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An Experimental Study on the Energy Harvesting System Using Piezoelectric Elements (PVDF)

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Abstract: Microelectronic devices such as wireless sensors nodes are designed by the use of harvesting technology of Piezoelectric energy. Necessary condition enhanced in the paper investigator existing vibration using piezoelectric material with AC power. The effect of tip masses and their mounting positions are investigated to enhance the system performance. The optimal resistive load is estimated to maximize the power output. Different capacitive loads are tested to store the output energy. The optimal resistive load is estimated to maximize the power output. The experimental results validated the theoretical analysis.
Keywords: Mechanical vibration; energy harvesting; resonant frequency; Bimorph Beam; Tip Mass

I. INTRODUCTIONS

Electric power generation can also done by energy harvesting technology with help of natural energy sources over the last decades the energy harvesting technology research is growing progressively. In ambient vibration the most typical wasted energy having biological system and machines. Piezoelectric material use it as an ideal source of energy. Energy can be harvested in three various way from vibration: electrostatics, electromagnetic and piezoelectric. For uses the ambient vibration the performance of piezoelectric material superior. Figure1 shows the representation of piezoelectric harvesting presence of the mechanical energy by the help of piezoelectric material is converted in electrical energy, then to load or storage stage. Therefore, all the three types of process are used in it as discussed above. 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].

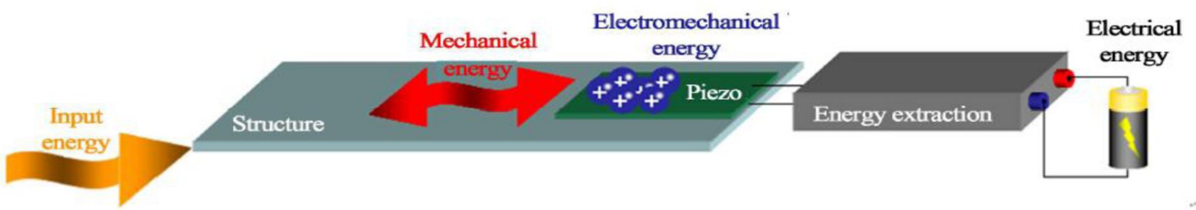

Fig 1. Schematic diagram of piezoelectric energy harvester

Household equipment, human body motion, buildings, heartbeat are the ambient vibration sources having frequency less than 100Hz. Therefore, the resonant frequency is broad down to match the ambient frequency as there is decrease in size of harvesting device which need to the increase in the resonant frequency of device which further makes harvesting of low frequency vibration difficult. This paper would tell about the extraction of AC electrical power from the existing vibration energy with the help of piezoelectric material.

II. THEORTICAL BACKGROUNDS

A. *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. Piezoelectric constitute are listed in several different on IEEE standard. Form used are generally known as d-form, and following equations are given below.

$$D=\epsilon^T E_f+d_{31}\sigma$$

$$S= s^E\,\sigma +d_{31}\,\sigma$$

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).

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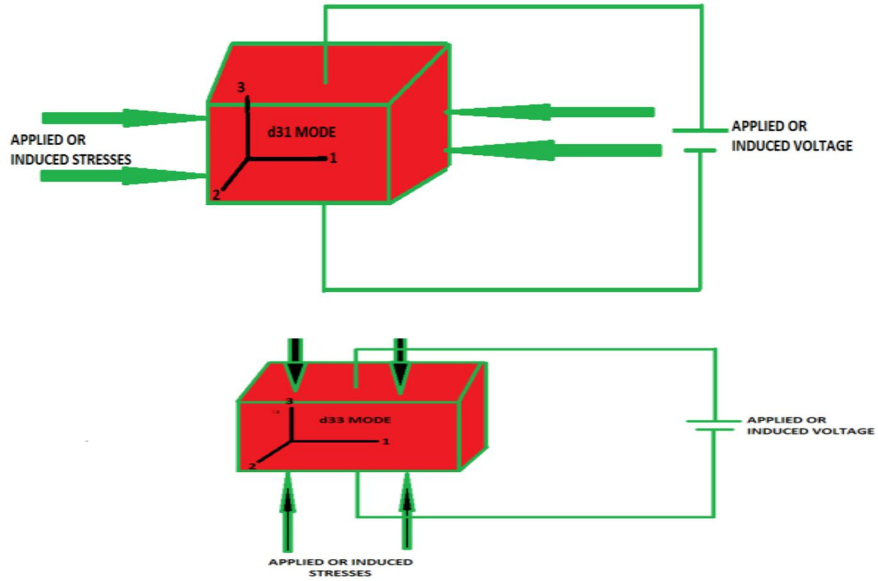

