed of a metal layer sandwiched by two piezoelectric layers is considered a bimorph. Figure 2 shows bimorph where the electrodes cover the overall top and bottom surfaces of the cantilever bender, and the poling direction is perpendicular to the stress direction, so the 31 mode is used. Figure 3 has interdigitated electrodes distributed sparsely on the top and bottom surfaces of the bender, while the poling direction and the stress direction are both in the longitudinal direction. As such, the 33 mode exists everywhere except directly below the electrodes.

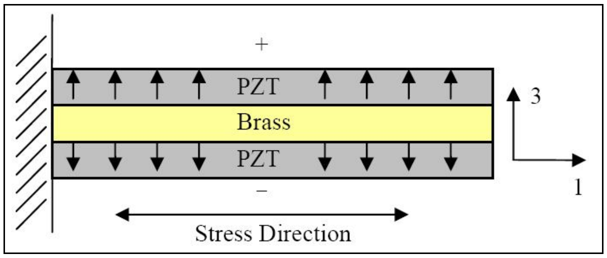

Figure 2: 31 Type piezoelectric bender converter

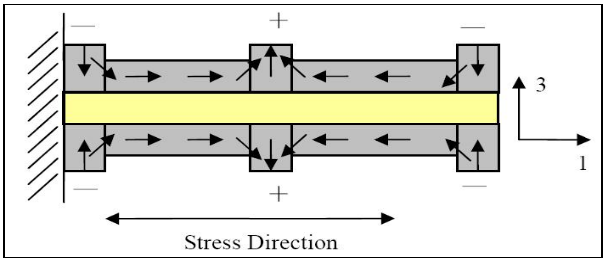

Figure 3: 33 Type piezoelectric bender converter

For a bimorph in operation, the top and bottom PZT layers are always experiencing opposite states of stress; one is in tension while the other is in compression. Therefore, if the two PZT layers are poled in the same direction and the electrodes are wired appropriately, the generated current will double, which is called parallel poling. Conversely, if the two piezoelectric layers are poled in the opposite direction, the produced voltage will double, which is called series poling. Theoretically, there is no difference in the power conversion under these two operating polings. The 31-mode piezoelectric bimorph (as shown in Figure 2) may be the simplest and most widely-used configuration for energy harvesting. The piezoelectric material is concentrated in regions of

Large strain and the strain across the cross-section is relatively constant. Further, the construction is considerably simpler than that of the 33-mode device shown in Figure 3. A very important characteristic of the bimorph configuration is the potential for bonding additional mass at the end of the beam, such that the resonant frequency of the structure can be adjusted. This may be quite useful, as it is very important to match the resonant frequency of the designed generator with the frequency of ambient vibration, in order to produce the largest strain energy and thus obtain the largest electrical energy.

4. Cantilever beam device configuration

The vast majority of piezoelectric energy harvesting devices uses a cantilever beam structure. A cantilever beam, by definition, is a beam with a support only one end, and is often referred to as a “fixed-free” beam. When the generator is subjected to vibrations in the vertical direction, the support structure will move up and down in sync with the external acceleration. The vibration of the beam is induced by its own inertia; since the beam is not perfectly rigid, it tends to deflect when the base support is moving up and down. Typically, a proof mass is added to the free end of the beam to increase that deflection amount. This lowers the resonant frequency of the beam and increases the deflection of the beam as it vibrates. The larger deflection leads to more stress, strain, and consequently a higher output voltage and power. Electrodes covering a portion of the cantilever beam are used to conduct the electric charges produced to an electrical circuit, where they can be utilized to charge a capacitor or drive a load.

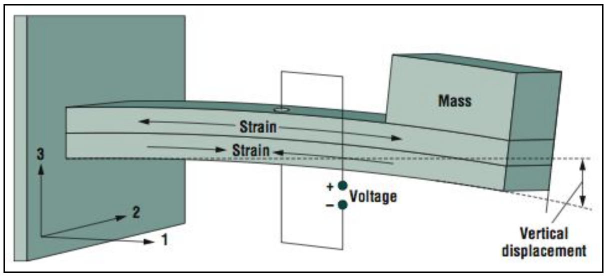

Figure 4: Configuration of Piezoelectric Cantilever beam

5. Modes of Vibration and resonance

A cantilever beam can have many different modes of vibration, each with a different resonant frequency. The first mode of vibration has the lowest resonant frequency, and typically provides the most deflection and therefore electrical energy. A lower resonant frequency is desirable, since it is closer frequency to physical vibration sources and generally more power is produced at lower frequencies. Therefore, energy harvesters are generally designed to operate in the first resonant mode.

6. Physical Vibration sources

Table 1 shows the commonly seen vibration sources. We can see that most ambient vibration sources have relatively low frequencies (under 200 Hz) and widely varying acceleration levels.

Vibration source	Frequency (Hz)	Acceleration (m/s^2)
Kitchen blender	121	6.4
Clothes dryer	121	3.5
Small microwave oven	60	0.2~1.5
External windows next to busy streets	100	0.7
Car engine compartment	200	12
Refrigerator	240	0.1

Table 1: Common sources of vibrations

7. Estimation of Resonant Frequency

The resonant frequencies of a beam can be estimated using Euler-Bernoulli beam theory. By solving the Euler-Bernoulli beam equation with the appropriate boundary conditions, the eigenvalues of the system can be determined, which then allow for the calculation of the resonant frequencies. The differential equation describing the motion of an Euler-Bernoulli beam is:

$$\frac{\partial^4 \delta}{\partial x^4} + \frac{\varrho A \partial^2 \delta}{EI\, \partial t^2} = 0 \qquad (7.1)$$

Where δ is the beam deflection as a function of position along the beam and time, ϱ is the density, A is the area of the cross section of the beam, E is the Young’s modulus, and I is the area moment of inertia. For a beam of rectangular cross section, the relevant moment is

$I = 1/12\ wt^3$

The general solution for sinusoidal vibration is as follows, with the constants and eigenvalues determined by the boundary conditions

$\delta(x,t) = (c1\sin\beta x + c2\cos\beta x + c3\sinh\beta x + c4\quad \cosh\beta x)\square\ \sin\omega t$

Where

$\beta^4 = \varrho A\omega^2/ EI$

For a fixed-free beam with no proof mass, the relevant boundary conditions for a beam of length

L are: $\delta(0,t) = \delta_x(0,t) = 0$ and

$\delta_{xx}(L,t) = \delta_{xxx}(L,t) = 0$. These first two boundary conditions indicate that the fixed end of the beam is stationary, and that the beam is flat at the point of attachment. The free end conditions mean that there are no forces applied at that point and no bending moment. The first nontrivial eigenvalue of this system is $\beta L \approx 1.875$, so the equation for the resonant frequency of the first mode is

$$f = \frac{\omega}{2\Pi} = \frac{(1.875)^2 \sqrt{EI}}{2\,\Pi L^2\ \sqrt{\varrho A}}$$

Equation for second mode is

$$f = \frac{\omega}{2\Pi} = \frac{(4.694)^2 \sqrt{EI}}{2\,\Pi L^2\ \sqrt{\varrho A}}$$

8. Conclusion

Piezoelectric cantilever can be used to harvest ambient vibrations which are available commonly. By the use of the constitutive equations for electromechanical coupling of the piezoelectric material, the electric field generated can be easily found out. The harvester if operated at its natural frequency will give maximum deflection of the beam and in turn generate maximum power.

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