Sensors for Energy Harvesting System

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ABSTRACT

A considerable attention has been given to the energy harvesting system, as the energy obtained from this system is used for powering up small electronic devices instead of using batteries. Battery manufactures make batteries of required size with long life of usage. However, it is difficult to replace such batteries once its life is expired. This difficulty can be partially overcome by using the energy produced from a suitable energy harvesting system. The input to the energy harvesting system is the ambient energy from the environment as external sources. One of the external source considered for this investigation is vibration. Vibration can be converted to voltage by using piezoelectric sensors which are fixed on the vibrating structure or unit, and the energy produced by piezo sensors can power up small electronic devices. As a result, electronic system becomes the self powered system or uses less battery. In order to obtain greater power and efficiency from the piezo sensors, a study has been made for selection of a suitable sensor depending upon the structure or unit. In this present work an aluminum beam has been taken as a structural membrane. Both the beam and the sensor thickness are varied and the experiments are conducted to find the best suitable sensor. It is observed that more energy is harvested using a thin sensors on a suitably thin structure as compared to stiff/thick structures.

Keywords

Energy harvesting system; Piezoelectric sensors; Cantilever beam.

1. INTRODUCTION

"Energy harvesting" or "Energy scavenging" is the process of extracting small amount of energy from ambient environment and then reusing it for electronic devices. While executing different machines or mechanical systems some vibrations are generated. The conversion of this ambient vibration energy into usable electrical energy is called energy harvesting. The vibrations are detected by the sensors. The best mechanism to convert the vibrations into electrical energy is piezoelectric mechanism. Piezoelectric mechanism has received greatest attention because these materials have the advantage of larger power and ease of application. The most commonly used piezoelectric material is PZT (Lead Zirconate Titanate) because it has very high electromechanical coupling ability. Piezoelectric materials are commercially available. These materials undergoes deformation when an electric field is applied across them (piezoelectric effect) and conversely produce voltage when strain is applied(converse piezoelectric effect). Thus they can be used as both actuators and sensors. It is the piezoelectric effect that is employed in an energy harvesting system.

A piezoelectric transducer is a device that uses the piezoelectric effect to measure pressure, acceleration, strain or force by converting them to an electrical charge. Piezoelectric transducers are used to convert one form of energy(mechanical energy) in to another form of energy (electrical energy). Piezoelectric sensors have proven to be versatile tool for the measurement of various parameters like strain, acceleration, load etc,. A piezoelectric transducer has very high DC output impedance and can be modeled as a proportional voltage source and filter network.

Piezoelectric generators are of major interest due to the solid state nature facilitating its integration. Different approaches of energy harvesting using piezoelectric materials have been developed [1–3]. Since a piezoelectric element subjected to a vibration generates an alternating voltage across its electrodes, most of the proposed electrical circuits include an AC-to-DC converter. Thus, an electrical energy is provided to a storage device, such as a capacitor or a battery, in order to feed the terminal electric load under a DC voltage. The AC-to-DC converter, usually a diode bridge, is sometimes followed by a DC-to-DC converter. This is used for power optimization or load voltage regulation [4–6].

2. MATERIALS AND METHODS

2.1 Sensors

A sensor is a device that detects the changes in electrical or physical or other quantities and thereby produces output as an acknowledgement of change in the quantity. A sensor converts the physical parameter into a signal which can be measured electrically. The sensors used in the present study are piezoelectric sensors.

2.2 Piezoelectric Sensors

The piezoelectric sensors use piezoelectric effect to convert the quantities such as force, strain, etc. into an electrical charge. Besides the voltage conversion, the piezoelectric sensors are used for the measurement of various process parameters. These piezoelectric sensors posses ruggedness, and have high natural frequency and an excellent linearity over a wide amplitude range. Additionally, piezoelectric technology is insensitive to electromagnetic fields and radiation, enabling measurements under harsh conditions [7].

