Modelling and analysis of piezoelectric cantilever energy harvester for different proof mass and material proportion

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Abstract. Energy harvesting using ambient energy sources is one of the fast growing trends in the world, research and development in the area of energy harvesting is moving progressively to get maximum power output from the existing resources. The ambient sources of energy available in the nature are solar energy, wind energy, thermal energy, vibrational energy etc. out of these methods energy harvesting by vibrational energy sources gain more importance due to its nature of not getting influenced by any environmental parameters and its free availability at anytime and anywhere. The project mainly deals with validating the values of voltage and electrical power output of experimentally conducted energy harvester, varying the parameters of the energy harvester and analyse the effect of the parameters on the performance of the energy harvester and compare the results. The cantilever beam was designed, analysed and simulated using COMSOL multi-physics software. The energy harvester gives an electrical output voltage of the 2.75 volts at a natural frequency of 37.2 Hz and an electrical power of 29μW. Decreasing the percentage of the piezoelectric material and simultaneously increasing the percentage of polymer material (so that total percentage of proportion remains same) increases the electrical voltage and decreases the natural frequency of the beam linearly upto 3.9V and 28.847 Hz till the percentage proportion of the beam was 24% piezoelectric beam and 76% polymer beam when the percentage proportion increased to 26% and 74% natural frequency goes on decreases further but voltage suddenly drops to 2.8V. The voltage generated by energy harvester increases proportionally and reaches 3.7V until weight of the proof mass reaches 4 grams and further increase in the weight of the proof mass decreases the voltage generated by energy harvester. Thus the investigation conveys that the weight of the proof mass and the length of the cantilever beam should be optimised to obtain maximum output efficiency of energy harvester.

1.Introduction
Energy is one of the basic and important needs to perform any function on the earth. Anything on this earth requires energy in one or the other forms to perform its function. Energy is supplied to the system by an energy source which is available in nature in various forms. Basically energy is defined as capacity of a physical system to do work, and energy source is defined as, something which is used to provide power to the various systems to perform its function. Energy crisis is the bottle neck in the supply of energy resources to an economy. Drastic increase in population and increase in industrialization are the major causes which welcomed energy crisis.
According to Figure 1, world uses 37% of oil, 25% of coal, 23% of natural gases etc. of the total percentage consumption of the energy sources in year 2008. Among these energy resources most are non-renewable energy sources.

![Percentage consumption of energy resources in world](image)

Energy harvesting is defined as the process in which energy is tapped from the physical environment and converted into useful electrical energy. There are different kinds of energy available from the physical environment such as solar energy, wind energy, thermal energy, kinetic energy, acoustic noise, salinity gradient, vibrational energy etc. which are generally known as ambient energy sources.

Solar energy is a very efficient source for powering electronic devices and has evolved greatly over the years. However, it is backed up with certain limitations such as: intensity of light will be minimum during cloudy weather, relatively large surface area is required according to the power requirement of the associated electronic system. Thermoelectric energy requires large temperature differentials to give large quantity of electrical energy. Wind energy is another attractive source to generate electrical energy, but most of the windmill generators are concentrated to mountain areas and coastal areas, where strong winds are common. Energy harvesting through noise should have high noise levels and it should be sensitive to the direction of noise propagation. Vibrational energy harvesting involves tapping the freely available vibrations available in the environment and converting that into electrical energy by designing suitable harvester mechanism to power various electronic devices. Out of these energies available in the environment, vibrational energy gain more importance because of its free availability at all time, vibrational energy cannot be affected by any environmental parameters like weather etc., design of energy harvester to convert the ambient vibrational energy into useful electrical energy is simple when compared with the design of the energy harvester of other energy sources.

Piezoelectric materials are the materials which produce an electric current when they are subjected to mechanical stress. Piezoelectric materials are occurred naturally and they can be man-made. The piezoelectric crystal material which are occurred naturally are quartz, Topaz, etc. and some organic substances are wood, silk, dentin, enamel, hair, bone and rubber. Quartz analogs, polymers, ceramics and composites are some of the man-made piezoelectric materials.

