Simulation and Analysis of Piezoelectric Energy Harvester with Various Proof-Mass Geometries

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Abstract—This paper aims to generate electricity, by decreasing fossil fuels consumption and conserving electricity for further use. In this project, the method is to produce pollution-free electricity using the technique i.e. piezoelectric effect technique. By applying mechanical stress electric charge is generated known as the piezoelectric effect. A sufficient amount of energy is produced as it can reduce the damage of pollution caused by power plants. So to make the use of moving vehicles on road, power generated helps the environment last longer. Different shape, proof mass geometries are analyzed and plotted a graph between frequency versus voltage and electrical energy. Among them, it is identified that stacked cylindrical block has a good Voltage of 2.04mV (milliVolts = 10^{-3}V) and Energy of 21.2fJ (femtoJoule = 10^{-15}J).

Keywords—energy harvester, COMSOL simulator, piezoelectric, mechanical stress, fossil fuels

1 Introduction

The demand for fossil fuel is tremendously increasing over time, power using non-renewable energy will come to a halt for further generations. The overconsumption of these fuels and the risk associated are influencing the environment and economy. The global energy consumption level of non-renewable energy has risen to 80% in the year 2004 and will remain increasing in the further years due to an increase in population as the main factor.

This results in the emission of the drastic amount of CO_2 and greenhouse gasses being pumped into the air, which intern causes the raising concerns about the rise of sea levels, increase in average temperature, and extreme weather conditions. The fossil fuel resources, such as oil and gas, are expected to get exhausted at the end of the 21st century [2].

Wireless technologies and microelectronics have led to the development of wearable devices in recent decades [3]. In coexistence with these approaches is the concept of the Internet of Things (IoT), most commonly used are wireless sensors networks [4]. IoT has led to an alternate elucidation for remote areas or places where batteries are impossible. Regardless of the progress made by low-power integrated circuit technology, the chemical batteries' energy density needs to be ameliorated, since it is difficult to fulfill the power requirement for the mentioned applications [5,6]. Therefore, to sustain such self-powered systems, developing new energy harvesting techniques is obligatory. And also a feasible and economically practical replacement to batteries, but it also cracks down the emission of greenhouse gas and maintains the environment [7].

The power produced by human activities is used by a variety of devices as Human body energy harvesters [5-10]. And solar energy, electromagnetic radiation, and environmental mechanical energy are highly relativist on the environment.

Harvesting of human body heat can be done using the principle of thermoelectric power generators, based on the See-beck effect of materials i.e., one can generate a difference in electrical energy between the human body and the ambient temperature. The inconvenience is considering the temperature difference to have a stable system [5].

The mechanical energy of the human body and environment is extensively utilized due to their abundance in daily life. Therefore, the most ubiquitous form of energy is mechanical energy [11]. Mechanical energy forage can provide an adequate amount of power, to guarantee long-term autonomy for self-powered systems [3]. In Figure 1 [11], the working-frequency level for different mechanical energy sources is shown approximately.

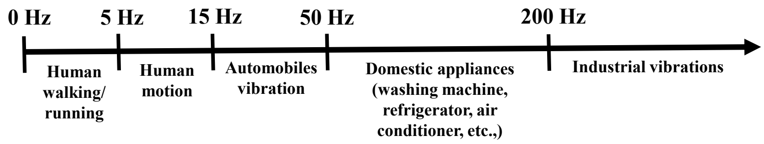

Fig. 1. Frequency level for different mechanical energy sources [11]

