Circuitry parameter analysis of piezoelectric materials for micro energy harvesting

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Abstract. Energy scavenging using piezoelectric materials is conventional and reliable method of energy harvesting in case of wireless sensor application. The mechanical stress or strain caused on the piezoelectric material leads to generation of voltage which in turn can be used for storage in batteries. This article deals with simulation of circular piezoelectric transducer using COMSOL software and the comparison of various parameters with respect to the structure is studied, also the experiment is conducted to compare the voltage values generated by piezoelectric transducers in different circuitry connections. This data signifies the efficiency and adaptability of piezoelectric transducers for various applications.

1. Introduction

Energy harvesting is a method of collection of energy from various physical sources such as heat, light, sound, vibration or movement etc. and to store it for the future use.[1] There are number of technologies and methodologies developed in past few decades to harvest the energy from different sources.[2] These include the harvesting of energy from solar, wind tidal, geothermal etc. which indulges in the ransom investments. In these forms of energy harvesting the chances of endurability is low which is a major disadvantage.[3] In order to overcome these limitations, there is need for development in technologies of energy harvesting.

Piezoelectric materials find major applicability in micro energy harvesting, these materials generate voltage in response to mechanical stress or strain which when combined in larger numbers can be used for various applications.[4] The piezoelectric effect is one of the mechanical vibrations to electric energy conversion mechanisms. This has three times higher energy density compared to that of electrostatic and electromagnetic transduction.[5] The disadvantage in the piezoelectric energy harvesting lies in the mismatching of excitation frequency and the optimal frequency of the harvester. [6-7]

Several researchers have studied different ways of optimizing the piezoelectric transducers in order to harvest energy. Ashtari et al. [8] Has studied the enhancing property of three piezoelectric bimorphs of cantilever array. It was noted that three bimorphs harvester can reach thrice the amount of power generated in comparison with single bimorph harvester and this bandwidth enhancement was successful only when the individual rectifiers were used for individual bimorphs. Choi et al. [9] studied the hybrid energy harvesting system using the solar and piezoelectric energy, in which the piezoelectric elements were impacted by bar which was reciprocated by rotary blades that were circulated by wind which in turn produced calculative amount of voltage supply of about 20V using 25 elements.

The studies have been made on different aspects of design of piezoelectric sensors and its shape, structure, thickness and material used to determine the efficiency of piezoelectric diaphragm in energy harvesting. [10-11] The circular diaphragm was proved to have better voltage and sensitivity. [12] There are different energy harvesting methods using vibration which is generally termed as vibrational energy harvesting (VEH). The different methods such as electromagnetic and electrostatic or combination of electromagnetic with piezoelectric [13-15] have the sole purpose to optimize the methods for harvesting energy in qualitative manner. In this work, simulation results of circular piezoelectric transducer determining the physical response and behavior to different frequency modes and the experimental data

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is presented and the comparison of the circuitry connections of piezoelectric transducers justifying its suitability for numerous applications.

2. Experimental details

2.1 Design and Analysis of Piezoelectric Transducer

The basic structure of the transducer has a piezoelectric material with the external electrode as a supportive coating. Initially this structure is analyzed using COMSOL Multiphysics tool (physics-structural mechanics and stationary study) for its dimensional dependency on the parameters like total displacement, Electric potential and natural frequency with the application of static Load of 1.96N in the downward direction (boundary load). The transducer has piezoelectric layer of 12.5mm radius and it is simulated by applying the mass of 0.2Kg to analyze the structural parameters. The Fig 1a shows the 3-dimensional simulated piezoelectric structure representing the deformation and the stress distribution on the surface. The Fig 1b shows the graph of the total distribution of the displacement on the surface indicating the greater stress concentration on the periphery of the structure.