William G. Kaval et.al [2] investigated the usage of electro active polymers like PVDF-TrFE for energy harvesting and they conducted various methods of converting mechanical vibrational energy into useful electrical energy, they concludes that PVDF-TrFE has large relative permittivity and piezoelectric β phase without stretching. A. Sharma et al. [4] designed a vibrational energy harvester using an Aluminium Nitride (AlN) piezoelectric layer, they fabricated harvester on an SOI wafer with a 30μm device silicon layer which acts as the structural beam and 0.5μm AlN layer is sandwiched between the top and bottom electrodes which is placed on structural beam handled silicon is provided as proof mass, they presents that harvester operates from 20 milli g to 0.2 g. An energy density of 3.04 μW/cm3/g2 and voltage output of 1.3 V is obtained at acceleration of 0.17g. Yuichi Tsujiura et al. [6] fabricated a piezoelectric MEMS energy harvester made out thin films of Pb(Zr,Ti)O3 (PZT) on stainless steel cantilever. Thin cantilevers are fabricated by making use of metal substrates which
gives large fracture toughness, output power of 1.1 μW is obtained under the vibration of 75 Hz, load resistance of 20 kΩ, and acceleration of 5 m/s². Umi Milhana Jamain et al. [5] used Zno as piezoelectric material and varied length and width of cantilever energy harvester using COMSOL software, results shows that as the length increases the deflection increases but when the width increases deflection decreases, hence they suggest that for maximum performance optimum width to length ratio has to be taken. Shanky Saxena et al. [15] carried out experiment on piezoelectric cantilever energy harvester carrying a seismic proof mass, they concluded that length of the cantilever is dominant factor in determining the Eigen frequency. Todd A. Anderson et al. [7] designed a cantilever energy harvester which consists of piezoelectric bimorph made of two PZT layers and a brass shim sandwiched between these piezoelectric layers, beam is provided with two proof mass one on the top and another on the bottom of the beam, they conducted experiment by varying the width of the proof mass, they concludes that as the width of the proof mass decreases the power output increases. Xuefeng He et al. [8] created a model of the cantilever energy harvester with a rolling mass and experimented it. They conclude that Impact-based VEH with a rolling proof mass is a promising candidate and low level vibration energy scavenging is improved by attaching rolling proof mass to energy harvester. X.D. Xie et al. [11] designed a tapered piezoelectric energy harvester surface bonded with piezoelectric patches to harvest energy from ambient vibration and it is compared with the cantilever harvester of a uniform shape in the direction of length, numerical simulation is done and the results shows that the RMS voltage decreases with an increase in the taper ratio of thickness and/or width of the cantilever and the width of the patch. N.H. Diyana et al. [12] designed a piezoelectric unimorph energy harvester with single and comb shaped beam structures and compared the output voltage of the EH using COMSOL multi-physics software and MATLAB, the results showed that in comb structure the voltage generated is maximum and they conclude that comb structure can be used to generate electrical power. Frank Goldschmidtboeing and Peter Woias [13] designed rectangular and triangular shaped piezoelectric cantilever energy harvester , validated the results with experimental results and compared the results between them, the results shows that triangular beam are more effective than rectangular shaped beams in generating power .Chung ket thein et al. [16] designed a rectangular cantilever beam energy harvester made out of piezoelectric bimorph which consists two PZT5A layer and one brass shim layer, later he carried out 27 trials to optimise the design to obtain maximum power output, then they compared the result of the triangular, rectangular and optimised design energy harvester using Ansys software, results yields that optimised design produce 25% more power output than the rectangular cantilever beam EH. Abid Iqbal and Faisal Mohd-Yasin [14] designed seven different types of the cantilever beam(straight , straight t shaped, u shaped, v shaped, v-t shaped, y shaped) energy harvester and used aluminium nitride as material for piezo layer and cubic silicon carbide as shim layer and molybdenum as proof mass. Open circuit voltage, resonant frequency are evaluated for all design and they concluded that y shaped and v-t shaped beam generates highest open circuit voltage.

2. Research methodology
The main focus of the project was to model a novel piezoelectric cantilever energy harvester using COMSOL Multi-physics software, perform analysis of the energy harvester and analyse the effect of length of the piezoelectric beam, polymer beam and proof mass on the output voltage and electrical power output
The project started with detailed literature survey where the experimentally conducted cantilever energy harvesting techniques was analysed, different piezoelectric materials and their properties are studied, effects of various parameters on the performance of the energy harvester was studied. On the basis of the literature review next step carried out was problem identification, which involves identifying the major problems of the previous energy harvesters. Performing analysis and simulation of the energy harvester is the next step which was done using COMSOL multi-physics software. Results of the energy harvester analysed using numerical methods was validated with the experimentally conducted energy harvester in the literature paper. Next step followed in the research
methodology is changing the parameters of the energy harvester, changing the parameters was accomplished in two ways, at first the proportion of the piezoelectric and polymer material was varied and then weight of the proof mass was varied. After changing the parameters next step was to record the results/data obtained by changing the parameters. Since varying the parameters will have some effect on the overall performance of the energy harvester, this effect of change is analysed in the next step. The final step was to analyse and compare the results obtained and also to compare the behaviour of energy harvester for changing the respective parameters.