2 Literature survey

Researchers are working on low power application energy harvesting so that people living in and around the world can make use of power or energy more efficiently. Mechanical vibration is one of the prominent source and challenging sources for researchers to harness energy from it. Using piezoelectric material, mechanical vibrations are converted to electrical energy. An investigation was made and acquired an analysis of unimorph type cantilever beam type of piezoelectric energy harvester is conducted using a finite element method (FEM) which consist of Lead Zirconate Titanate (PZT-5A) as piezoelectric material, the substrate as silicon and support and proof mass as structural steel was designed for a frequency of 181.11Hz, the voltage of 129.9mV [14]and the other paper is of a macro scale unimorph piezoelectric power generator prototypes consist of an active piezoelectric layer, stainless steel substrate, and titanium proof mass was designed for a frequency of 153.22Hz, a voltage of 123.2mV, and energy of $5.815X10^{76}$J[15]. And the other paper is of a bimorph cantilever located on a vibrating host structure, to generate electrical energy from base excitations using different combinations of the affecting parameters using Taguchi's orthogonal array for optimization of the parameters in COMSOL 2D, a piezoelectric material as piezo-ceramics, support, and proof mass of stainless steel was designed for a frequency 75Hz and voltage of 5mV[16].

2.1 Energy harvesting methods

Energy generated and harvested by human walk is called mechanical energy harvester. There are two types of mechanical energy storage devices: Flywheels, and Springs. The combination of these harvesters with a ratchet can be stored subsequently. There are three typical ways to convert mechanical energy into electrical energy: electromagnetic, electrostatic/triboelectric, and piezoelectric.

Electromagnetic systems are the most suitable to transfer high-efficiency energy as they involve coils and magnets [18]. Piezoelectric energy harvesting is the best solution for applications that require high voltage, high energy density, high capacitance, and little mechanical damping [19-21]. From the observation, piezoelectric materials can be brittle or rigid, and toxic [22,23]. Electromagnetic devices have high output current, and low output impedance [21, 24]. These usually have coil losses, low efficiency at low frequencies, and low output voltages [21,25].

In comparison with piezoelectric and electromagnetic, triboelectric energy harvesting presents a multitude of advantages [26, 27]. And it also has reliability and durability issues [26, 28]. Techniques to increase efficiency for piezoelectric energy harvesting include Nonlinearity, Double pendulum system, Frequency upconversion, Circuit management.

2.2 Piezoelectric energy harvesting

The main principle of piezoelectric devices to urban roads is significant, at this stage. A renewable energy harvesting method leads the power generation into a more reliable source of energy. Solar panels or wind turbines produce electrical energy by utilizing the energy present in the environment i.e from the sun and wind [29]. However, energy formed from various vibration machines or any other source of mechanical energy is not being captured. Therefore, this type of energy is dispersed and thus wasted. The piezoelectric material is used to absorb the wasted mechanical energy and convert it to electrical energy which is an effective method to utilize this loss [30].

The piezoelectric principle supports the crystals. As shown in Figure 2, electrical voltage is induced when crystalline materials are subjected to an external force. Ex: natural crystals like clear quartz and amazonite are found at the surface or deep within the earth, which can be used these days to apply piezoelectricity effects. A variety of artificial crystals are formed by chemical compounds, including Barium Titanate, Lead Titanate, Lead Zirconate Titanate, etc. [31].

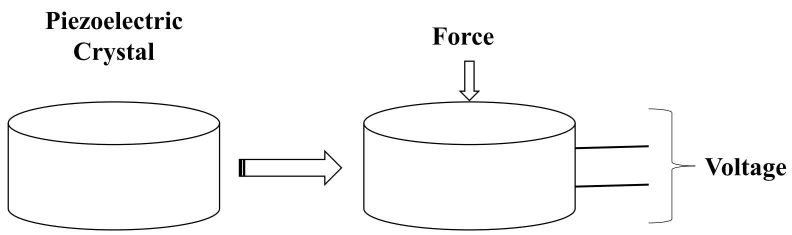

Fig. 2. Principle of piezoelectric effect [30]

The efficiency of piezoelectric devices is influenced by the type of crystals. However, Lead Zirconate Titanate (PZT) crystals are being used widely to achieve a high piezoelectric effect, ease of fabrication, high material strength, long-life service, resistance to humidity, and heat temperature over 100°C. Table 1 shows other parameters to determine the best outcomes of piezoelectricity [29].