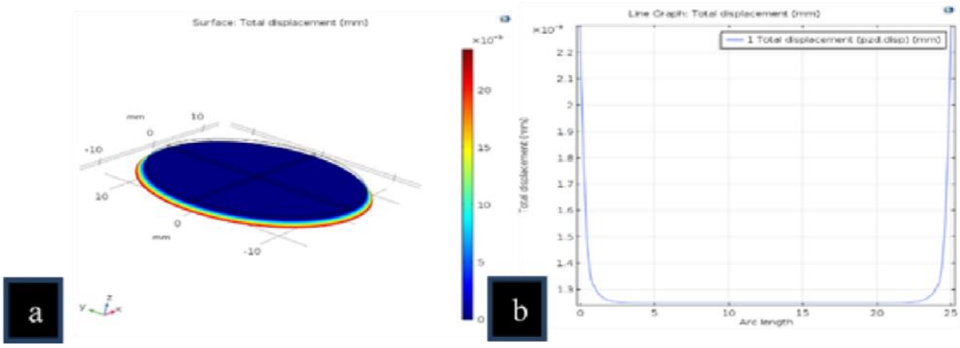

Figure 1 (a) The 3D structure of Piezoelectric transducer showing total displacement **(b)** Linear graph of arc length v/s total displacement

The piezoelectric structure was analyzed for the electric potential distribution, the electric potential was observed along the diameter of the piezoelectric structure which clearly indicates the higher potential in the periphery where the stress concentration level is high. This potential distribution is shown in the 3- dimensional structure of the Piezoelectric transducer in the Fig 2a and the potential distribution over the diameter of the structure is graphically represented in the Fig 2b. This indicates the electric potential concentration is higher in the periphery of the transducer which is shown as a peak in the graph.

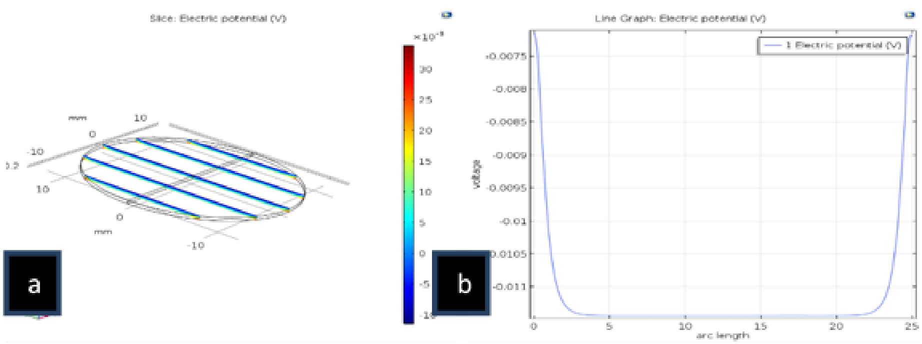

Figure 2 (a) The 3D structure of piezoelectric transducer showing distribution of electric potential **(b)** the graph of arc length v/s electric potential

2.2 Eigen Frequency analysis

In order to understand the behavior of the simulated Piezoelectric structure under dynamic input (vibration source), the COMSOL Multiphysics study as Eigen frequency was chosen. The six dominant modal frequencies were chosen and the corresponding deflection under each frequency was noted in Fig 3. The six Eigen frequencies ranging from 8.76e5 to 8.85e5 are obtained. In the Fig 3b and 3c with Fig 3d and 3f are the duplicates representing the identical natural frequencies. Further the total displacement, von mises stress and the electric potential for the eigen modes are discussed in the results and discussion section.