Fig.2 (a) d_{31} mode (b) d_{33} mode

Two primary modes for piezoelectric material of electromagnetic coupling are present:3-3 and 3-1 mode the production for electric field on orthogonal axis to applied strain in 3-1 mode and 3-3 mode here electric field produce is on same axis as of 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:

1) Material type as PZT, PVFD, Quick-Pack, and PVFD. Material with high quality factor (Q-factor) produces more power.
2) Geometry, tapered form produces more power while the strip form is commercially available.
3) Thickness, thin layers produce more energy.
4) Structure, bimorph structure doubles the output than unimorph structure. Loading mode, d31 produces large strain and more energy for small applied forces.
5) Resonant frequency fundamental vibration frequency would be same as it would match resonant frequency.
6) Electrical connection in series for increasing the output voltage and in parallel for increment of output current.
7) Fixation, the production of more strain then the simple beam is done with the cantilever beam.
8) Load impedance, piezoelectric impedance with have to match at the operating frequency.

B. Modelling of Power Generation by Piezoelectric Material

Cantilever structure with tip mass is the most widely used configuration for piezoelectric energy harvesting device. According to figure 3, the governing equation of motion can be obtain from energy balance and D' Alembert principle. shown in Fig. 3 (a) and (b)

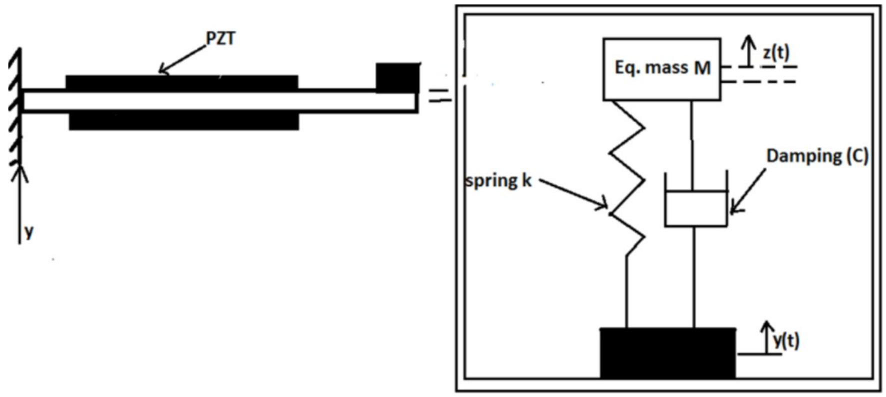

Fig-3 (a) Cantilever bimorph beam with tip mass (b) Equivalent lumped mass system of a vibrating rigid body

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(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

$$\xi=\frac{c}{C_C}=\frac{C}{2\sqrt{mK}}$$

The natural frequency of a spring mass system is defined

$$\omega_n = \sqrt{\frac{K}{m}}$$

K= stiffness for the condition of loading and should be calculated. 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]

$$m_{eff}= m_t+.236\rho AL$$

Then natural frequency,

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

Piezoelectric system power output will be higher when system operation of natural frequency from which selection of material and dimensions are dedicated. The terms "natural frequency" and "resonant frequency" are used alternatively in literature. Piezoelectric systems natural frequency would not confuse mechanical system natural frequency. The ratio of input over output is obtain by Laplace transformation as shown in equation (1) as: [5]

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

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),

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

The output input phase angle can be written as $\phi = \tan^{-1}$ (Cω/ (k- ω2M)). Above condition can be obtain for the velocity and force of product masses.

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

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:

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

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]

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

C. 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. Moment of support structure up and down when the subjection of generator in vertical direction to vibration with additional acceleration. To increase the deflection amount addition of proof mass is done to free end. High output voltage and power, more strain and stresses lead to larger defection. Piezoelectric generator is mounted on 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.