Table 1. Piezoelectricity parameters

Geometry	The most efficient energy is produced in a stacked form of cylindrical model
Thickness	More energy is produced when the size of the material is thin
Loading Mode	By increasing the mass or force more amount of energy is produced
Fixation	Fixing one end will result in more deflection, and more energy is produced when subjected to external force, than when fixed at two ends
Structure	Bimorph structures produce double the output energy than unimorph structure

A piezoelectric energy harvester has two basic parts: the mechanical module and the electrical module. The effectiveness of the energy harvester is dependent on the piezoelectric transducer, and also on its integration with the electrical circuit. These systems are generally associated with three phases (Figure 3) i.e Mechanical to mechanical energy conversion, Mechanical to electrical energy conversion, Electrical to electrical energy conversion.

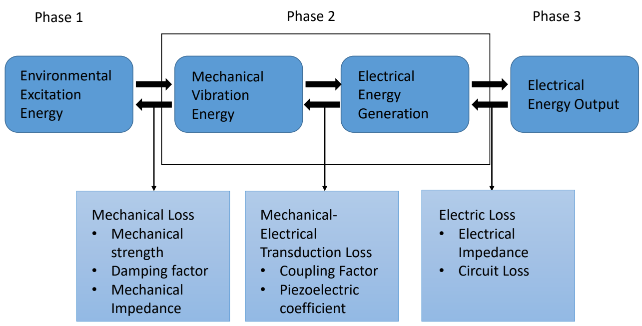

Fig. 3. The three phases associated with piezoelectric energy harvesting

2.3 COMSOL tool

Experimentation was performed by applying the different shapes, thicknesses, and stack structures. We used COMSOL Version 5.2, to compute the values of the output voltage, energy, and frequency. The simulated result presents the range of frequency and output voltage, energy for the design parameters. This study helps us to know which is more effective in producing a good voltage and energy of the energy harvester.

3 Flow steps for simulation using COMSOL

Figure 4 describes the flow graph of energy harvesting using piezoelectric material.

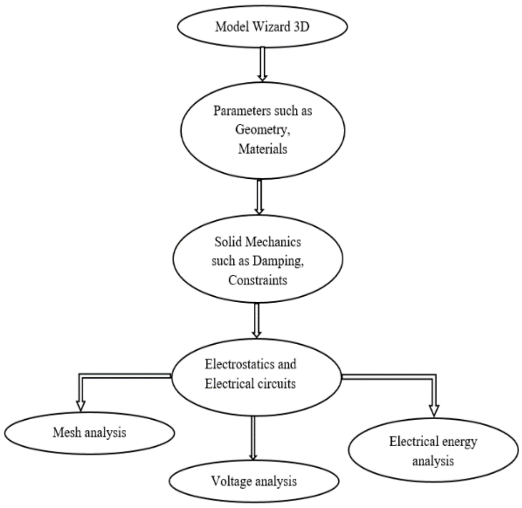

Fig. 4. COMSOL flow steps

- Step1: Create a Model Wizard 3D.
- Step2: Define all the Specifications.
- Step3: Model the piezoelectric cantilever using solid works.
- Step4: Define Solid Mechanics such as Damping, Constraints.
- Step5: Define Electrostatics and Electrical circuits.
- Step6: Analyze
  a) Mesh analysis
  b) Frequency Response: Voltage analysis
  c) Frequency Response: Electrical energy analysis
- Step7: Extract all the values and represent them in graphical form.

4 Modelling of piezoelectric energy harvesters of various proof mass geometries

The critical element for a piezoelectric harvester is its cantilever beam. It has a thin layer of piezoelectric material and a non-part electric layer or 2 layers. Depending on the number of piezoelectric layers involved, they can be classified as Unimorph and Bimorph. The bimorph cantilever structure is established in piezoelectric energy harvests as it doubles the production of electric power without a change in unit volume.

Figure 5 and 6 represent the rectangular and cylindrical proof mass. The structure consists of 5 blocks, with a PZT thickness of 0.4mm. The lower or first block is fixed at the point and is a structural steel material. The second block is PZT-5A. The third block is silicon. The fourth block is again PZT-5A and the fifth block is structural steel. The structure with rectangular proof mass produces a maximum voltage of 1.508mV and energy of 11.0fJ at a frequency of 241Hz. And the cylindrical proof mass produces a maximum voltage of 1.4905mV and energy of 10.6fJ at a frequency of 221Hz.