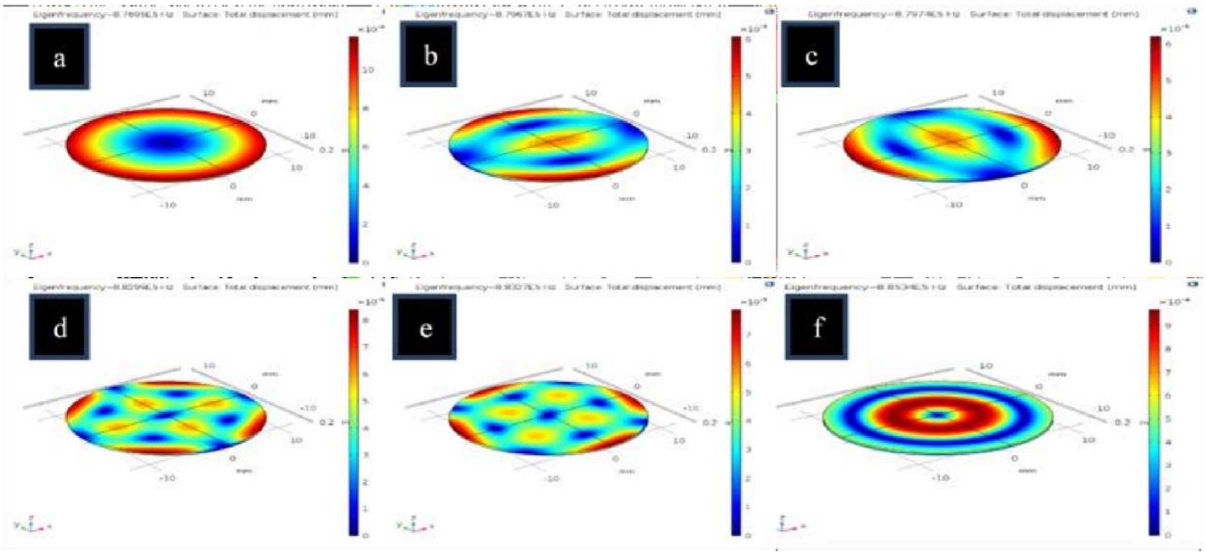

Figure 3 (a),(b),(c),(d),(e) shows the 3D structure of the eigen modes of the Piezoelectric transducer

2.3 Experimental Procedure

The Piezoelectric transducers are optimised to check the individual voltages and the values for the peak voltage is noted and verified with the manufacturer guide. Then the circuit is built for Series, Parallel and Series-Parallel connections using individual sensors on a flexible sheet which is built in layers, where two layers consist of the six sensors with respective circuitry arrangements, the layers of that particular circuitry arrangements are placed opposite to each other with a separation in between them which induces voltages on both compression and relaxation upon the applied load. The circuitry arrangements are tested with Digital Cathode ray oscilloscope for variation in the peak voltages upon different applied load conditions, each circuitry arrangements are tested with 0.20Kg, 0.25Kg and 0.30Kg mass which are applied from a fixed vertical distance of 0.05m and the graphs obtained for all the circuitry arrangements at each load conditions are noted for comparing all the three circuitry connections and the results are discussed. Fig 4a and 4b shows the experimental setup and the Piezoelectric transducer respectively Fig 5 a, b, c shows the circuitry setup of the series parallel and series-parallel circuits

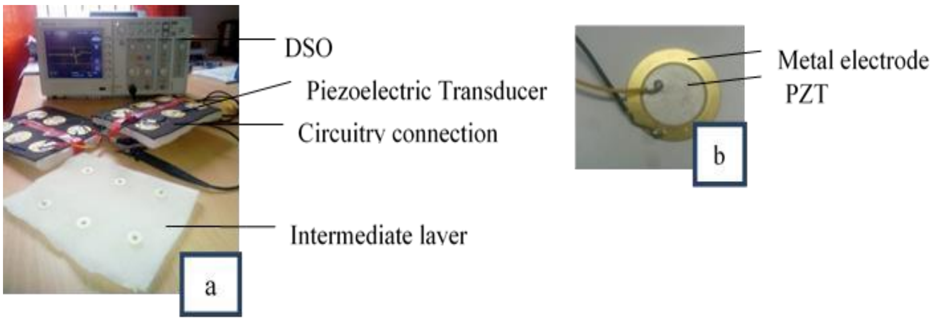

Figure 4 (a) shows the experimental setup **(b)** shows the Piezoelectric transducer

Figure 5 (a) Series arrangement **(b)** Parallel arrangement **(c)** Series-Parallel arrangement

Series Connection: The Circuitry arrangement for series is tested by applying three different loads with fixed impact distance and the amount of voltage obtained is noted. It was observed that output voltage increased as the mass of the load applied increased. The variation in the waveforms for all the three load conditions in Series circuitry arrangement are shown in the Fig 6 (a) (b) & (c). The output voltage for series connection was in the range of 132V-270V.

Figure 6 (a) Series waveform for 0.2kg **(b)** series waveform for 0.25kg **(c)** series waveform for 0.3kg

Parallel Connection: In the Parallel connection the Output Voltage increased as the mass of the load applied increased and the voltage was in the range of 8.2V-22V. The variation in the waveforms for all the three load conditions in Parallel circuitry arrangements are shown in the Fig 7 (a) (b) & (c). It was observed that the amount of output voltage received from the parallel connection was less compared to that of series connection.

