# Harvesting Vibrational Energy Due to Intermodal Systems Via Nano Coated Piezo Electric Devices

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**NCITEC Project N**o. 2013-31
conducted for
**NCITEC**

December 2015

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# ABSTRACT

Vibrational energy resulting from intermodal transport systems can be recovered through the use of energy harvesting system consisting of PZT piezo electric material as the primary energy harvesting component. The ability of traditional PZT piezo electric materials can be enhanced to generate substantially more power by using special coatings made of nano-coating mixtures. It can be demonstrated that the enhanced system can be utilized to power intermodal transport safety lighting systems from roadway vibrations. The objectives of the project was achieved by performing three tasks; design and construction of the special nano coated piezo electric energy harvester, testing and enhancement of the newly designed and constructed system in the lab and implementation of the energy harvesting system to power a lighting system. Nano-coated PZT energy harvesting system showed substantial and explicit improvement as compared to non-coated PZT energy harvesting system. Also, in the experimental analysis of this project work, rectangular cantilever system performed substantially better than trapezoidal and triangular cantilever systems in terms of power harvesting capability. To incorporate this power harvesting system for the application to power LED bulbs, more number of PZTs was integrated into the system. The new multi nano-coated PZT composite cantilever system with six PZT composites was designed and constructed. This power output charged totally discharged 3.6 Volts NiMH Battery to 3.054 Volts in two hours. The charged battery easily lighted the LED bulb in the laboratory.

# ACKNOWLEDGMENTS

Our team sincerely thanks the National Center for Intermodal Transportation for Economic Competitiveness (NCITEC) for their excellent guidance and financial support for this project.

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# INTRODUCTION

Lead zirconium titanate (PZT) [*1*] is a piezoceramic material with proficient piezoelectric effect and it is one of the most widely researched piezoelectric materials in the area of vibrational energy harvesting [*2*]. There is a great opportunity to tap into an existing source of energy being lost to the environment in the form of vibrations [*3*]. These vibrations result from intermodal transport systems such as passenger cars and freight trucks moving on streets and highways, trains moving on railway tracks, and planes moving on airport runways. Energy harvesting systems consisting of PZT [*4*] as the primary energy harvesting component can be incorporated into the intermodal transport systems to recover vibrational energy. Recovering energy from these lost vibrations will have considerable economic impact when used for street and highway lighting in high traffic areas for safety concerns. The broader impacts of this research include reducing the load demands on the existing power grid. Other benefits of this system could involve enhancing traffic weigh-in-motion sensing, and monitoring of pavement conditions of roads and structural response of bridges for timely maintenance.

The energy harvesting capability of conventional PZT piezo electric materials can be enhanced with the application of special nano-coating mixture on it [*5*]. The enhanced nano-coated system will have encouraging economic impact when integrated in the intermodal transport system. Optimization of power output can be done with the nano-coating mixture consisting of the optimum concentration of ferrofluid and ZnO. In order to generate sufficient power for applications associated with roadways, like road lighting systems, multiple nano coated piezo electric energy harvesting systems must be designed, constructed, tested, and optimized.

# OBJECTIVE

The objectives of this project is to enhance the ability of traditional PZT piezo electric materials to generate power by using special coatings made of nano particle mixtures and to demonstrate that the enhanced system can be utilized to power intermodal transport safety lighting systems from roadway vibrations.

# METHODOLOGY

## PZT Composite and Nanoparticle Mixture Solution for Coating

The constituents of nano-coating mixture are ferrofluid, ZnO and epoxy binder. Based on the previous study by UM researchers, it was found that the optimum percentage of ZnO in the mixture for maximum energy harvesting was 40 %. Thus, composition of the constituents considered are 40 % ZnO, 58 % ferrofluid and 2 % epoxy binder for this project. The percentage of epoxy binder is increased to 2 for the stability of nano-coating on PZT substrate during the course of vibrational experiment. A schematic of the nano-coated PZT composite is shown in Figure 1.1 and Figure 1.2. Nano-coating mixture is applied in such a way that the coating mixture does not come in contact with leads which otherwise causes the output signal from PZT composite to be disturbed or even lost due to discontinuity in the circuit.

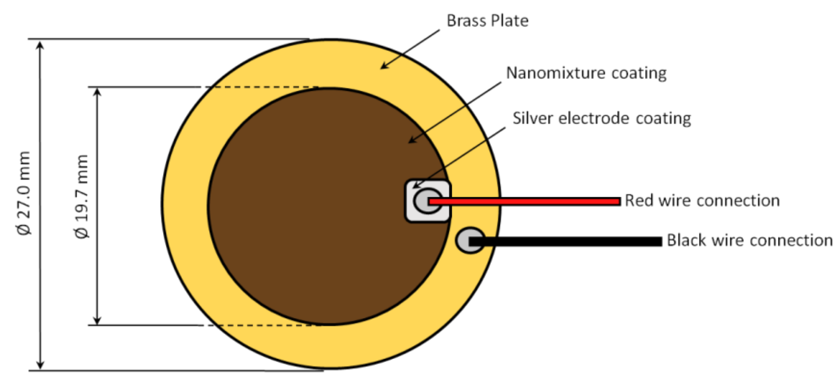



**Figure 1.1 Schematic of PZT Composite.**

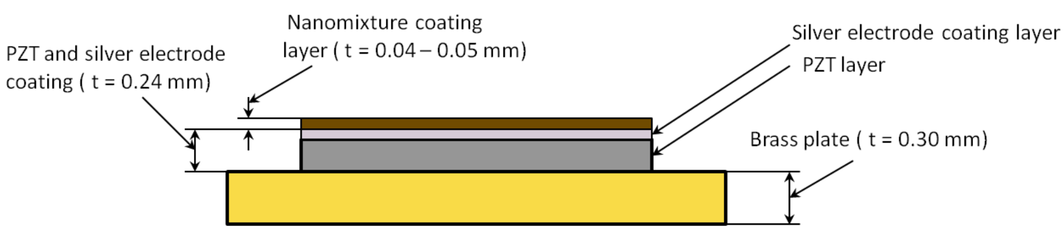



**Figure 1.2 Schematic of Nano-coated PZT Composite with Thickness, t of Various Layers (Side View).**

The curing of the coating mixture on the PZT composite is done by placing the nano-coated PZT composite inside desiccator for 36 hours at ambient temperature and pressure conditions. The cured nano-coated PZT composite is mounted on a standard stainless steel cantilever beam [*6*] through a taping procedure.

**Experimental Setup**

Nano-coated PZT composite system is the main energy harvesting component of the experimental procedure. The schematic and the actual picture of the experimental laboratory setup with the labeling of the parts of the overall system is illustrated in Figure 1.3 and Figure 1.4 respectively. The nano-coated composite system is mounted on the vibration exciter. A sine wave signal (Specifications: Sine Curve, Phase – 0.00 and Amplitude – 1.000 $V_{pp}$) from signal generator is supplied as an input signal to the vibration exciter. The amplifier is connected between signal generator and vibration exciter to amplify the input signal so that it reaches the requirement of the vibration exciter for the experimental process.

Vibrational energy is provided by the vibration exciter to the nano-coated PZT composite for its excitation. The output voltage generated from the nano-coated PZT composite is displayed on an oscilloscope and the output current is measured using a multimeter. The stainless steel cantilever beam system is excited in a frequency range of 20 Hz to 1000 Hz. The waveform voltage data from oscilloscope and digital data from multimeter is found to be stable and continuous in 60 seconds. Thus the voltage and current data are taking after running the vibration exciter for 60 seconds.