3. PIEZOELECTRIC ENERGY HARVESTING SYSTEM

3.1 Principle and working

Among various approaches of converting mechanical vibration to electric energy, using piezoelectric materials on the vibrating structures is one of the most economical/ simple approach. Piezoelectric materials produce electric charge when subjected to external mechanical loads [8]. According to the definition of "direct piezoelectric effect", when a mechanical strain is applied to crystals by an external stress, an electric charge occurs on the surface(s) of the crystal and the polarity of this electric charge can be reversed by reversing the direction of the mechanical strain. This phenomenon is shown in Fig. 1. [9]

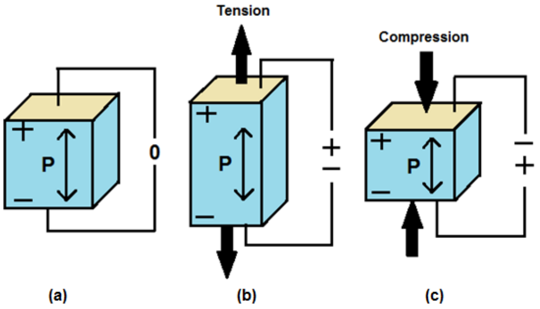

Fig 1: Schematic of direct piezoelectric effect; (a) piezoelectric material, (b) energy generation under tension, (c) energy generation under compression.

Sometimes, piezoelectric material itself works as structures for energy harvester, in the form of cantilever beam. It may contain one or two piezoelectric thin sheets to form the main structure, that is unimorph or bimorph . In this study, we used unimorph configuration for conducting experiment and is shown in Fig. 2.

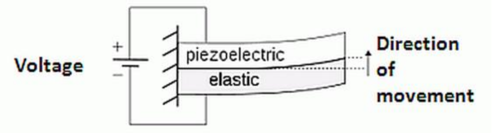

Fig 2: Unimorph cantilever beam

A unimorph cantilever consists of one active layer and one inactive layer. The active layer is piezoelectric, deformation in that layer may be induced by the application of an electric field. This deformation induces a bending displacement in the cantilever as shown in Figure 3. The inactive layer may be fabricated from a non-piezoelectric material (aluminum beam).

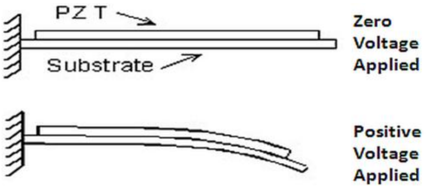

Fig 3: Schematic representation of the response of a unimorph cantilever

3.2 Energy Harvesting System Approach

A simplified vibrational energy harvesting system is shown in Fig. 4. It consists of vibration amplifier, force transducer, a piezoelectric element, energy harvesting circuit and an energy storage unit. Piezoelectric sensors has a small displacement and high force output. Hence, a monolithic is rarely used directly as a device. A mechanical impedance matching structure such as a beam with PZT patch above the root is employed in this approach for harvesting energy. This element is attached to a full-wave rectifier. This is in turn connected to a filter which would allow output of only a certain frequency range. Then a regulator is connected where the energy harvesting unit stores the acquired energy.

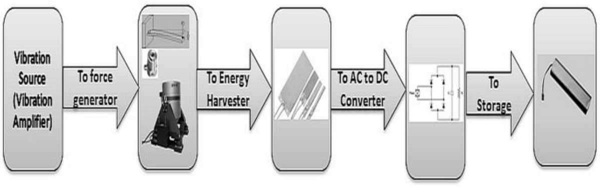

Fig 4: Piezoelectric Energy Harvesting System

When the input signal is applied to vibration amplifier, it amplifies the input signal for the required level and then feeds it into the force transducer. The force transducer produces the force to the cantilever beam and it start vibrating at a particular resonant frequency which will match. When a PZT is subjected to vibrations, a voltage is developed across its thickness. As a result the PZT acts as a sensor. The voltage generated from the PZT material is AC (Alternating Current). Since AC can periodically change its direction, it has to be converted into DC (Direct Current) which flows in only one direction. The AC – to – DC converter (rectifier) is used for the conversion and then it is filtered by using the capacitor filter. After filtering the energy is stored in the storage device which will be used for low power applications.

