Modelling of a Low Frequency Based Rectangular Shape Piezoelectric Cantilever Beam for Energy Harvesting Applications

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ABSTRACT

Harvesting few amount of charge from environmental ambient sources namely, wind, thermal, heat, vibration, solar utilizing micro scale energy harvesting devices, offers vast view of powering for numerous portable low power electronic devices. However, power harvesting using piezoelectric crystal from low power ambient source nowdays has increasing popularity with the advantages of low cost, long life time, stability and clean energy. Recent trends have shown that most researchers are interested in designing a low resonance frequency vibration based energy harvesting devices despite of its challenges ahead. In this paper, a low frequency based rectangular shape piezoelectric cantilever beam has been developed for energy harvesting applications. The proposed vibration based low frequency cantilever beam using piezoelectric element has been developed by finite element analysis (FEA) employing COMSOL Multiphysics platform. The main goal of the study is to analyze the outcome of geometric model of a piezoelectric cantilever beam and to calculate the resonance frequency of the structure according to its length. The material of PZT-5H, has been considered to enhance the efficiency of the low frequency based cantilever beam. Finally, the proposed result is compared with other existing works.

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1. INTRODUCTION

There are three kind of popular energy harvesting based on vibration modes such as piezoelectric, electromagnetic and electrostatic transducer [1]-[3]. Energy harvesting from piezoelectric vibration transducer has gained more popularity in terms of its large energy harvesting ability with low range of resonance frequencies, there are many applications utilizing its easy structure and simple controller with higher efficiency rather than other models. [4], [5]. The efficiency of energy alteration from mechanical force vibration to electrical energy is relatively large [6]. There are two kind of cantilevers structures namely unimorph and bimorph mode. Both modes are suitable to harvest energy because it allows comparatively huge pressure stages on the piezoelectric element when reducing the size of these devices [7]-[9].

It is little known scopes of energy harvesting applications, however the ultimate frequencies of the beam resonators is wide in range. Thus, the necessary frequency perhaps can be obtained by the insertion of extra pressure, denoted to as a peak/proof mass, and another side of the cantilever is free to move, in which consequently piezoelectric delivers huge voltage and small currents [10], [11]. Because of these bi-directional properties, piezoelectric elements are broadly utilized. Some applications of this type are utilized to produce electrical power to run low power devices extracted from human daily life and produce in industrial mass at large [12], [13].

In the past, few authors had managed to accomplish in developing the actual energy harvesting transducer based on vibration source applying piezoelectric elements for low resonance frequencies [14]. Several techniques were used to enhance the harvested voltage of micro piezoelectric based energy harvesting system at micro power level. However the low frequency variations are limited to certain type applications and need further improvement for higher power with much lower frequencies.

In construction, piezoelectric elements are obtainable in numerous forms together with solid material (e.g. crystals), Piezoelectric materials such as lead zirconate titanate (PZT-5H), Barium Sodium Niobate, Tellurium Dioxide and Cadmium Sulfide [15]. Furthermore, PZT is basically poled and has a huge boundary of dielectric constant. Energy harvesting with piezoelectric elements are increasing popularity rather than other vibration-based energy harvesting techniques. The main reason piezoelectric energy harvesting technique out perform others is by its property, where its elements produces an electrical amount of charge, and generates a mechanical deformation in various design shapes [16]-[18].

The main focus of this paper is to design a low resonance frequency based rectangular shape piezoelectric cantilever beam for energy harvesting applications. The organization of the paper is as follows: Section 2 denotes method and matherials of the proposed rectangular shape cantilever beam from force vibrations. Section 3 presents results and discussion. Finally, conclusion is given in section 4.

2. METHOD AND MATERIALS

The proposed unimorph mode of energy harvester cantilever beam is shown in Figure 1. Unimorph mode of energy harvester cantilever beam contains of a particular level structure of piezoelectric element merged to a level structure of non-piezoelectric element, denoted to as ‘substrate tier’. The structure calls as Electrodes, produces an amount of charge and combined to the top and bottom layer of the beam with piezoelectric elements.