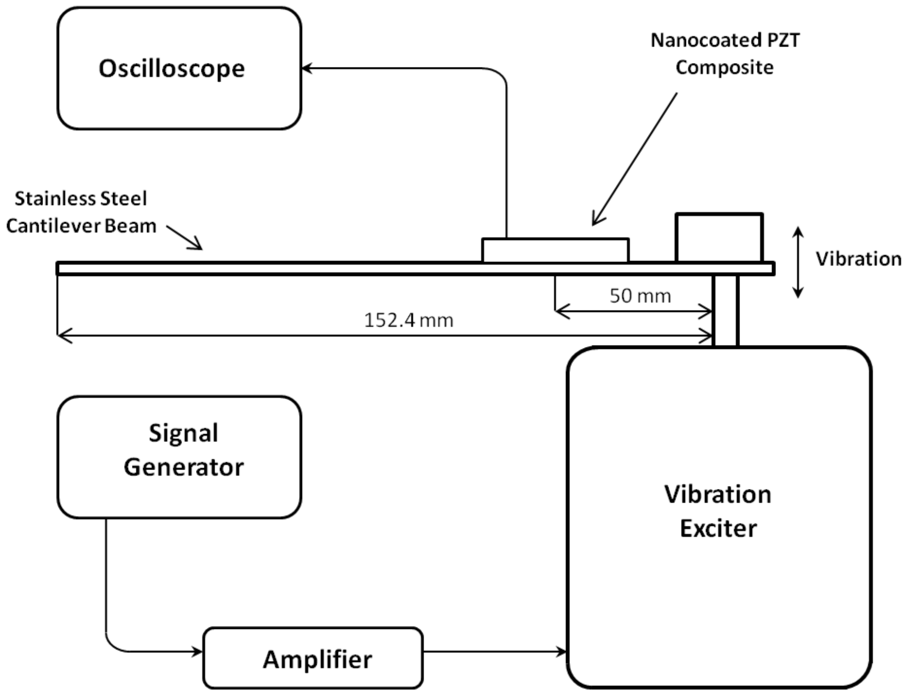



**Figure 1.3 Schematic of Experimental Laboratory Setup.**

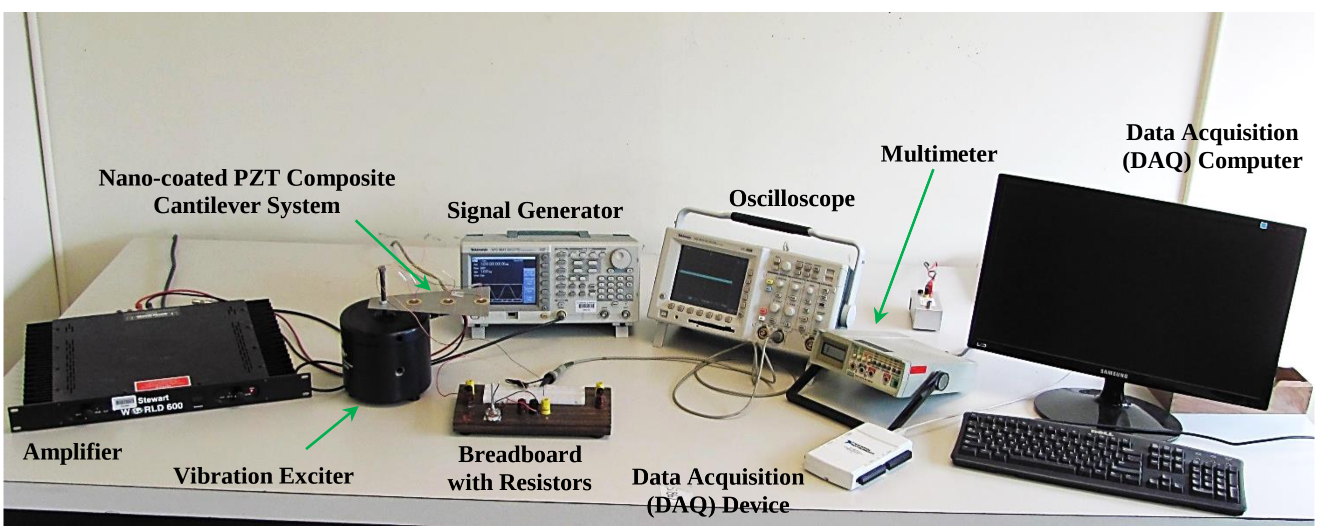



**Figure 1.4 Experimental Laboratory Setup.**

Based on the different previous study by UM researchers, it was found that when the external and internal impedance match, the power output is maximum [2]. In this project work, optimal resistive load for maximum power output was found to be 1 MΩ. RMS voltage ($V_{rms}$) data is recorded from oscilloscope. Power calculation is done using optimal resistive load and RMS voltage using the equation $P = V_{rms}^2/R$ and also the current is calculated using the equation $I = V/R$ [7].

### Optimization Process and Conceptual and Actual Design

For the real world application of the energy harvesting system in intermodal transport system, multiple single nano-coated piezoelectric component must be incorporated into the integrated system. Initial conceptual design of multiple nano-coated piezoelectric energy harvester is modeled as shown in Figure 1.5 (rectangular shape), Figure 1.6 (trapezoidal shape) and Figure 1.7 (triangular shape) respectively for the analysis and implementation of the energy harvesting systems in intermodal transport system. Optimization process for energy harvesting capability is done for the three shapes of multi nano-coated PZT composite system. The main focus is given to the power output trend and the maximum power output at the considered frequency range of 20 Hz to 1000 Hz. Thus the non-coated PZT composite cantilever system and nano-coated composite cantilever system is constructed and investigated for the three shapes.