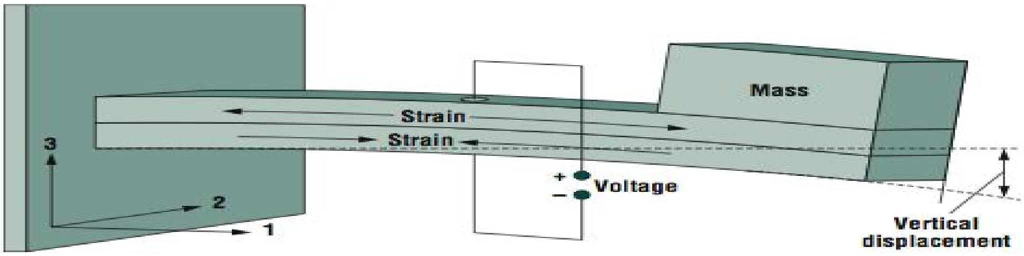

Fig-4 Strain is generated along the length of the beam, hence the use of the 3-1 mode

III. EXPERIMENTAL SET-UP DETAIL

A. Harvester Fabrication

1) *Copper shim:* are available in market in pieces. Grinding, file and abrasive paper finishing are done to make it prismatic.
2) *PZT (Lead Zirconate Titanate) 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

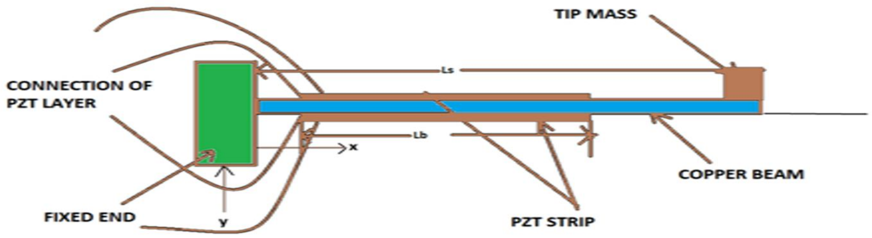

Fig.5Energy harvesting from piezoelectric bimorph cantilever beam

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B. Experimental Setup

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

1) 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;
2) Desktop shaker to generate mechanical vibrations
3) Harvester module using a Lead ZirconateTitanate (PZT) material with dimensions of 50mmx10mmx0.5mm;
4) Different resistance, 1Ω, 2Ω, 10Ω, 1kΩ, 2kΩ, 10kΩ, 220kΩ, 270kΩ Mustimeters use to show the function generator frequency
5) 2-channel Oscilloscope is measured the output voltage of the harvester and harvester frequency and is connect to the computer.
6) Tip masses: different tip masses are used i.e. 1g,2g ,3g, 4g,5g

