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Power Enhancement for Piezoelectric Energy Harvester

Rajkumar Gupta[1], Dinesh Kumar Tyagi[2]

[1]B.Tech Students, Assistant Professor Department of Mechanical Engineering

[2]Raffles University, Japanese Zone Neemrana (Rajasthan), 301705-India

Abstract: ***Piezoelectric energy harvesting technology has received a great attention during the last decade to activate low power microelectronic devices such as wireless sensor nodes (WSN). This paper investigates the necessary conditions to enhance the extracted AC electrical power from the exciting vibration energy using piezoelectric material. The effect of tip mass and its mounting position on maximum power extraction are investigated theoretically and experimentally. The optimal load impedance is also investigated to maximize the output power. The experimental results validated the theoretical and concluded remarks in the paper.***

Keywords: Energy harvesting, piezoelectric materials, resonance frequency, impedance matching

1. Introductions

Energy harvesting technology is used to generate electrical power from natural (green) energy sources. The concept of energy harvesting generally relates to the process of using ambient energy, which is converted into electrical energy. Research on energy harvesting technology became progressively larger over the last decade to design self-powered microelectronic devices [1].

One of typical wasted energy is an ambient vibration that presents around most of machines and biological systems. This source of energy is ideal for the use of piezoelectric materials, which have the ability to convert mechanical strain energy into electrical energy and vice versa. In general, there are three techniques to harvest the energy from the vibration: electrostatic, electromagnetic, and piezoelectric. Piezoelectric materials have a superior performance to be used for energy harvesting from ambient vibrations, because they can efficiently convert mechanical strain to an electric charge without any additional power. In general, a piezoelectric energy harvesting can be represented as shown in **Figure 1**. The mechanical energy (e.g., applied external force or acceleration) is converted into mechanical energy in the host structure. Then, this energy is converted into electrical energy by the use of piezoelectric material, and is finally transferred into electrical form to a load and/or a storage stage. Therefore, three basic processes are performed: conversion of the input energy (vibration) into mechanical energy (strain) using a cantilever structure, electromechanical conversion using piezoelectric material, and electrical energy transfer. Most of the reported piezoelectric EHs working on resonance based mechanism typically use simple piezoelectric cantilever structure and incorporate proof mass to increase the average strain in the piezoelectric layer and thus enhance the power output [2-4].

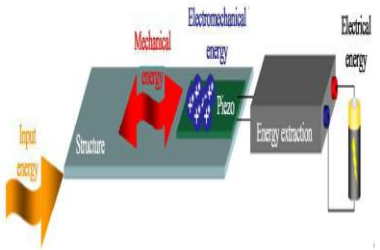

Figure 1: Schematic diagram of piezoelectric energy harvester [5]

The frequency of ambient vibration sources, such as household equipment, buildings, human body motion and heart beat, are typically less than 100 Hz. Therefore, it is necessary to bring down the resonant frequency of EHs to match the ambient excitation frequency. As the size of the energy harvesting device decreases to a smaller form factor, the resonant frequency of the device increases which makes it difficult to harvest low frequency vibrations less than 100 Hz. The traditional solution for reducing the resonant frequency of the EHs is to attach a proof mass at the free end of the cantilever. In the literature, several books are recently published in this research domain [6]-[9]. Several review papers are also published in all different aspects concerning energy harvesting technologies [10]-[16]. This paper investigates the necessary conditions to enhance the extracted AC electrical power from the exciting vibration energy using piezoelectric material.

2. Theoretical Backgrounds

2.1 Piezoelectric Effect

The piezoelectric effect is a direct transformation of mechanical energy into electrical energy. Piezoelectricity was discovered by Jacques Curie and Pierre Curie in 1880. They observed that certain crystals respond to pressure by separating electrical charges on opposing faces and named the phenomenon as piezoelectricity. The IEEE standard on piezoelectricity lists several different forms for the piezoelectric constitutive equations. The form used here is known as the d-form, and the equations are as follows

$$D=\epsilon^{T}E_f+d_{31}\sigma$$
$$S=s^{E}\sigma+d_{31}\sigma \qquad (i)$$

Where, σ−Dielectric-Stress (N/m^2), S-Strain(m/m), E_f-Electric field Strength (V/m), and D-Dielectric displacement (C/m^2), s-Elastic compliance (m^2/N), ε-Permittivity (F/m), d-Piezoelectric constant (C/N or m/V).