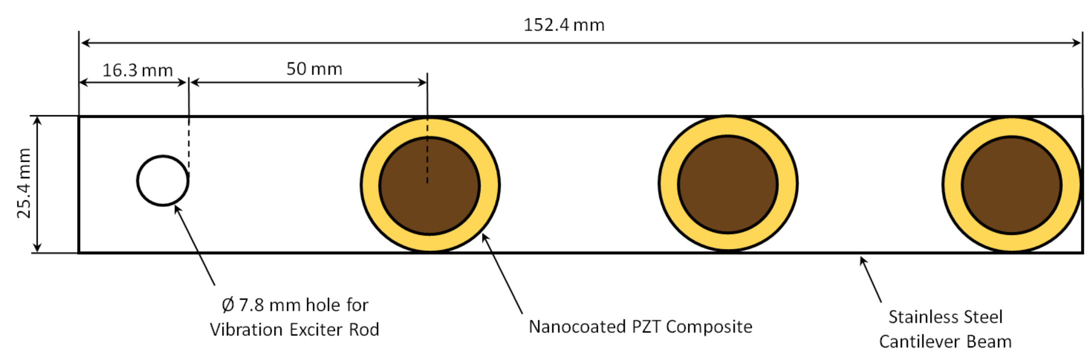



**Figure 1.5 Rectangular Stainless Steel Cantilever Beam with Three Nano-coated PZT Composite.**

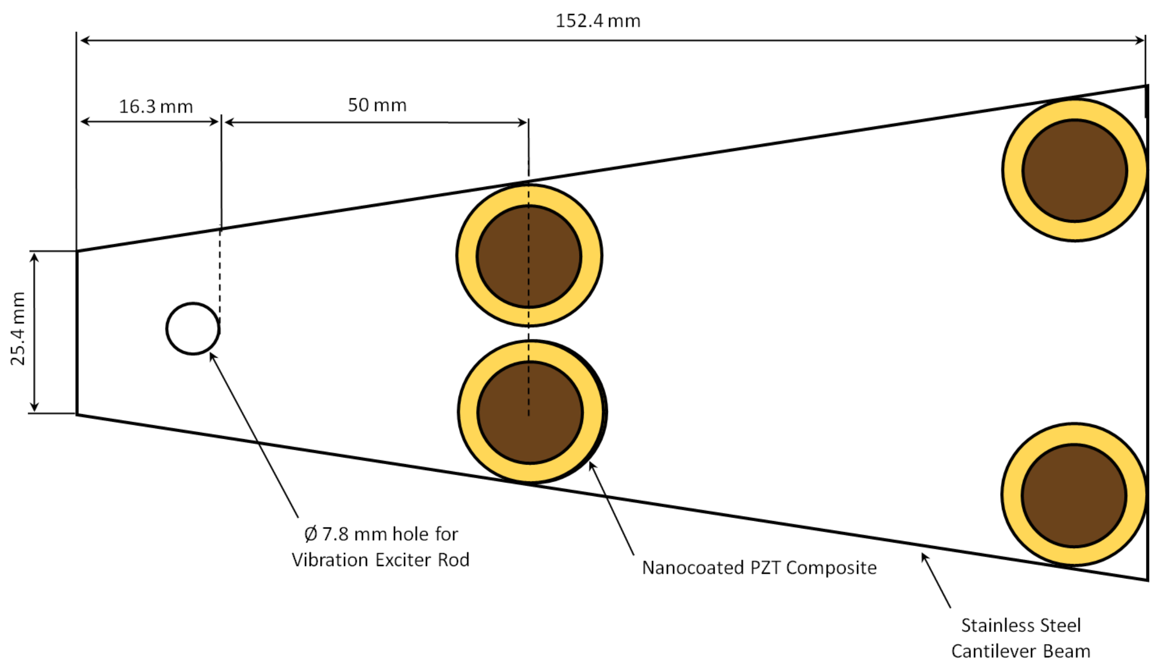



**Figure 1.6 Trapezoidal Stainless Steel Cantilever Beam with Four Nano-coated PZT Composites.**

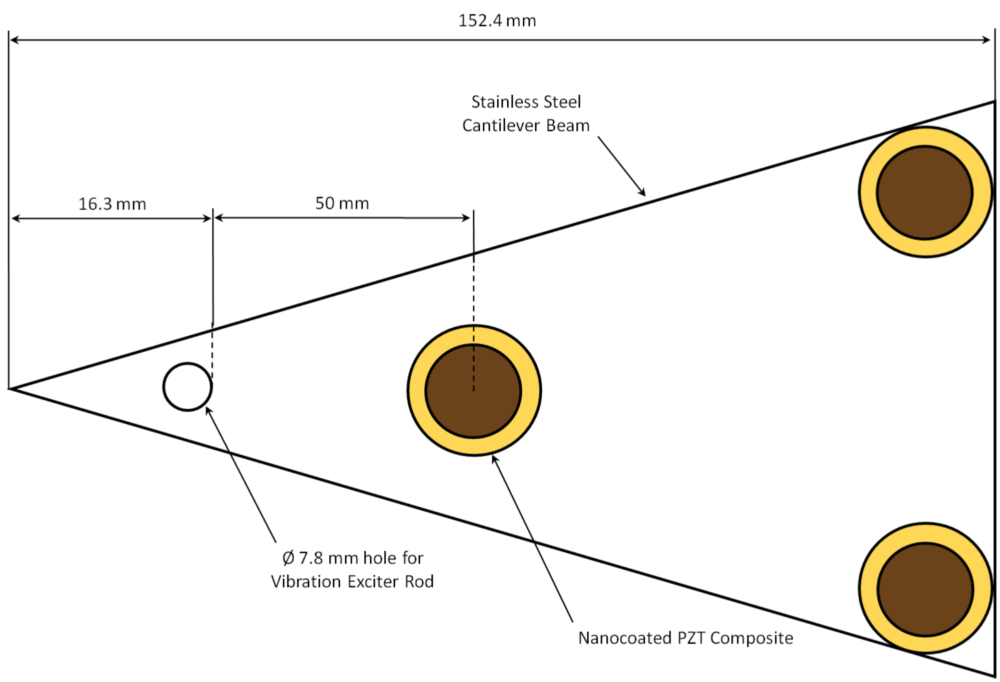
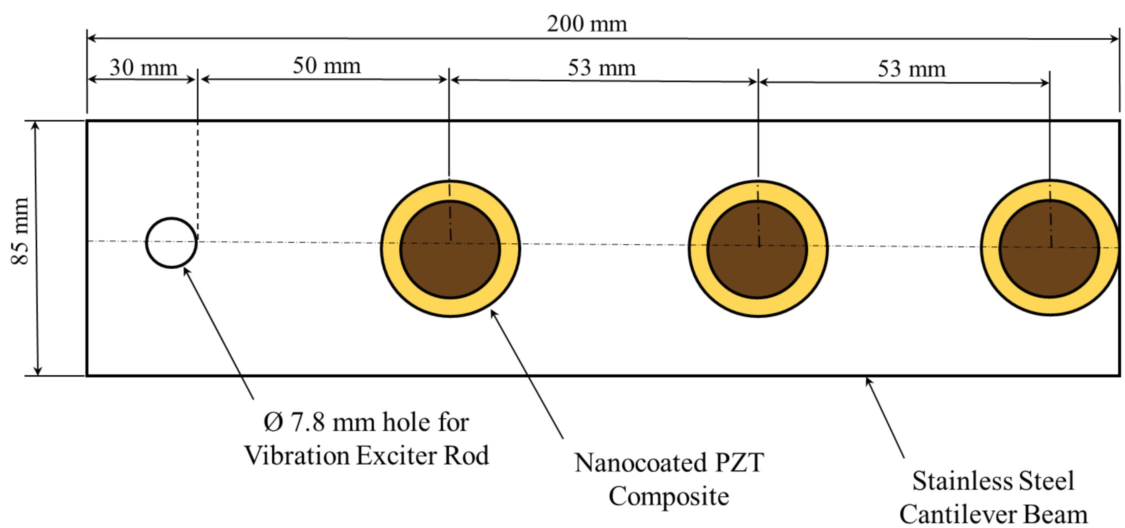
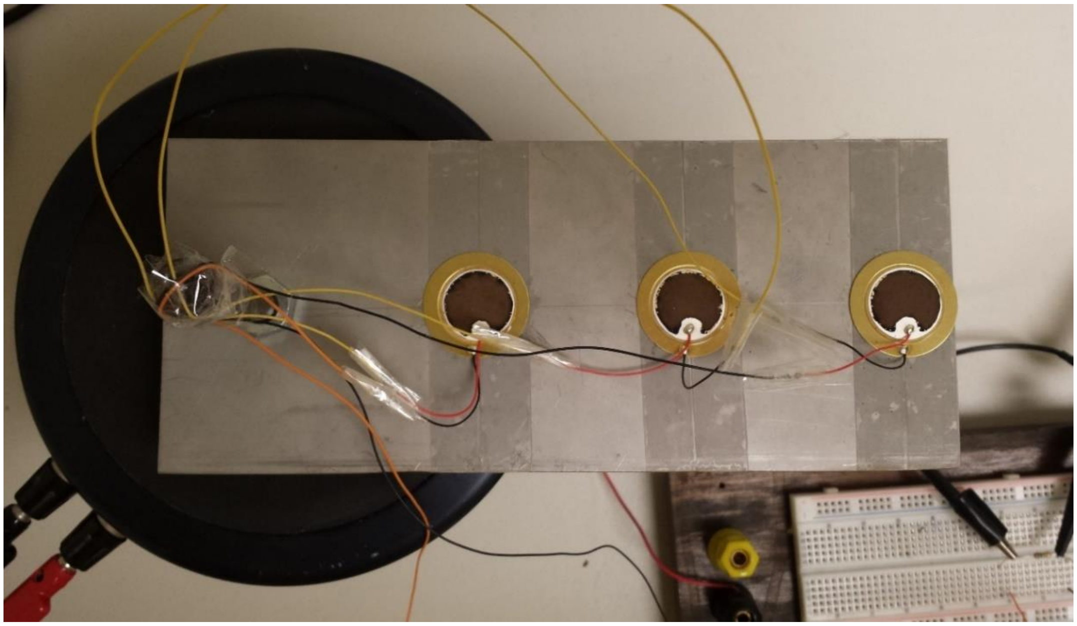



**Figure 1.7 Triangular Stainless Steel Cantilever Beam with Three Nano-coated PZT Composites.**

For the comparison in the course of optimization process through three shapes, these shapes should have consistent structural dimensions, number of PZT composites and the position of PZT composites in the steel cantilever. For this objective, the conceptual design of the PZT composite cantilever system is changed to the more methodical design. This new design schematics and actual pictures of the constructed systems is depicted in Figure 1.8 (rectangular), Figure 1.9 (trapezoidal) and Figure 1.10 (triangular) respectively. These three systems have same number of PZT composites which assures the equal volume of the core PZT compound. The thickness, top view area and characteristic length (200 mm) of three cantilever system steel cantilever area are kept same for the structural similarity. And also the position of three PZT composites in three cantilever systems is consistent in axial direction and distance from the source of vibration.