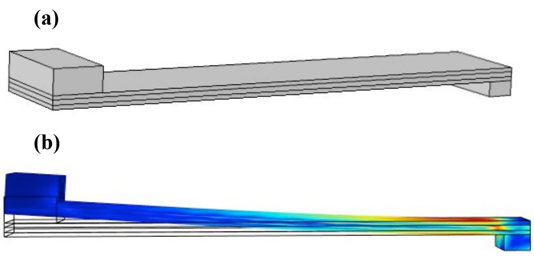

Fig. 5. (a) Structure (b) Stress applied on Bi-morph PZT energy harvester with rectangular block as proof mass PZT thickness of 0.4mm

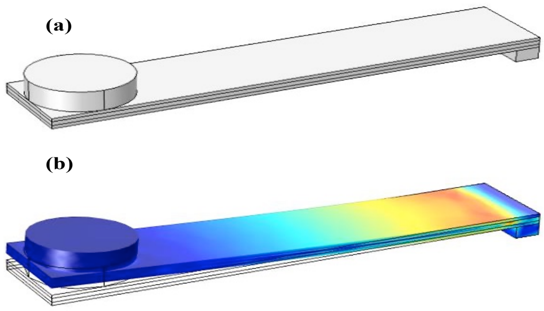

Fig. 6. (a) Structure (b) Stress applied on Bi-morph PZT energy harvester with cylindrical block as proof mass PZT thickness of 0.4mm

Figure 7 and 8 represents the rectangular and cylindrical proof mass. The structure consists of 7 blocks with a PZT thickness of 0.8mm. The lower or first block is fixed at the point and is a structural steel material. The second block is PZT-5A with a thickness of 0.4mm. The third block is PZT-5A with a thickness of 0.4mm. The fourth block is silicon. The fifth block is again PZT-5A with 0.4mm thickness. The sixth block is again PZT-5A with thickness0.4mm and the final or seventh block is structural steel. The structure with rectangular proof mass produces a maximum voltage of 1.5873mV and energy of 8.07fJ at a frequency of 381Hz. And the cylindrical proof mass produces a maximum voltage of 1.2039mV and energy of 3.55fJ at a frequency of 361Hz.

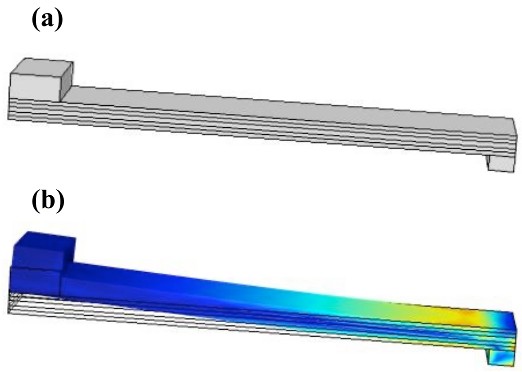

Fig. 7. (a) Structure (b) Stress applied on Bi-morph PZT energy harvester with rectangular block as proof mass PZT thickness of 0.8mm

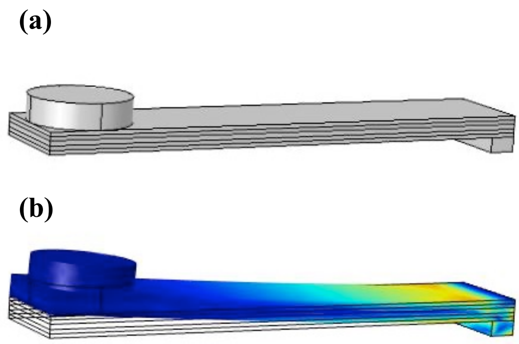

Fig. 8. (a) Structure (b) Stress applied on Bi-morph PZT energy harvester with cylindrical block as proof mass PZT thickness of 0.8mm