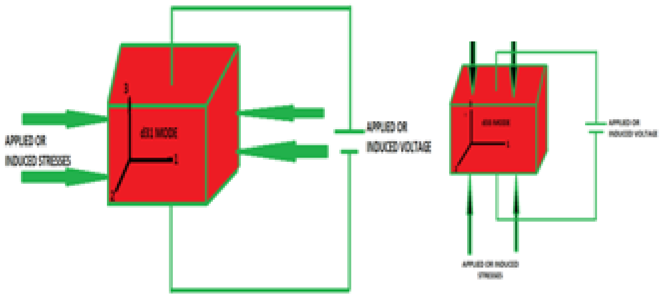

Figure 2: (a) d_{31} mode (b) d_{33} mode

There are two primary modes of electromechanical coupling for piezoelectric materials: the 3-1 mode and the 3-3 mode. In the 3-1 mode (Figure 2a), the electric field is produced on an axis orthogonal to the axis of applied strain, but in the 3-3 mode (Figure 2b), the electric field produced is on the same axis as the applied strain In the literature, several design parameters have been investigated to maximize the generated power from mechanical vibrations to electrical output using piezo-electric material. These parameters are summarized as:

- **Material**type as PZT, PVFD, Quick-Pack, and PVFD. Material with high quality factor (Q-factor) produces more power.
- **Geometry**, tapered form produces more power while the strip form is commercially available.
- **Thickness**, thin layers produce more energy.
- **Structure**, bimorph structure doubles the output than unimorph structure. **Loading mode**, d31 produces large strain and more energy for small applied forces.
- **Resonant frequency** has to be matched with the fundamental vibration frequency.
- **Electrical connection** parallel (to increase the output current) and series (to increase the output voltage source).
- **Fixation**, cantilever produces more strain than simple beam.
- **Load impedance**, it has to be matched with the piezoelectric impedance at the operating frequency.

2.2 Modelling of Power Generation by Piezoelectric Material

Cantilever structure with tip mass is the most widely used configuration for piezoelectric energy harvesting device. The stiffness of the structure depends on the loading condition, material, and cross-sectional area perpendicular to the direction of vibration. The governing equation of motion for the system shown in Fig. 3 can be obtained from energy balance equation or D'Alembert's principle. This configuration applies to both the energy harvesting mechanisms shown in Fig. 3 (a) and (b)

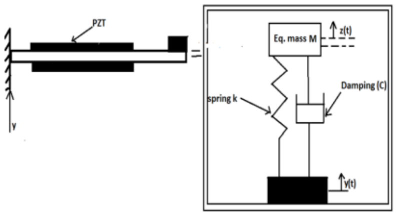

Figure 3: (a) Cantilever bimorph beam with tip mass (b) Equivalent lumped mass system of a vibrating rigid body

The governing equation of motion of a lumped spring mass system can be written as:

$$m\ddot{z}+c\dot{z}+kz=m\ddot{y}$$

Where y(t)is the input vibration,$\ddot{y}$(t)is the input acceleration; z(t) is the relative displacement of the mass with respect to the vibrating cantilever, Equation (1) can also be written in terms of damping constant(C) and natural frequency. A damping factor ξ, is a dimensionless number defined as the ratio of system damping to critical damping as

$$\xi=\frac{C}{C_c}=\frac{C}{2\sqrt{mK}} \qquad (ii)$$

The natural frequency of a spring mass system is defined

$$\omega_n=\sqrt{\frac{K}{m}} \qquad (iii)$$

Where the stiffness K for each loading condition should be initially calculated. For example, in case of a cantilever beam, the stiffness K is given by K = 3EI/L3, where E is the modulus of elasticity, I is the moment of inertia, and L is the length of beam. The moment of inertia for a rectangular cross-sectional can be obtained from expression, I = (1/12) bh3, where b and h are the width and thickness of the beam in transverse direction, respectively. The effective mass of the beam itself is approximately 0.236 times the beam's actual mass, and if the proof mass is modelled a point load at the tip, , the total effective mass is approximately: [3]

$$m_{eff}=m_t+.236\rho AL \qquad (iv)$$

Then natural frequency,

$$\omega_n=\sqrt{\frac{Ebh^3}{4L^3(m_t+0.236\rho AL)}} \qquad (v)$$

The power output of piezoelectric system will be higher if system is operating at natural frequency which dictates the selection of material and dimensions. The terms "natural frequency" and "resonant frequency" are used alternatively in literature,[3,4] where natural frequency of piezoelectric system should not be confused with natural frequency of mechanical system. The ratio of output z (t) and input y (t) can be obtained by applying Laplace transform with zero initial condition on Eq. (1) as: [5]