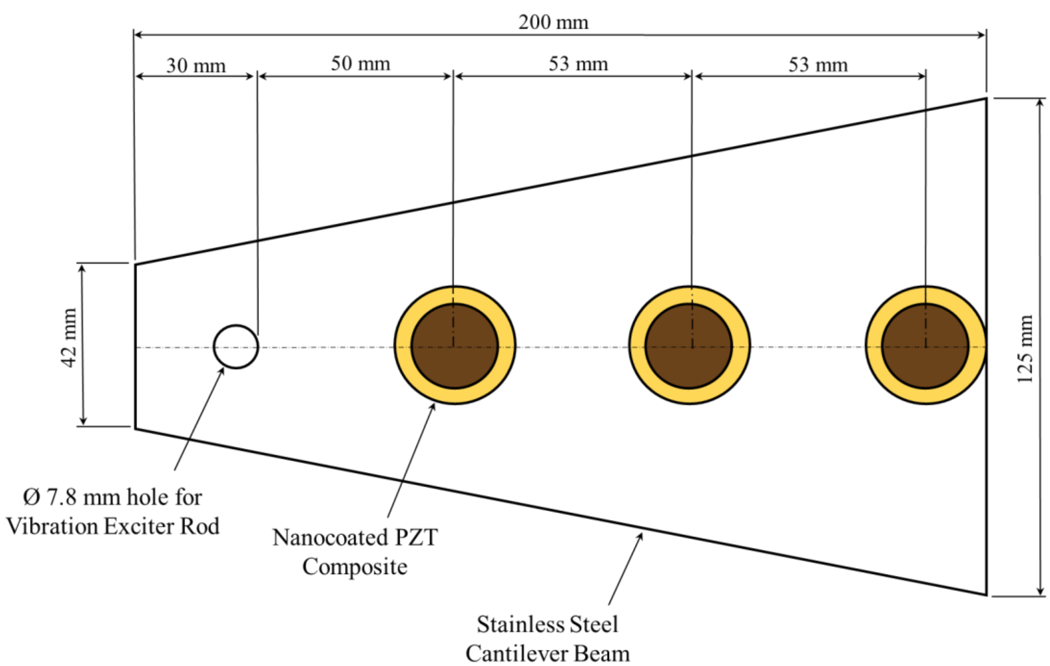



**a. Design Schematic.**

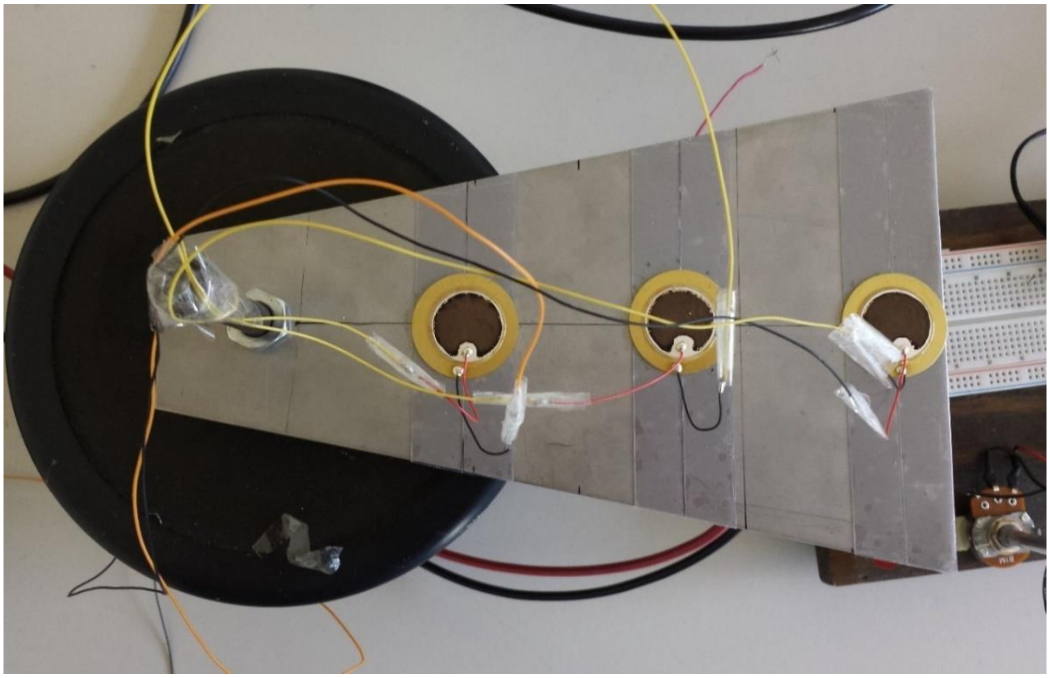


**b. Actual Picture.**

**Figure 1.8 Rectangular Stainless Steel Cantilever Beam with Three Nano-coated PZT Composites.**

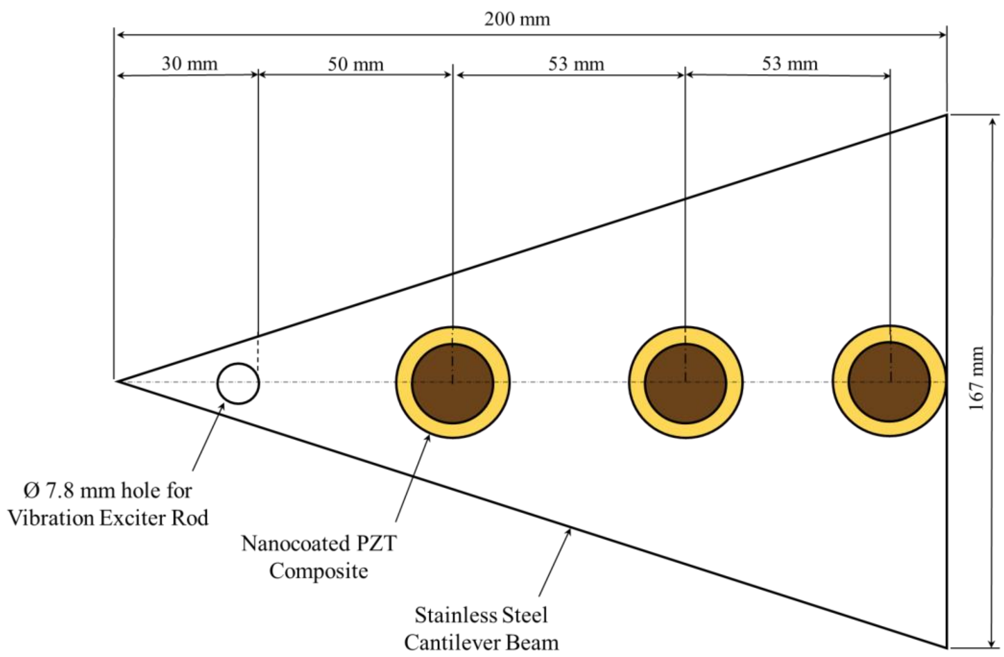



**a. Design Schematic.**

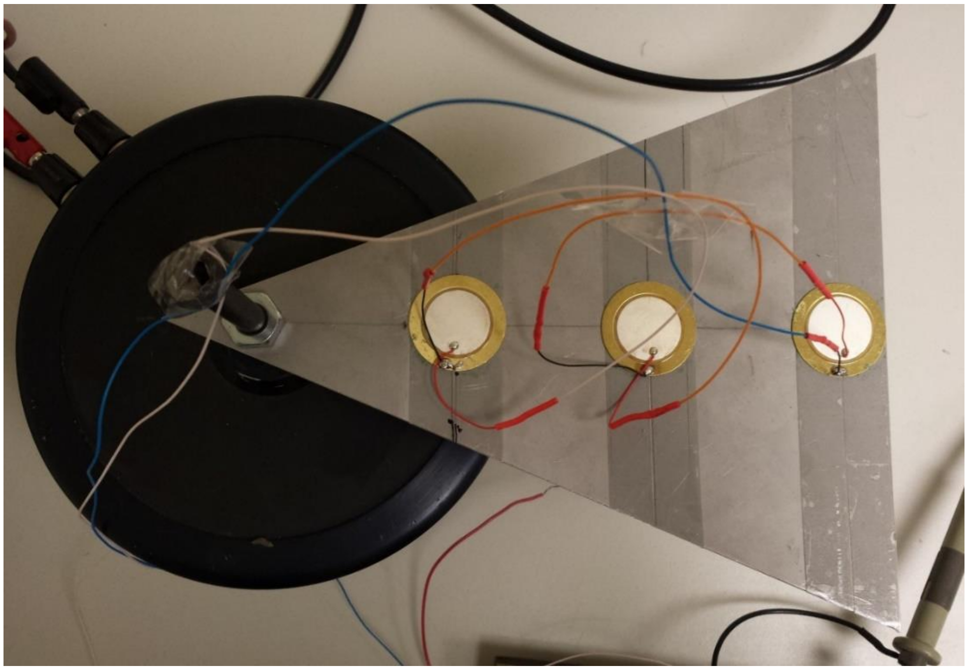


**b. Actual Picture.**

**Figure 1.9 Trapezoidal Stainless Steel Cantilever Beam with Three Nano-coated PZT Composites.**




**a. Design Schematic.**



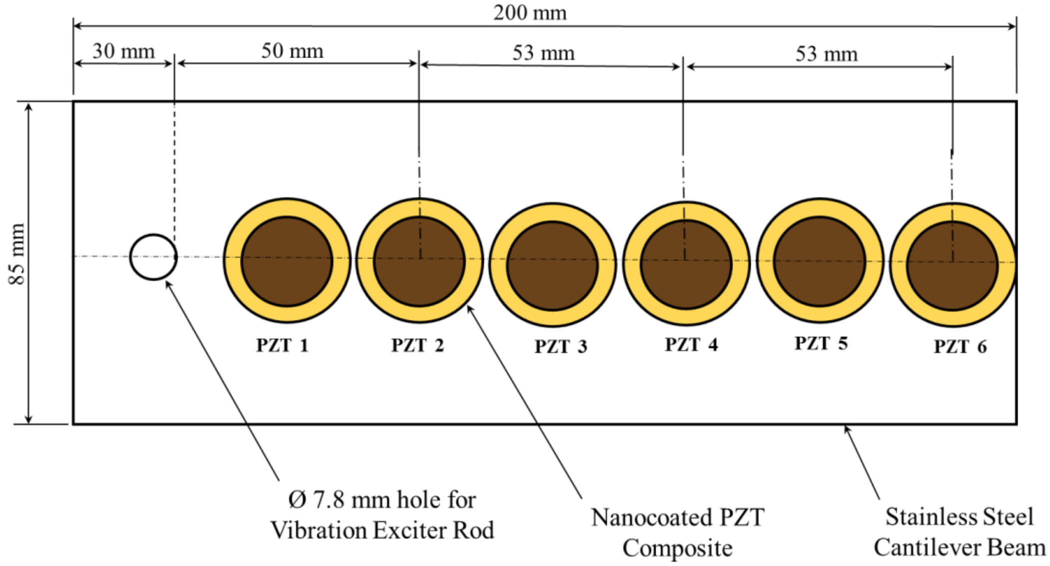
**b. Actual Picture.**

**Figure 1.10 Triangular Stainless Steel Cantilever Beam with Three Non-coated PZT Composites.**

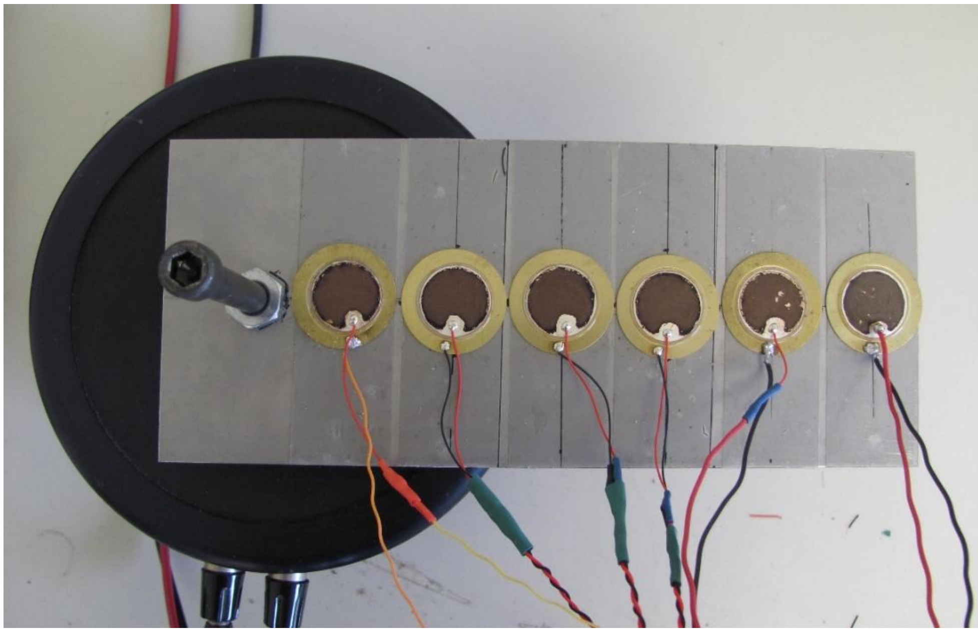
### Implementation of Energy Harvesting System to Power a Lighting System

