Future Energy Source for Remote IoT Systems using MEMS-based Piezoelectric Energy Harvesting Devices.

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Abstract:
Piezoelectric energy harvesting (PEH) device is an energy converter that will convert mechanical vibration energy into electrical energy. The energy converter is implemented using Micro-Electronic Mechanical System (MEMS). The vibration is extracted from the surroundings, and the extracted vibration is converted into electrical energy using PEH for low power sensors used in the IoT environment. PHE device will generate the maximum power when the vibration of the surrounding is exactly matched with the resonant frequency of the device. This paper presents two different PHE MEMS devices which will convert the vibration into electrical energy. The proposed device has two design materials; T shape resonant model is designed by arranging beams in multilayer and an ultra-violet resin seismic mass. There are four-layer formed together; the substrate first layer is built using polyethylene terephthalate (PET). The third layer is formed by using piezoelectric material; the second and fourth layers are built using aluminium and platinum electrode. In the model, two different types of piezoelectric materials are used to build the PEH device. Two types of material used in the devices are ZnO and PZT-5A. Rayleigh-Ritz and Macaulay methods are used to model the system for analysing the mechanical behaviour of the model and structural analysis for the better energy extraction using FEM. The proposed PHE device using ZnO and PZT-5A is generating power at the rate of 1.8 W and 1.35 W with a voltage rating of 545 and 45 mV, respectively. The Proposed PHE device is built for remote location low power IoT devices.

Keywords: MEMS, Piezoelectric energy harvesting, Macaulay method, Rayleigh-Ritz method, Euler–Bernoulli beam theory, resonant frequency, low power IoT devices.

1. Introduction
Smart home, smart city, smart industry, smart farm, and so on with smart technology is built on the top of IoT (Internet of Things) Technology [1]. IoT will improve the operational efficiency of the system. It provides better controllability with proper communication and feedback.
system, which will monitor every change in the system physically [2]. In the near future, everyday objects like the fridge, washing machine, lights, fan, air conditioner, wearable’s and will soon be connected to the internet, and it will monitor its status around the clock [3, 4]. IoT is a collection of four fundamental building blocks, sensor nodes, gateway via the internet, cloud for data processing, and user interface for better monitoring and controlling. In the entire IoT infrastructure, sensor nodes are installed in remote places, rest all the building blocks are installed in the conventional existing network infrastructure. The power supply to the remote devices becomes more critical. Installing battery for the IoT sensor nodes will increase the cost of the system and also increases the operation cost. This paper proposes a new model for extracting power from the mechanical energy via vibration[5]. These proposed devices able to convert different types of energy (e.g., vibrations, heat, and electromagnetic waves) into another form of electrical energy[6]. Hence, the PEH devices can be a substitute for the lithium-based conventional batteries[7].

For the last two decades, energy conversion devices have been studied by lots of researchers, and different types of energy converters have been proposed based on the various source of energy conversion techniques. The major advantage of the piezoelectric effect gains lots of attention for better energy harvest; harvesting platform is build using MEMS. The obtained energy is polarized using PEH device material is exposed to the mechanical deformations [6]. The entire energy generating device is constructed in the structure of cantilever to extract more vibration from the mechanical environment [6]. The obtained mechanical and electrical coupling effect in their conversion model, the proposed model, is just a simple cantilever model [7]. The spectrum of vibration is modelled using the Montreal subway network in the transducer to the vibration (15.5 Hz) [8]. To obtain the optimized performance of the transducer, the output voltage and the powers are 44.5 V and 130 watts. The effect of the position and the material model is simulated along in the cantilever beam model using multiple computational simulation systems[9]. Most of the proposed model is using only the mathematical and numerical simulations. To predict more accurately, the system is analysed using finite element methods (FEM)[10].