Figure 9 and 10 represents the rectangular and cylindrical proof mass. The structure consists of 7 blocks, 6 blocks are rectangular and 1 block of cylindrical with a PZT thickness of 0.4mm. The lower or first block is fixed at the point and is a structural steel material. The second block is PZT-5A. The third block is silicon. The fourth block is again PZT-5A. The fifth block is silicon. The sixth block is PZT-5A. The final block is structural steel. As this is stacked an alternate layer of PZT-5A and silicon are placed. The structure with rectangular proof mass produces a maximum voltage of 0.977mV and energy of 4.51fJ at a frequency of 451Hz. And the cylindrical proof mass produces a maximum voltage of 2.0488mV and energy of 21.2fJ at a frequency of 421Hz.

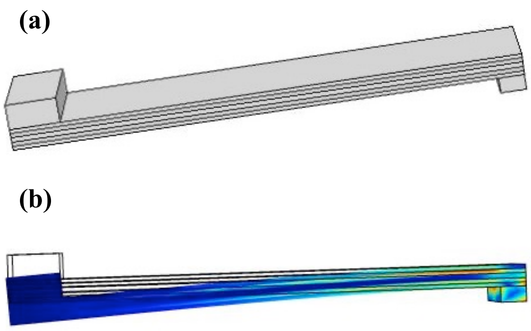

Fig. 9. Structure (b) Stress applied on stacked Bi-morph PZT energy harvester with rectangular block as proof mass PZT thickness of 0.4mm

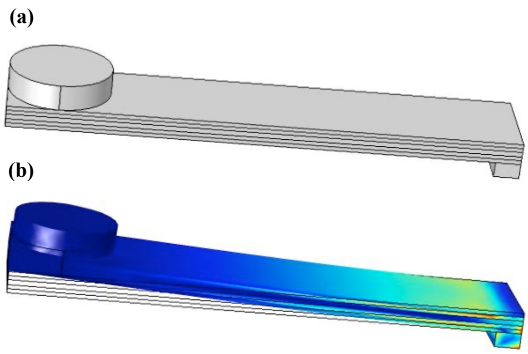

Fig. 10.(a) Structure (b) Stress applied on stacked Bi-morph PZT energy harvester with cylindrical block as proof mass PZT thickness of 0.4mm

Table 2 concludes that the stacked Bi-morph PZT energy harvester with cylindrical block as the proof mass has a good Voltage of 2.04mV and Energy of 21.2fJ (femto-Joule = 10^{-15}J). Tables 3, 4 represent the comparison of Unimorph and Bimorph structures with their dimensions and material used.

Table 2. Comparison of piezoelectric energy harvester geometries by varying the thickness and stack structure

Geometry Dimensions	Frequency (Hz)	Voltage (mV)	Energy (fJ)
Rectangular proof mass (10X5X2.5) and PZT thickness 0.4mm	241	1.508	11.0
Cylindrical proof mass (5X2.5) and PZT thickness 0.4mm	221	1.4905	10.6
Rectangular proof mass (10X5X2.5) and PZT thickness 0.8mm	381	1.5873	8.07
Cylindrical proof mass (5X2.5) and PZT thickness 0.8mm	361	1.2039	3.55
Rectangular proof mass (10X5X2.5) and PZT thickness 0.4mm [STACK]	451	0.977	4.51
Cylindrical proof mass (5X2.5) and PZT thickness 0.4mm [STACK]	421	2.0488	21.2

Table 3. Comparison table of different dimensions

Components	Dimensions		
	Unimorph Structure[14]	*Unimorph Structure[15]*	*Bimorph Structure[16]*
Substrate layer	Length 50mm Width 10mm Thickness 0.5mm	Length 60mm Width 30mm Thickness 1mm	Length 21mm Width 14mm
Piezoelectric layer	Length 50mm Width 10mm Thickness 0.4 mm	Length 60mm Width 30mm Thickness 0.11mm	Length 21mm Width 14mm
Proof mass	Length 5mm Width 10mm Thickness 2.5mm	Length 12mm Width 30mm Thickness 3.5mm	Length 4mm Width 1.7mm

Table 1. Comparison table of different materials

Material/ Parameter	PZT-5A [14]	PVDF [15]	PZT-5H [15]	PMN-0.33Pt [15]	PZT-5A [16]
Frequency[Hz]	181.11	153.22	153.22	153.22	74
Voltage [mV]	129.19	116.6	123.2	1209.7	5
Energy [J]		$2.099x10^{-8}$	$5.815x10^{-76}$	$3.3x10^{-5}$	

5 Results and discussion

Each peak in the graph represents the maximum voltage or energy levels at a particular frequency. Individual voltages and energies vary depending on the structure.