From the analysis of the three shapes of non-coated PZT composite cantilever system and nano-coated PZT composite cantilever system, the system with the optimum power output is selected for lighting system. Rectangular shape is selected and considered for further analysis since it gives optimum power output value and power output trend which is described further in results and discussion chapter.

Since the battery charging requires DC power source and the energy harvesting system generates AC power, the AC power is should be rectified to DC power. This is done through circuit configuration which mainly consists of rectification of AC current to DC current through full wave rectifier and capacitor. Battery is charged for 2 hours through rectangular nano-coated PZT composite cantilever at frequency of 350 HZ for which power output is maximum. And the battery is checked for the rise in voltage and lighting bulb. Since the rise in voltage is less and the battery couldn't light bulb after the predetermined charge time, new design with additional number of nano-coated PZT is considered. For this, six PZT composites is incorporated into the nano-coated PZT composite cantilever system is such way that the position configuration of three PZT composite considered in previous cantilever system is same. This new nano-coated PZT composite cantilever system with six PZT composites is depicted in Figure 1.11. The experimental setup for charging the battery is as shown in Figure 1.12.




**a. Design Schematic.**



**b. Actual Picture.**

**Figure 1.11 Rectangular Stainless Steel Cantilever Beam with Six Nano-coated PZT Composites.**

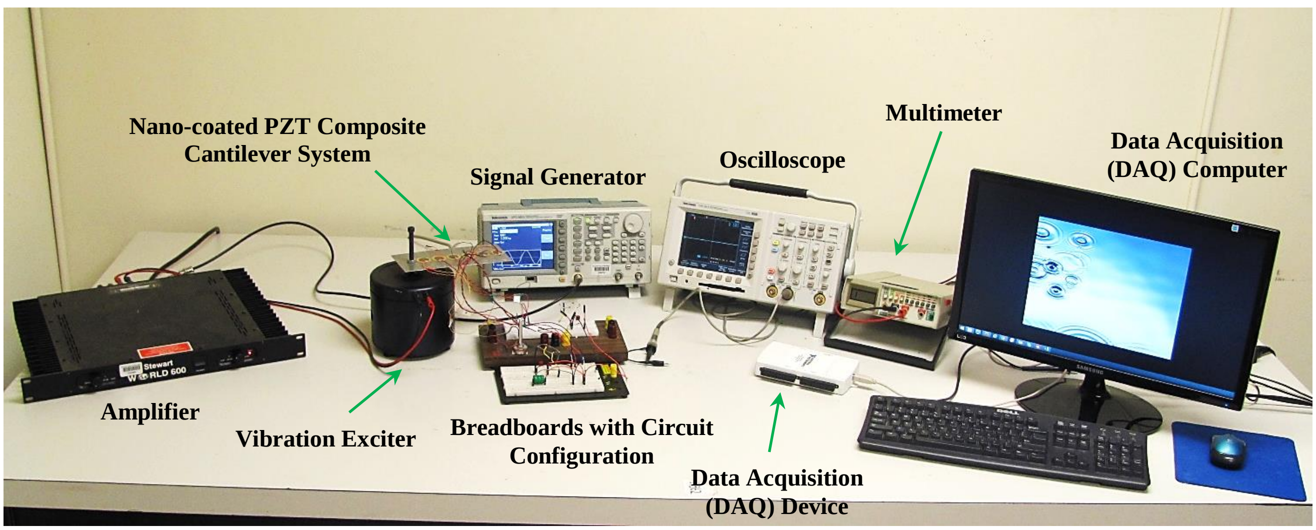



**Figure 1.12 Experimental Laboratory Setup with Six Nano-coated PZT Composites for Charging Battery.**

The new design with six PZT composites is run in the predetermined frequency range of 20 Hz to 1000 Hz. The system is tuned for the optimum frequency for which power output is maximum. When charging a battery, the most important electrical factor of the power supply is the amount of current supplied to it. The charge time of rechargeable battery is directly dependent on the amount of current supplied to it. In this work, first a 50 mAh lithium ion battery is experimented for charging process. Because of the high voltage and low current of the harvested energy, the battery will not be charged without a charge controller or voltage regulator. Thus for the charging the battery from the harvested energy, nickel metal hydride (NiMH) batteries is chosen because they have high charge density, and unlike lithium ion batteries, they do not require any type of charge controller or voltage regulator to be incorporated in the circuitry.

The circuit constructed to charge the battery consists of full wave rectifiers, capacitors, and a 240 mAh/3.6 volts NiMH battery. The simplicity of this circuit allows it to be constructed very compactly and without additional components that would result in additional power dissipation. Various configurations of series and parallel combinations of the six nano-coated PZTs is considered and tested at the optimum frequency for the maximum power output. The schematic of optimal series and parallel circuit configuration for the maximum power output is shown in Figure 1.13. And the final laboratory setup of energy harvesting circuit for charging the battery is depicted in Figure 1.14. The full discharged battery is charged from the energy harvested from the multi nano-coated PZT composite cantilever system for 120 minutes. The charge history data in the form of voltage rise in the discharged battery is taken at every 6 minutes time interval. After the battery is charged, LED light bulb is tested for its performance.