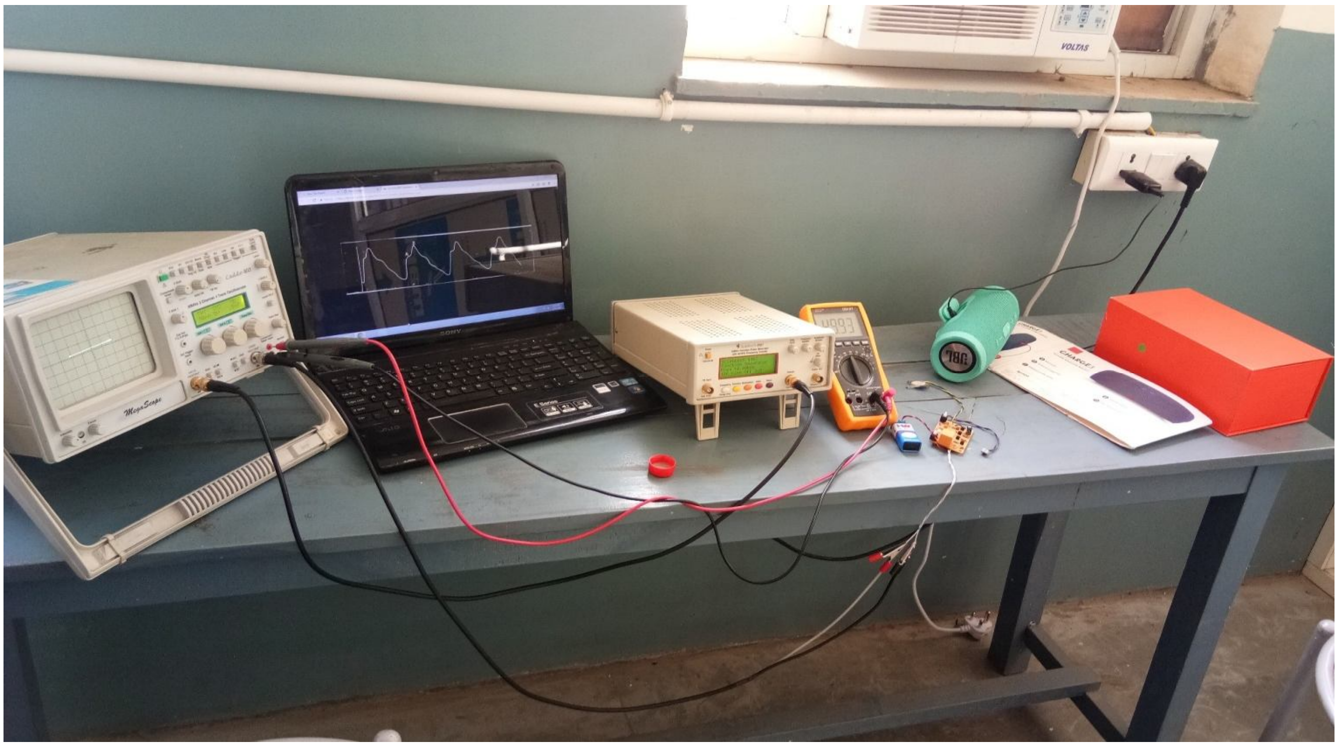

Fig 6–Experimental set of energy harvesting

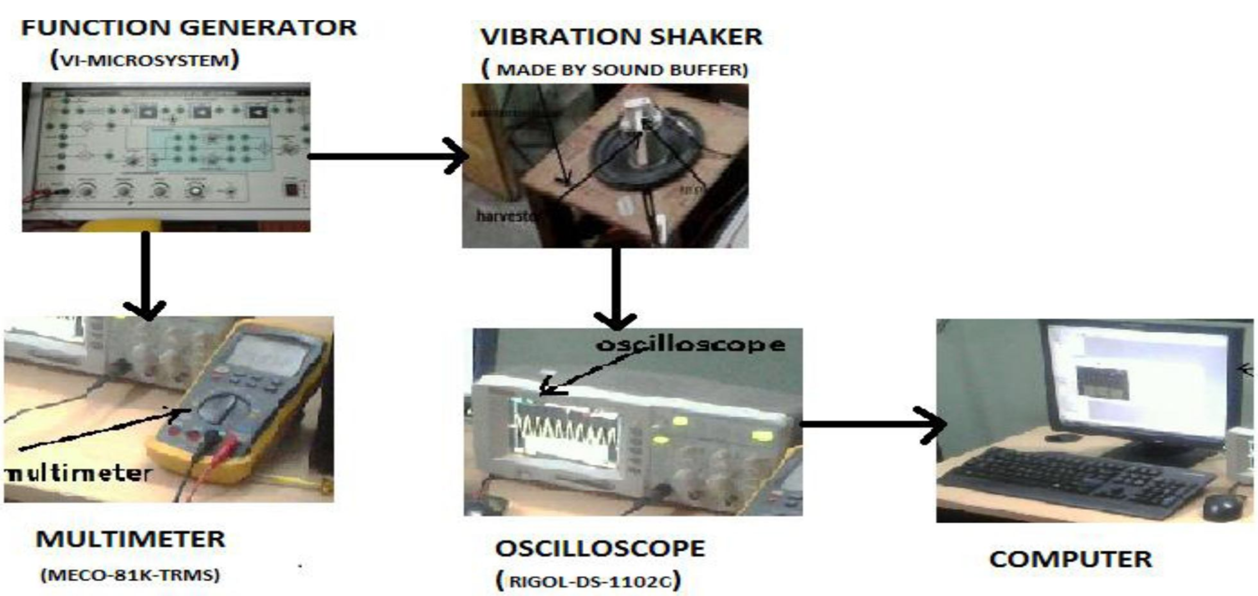

Fig7- Schematic diagram for experimental validation

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.

IV. RESULT AND DISCUSSION

A. Resonant Frequency, Power and Voltage Generated Without Tip Mass

The excitation frequency of power and voltage is maximized by monitoring the excitation level of resonant frequency. 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. physical system is phenomena in which multiple resonant frequency have flexible structure.