$$\frac{Z(t)}{Y(t)}=\frac{S^2}{S^2+2\xi\omega_n s+\omega_n^2} \qquad (vi)$$

The time domain of the response can be obtained by applying inverse Laplace transform on Eq. (6) and assuming that the external base excitation is sinusoidal given as: y = Y sin(ωt - ϕ),

$$Z(t)=\frac{\left(\frac{\omega}{\omega_n}\right)^2}{\sqrt{\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2+\left(2\xi\frac{\omega}{\omega_n}\right)^2}}Y\sin(\omega t-\phi) \qquad (vii)$$

The phase angle between output and input can be expressed as ϕ = $\tan^{-1}$ (Cω/ (k- ω2M)). The approximate mechanical power of a piezoelectric transducer vibrating under the above mentioned condition can be obtained from the product of velocity and force on the mass as:

$$P(t) = \frac{m\xi Y^2\left(\frac{\omega}{\omega_n}\right)^2\omega^2}{\sqrt{\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2+\left(2\xi\frac{\omega}{\omega_n}\right)^2}} \quad \text{(viii)}$$

Where; *Y* is the amplitude of vibration. The maximum power dissipated in the damper occurs at $\omega=\omega_n$ (resonance condition) and power can be calculated by the following formula:

$$P_{max}(t) = \frac{mY^2\omega_n^2}{2} \quad \text{(ix)}$$

Maximum power conversion to electrical domain occurs when the mechanical damping equals the electrical damping. Therefore, the maximum electrical output power is equal to half the value in the Equation (a). [5]

$$P_e(max) = \frac{mY^2\omega_n^2}{4} \quad \text{(x)}$$

2.3 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 **(see Fig4).** 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. Piezoelectric generators on a two-layer bender (or bimorph) mounted as a cantilever beam. The device's top and bottom layers are composed of piezoelectric material. As the figure shows, bending the beam down produces tension in the top layer and compresses the bottom layer. A voltage develops across each of the layers, which we can condition and use to drive a load circuit. If we wire the layers in series, their individual voltages add. If we wire them in parallel, their individual currents add.

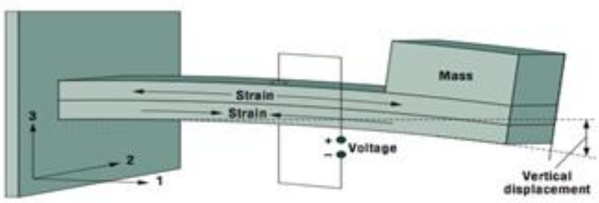

Figure 4: Strain is generated along the length of the beam, hence the use of the 3-1 mode

3. Experimental Set-Up Detail

3.1 Harvester Fabrication

(i) Copper shim: the copper shim is taken piece are available in the market. It is finely finished by grinding, file and abrasive paper to make it prismatic**.**

(ii) PZT (Lead ZirconateTitanate) Material: PZT material is used in the form of piezoelectric sim.PZT material is purchase from "DoonCeratronics Pvt. Ltd. Dehradoon (U.K). In the fig.6 show the energy harvester of bimorph structure of the cantilever beam. The dimensions of the PZT and copper layers are provided in Table 1.

Table 1: Dimensions of the Energy Harvesting Beams

	L (mm)	B (mm)	h mm	ρ (kg/m3)	E (Pa)
PZT shim	50	10	0.5	7500	$72X10^9$
Copper shim	120	12	523	8900	$100X10^9$
Steel mass				7900	$200x10^9$

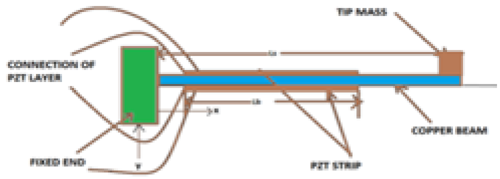

Figure 5: Energy harvesting from piezoelectric bimorph cantilever beam

3.2 Experimental Setup

The experimental set-up consists of (see **Figure 6-7**):

- **Function generator** to generate the vibration signal at different levels and different frequencies ranged from 5 Hz to 30 Hz with incremental step of 1 Hz;
- **Desktop shaker** to generate mechanical vibrations
- **Harvester module** using a Lead zirconatetitanate (PZT) material with dimensions of 50mmx10mmx0.5mm;
- **Different resistance**, 1Ω, 2Ω, 10Ω, 1kΩ, 2kΩ, 10kΩ, 220kΩ, 270kΩ **Multimeter**is use to show the function generator frequency
- **2-channel Oscilloscope** is measured the output voltage of the harvester and harvester frequency and is connect to the computer.