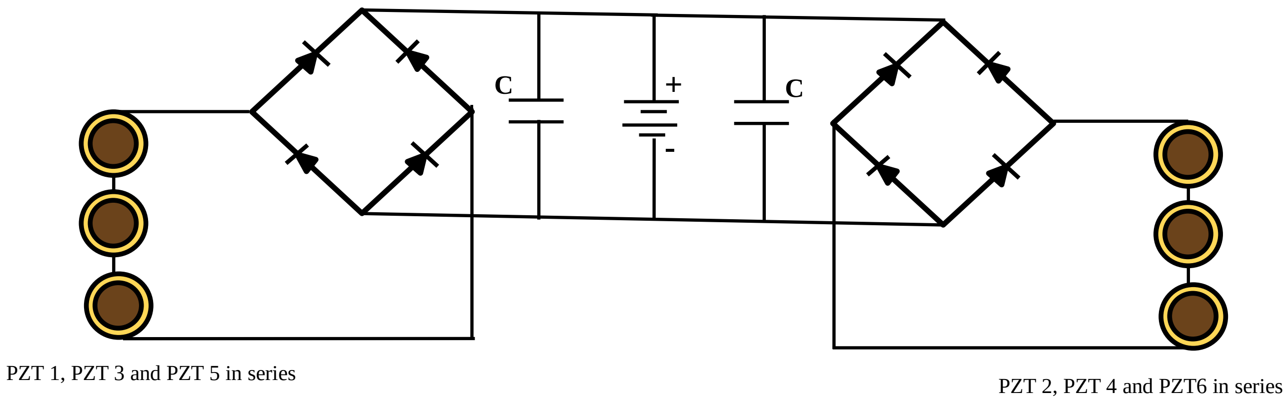



**Figure 1.13 Schematic Diagram of Energy Harvesting Circuit for Charging Battery.**

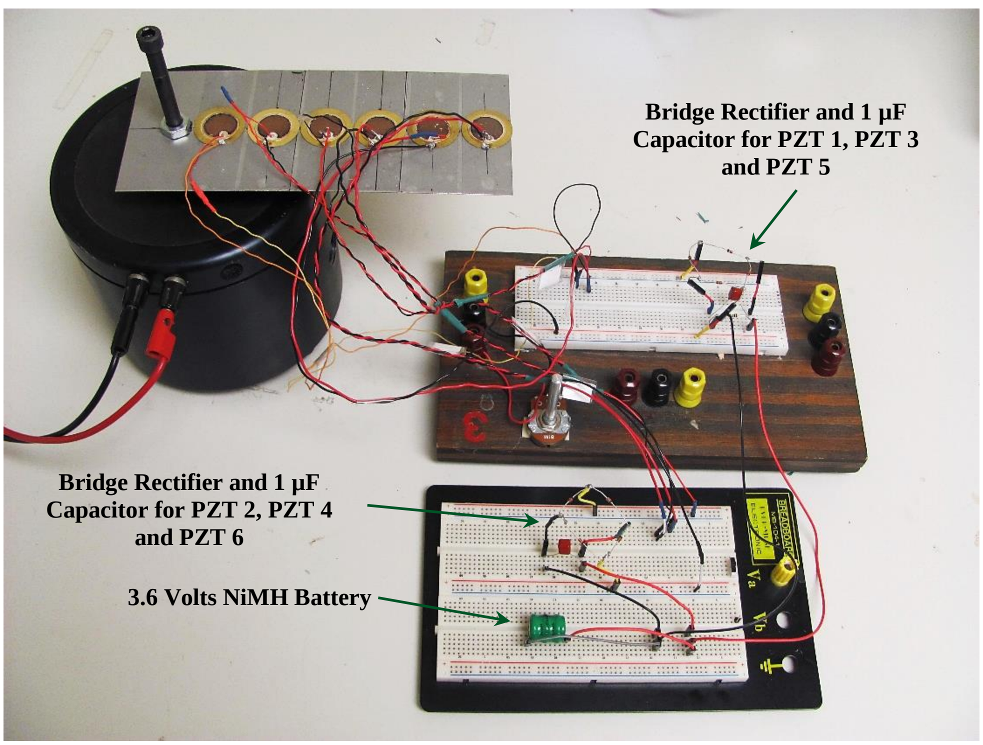



**Figure 1.14 Laboratory Setup of Energy Harvesting Circuit for Charging Battery.**

# DISCUSSION OF RESULTS

## Testing and Enhancement of Conventional Non-coated PZT Composite with Special Nano-coating

In this project work, conventional non-coated PZT composite was enhanced in terms of power harvesting capability by coating it with special nanoparticle mixture. This special nanoparticle mixture consisted of 40 % ZnO, 58 % ferrofluid and 2 % epoxy binder. For the analysis of multi PZT composite system, three shapes were designed and investigated as to enhance through the shape of cantilever system in the multi PZT composite system. As the main focus in this project is to improve the performance of conventional non-coated PZT composite, the non-coated multi PZT cantilever system and nano-coated PZT cantilever system were experimented for its power harvesting capability at the frequency range of 20 Hz to 1000 Hz. The experimental results for the three different shapes of non-coated multi PZT cantilever system and nano-coated multi PZT cantilever system are presented in Table 1.1, Table 1.2 and Table 1.3. The graphs from these results showing the power output trend for the frequency range of 20 Hz to 1000 Hz is depicted in Figure 1.16, Figure 1.17 and Figure 1.18 respectively.

It can be seen for rectangular shape in Table 1.1 that at 80 Hz frequency non-coated multi PZT cantilever system has power output of 395.612 microwatts which is improved to 503.105 microwatts in nano-coating multi PZT cantilever system. This enhancement of power output can also be seen at 400 Hz frequency for non-coated system and 350 Hz for nano-coated system. For the latter case, power output improved from 326.886 microwatts to 615.536 microwatts due to the application of nano-mixture coating. For these two cases the enhancement due to the nano-mixture coating is 27.17 percentage and 88.30 percentage.

For trapezoidal shape the power output is enhanced from 54.760 microwatts to 188.513 microwatts at 80 Hz frequency, which is improvement of 244.25 percentage. And for the frequency of 250 Hz the power output improvement is 5.36 percentage from 195.440 microwatts for non-coated system to 205.923 microwatts for nano-coated system. Single peak value output can be observed for triangular case at 60 Hz frequency in which the power output is 9.181 microwatts for non-coated system and 68.890 microwatts for nano-coated system. This is improvement of 650.35 percentage improvement in the system.

**Table 1.1 Rectangular Cantilever Energy Harvesting System**

| S.No. | Frequency (Hz) | Resistance (megaohm) | Non-coated multi PZT Cantilever System | | Nano-coated multi PZT Cantilever System | |
|---|---|---|---|---|---|---|
| | | | Voltage (volt) | Power (microwatt) | Voltage (volt) | Power (microwatt) |
| 1 | 20 | 1 | 2.125 | 4.516 | 5.316 | 28.260 |
| 2 | 40 | 1 | 2.893 | 8.369 | 4.439 | 19.705 |
| 3 | 60 | 1 | 6.624 | 43.877 | 6.811 | 46.390 |
| 4 | 80 | 1 | 19.890 | 395.612 | 22.430 | 503.105 |
| 5 | 100 | 1 | 6.058 | 36.699 | 6.615 | 43.758 |
| 6 | 150 | 1 | 2.281 | 5.203 | 2.253 | 5.076 |
| 7 | 200 | 1 | 2.725 | 7.426 | 1.510 | 2.280 |
| 8 | 250 | 1 | 0.640 | 0.410 | 2.887 | 8.335 |
| 9 | 300 | 1 | 2.683 | 7.198 | 3.488 | 12.166 |
| 10 | 350 | 1 | 5.179 | 26.822 | 24.810 | 615.536 |
| 11 | 400 | 1 | 18.080 | 326.886 | 9.615 | 92.448 |
| 12 | 600 | 1 | 0.664 | 0.441 | 0.842 | 0.709 |
| 13 | 800 | 1 | 0.858 | 0.736 | 1.533 | 2.350 |
| 14 | 1000 | 1 | 0.662 | 0.438 | 0.361 | 0.130 |

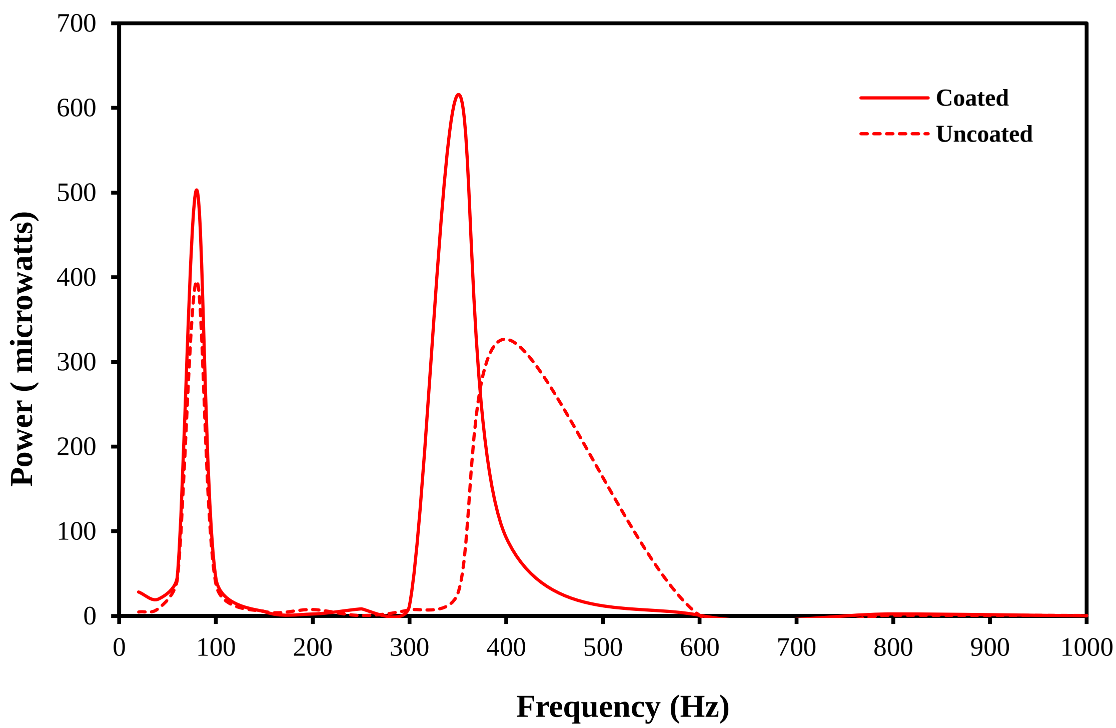



**Figure 1.15 Power Generation Profiles for Non-coated Multi PZT Rectangular Cantilever System and Nano-coated Multiple PZT Rectangular Cantilever System at Different Frequencies.**

**Table 1.2 Trapezoidal Cantilever Energy Harvesting System**

| S.No. | Frequency (Hz) | Resistance (megaohm) | Non-coated multi PZT Cantilever System | | Nano-coated multi PZT Cantilever System | |
|---|---|---|---|---|---|---|
| | | | **Voltage** | **Power** | **Voltage** | **Power** |
| | | | (volt) | (microwatt) | (volt) | (microwatt) |
| 1 | 20 | 1 | 0.981 | 0.962 | 1.824 | 3.327 |
| 2 | 40 | 1 | 1.108 | 1.228 | 2.351 | 5.527 |
| 3 | 60 | 1 | 2.217 | 4.915 | 4.705 | 22.137 |
| 4 | 80 | 1 | 7.400 | 54.760 | 13.730 | 188.513 |
| 5 | 100 | 1 | 2.300 | 5.290 | 3.466 | 12.013 |
| 6 | 150 | 1 | 1.744 | 3.042 | 1.579 | 2.493 |
| 7 | 200 | 1 | 1.004 | 1.008 | 1.958 | 3.834 |
| 8 | 250 | 1 | 13.980 | 195.440 | 14.350 | 205.923 |
| 9 | 300 | 1 | 0.740 | 0.548 | 1.612 | 2.599 |
| 10 | 350 | 1 | 1.749 | 3.059 | 1.555 | 2.418 |
| 11 | 400 | 1 | 1.885 | 3.553 | 1.535 | 2.356 |
| 12 | 600 | 1 | 1.748 | 3.056 | 1.661 | 2.759 |
| 13 | 800 | 1 | 1.950 | 3.803 | 1.575 | 2.481 |
| 14 | 1000 | 1 | 1.752 | 3.070 | 1.574 | 2.477 |