3.3 Operating Modes of a Piezoelectric Transducer

Piezoelectric materials are manufactured in such a manner that the piezoelectric cause and effect are made more prominent along some particular direction. This way, the piezoelectric materials can be efficiently used as sensors and actuators. In the present study, PZT5H piezo sensor manufactured by M/s Sparkler Piezoceramics, Pune were used. The properties of the PZT5H are mentioned in the Table 1. Most common operating modes for a cantilever beam are "31"operating mode and "33" operating mode.

- A 31-mode piezoelectric actuator produces displacement perpendicular to an electric field applied parallel to the material's polarization direction. Approximately twice the strain can be obtained from a 33-mode piezoelectric actuator than a 31-mode piezoelectric actuator for the same applied field; this is due to the relative magnitudes of the piezoelectric coefficients. In this case the bending beam has electrodes on its top and bottom surfaces.
- A 33-mode piezoelectric actuator produces displacement in the same direction as an electric field applied parallel to the materials polarization direction. Here the bending beam has all electrodes on its top surface.

Although piezoelectric materials working in d_{31} mode normally have lower coupling coefficient than d_{33} mode, d_{31} mode is more commonly used. This is because, when a single layer cantilever beam bends, more lateral stress is produced than vertical stress, which makes it easier to couple in d_{31} mode. While operating in d_{31} mode, electric fields are more pronounced in 3-direction and stresses and strains are more pronounced in 1 direction. In case of sensors, the electric field is generated in 3-direction because of the stress and strain developed in 1-direction. In case of actuators, electric field is applied in 3-direction and stress and strain in 1-direction; these are utilized for extension or bending in the material. [10].

In 31-operating mode, it is assumed that

$$E_1 = E_2 = 0$$

$$€_{yy} = €_{zz} = \gamma_{yz} = \gamma_{xy} = \gamma_{xz} = 0$$

So, the constitutive relations gets reduced to

$$\sigma_{xx} = C_{11}\, €_{xx} + d_{31} E_3 \quad \text{. . . . (1)}$$

$$D_3 = d_{31} €_{xx} + k_{33} E_3 \quad \text{. . . . (2)}$$

$$€_{xx} = S_{11}\, \sigma_{xx} + e_{31} E_3 \quad \text{. . . . (3)}$$

$$D_3 = e_{31}\, \sigma_{xx} + k_{33} E_3 \quad \text{. .. . (4)}$$

From equation (1), we can write

$$€_{xx} = (\sigma_{xx} - d_{22} E_3) / C_{22} \quad \text{. . . .(5)}$$

Substituting the above equation in equation (2), we get

$$D_3 = d^T_{13}\, €_{33} + (K_{33} - d^2_{13}/C_{22}) E_3 \quad \text{. . . . (6)}$$

$$C_p = A/\tau(K_{33} - d^2_{13}/C_{11})E_3 = A/\tau\, (K_{33}(1 - K_{31}^2)) \quad \text{. . . . (7)}$$

Above equation is called open loop capacitance or free capacitance, where

$$K_{31} = \frac{d_{13}}{\sqrt{C_{11}\mathcal{K}_{33}}}$$

is the coupling coefficient of 31 piezoelectric transducer.
Thus, the charge produced on the surface of the PZT can be written as

$$Q = C_p * V \quad \text{. . . . (8)}$$

As a result, the voltage is generated from PZT by mechanical stress.