3. Numerical analysis

Numerical analysis was done using COMSOL multiphysics software. The numerical analysis begins with defining parameters. Parameters are nothing but the constants applied to the system. In piezoelectric energy harvester 3 parameters are used they are

Acceleration (0.2g)
Load resistance (100kohm)
Width of the beam (6.4mm)

![Figure 2 Geometric model of the energy harvester](image)

Figure 2 shows geometric model of the energy harvester. Energy harvester was modelled as a composite cantilever beam which consists of piezoelectric beam, polymer beam and a proof mass at the free end of the cantilever beam. The entire model was divided into five domains. Domain 1 and 3 are piezoelectric material, domain 2 is shim material in piezoelectric beam, domain 4 is polymer beam and domain 5 is proof mass.

After geometric modelling next step was to assign different materials to various domains of the energy harvester. The materials used in the energy harvester are PZT 5A, lead(proof mass material), brass(used between two pzt layers), polyethyleneterephatalate(mylar)(polymer material).
Figure 3 Assignment of brass material to the harvester

Figure 4 Assignment of polymer material polyethylene terephatalate to the energy harvester

Figure 5 Assignment of lead material to the energy harvester

After applying materials next step is to do analysis by applying various physics interfaces. After applying physics interfaces next step is to apply mesh to the entire geometric model. For the energy harvester entire model was meshed using triangular nodes.

4. Varying the Parameters of the Energy Harvester

Variation of parameters of the energy harvester was done in two methods

- Varying the Proportion of the Polymer Material and Piezoelectric Material of the Cantilever Energy Harvester:

Piezoelectric cantilever energy harvester is a composite cantilever beam energy harvester consists of piezoelectric layer and a polymer layer. The results of the experimentally conducted composite cantilever energy harvester as in the literature paper was composed of 60% of piezoelectric material of the total cantilever beam and the rest of 40% is polymer material. This configuration was taken as standard configuration. The effect of the percentage proportion of polymer and piezoelectric material of the energy harvester on the output performance like electrical output voltage is investigated. To accomplish this, the proportion
of the material in the cantilever energy harvester was varied in such a way that the sum of the varied percentage of the each material of the energy harvester must be equal to the overall percentage of the standard configuration of the energy harvester i.e. the sum of the length of the piezoelectric and polymer beam should be equal to length of the standard configuration of the energy harvester.

- Varying the Weight of the Proof mass:
  Varying the weight of the proof mass was another parameter of the energy harvester which was varied and the response of the output performance of the harvester for respective varied parameters are recorded. The weight of the proof mass of the standard configuration energy harvester was 0.72 grams, and the volume of the material of the proof mass was calculated. The effect of parameter was investigated by varying the weight of the proof mass which can be done by changing the dimensions of the proof mass without sacrificing the volume of the material of the proof mass i.e. the weight of proof mass was varied by changing the dimension of the proof mass in such a way that volume of the varied proof mass must be equal to the volume of the proof mass in the standard configuration.

5. Results and discussions
For the validation of the experimental work as per the journal paper the energy harvester was modelled which composed of 60% of the piezoelectric beam, length of the piezoelectric beam is 31.88mm and 40% of polymer beam, length of the polymer beam is 21.33mm and the total length of the cantilever beam is 53.21mm. The first natural frequency of the energy harvester was 37.2 Hz.

![Figure 6 RMS output voltage](image1)

Figure 6 shows the plot of RMS output voltage of the energy harvester. The energy harvester gives the output RMS electrical voltage of 2.75 V at the natural frequency of 37.2 Hz.

![Figure 7 Electrical power output](image2)

Figure 7 Electrical power output
The electrical power output of the energy harvester was 29μW. The graph as shown in figure 7 gives us the electrical power output against load resistance. From the graph we can see that at 100KΩ load resistance and acceleration of 0.2g the energy the harvester yields the electrical power of 29μW.

Performance of the Energy Harvester for Varying the Parameter Proportion of the Material of the Composite Cantilever Beam:

1. **80% Piezoelectric beam 20% Polymer beam:**
   This configuration consists of 80% piezoelectric material beam and 20% of polymer material beam and their respective lengths are 42.57mm and 10.64 mm whose total length is equal to 53.21 mm. This configuration yields a natural frequency/Eigen frequency of 45.021 Hz.

![Figure 8 RMS output voltage of the 80% piezoelectric and 20% of polymer configuration](image)

2. **70% Piezoelectric beam 30% Polymer beam:**
   This configuration consists of 70% piezoelectric material beam and 30% of polymer material beam and their respective lengths are 37.25mm and 15.96 mm and their total length is equal to 53.21 mm. This configuration yields a natural frequency/Eigen frequency of 41.988 Hz.