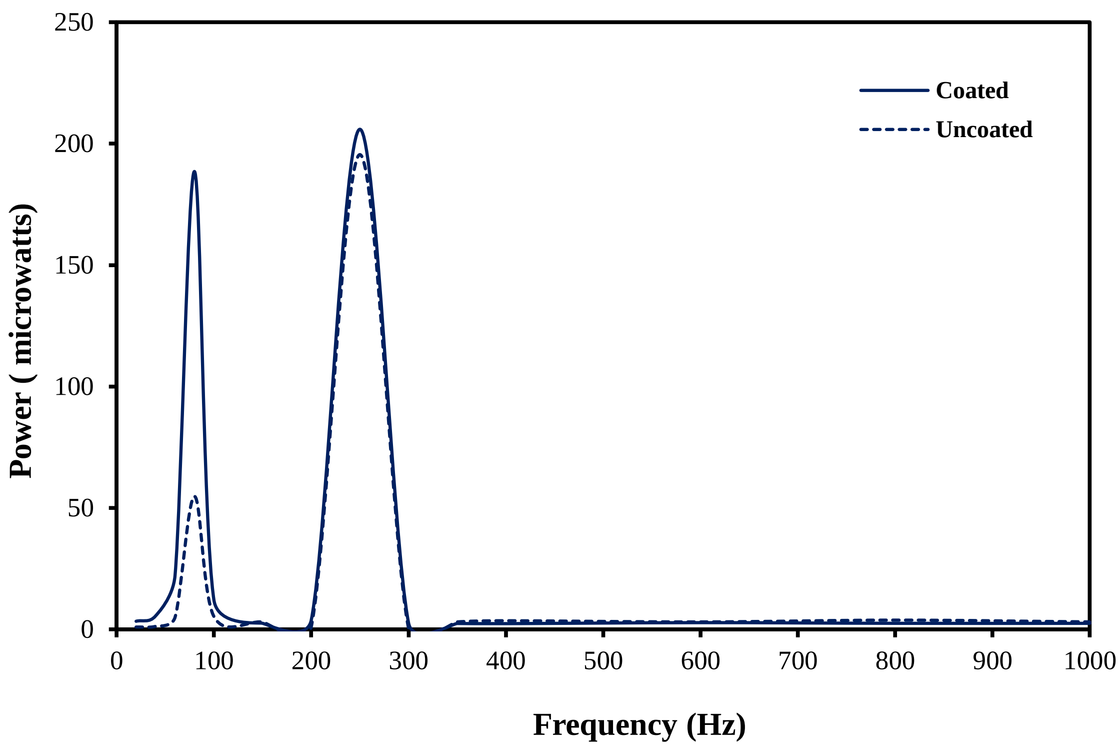



**Figure 1.16 Power Generation Profiles for Non-coated Multi PZT Trapezoidal Cantilever System and Nano-coated Multiple PZT Trapezoidal Cantilever System at Different Frequencies.**

**Table 1.3 Triangular Cantilever Energy Harvesting System**

| S.No. | Frequency (Hz) | Resistance (megaohm) | Non-coated multi PZT Cantilever System | | Nano-coated multi PZT Cantilever System | |
|---|---|---|---|---|---|---|
| | | | Voltage (volt) | Power (microwatt) | Voltage (volt) | Power (microwatt) |
| 1 | 20 | 1 | 0.732 | 0.536 | 0.844 | 0.712 |
| 2 | 40 | 1 | 1.051 | 1.105 | 1.983 | 3.932 |
| 3 | 60 | 1 | 3.030 | 9.181 | 8.300 | 68.890 |
| 4 | 80 | 1 | 2.410 | 5.808 | 7.556 | 57.093 |
| 5 | 100 | 1 | 0.887 | 0.787 | 2.544 | 6.472 |
| 6 | 150 | 1 | 0.585 | 0.342 | 0.806 | 0.650 |
| 7 | 200 | 1 | 1.327 | 1.761 | 1.007 | 1.014 |
| 8 | 250 | 1 | 0.880 | 0.774 | 0.911 | 0.830 |
| 9 | 300 | 1 | 0.641 | 0.411 | 0.706 | 0.498 |
| 10 | 350 | 1 | 0.658 | 0.433 | 0.863 | 0.745 |
| 11 | 400 | 1 | 0.758 | 0.575 | 1.045 | 1.092 |
| 12 | 600 | 1 | 0.637 | 0.406 | 0.301 | 0.091 |
| 13 | 800 | 1 | 0.619 | 0.383 | 0.413 | 0.171 |
| 14 | 1000 | 1 | 0.584 | 0.341 | 0.212 | 0.045 |

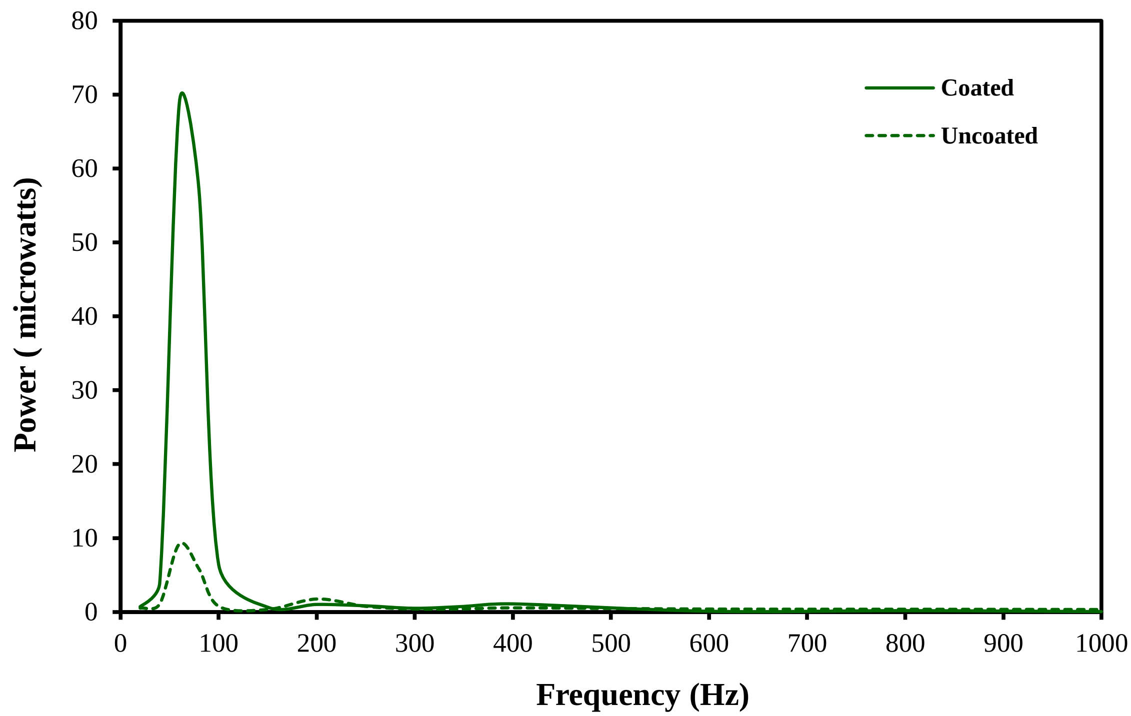



**Figure 1.17 Power Generation Profiles for Non-coated Multi PZT Triangular Cantilever System and Nano-coated Multiple PZT Triangular Cantilever System at Different Frequencies.**

## Optimization Process through Cantilever Beam Shapes

For the rectangular cantilever energy harvesting system, the maximum power harvested was found to be 395.612 microwatts for non-coated multi PZT system at 80 Hz frequency and 615.536 microwatts for nano-coated multi PZT system at 350 Hz. Alternative shapes of the cantilever energy harvesting system was considered, designed, constructed and experimented in the laboratory. Trapezoidal and triangular shapes were analyzed for the cantilever energy harvesting system with the anticipation of better power output.

But the trapezoidal and triangular energy harvesting systems exhibited decline in power output. Maximum power output for the trapezoidal shape is 195.440 microwatts at 250 Hz frequency for the non-coated system and 205.923 microwatts at the same frequency for nano-coated system. Similarly, for the triangular shape maximum power output is 9.181 microwatts at 60 Hz frequency for non-coated system and 68.890 microwatts at the same frequency for nano-coated system. The trapezoidal system showed decline of 50.60 percentage for non-coated system and 66.54 percentage for nano-coated system as compared to the rectangular system. As compared to the rectangular system, triangular system showed decline of 99.77 percentage for non-coated system and 88.81 percentage for nano-coated system. These results are clearly presented in Table 1.4. Thus rectangular system demonstrated to be more proficient selection as compared to trapezoidal and triangular systems in terms of power harvesting capability.