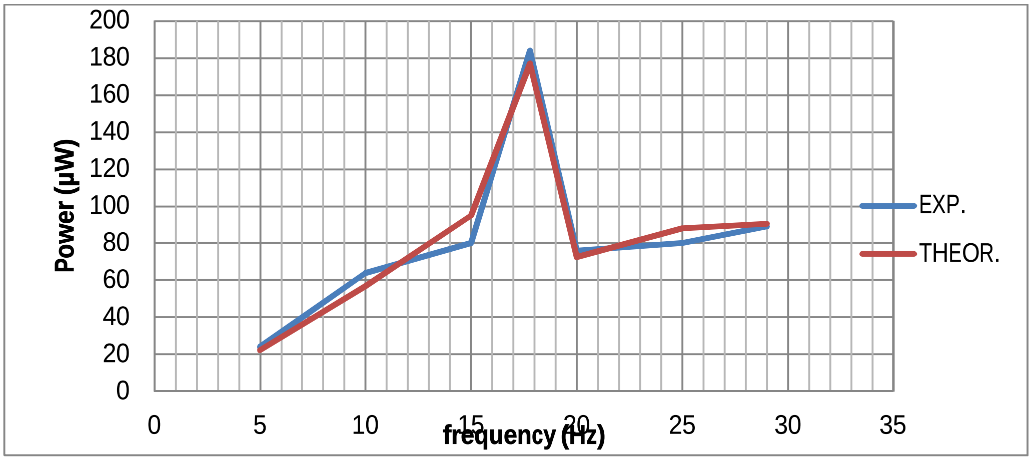

Fig8-Experimentally and theoretical generated power without tip mass

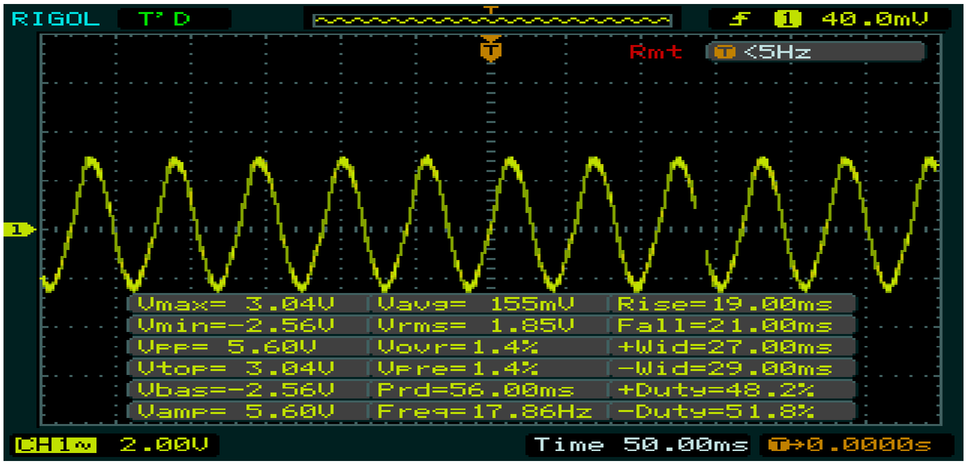

Fig9- Experimental voltage generated without tip mass

B. Different Tip Mass at Different Mounting Positions on the Cantilever:

The mounting position of tip mass is varied from 1 to 6 cm from the free end to fixed end of the cantilever. The resonant frequencies are increases from free end to fixed end of mounting positions. The power and voltage output increase from 1cm to 4cm and 5cm to 6cm decrease Table-3summarizes the complete results.

Table-3generated power with different mounting positions and different tip mass

TIP MASS POSITION	1gm		2gm		3gm		4gm		5gm	
	P_{MAX} (µW)	f_n(Hz)	P_{MAX} (µW)	f_n(Hz)	P_{MAX} (µW)	f_n(Hz)	P_{MAX} (µW)	f_n(Hz)	P_{MAX} (µW)	f_n(Hz)
1cm	415	15.63	373	13.16	307	11.63	194	11.10	276	10.20
2cm	436	14.53	331	13.00	315	11.00	256	10.10	307	09.08
3cm	359	16.67	294	14.29	332	13.16	445	12.00	346	10.00
4cm	236	16.00	236	15.15	107	14.00	161	13.50	100	12.56
5cm	225	17.00	194	16.00	165	15.00	123	14.00	131	13.00
6cm	215	17.50	236	16.50	175	16.00	175	15.00	139	14.50