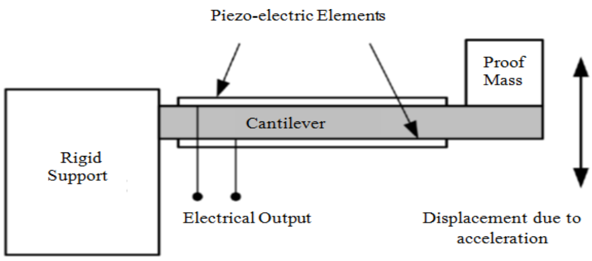

Figure 1. Diagram of proposed piezoelectric power generator

Meanwhile, Table 1 shows the properties of particular popular materials for energy harvesting elements and made comparison to piezoelectric elements. It is obvious that piezoelectric material has a higher electromechanical combination constant and higher temperature variations [22], thus this research has made a selection on to have a PZT-5H piezoceramic based material for model development.

Table 1: Transducer Technologies available for Energy Harvesting [22,23]

Transducer Type	Excitation Source	Materials	Efficiency (%)	Attributes
Photovoltaic Cell (PV)	Solar/Visible spectrum (Outdoor/Indoor	Crystalline Silicon GaAs Amorphous Silicon /CdTe CuInSe2	10%-20% 25%-30% 5%-9% ~17%	-High cost of materials -Low light absorptivity of silicon -Low power density
Thermoelectric	Temperature Gradient (Waste Heat)	Doped Bi2Te3 both p and n doped), pb2Te3, Si-Ge, YbAl3	Less than 5%	Limited by Carnot efficiency and operating temperature -Material selection based on operating temperature
Electrostatic	Vibrations	MEMS scale Capacitor	~13.33% (5.6μW)	Active system requiring capacitor excitation voltage
Piezoelectric	Vibrations, Pressure variations	Ceramics, Single crystals, Polymer	~5-30%	Depends on source excitation -Piezoelectric material property

The proposed low resonance frequency rectangular shape cantilever of Figure 1, is designed and simulated using COMSOL multiphysics software. The proposed step procedures show the process flow of the design of the piezoelectric cantilever beam. The simulation design procedure of micro cantilever beam in COMSOL presented steps by steps as shown in Figure 2.

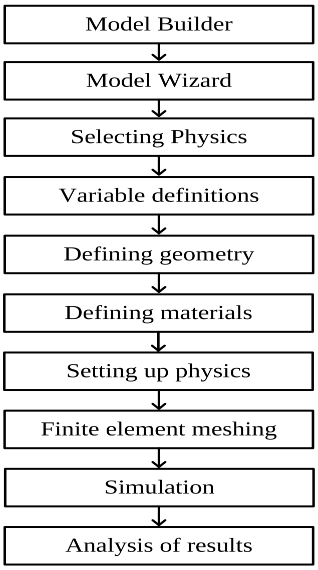

Figure 2. Steps in developing the micro cantilever beam in COMSOL

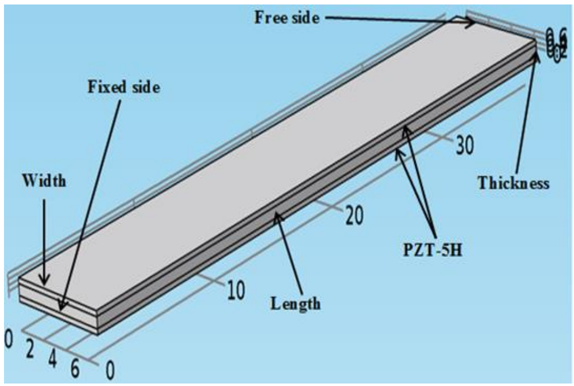

Figure 3. Finite element model of the rectangular cantilever beam in COMSOL

The finite element model of the rectangular shape cantilever beam is built using COMSOL multiphysics. The COMSOL multiphysic has been used to model piezoelectric energy harvester cantilever beam based on force vibration. The cantilever beam is a two-layered bending element mounted on a fixed support. In this model, PZT-5H material is added on the piezoelectric surface cantilever beam and the performance of the beam is tested based on difference resonance frequencies.

2.1. Model Builder

The Model Builder windows based on model tree and the linked toolbar buttons provides an outline of the design. The performance procedure is required for creating the design and preparing the results. Model Wizard build up the space dimension, physics, and survey category can be performed in short periods.

2.2. Model Wizard

Position dimensions can be built up using Model Wizard. To design these, model position dimensions must be chosen.