**Table 1.4 Triangular Cantilever Energy Harvesting System**

| **Shape of the System** | **Maximum Power Output (microwatts)** | | | | **Power Output Decline with respect to Rectangular Shape** | |
|---|---|---|---|---|---|---|
| | Frequency (Hz) | Non-coated System | Frequency (Hz) | Nano-coated System | Non-coated System | Nano-coated System |
| Rectangular | 80 | 395.612 | 350 | 615.536 | N/A | N/A |
| Trapezoidal | 250 | 195.440 | 250 | 205.923 | 50.60 % | 66.54 % |
| Triangular | 60 | 9.181 | 60 | 68.890 | 97.77 % | 88.81 % |

## Implementation of Energy Harvesting System to Power a Lighting System

For the rectangular nano-coated PZT composite cantilever system, the maximum power output was found to be 615.536 microwatts which is considerably higher as compared to trapezoidal and triangular system as discussed in previous section. Thus due to its efficiency in power harvesting capability, the rectangular nano-coated PZT composite cantilever system was considered to power a lighting system. Furthermore to harvest enough power to charge battery from the vibrational experiment, multi PZT energy harvesting system with additional number of PZT's were considered and designed. This new multi nano-coated PZT composite cantilever system with six PZT composites was constructed as discussed in methodology chapter.

The new design with six PZT composites is investigated in the predetermined frequency range of 20 Hz to 1000 Hz for the optimum frequency for which power output is maximum. The first optimum frequency for the system was tested to be 75 Hz and at this frequency, the power generation from the energy harvesting system was found to be 1210.340 microwatts (1.210 milliwatts). The circuit designed and constructed to charge the battery consisted of full wave rectifiers, capacitors and a 240 mAh/3.6 volts NiMH battery. The completely discharged battery was charged with the help of the energy harvested from the multi nano-coated PZT composite cantilever system for 120 minutes. Battery charging process couldn't be achieved beyond this time frame because of breakage of soldering between wire and PZT substrate. This is due to the higher current flow in the energy harvesting circuit at the optimum power output condition than the capacity of the PZT substrate.

The charge history data in the form of voltage rise in the discharged battery is presented in Table 1.5. Moreover this charge history trend is clarified in a graph plot depicted in Figure 1.15. The charged battery was examined if it could light a LED bulb. It was found that the charged battery had sufficient power to light the LED bulb.

**Table 1.5 Charge History of 240 mAh Battery with Resonant Excitation of Multi PZT Energy Harvesting System**

| S.N. | Time (Mins) | Time (Hours) | Voltage |
|---|---|---|---|
| 1 | 0 | 0 | 2.042 |
| 2 | 6 | 0.1 | 2.186 |
| 3 | 12 | 0.2 | 2.226 |
| 4 | 18 | 0.3 | 2.276 |
| 5 | 24 | 0.4 | 2.324 |
| 6 | 30 | 0.5 | 2.371 |
| 7 | 36 | 0.6 | 2.431 |
| 8 | 42 | 0.7 | 2.496 |
| 9 | 48 | 0.8 | 2.564 |
| 10 | 54 | 0.9 | 2.619 |
| 11 | 60 | 1 | 2.681 |
| 12 | 66 | 1.1 | 2.739 |
| 13 | 72 | 1.2 | 2.791 |
| 14 | 78 | 1.3 | 2.858 |
| 15 | 84 | 1.4 | 2.89 |
| 16 | 90 | 1.5 | 2.928 |
| 17 | 96 | 1.6 | 2.964 |
| 18 | 102 | 1.7 | 2.993 |
| 19 | 108 | 1.8 | 3.015 |
| 20 | 114 | 1.9 | 3.033 |
| 21 | 120 | 2 | 3.054 |

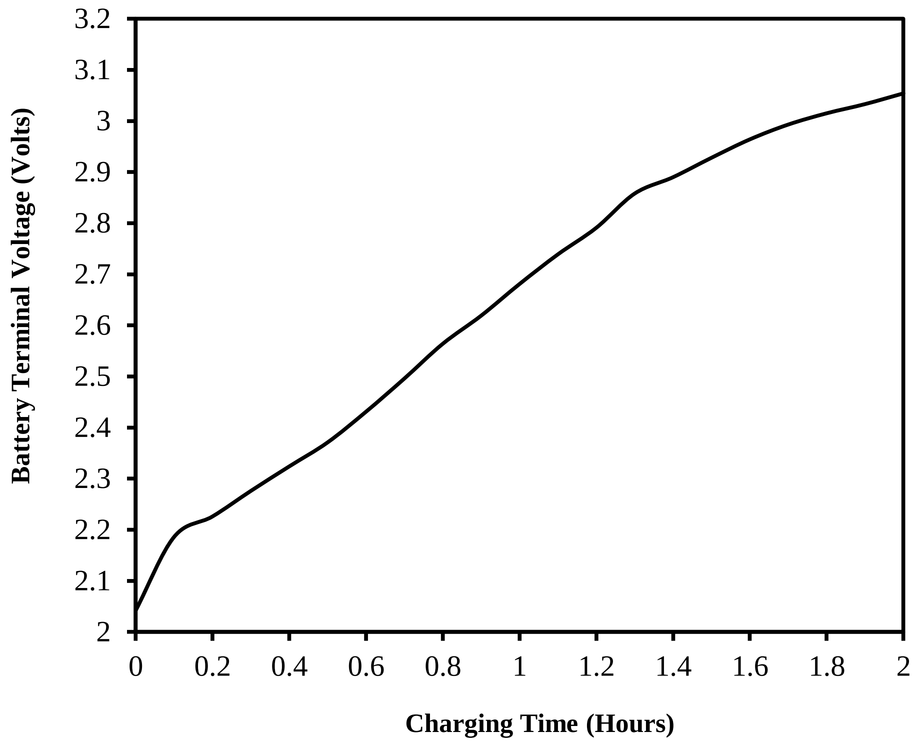



**Figure 1.18 Charge History of 240 mAh NiMH Battery with Resonant Excitation of the multi PZT Energy Harvesting System.**

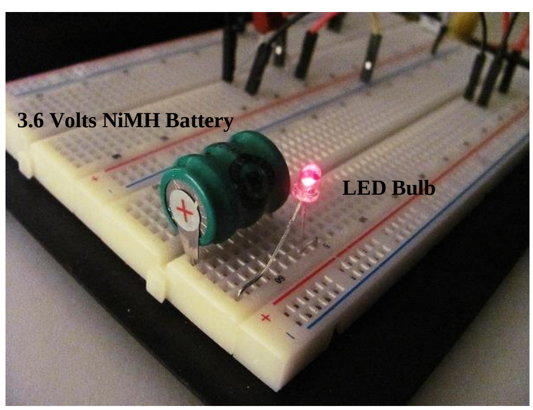



**Figure 1.19 Lighting LED Bulb from Battery Charged through Energy Harvesting System.**

# CONCLUSIONS

Nano-coated PZT energy harvesting system showed substantial and explicit improvement as compared to non-coated PZT energy harvesting system. In the rectangular cantilever system, the maximum power output in nano-coated PZT system is 615.536 microwatts and the corresponding power output for non-coated PZT system is 326.886 microwatts. Thus the enhancement due to the nano-mixture coating is 88.30 percentage. In the trapezoidal cantilever system the power output is enhanced from 54.760 microwatts to 188.513 microwatts at 80 Hz frequency, which is an improvement of 244.25 percentage. Similarly, in the triangular case the power output is enhanced from 9.181 microwatts to 68.890 microwatts at 60 Hz frequency, which is an improvement of 650.35 percentage.

In the experimental analysis of this project work, the rectangular cantilever system performed substantially better than the trapezoidal and triangular cantilever systems in terms of power harvesting capability. To incorporate this power harvesting system for the application to power LED bulbs, more number of PZTs needs to be integrated into the system. The new multi nano-coated PZT composite cantilever system with six PZT composites generated 1210.340 microwatts (1.210 milliwatts) at the optimum frequency of 75 Hz. This power output charged the discharged 3.6 Volts NiMH Battery to 3.054 Volts in two hours. The charged battery had sufficient power and it lit the LED bulb in the laboratory.

# RECOMMENDATIONS

Alternatives to the main piezo electric nano component, ZnO, of the nano-coating mixure of this study, having better piezo electric characteristic in terms of power output should be investigated. Additionally, different base piezo electric materials, other than PZT, should be explored. These two recommendations could lead to sufficient increase in the power output which could immensely impact the economic feasibility of vibrational energy harvesting.

## ACRONYMS, ABBREVIATIONS, AND SYMBOLS

| | |
|---|---|
| PZT | Lead Zirconium Titanate |
| ZnO | Zinc Oxide |
| UM | University of Mississippi |
| AC | Alternating Current |
| DC | Direct Current |
| Hz | Hertz |
| RMS | Root Mean Square |
| MΩ | Megaohm(s) |
| mm | millimeter(s) |

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