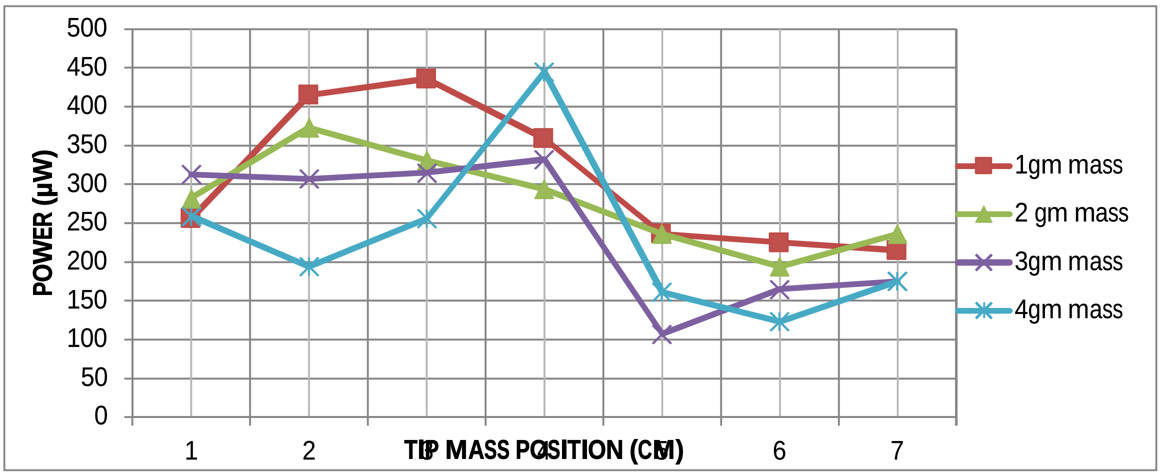

Fig 12- Power generation due to different mounting position for tip mass

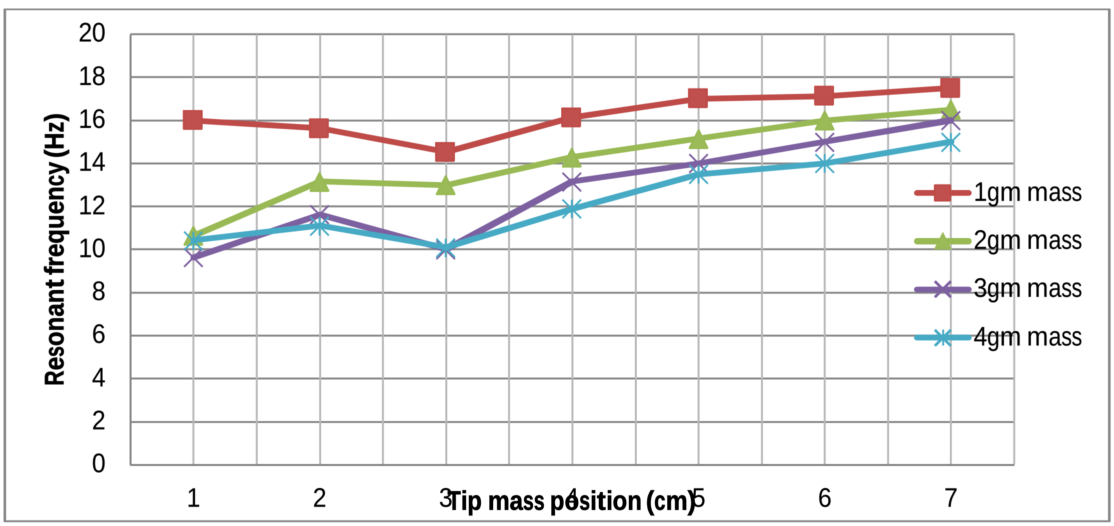

Fig 13-Generated resonant frequency due to different mounting position for tip mass

V. 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:

1) Resonant frequency of the harvester can be identified experimentally by tracking the maximum extracted electrical power.
2) Increasing tip mass decreases the resonant frequency and Output power increases
3) After certain limit; increasing tip mass decreases the power output due to the increasing of the damping effect.
4) The position of tip mass has a great effect on the effective mass of the harvesting cantilever and also its resonant frequency
5) Different position of tip masses causes great effect on the output power and resonant frequency and its position keeps on changing which needs to the incremental output power and decremental resonant frequency after certain limit power output will decrease and resonant frequency will increase due to damping effect.

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