Table 1. Material properties of PZT

Property	PZT
Density	7500Kg/m^3
Young's modulus	48e9N/m^2
Poisson's ratio	0.22
Piezoelectric strain constants(d)	d 33 =550e-12 C/N d 31= -265e-12 C/N
Piezoelectric stress constant(e)	e 31 =-0.0101 e32 =-0.0101 e33=0.0719
Relative permittivity	1699
Maximum voltage	180 V

3.4 Modes of Vibration

A complex body can vibrate in many different ways, each having its own frequency. The frequency can be determined by the moving mass in that mode and the restoring force which tries to return the specific distortion of the body back to its equilibrium position. When any complex body vibrates there is no one "simple harmonic oscillator", as a reason many modes are excited and vibrate together. The shape of vibration is very complicated and changes from one instant to another and also, it is difficult to determine the shape of the modes. However, by using resonance both the frequency and the shape of the mode can be obtained. If vibration is given to a body to the nearest resonance frequency of the mode then that mode responds. If a beam with tension is vibrated, the beam has the variety of modes of vibration with different frequencies [11-12]. For the energy harvesting system using sensors, three modes of vibrations are used as discussed below.

3.4.1 Mode 1

In this mode, low frequency is used. The lowest frequency is a mode where the whole beam just oscillates back and forth as one- with the greatest motion in the center of the beam. In mode 1 , the shape of the mode is at its maximum vibration in one direction and is shown in Fig. 5 (a).

3.4.2 Mode 2

In this mode, the frequency of the vibration is increased to twice the mode 1 frequency. As the frequency is increased, it is seen that the beam again vibrates back and forth but in a different shape than the previous one. Here, the two halves of the beam vibrates in opposite direction to each other. One half vibrates down and the other moves up and vice versa and is shown in Fig. 5 (b).

3.4.3 Mode 3

In mode 3, the frequency is increased to thrice the mode 1 frequency and it is seen that the vibrations are large, that is vibrating at the resonant frequency of third mode. In this mode the hump is divided equally where each vibrating length is opposite to the adjacent piece as shown in Fig. 5 (c).

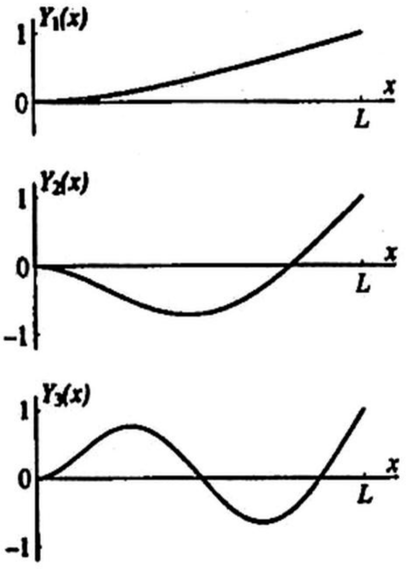

Fig. 5: Modes of Vibration (a) Mode 1, (b) Mode 2, (c) Mode3

4. EXPERIMENTAL SETUP

An experimental study was made on the physical model, along with the energy harvesting circuit setup as shown in Fig. 6. As discussed in Section 3, energy harvesting circuit captures the energy from the system and converts it into an useful and storable form. An aluminum beam was mounted with PZT patch at the top near the root, using adhesive (Araldite®). An assumption is taken that the adhesive transfers the mechanical disturbance without any losses.

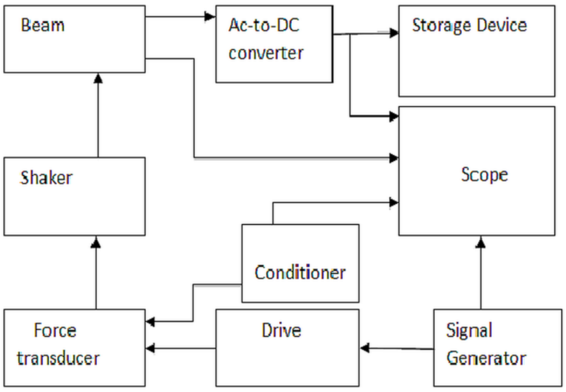

Fig 6: Experimental setup for Energy Harvesting

The vibrations were generated using signal generator that amplifies and drives to force transducer. Then, it was fed into shaker, and it produces same frequency (vibration). If this resonance frequency matches to PZT resonance frequency, it starts vibrating more, due to which, reaction PZT produces AC signal. Output of the PZT is converted to DC voltage by using rectifier and further stored in a battery or capacitor.