Figure 11, 12 represent the frequency versus voltage and frequency versus energy respectively. With a thickness of geometries 0.8mm, 0.4mm, and stack, with cylindrical and rectangular proof mass. The peak represents the maximum voltage and energy levels at that particular frequency of that geometry. Among them, stacked cylindrical represents the maximum voltage of 2.04mV and the maximum energy of 21.2fJ.

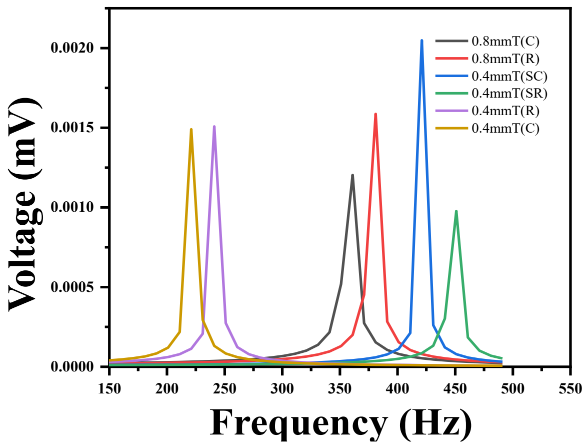

Fig. 11. Graphical representation of frequency versus voltage

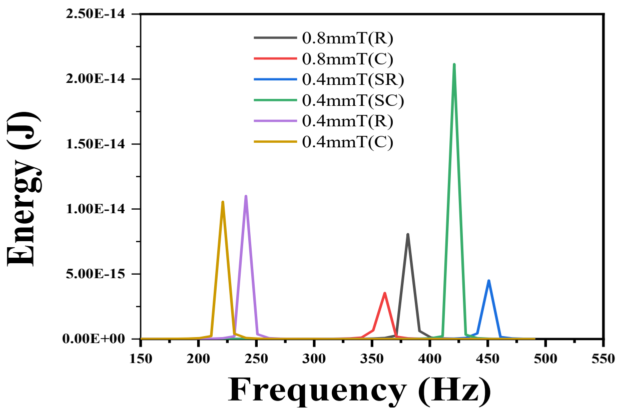

Fig. 12. Graphical representation of frequency versus energy

6 Conclusion

In this study, the simulation and analysis of a piezoelectric energy harvester have been presented. The geometry of the cantilever is being designed based on the thickness of PZT and the stack implementation. With a proof mass of the rectangular and cylindrical shape. A force of 2N is applied and frequency, voltage, and energy values have been observed. Among all the geometry implementations, a stacked cylindrical proof mass of 5mm radius and 2.5mm thickness, with the PZT and silicon acting as a cantilever of 0.4mm thickness have produced the best result. The voltage of 2.04mV and energy of 21.2fJ. The energy of the Bimorph structure is double that of the Unimorph structure. As the force increases the voltage and energy value increase. In all the cases the proof mass dimension is kept constant but the shape is varied as rectangular and cylindrical. Thus COMSOL simulative study efflorescence is an effective tool to provide confidence to designers to design time and cost-effective designs.

7 Future scope

In this study, we have analyzed when a force of 2N on different shape geometry exhibits the different voltages which can be used for the charging. In the future, we can also use this piezoelectric device for different IoT applications, such as tier condition monitoring, power shoes, pacemakers, etc. And also more such shapes and dimensions can be varied along with the length and width of the piezoelectric plate might give a different output which is included in a future study. Where the energy is conserved and used for further use. So that the entire world can use electricity.

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