T-shape cantilever device is better for obtaining better resonant frequency to generate maximum power even in the low vibration environment [11]. The proposed work is to develop a mathematical model to understand and predict the mechanical vibration behaviour of proposed two PEH MEMS devices composed of resonant structures with a T shape [12]. The proposed structure is composed of a multi-array of beams and mass of UV resin seismic. The beams consist of two structures of PHE using ZnO and PZT-5A [13]. The mathematical model is proposed using Macaulay methods and Rayleigh-Ritz methods [14]. For understanding the beam model, Euler–Bernoulli beam theory is used [15]. The performance of both mechanical devices is analysed in the FEM model. The entire model is given with proper load resistance of 151 and 1.5 kW, which will generate power at the up to 1.97 ad 1.35 watts, Voltage of 535, and 42 mV, respectively [16]. Based on this power analysis, the author has decided that the proposed energy harvester will be ideally suited for the remote IoT devices sensors and data loggers[17].

The proposed paper, the second section, deals with electromechanical modelling of two PEH devices using ZnO and PZT-5A, and the same is analysed using FEM [18, 19]. Section 3 describes the functionality and behaviour of the model, and the last section discusses the future scope of the paper.
2. MEMS Modelling of Proposed System.

This section proposes two different MEMS PEH energy harvesters design using ZnO and PET-5A on a polyethylene (PET) substrate. The design of the PEH device with T shape resonant structure is shown in Figure 1. An array of multilayer beam and UV seismic mass is selected adhesion, homogeneity, and easy fabrication. The first PET design is constructed with 150um thickness, ZnO of thickness 1.5 um, UV resin of thickness 810 um. The second design is PET substrate 150um, PZT-5A 1.5 um thickness, UV resin of 600 um. Both designs second and fourth layer is Al, and Pt is 100 nm thicknesses.

![Design of MEMS PEH devices with a T-shaped structure](image)

Figure 1: Design of MEMS PEH devices with a T-shaped structure (a), isometric view, (b) top view, and (c) side view of the Harvesting device.

Rayleigh-Ritz, an energy conservation model, is obtaining the first level of bending frequency of a single clamped beam. The proposed model potential and kinetic energy are given below in equations 1 and 2.

\[
P_{\text{max}} = \frac{1}{2} \int_0^L EI(x) \left( \frac{\partial^2 y(x)}{\partial x^2} \right)^2 dx
\]

\[
K_{\text{max}} = \frac{(2\pi f)^2}{2} \int_0^L \rho A(x) (\dot{y}(x))^2 dx
\]

Where \(y(x)\) is the beam deflection, \(E\) is the material young’s modulus, \(L\) is the beam length, \(I(x)\), and the \(A(x)\) are the bending moment and cross-section, \(f\) is the resonant frequency, and \(\rho\) is beam density. By applying the energy conversion law \(P_{\text{max}} = K_{\text{max}}\) and solving first bending resonant frequency in the single clamp beam. The same is shown in equation 3.
The Rayleigh-Ritz method is used to obtain the first bending resonant frequency of the PEH devices in a T-shaped structure. The proposed model in the \(yz\) plane with a homogenous and isometric plane. The same is shown in Figure 2. PEH geometry of the devices is symmetric with the plane XY [20]. The two electrodes of the PEH devices are negligible because of this thickness in comparison to PET and PEH systems [21, 22]. By applying the energy conversion law with the cross-section model, so we obtain the first resonant frequency model by applying the PEH device. The same is shown in equation 4.

\[
f_r = \frac{1}{2\pi} \sqrt{\frac{A}{B}}.
\]

Figure 2: Schematic view of a cross-section of the i-th layer on the j-th section of the MEMS-based PEH devices.

| Geometrical Parameter | Dimension (mm) | Geometric Parameters | Dimension (um) |
|-----------------------|----------------|----------------------|----------------|
| \(L_{s1}\)            | 8              | \(T_{1s1}\)          | 150            |
| \(L_{s2}\)            | 5              | \(T_{2s1}\)          | 1.5            |
| \(B_{s1}\)            | 10             | \(H_{1s1}\)          | 751.5          |
| \(B_{s2}\)            | 15             | \(H_{2s1}\)          | 961.5          |
Table 1 explains the mechanical properties of the materials PEH devices. The proposed geometrical model parameters of both PEH devices based on the ZnO and PZT-5A layers. Material properties are shown in Table 2; all the physical properties are PEH is density, Young’s Modulus, and Poisson Ratio. In this model, the analytic is shown that the first bending resonant frequency of the ZnO and the PZT-5A based on the interested 106.1 and 104.8 Hz.

| Material     | Density | Young’s modulus | Poisson Ratio |
|--------------|---------|-----------------|---------------|
| PZT – 5A     | 7750    | 65              | 0.31          |
| ZnO          | 5665    | 137             | 0.25          |
| PET          | 1400    | 2.4             | 0.36          |
| UV - resin   | 1037.8  | 2.4             | 0.34          |

The FEM model analysis of the PEH device, the proposed model, is hexahedral elements with multiple thousands of mesh in each layer. The proposed model is shown in Figure 3.