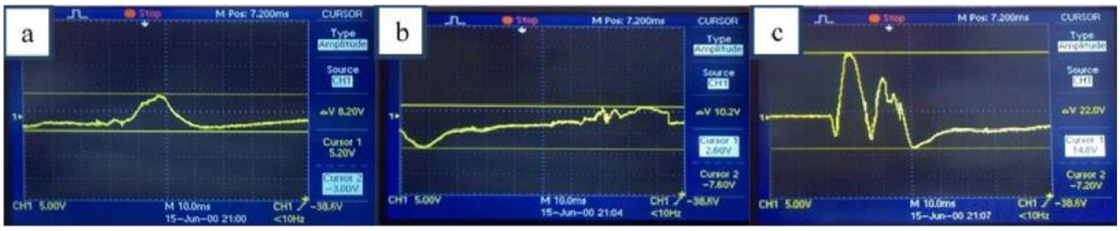

Figure 7 (a) Parallel waveform for 0.2kg **(b)** Parallel waveform for 0.25kg **(c)** Parallel waveform for 0.3kg

Series-Parallel Connection: In Series-Parallel connection the output voltage increased as the mass of the load applied increased and the voltage was in the range of 114V-174V. The variation in the waveforms for all the three load conditions in the series-parallel circuitry arrangement are shown in the Fig 7 (a) (b) & (c). It was observed that the amount of output voltage received from the parallel connection was less compared to that of series connection and slightly high compared to that of Parallel connection.

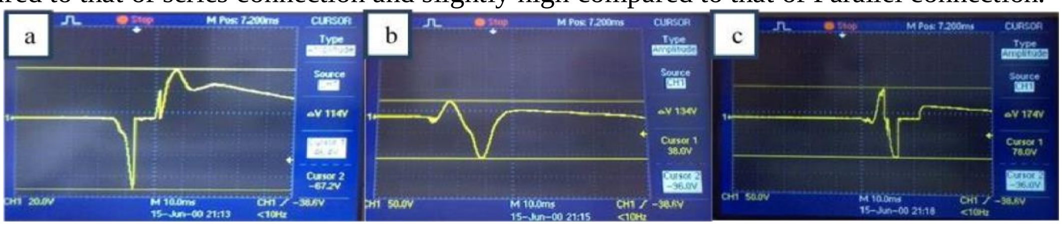

Figure 8 (a) Series-Parallel waveform for 0.2kg **(b)** Series-Parallel waveform for 0.25kg **(c)** SeriesParallel waveform for 0.3kg

3. Results and Discussions

3.1 Variation of total displacement and Von-mises stress for different eigen modes

The eigen modes represents the shapes of the structure on vibration which is an important structural analysis to determine the behaviour of the material in different situations. This study is focussed on the displacement and stress distribution of the piezoelectric structures in different eigen modes. The Fig 9a shows the graph of the total displacement along the diameter of the structure indicating the maximum displacement towards the periphery of the structures, similarly for all the eigen modes the displacement is maximum at its individual periphery as the position of the mode's changes. The Fig 9b shows the stress distribution on the structure for the various modes representing the maximum stress concentration in the peaks of the curve and the minimum stress concentration at the wells. This study helps in gaining information on the change in the shape of structure and its behavioural response of displacement and stress concentration.

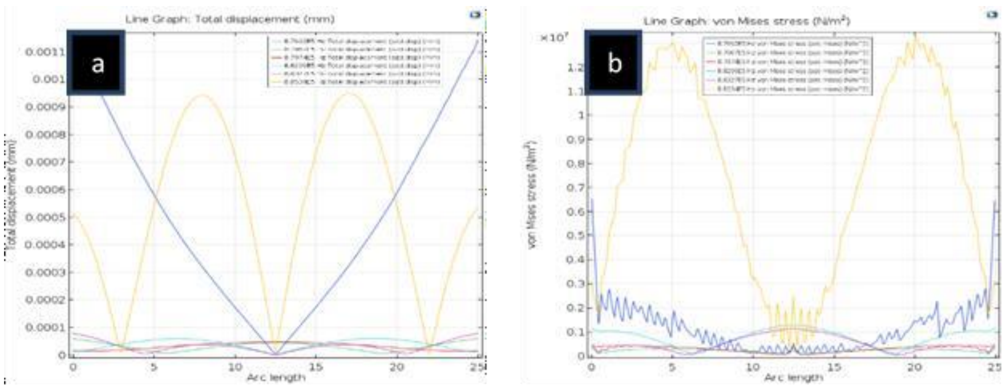

Figure 9 (a) Graph of arc length v/s total displacement **(b)** graph of arc length v/s von-mises stress