Figure 6: Experimental set of energy harvesting

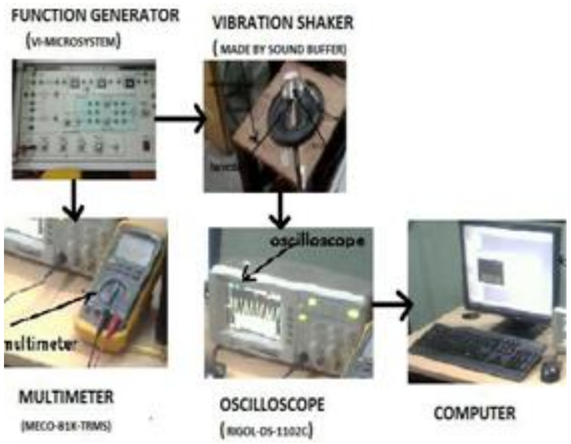

Figure 7: Schematic diagram for experimental validation

Experiments were conducted with a bimorph harvester and a bimorph harvester with a tip mass and without tip mass. To test the energy harvesters the cantilever beams were clamped to an electromagnetic shaker. In order to measure charge output lead wires were attached to the beam with a two part conductive epoxy of both the PZT strip and the series connection of the strip. The shaker is excited by an amplifier module to generate vibrations. Under exciting vibration, the piezoelectric harvester produces AC electrical output. Then, the output signal from the harvester is connected to a variable resistive load. 2-channel oscilloscope is used to perform real time measurements.

The vibration frequency and its excitation level (amplitude) are varied to test the performance of the harvester. The maximum voltage or maximum power is used to evaluate the system performance. The harvester produces significant power when it works under excitation frequency that closing to its resonant frequency. The resonant frequency of the harvesting cantilever under a given set conditions is identified experimentally by monitoring the peak of power output. The resonant frequency is changed by adding or removing tip masses. Different tip masses are used to investigate their effect to the resonant frequency. The effect of different mounting positions for this tip mass is also investigated.

4. Result and Discussion

4.1 Resonant Frequency, Power And Voltage Generated Without Tip Mass:

The resonant frequency under fixed excitation level is identified by monitoring the maximum output power and voltage as a function of excitation frequency. The excitation frequency from the amplifier module is varied from 5 to 30 Hz. In this experiment, no tip mass is mounted on the cantilever and the load is fixed to be 50 kΩ. Figure -8&9 shows the generated power and voltage from the harvesting system without tip mass.

It is observed that the resonant frequency of the harvester is 17.8 Hz (maximum peak of the extracted power). Under this excitation frequency; the power output and voltage reached to its maximum value equal to 184 μW and 3.04 V. Another local peak is also observed at 29 Hz with lower power output and voltage output. This phenomenon is commonly known for physical systems, in which such systems have multiple resonant frequency modes due to its flexible structure.