2.3. Selection of the Physics Modules

Finite element model of the micro energy harvester is performed in COMSOL through utilizing "structural mechanics" with piezoelectric devices applications mode from ADD PHYSICS tree and choosing frequency domain found from survey.

2.4. Geometry Modeling and Defining the Materials

The COMSOL multiphysics drawing tools are used to create the three dimensional (3-D) micro cantilever beams. The PZT-5H material is used as a layer on both sides at top and bottom on the cantilever beam. The model of rectangular shape micro cantilever beam consists of length, width and thickness in mm. It is important to note that one end of the beam is kept fixed while other parts are free to move as denoted in Figure 3. It is done by using structural mechanics module of the COMSOL.

2.5. Meshing

The mesh application, which describes the interaction between the 3-D structure and the actual structure, solves mesh smoothing equations inside the COMSOL to define the coordinate transformations of the beam. Figure 4 depicts the mesh modelling of the cantilever beam. In this work variation of the resonance frequencies of the piezoelectric energy harvester shape are involved for different length of the cantilever beam.

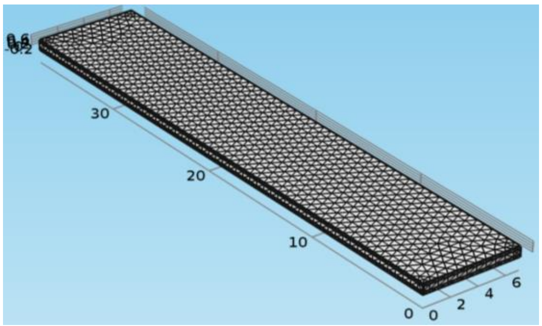

Figure 4. Model of mesh in COMSOL

3. RESULTS AND DISCUSSION

The FEA of the micro cantilever is performed to assess the shape feedbacks. The work also investigates on how the resonance frequencies of the piezoelectric energy harvester shape are involved through difference length of the cantilever beam. First, the length of the cantilever is expanded from 5mm to 100mm, other parameters of the cantilever are fixed. Different simulation results are plotted in Figure 5 for variation of the cantilever length. It has been shown that the effect of the cantilever length dimensions on difference resonance frequencies, which is the higher the length the lower the frequency. Meanwhile, Figure 6 shows the resonance frequencies with difference length and displacement. Figure 6(a) shows that when the width and thickness of the cantilever beam are fixed, the resonance frequency drops and rise for all the difference beam length of the cantilever beam. This is in agreement to Figure 5. Figure 6(b) shows the displacement with the frequency response curve for 40mm cantilever length. From Figure 6(a) and 6(b) it is clear that the proposed model resonance frequency is very low for the length dimension of 40mm length to come out for the frequency resonance at 27Hz. The model has been compared with other works in order to produce lower resonance frequency as tabulated in Table 2.

Table 2. Comparison of the resonance frequency

PZT device description	Design/ dimensions	Resonant frequency	References
Energy harvesting MEMS device based on thin film PZT cantilevers	Cantilever size: length = 13.5 mm, width = 9 mm, thickness = 192 μm	48.5 kHz	[19]
PZT-based MEMS with inter digital electrodes)	Cantilever size: length = 3.000 μm, width = 1.500 μm, thickness = 22 μm	570–575 Hz	[20]
Thin film PZT-based MEMS power generator array for vibration energy harvesting, operating in d31 mode	Cantilever size: 2.000–3.500 μm, width = 750–1.000 μm	226–234 Hz	[21]
Force vibration based rectangular shape piezoelectric cantilever beam	Cantilever size: length = 40 mm, width = 6 mm, thickness = 1.5mm	27 Hz	**This work**