A typical energy harvesting circuit with full wave rectifier is shown in Fig. 7. A filter was used to eliminate the AC ripples and to convert it to pure DC voltage. For rectification, Schottky barrier diode DO-34 package BAT85 (D1-4) was used. The filter capacitor (C1) is a Metalized Polyester, Round type capacitors (MER Series) of value 10K/100 which has very low dissipation factor less than 0.8% for less than 1kHz. The load resister R1 is the carbon type resistor. The load resistor was selected based on the maximum power recorded as shown in the Figure 8. The maximum power recorded at 1.7K Ω. The voltages were measured across the resister R1 (1.7K Ω) for all experiments conducted on beams. As a result, comparison of the power in all experiments gives the measured voltages. This is equal to the power/energy generated by the PZT attached for the beams.

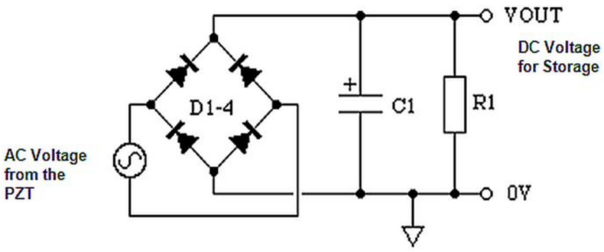

Fig. 7: Full wave rectifier circuit

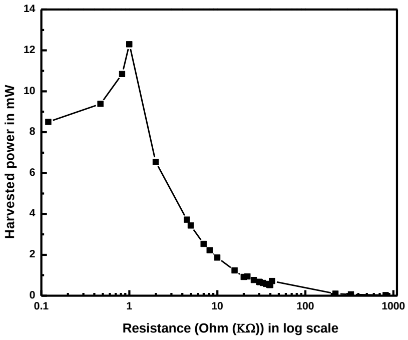

Fig. 8: Variation of power with respect to load resistance

The experiments were conducted on the beams. The PZTs of thickness 1mm, 2mm, 4mm, 6mm, 8mm, and 10mm were fixed near the root of the beam as shown in Fig. 9. The dimensions of aluminum beam are 300(L) X 35(W) X 3(T) mm. The other type of the specimens prepared with a thickness of the beam 1mm, 1,5 mm, 2 mm and 3 mm by keeping the length and breadth constant. The actual specimens are shown in Fig. 9.

Fig. 9: The actual specimens with variation of thickness of PZT

5. RESULTS AND DISCUSSION

The performance of the piezoelectric sensor in energy harvesting system with variation in thickness at different modes are discussed in detail.

Initially, the modal frequencies are found for the beams with variation of PZT thicknesses, and is as shown in Figure 10. The observation is that as the thickness is increased the frequency decreases. The reason for increase in thickness of PZT is due to increase in mass of the beam. The 1 mm and 2 mm PZT beam may not have influence on the weight of the beam. This shows a nominal change in frequency values.

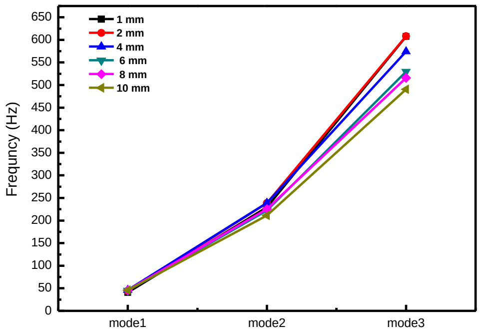

Fig 10: Frequency variation for different modes of sensor thickness

With varying force at different beam thickness of 1.0 mm, 1.5 mm, 2.0 mm and 3.0 mm the frequency at three different modes are measured as shown in Fig. 11.