![Figure 3: FEM model of the Proposed PEH.](image)

The proposed model fundamental resonant frequency of the PEH device with ZnO and PZT-5A layers is obtained at the rate of relative errors of 2.45% and 3.36% compared to FEM models.

3. Results and Discussion.
This section gives the implementation results of the proposed model analysis. Figure 4 and Figure 5 shows the deflection of the resonance of both proposed model. The proposed implemented model is compared with the FEM analysis model. The relative error is shown in the model 5.38% and 5.33% with FEM design. The maximum deflection is obtained as 8.34 and 8.48 mm. The proposed model of normal stress is given as 38.3 and 11.74 MPa. The tensile strength of the proposed device is 412 and 502 MPa. The device operating resonant frequency acceleration is given as 5.2 m/s$^2$ and 18.3 m/s$^2$. The output power is calculated based on the various root mean square values. The output power model of the proposed system is shown in the equation.

$$P = \frac{V_{rms}^2}{R_{opt}}$$

![Graph showing deflection vs. length of PEH device](image)

Figure 4: Maximum displacement of the PEH device using ZnO.
The output power is calculated based on the value, and the proposed model using ZnO and PZT-5A of the MEMS-PEH is 1.97 and 1.35 um. This output power can supply electrical energy to low-power electronic devices, such as pressure and temperature sensors. The proposed PEH devices can operate at resonance with frequencies caused by vibration sources. The output voltage and the output power of the proposed model are analysed based on a different frequency. Figure 6 shows the output voltage of the proposed system based on the model of the PEH device. The power generation of the proposed system implemented with ZnO is shown in Figure 7 concerning its Frequency, and Figure 8 is showing the power generation of PZT-5A.

Figure 5: Maximum Displacement of the PEH device using PZT-5A.

Figure 6: Proposed system voltage generation with a different frequency (a) ZnO, (b) PZT-5A.
The operational resonant frequency of the proposed system is shown with all the required parameters for both PEH device ZnO and PZT-5A. Table 3 is showing first bending frequency, maximum deflection at resonance, maximum normal stress, maximum output voltage, optimal load resistance, and output power is shown for both the model ZnO and PZT-5A. Hence the proposed model is very efficient in generating maximum power for the low power IoT devices.
Table 3: Proposed model results with all the necessary parameters.

| Parameters                                      | ZnO based PEH | PZT-5A based PEH |
|-------------------------------------------------|---------------|------------------|
| First bending resonant frequency (Hz)            | 108.84        | 108.32           |
| Maximum deflection at resonance (mm)            | 7.83          | 8.09             |
| Maximum normal stress at x-axis (MPa)           | 38.45         | 11.74            |
| Maximum Output Voltage (mV)                     | 545.32        | 45.10            |
| Optimal Load Resistance (kΩ)                    | 151.12        | 1.5              |
| Output Power (µW)                               | 1.97          | 1.35             |

4. Conclusion
The proposed MEMS-based Piezoelectric Energy Harvesting device is implemented with ZnO and PZT-5A. This system analysis the first bending frequency, maximum deflection, maximum normal stress, output voltage, and output power. The mechanical behaviour of the proposed system is done using Rayleigh-Ritz and Macaulay methods, as well as the Euler–Bernoulli beam theory. The FEM model of the cantilever beam is used to analyse the electromechanical behaviour of the PEH device. The proposed PEH design using ZnO and PZT-5A has multiple layers generated 1.97 and 1.35 mW with a voltage difference of 545 and 45.1 mV and the load resistance of the 151 and 1.5 kW. Hence the proposed model is ideally suited for the low power IoT applications.

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