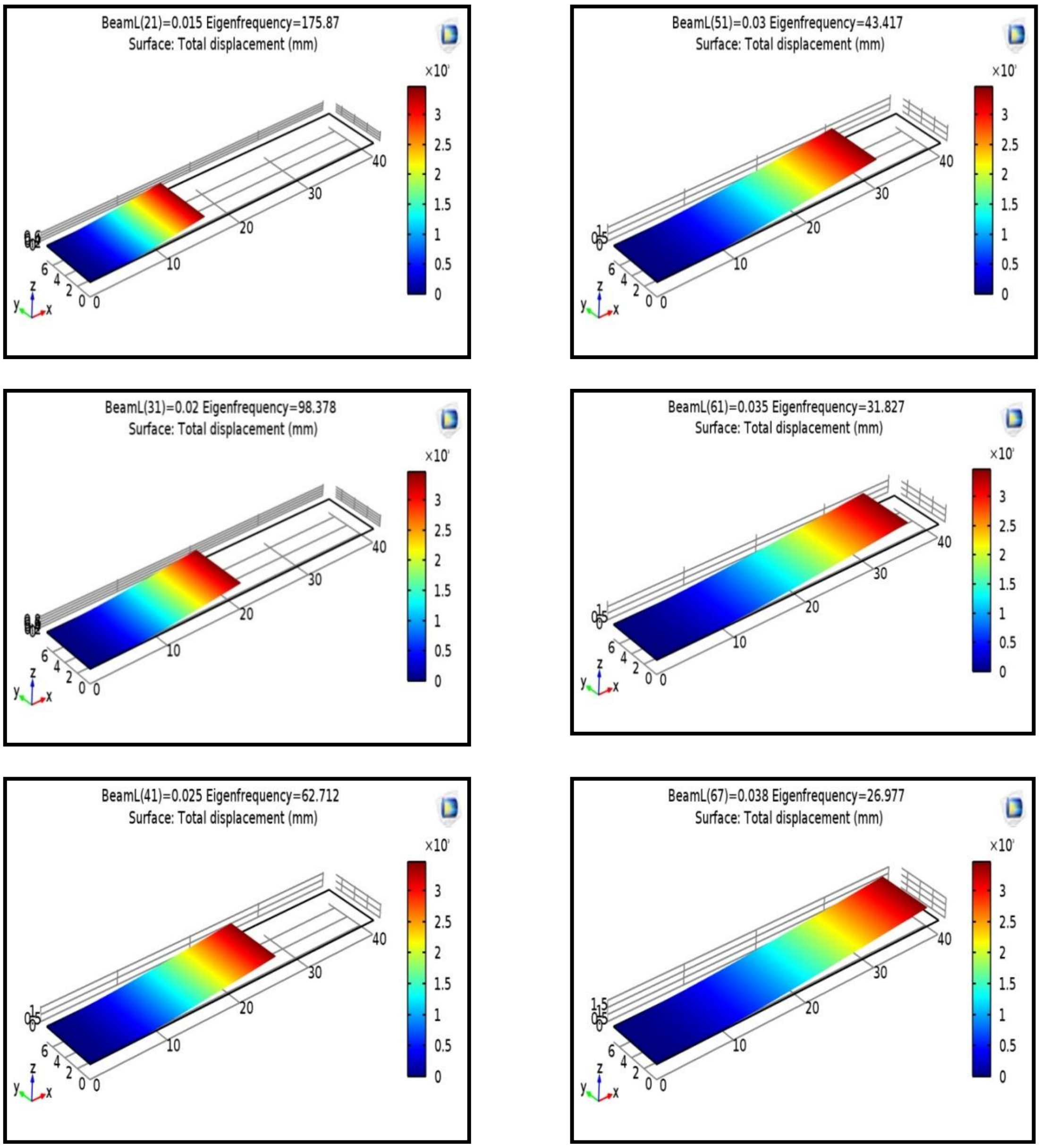

Figure 5. Length of the cantilever is rise slowly from 5mm to 100mm

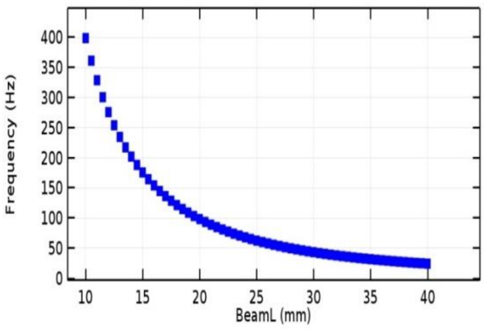

Figure 6(a). Cantilever length effect with resonance frequency

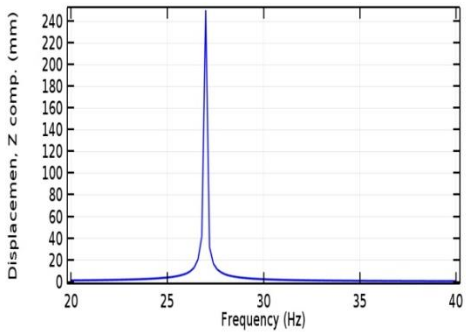

Figure 6(b). Cantilever resonance frequency with displacement.