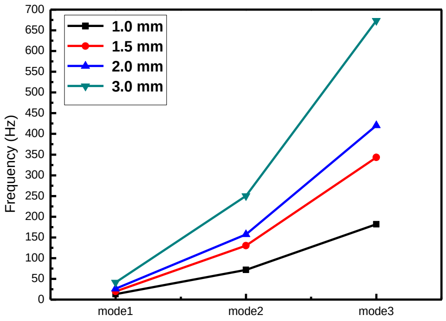

Fig 11: Frequency variation for different modes of different thickness beams

The AC output voltage is measured by varying the applied input vibrational force and is shown in Fig. 12 for 1 mm thickness PZT beam. It is observed that for mode 2 frequency, the voltage is higher than the output voltage at the other two modes. The reason is as explained in the modal shapes in Fig. 5 shows, the transfer of the vibration energy is more in mode 2 as compared to other modes.

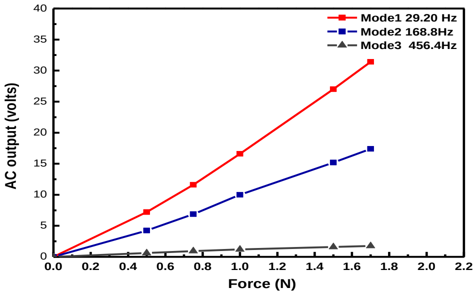

Fig 12: Variation of voltage with respect to applied force

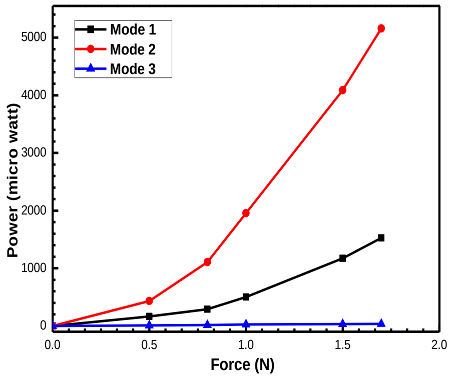

Fig 13: Variation of current with respect to applied force

It is also observed that the mode2 gives more DC power as compared to the other modes in the PZT with variation in the thickness beams. The power recorded for 1 mm thickness beam fixed with 1 mm PZT sensor output recorded and shown in the Fig. 13. This gives an idea that the thin structure vibrates more and transfers more energy to the piezo sensor. The order of the power harvested is approximately 500 µW in mode 2.

6. CONCLUSIONS

An energy harvesting electronic circuit using piezoelectric sensor was designed for vibrational energy conversion application. From the results, it is concluded that the thinner PZT's generates more power and is independent of the thickness of the structure or unit. It is further suggested that there is a good mechanical coupling for thin PZTs as the PZT is closely attached / fixed to the structure as compared to thick PZTs. It is also observed that more energy is harvested from thin structures as compared to stiff / thick structures. Moreover, selection of the sensors is one of the most critical aspect for the energy harvesting system. The energy harvested from the structural vibrations is stored in smaller capacitances used in place of batteries to power up the electronics. This is going to be a futuristic method for self powered electronic system.

7. ACKNOWLEDGMENT

Authors would like to thank the Director, CSIR-NAL, Bengaluru for driving the confidence. Dr. S. Satish Chandra, Head, STTD, NAL, Bengaluru is profusely thanked for providing all facilities for completing the developmental work. The technical support by the STTD staff, NAL, Bengaluru and project trainee personnel is sincerely acknowledged.

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