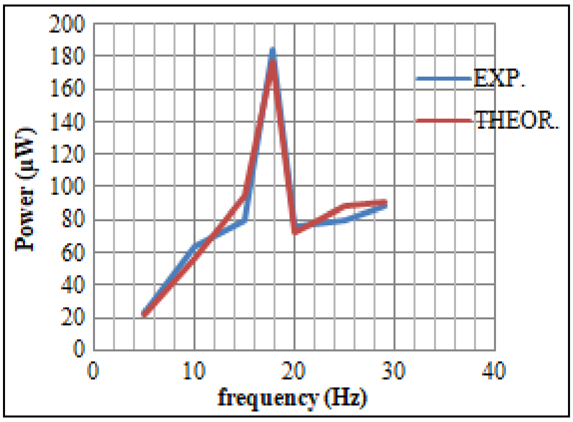

Figure 8: Experimentally and theoretical generated power without tip mass

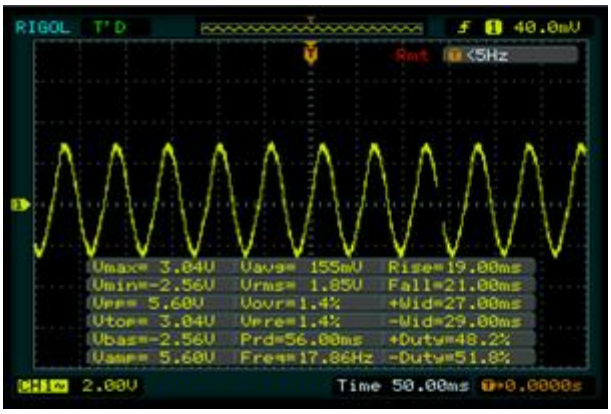

Figure 9: Experimental voltage generated without tip mass

4.2 Effect of Mounting Positions for Tip Mass on Bimorph Cantilever Beam

Resonant frequency of a cantilever depends on its effective mass rather than its total mass. Two cantilevers with similar material and mass but with different shape or mass density distribution will have distinct resonant frequency. The closer the centre of gravity to the free end of the cantilever, the greater the effective mass is achieved, and hence the lower resonant frequency. The mounting position of tip mass is varied from 1cm to 6 cm away from the fixed end of the cantilever and using different tip masses.

4.2.1- 1 Gram Tip Mass At Different Mounting Positions On The Cantilever

The mounting position of tip mass is varied from 1cm to 6 cm away from the fixed end of the cantilever. The resonant frequencies are 15.63, 16.23, 16.67, 16, 17, 17.5Hz respectively for 1, 2, 3, 4, 5, and6 cm mounting positions. Table-2 summarizes the complete results for these experiments.

Table 2: Experiment results for mounting positions

Mounting Positions	EXP. Power (µW)	Theor. Power (µW)	Resonant Frequency (Hz)	EXP.Voltage (V)
1cm	415	433	15.63	4.56
2cm	436	412	16.23	4.67
3cm	359	379	16.67	4.24
4cm	236	239	16.00	3.44
5cm	225	227	17.00	3.36
6cm	215	218	17.50	3.28

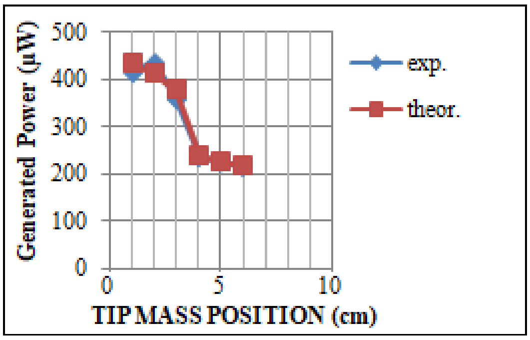

Figure 10: Generated power with different mounting positions.

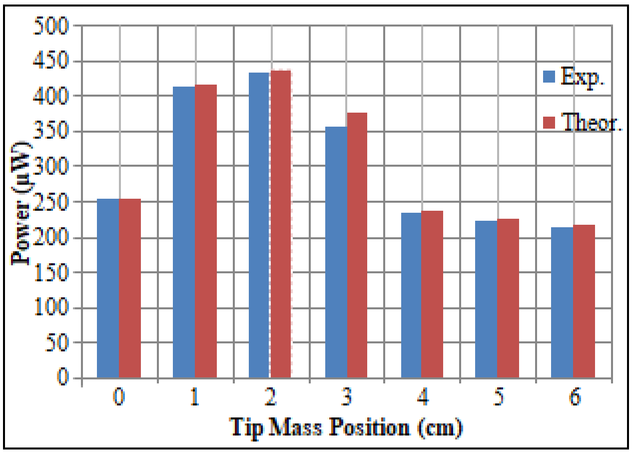

Figure 11: Experimental and theoretical power generation by 1gm mass of different position

5. Conclusions and Future Scope

Piezoelectric energy harvesting is a promising avenue of research to develop self-powered microelectronic devices. Wireless remote monitoring of mechanical structures, low power wireless sensors, and biomedical sensors are strongly candidates for piezoelectric energy harvesting applications. The piezoelectric energy harvester has a limited power and the optimization to extract maximum power in the whole stages is needed to enhance the device performance. The maximum (mechanical/electrical) power transfer depends on piezoelectric material properties and other matching operating conditions. In this paper, the experimental results validated the theoretical analysis to enhance the system. The experimental results highlighted the following points:

- The position of tip mass has a great effect on the effective mass of the harvesting cantilever and also its resonant frequency
- The position of the tip mass has the great effect on the power output and resonant frequency the tip mass position change from the free end of the cantilever beam, the power output increase and resonant frequency decrease, after certain limit power output decrease and resonant frequency increase due to damping effect.

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