3.2 Variation of Electric potential for different eigen modes

The Piezoelectric material has the capability to produce the electric potential on the applied load and this depends upon the amount of the mechanical stress applied on the structure and its distribution over the region of the structure. The electric potential varies as the applied pressure varies in piezoelectric materials. The stress concentration is found to be distributed in the periphery of the piezoelectric structure where the high electric potential is generated. The eigen modes have different structural periphery in every mode and the electric potential distribution is along the higher stress concentration regions. The potential variation is clearly shown in the Fig 10 for all the eigen modes and their curves vary as the stress concentration varies.

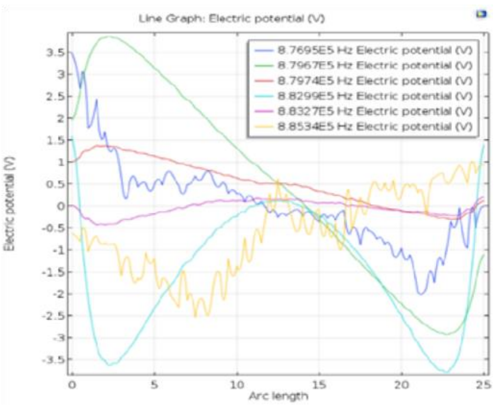

Figure 10 Graph of arc length v/s Electric potential

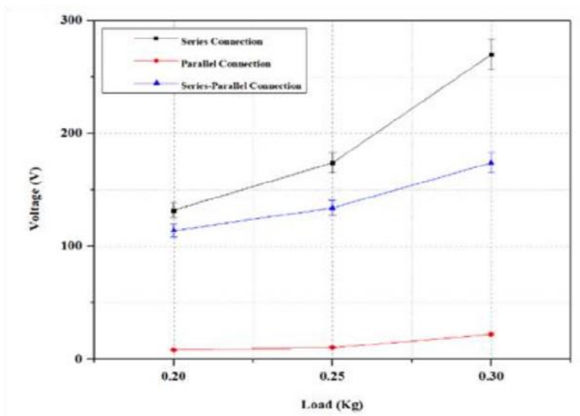

Figure 11 Graph of Load v/s voltage

3.3 The variation of voltage v/s load for different circuitry arrangements

The voltage generation in the piezoelectric materials not only depends on the applied mechanical stress but also the circuitry arrangement. The generation in the voltage is directly proportional to the applied load and this is shown in the Fig 11. The trend in increase of the voltage generated as the applied load increases is observed in all the circuitry arrangements. The series arrangement generates the higher voltage in comparison to the parallel and series-parallel circuitry arrangements and series-parallel circuitry arrangement is found to be generating more voltage in comparison to the parallel arrangement. Thus, the transducers in all the circuitry connections are operating in the linear region of operation.

4. Conclusion

Individual sensors with PZT piezoelectric material sandwiched between two electrodes is simulated in COMSOL Multiphysics for its change in total displacement and the electric potential variation. The eigen frequency analysis is performed and the total displacement variation, stress distribution and the electric potential generation are studied. The experimental set up for different types of circuitry arrangements is tested for different range of loads which are practically available. It has been observed that, the series, parallel and series-parallel connection of six sensors each with two layers separated by an insulating layer gave a voltage of the range 132V-270V, 8.2V-22V and 114V-174V respectively. The magnitude of the voltages available indicates that even though they are instantaneous (dynamic) voltages, they are of good value for micro energy harvesting with power conditioning circuit. Thus, these micro energy harvesters may be implemented on the floor of Gym, stairs and on the floor where natural application of the load due to movement of people is more.

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