3. **50% Piezoelectric beam 50% Polymer beam:**
   This configuration consists of 50% piezoelectric material beam and 50% of polymer material beam and their respective lengths are 26.605mm and 26.605mm whose total length is equal to 53.21 mm. This configuration yields a natural frequency/Eigen frequency of 36.21 Hz. RMS output of this configuration is 2.7 V

   The proportion of the piezoelectric material in the beam was decreased and simultaneously proportion of polymer material was increased to determine the electrical voltage generated by the harvester. At percentage of 26% and 74% of piezoelectric and polymer material the voltage generation reaches up to a maximum voltage of 3.9 volts. When the material proportion exceeds this proportion the voltage suddenly drops.

4. **24% Piezoelectric beam 76% Polymer beam:**
   This configuration consists of 24% piezoelectric material beam and 76% of polymer material beam and their respective lengths are 12.78mm and 40.43mm whose total length is equal to 53.21 mm. This configuration yields a natural frequency/Eigen frequency of 28.361 Hz, this configuration gives an electrical output voltage of 2.8V
Figure 9 RMS output voltage of the 24% piezoelectric and 76% of polymer configuration

Performance of the Energy Harvester for Varying the Weight of Proof Mass of the Composite Cantilever Beam:
The weight of the proof mass used in the standard configuration was 0.72 grams, the weight of the proof mass was varied and the corresponding results are recorded. The weight of the proof mass has the influence on the Eigen frequency and voltage generated by the energy harvester.
The weight of the proof mass was increased linearly and the results were observed. As the weight of proof mass increased voltage generated by the harvester also increased correspondingly, but at the weight of 5 grams of the proof mass its natural frequency and the voltage decreases

Figure 10 RMS output voltage of the energy harvester for proof mass of weight 0.25 grams

Figure 11 RMS output voltage of the energy harvester for proof mass of weight 5 grams
Table 1 Natural frequency and voltage of energy harvester corresponding to change in length of polymer and piezoelectric beam in composite beam

| Sl no | Percentage of piezoelectric and polymer material | Natural frequency | RMS output voltage (in volts) |
|-------|------------------------------------------------|------------------|-----------------------------|
| 1     | 80% piezo 20% polymer                           | 42.021           | 2.2                         |
| 2     | 70% piezo 30% polymer                           | 39.988           | 2.3                         |
| 3     | 50% piezo 50% polymer                           | 35.1             | 2.8                         |
| 4     | 40% piezo 60% polymer                           | 32.476           | 3.2                         |
| 5     | 30% piezo 70% polymer                           | 29.851           | 3.55                        |
| 6     | 28% piezo 72% polymer                           | 29.7             | 3.8                         |
| 7     | 26% piezo 74% polymer                           | 28.847           | 3.9                         |
| 8     | 24% piezo 76% polymer                           | 28.361           | 2.8                         |
| 9     | 20% piezo 80% polymer                           | 27.397           | 2.6                         |

Table 2 Natural frequency and voltage of energy harvester corresponding to change in weight of the proof mass

| Sl no | Weight of the proof mass (in grams) | Natural frequency (in Hz) | RMS output voltage (in volts) |
|-------|------------------------------------|---------------------------|------------------------------|
| 1     | 0.25                               | 49.749                    | 2                            |
| 2     | 0.5                                | 43.696                    | 2.2                          |
| 3     | 1                                  | 35.817                    | 2.6                          |
| 4     | 1.5                                | 31.834                    | 2.9                          |
| 5     | 2                                  | 28.779                    | 3                            |
| 6     | 2.5                                | 26.506                    | 3.2                          |
| 7     | 3                                  | 24.725                    | 3.3                          |
| 8     | 4                                  | 22.09                     | 3.6                          |
| 9     | 5                                  | 24.155                    | 3.5                          |
| 10    | 6                                  | 27.825                    | 3                            |

6 Conclusions:
The project was carried out on piezoelectric cantilever energy harvesting, the energy harvester was modelled, analysed and simulated using COMSOL multi-physics software. The model analysed by numerical method was validated with the experimentally carried out energy harvester in the literature paper. Parameters like weight of the proof mass and percentage proportion of the polymer beam and piezoelectric beam was varied and their influence on the performance of the energy harvester was investigated.

Results shows that natural frequency of the energy harvester increases constantly corresponding to increase in the weight of the proof mass, till the weight of the proof mass reaches 4 grams, further increase in the weight of the proof mass decreases the natural frequency of the harvester. The voltage generated by the energy harvester was proportional to the natural frequency hence the voltage
generated by the harvester decreases after 4 grams. Varying the percentage composition of the polymer and piezoelectric beam has influence on the voltage generated by the energy harvester. voltage increases as the proportion of the polymer beam increases or piezoelectric beam decreases till their composition reaches 24% piezoelectric and 76% polymer beam, after that further change in the composition causes voltage to drop. For the generation of maximum electrical power the weight of the proof mass and the length of the cantilever harvester must be optimum depending on the type of the configuration.

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