4. CONCLUSION

This work has presented a low frequency based rectangular shape piezoelectric cantilever beam for energy harvesting application. The proposed rectangular shape cantilever beam was designed using a solid mechanics finite element model in COMSOL. As depicted in Table 2, the work has successfully modelled the way that the cantilever beam may generate high energy generation at low frequency compared to others. The rectangular shape piezoelectric cantilever beam is using the PZT-5H piezoceramic material and has obtained suitable resonance frequency at 27Hz. This has an advantage of giving desired output for low frequency applications with multivariable dynamic force.

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REFERENCES

[1] Saggini S, Ongaro F. Low-Power Energy Harvesting Solutions for Wiegand Transducers. *IEEE journal of emerging and selected topics in power electronics*, 2015; 3(3): 766-779.
[2] Hwang JH, Hyoung CH, Park KH. Kim YT. Energy harvesting from ambient electromagnetic wave using human body as antenna. *Electronics Letters.* 2013; 49(2): 149 -15.
[3] Priya S. Advances in energy harvesting using low profile piezoelectric transducers. *Journal of Electroceramics*. 2007; 19: 167–184.
[4] Rezaeisaray M, Gowini M, Sameoto D, Low frequency piezoelectric energy harvesting at multi vibration mode shapes. *Sens. Actuators A Phys.* 2015; 228: 104–111.
[5] Elfrink R, Kamel TM, Goedbloed M, Matova S, Hohlfeld D. Vibration energy harvesting with aluminum nitride-based piezoelectric devices. *J. Micromech. Microeng.* 2009; 19: 249-252.
[6] Qian Z, Kim ES, Vibration Energy Harvesting Based on Magnet and Coil Arrays for Watt-Level Handheld Power Source. *Proc. IEEE;* 2014; 102(11)1747-1761.
[7] Saker MR, Mohamed A. Mohamed R. Develop a vibration based MEMS piezoelectric energy harvester using micro cantilever beam. *International Journal of Applied Engineering Research*, 2016; 11(5): 3421-3426.
[8] Maiwa H, Sakamoto W. Vibrational Energy Harvesting Using a Unimorph with PZT- or BT-Based Ceramics. *Ferroelectrics.* 2013; 446: 67-77.
[9] Yang Z, Zu J. Toward Harvesting Vibration Energy from Multiple Directions by a Nonlinear Compressive-Mode Piezoelectric Transducer. *IEEE/ASME Transactions on Mechatronics*, 2016; 21: 1787 – 1791.
[10] Xiaobin C, Mingming T, Junhui H. PSPICE-Based Analyses of the Vibration Energy Harvester System with Multiple Piezoelectric Units. *Canadian journal of electrical and computer engineering*, 2015; 38: 246 – 250.
[11] Sarker MR, Mohamed A, Mohamed R. A New Method for a Piezoelectric Energy Harvesting System Using a Backtracking Search Algorithm-Based PI Voltage Controller. *Micromachines.* 2016; 7:1-16.
[12] Tang G. Liu J.Q, Yang B, Liu, HS, Li YG, Yang CS, Dao V.D, Tanaka K, Sugiyama S. *Piezoelectric MEMS low-level vibration energy harvester with PMN-PT single crystal cantilever. IET Journals & Magazines*. 2012;. 48: 784–786.
[13] Mohamed R, Sarker MR, Mohamed A. An optimization of rectangular shape piezoelectric energy harvesting cantilever beam for micro devices. *International Journal of Applied Electromagnetics and Mechanics*. 2016; 50: 537-548.
[14] Wang Y, Luo C, Li P. Linear multi-degree-of-freedom low-frequency piezoelectric vibration energy harvester. *Ferroelectrics*. 2016; 502: 57-68.
[15] Sarker MR, Mohamed A, Mohamed R. Performance evaluation modeling a Microelectromechanical system based Finite Element piezoelectric Shear Actuated Beam. *Przegląd elektrotechniczny.* 2015; 91(3): 5-8.
[16] Roundy S, Wright PK, Rabaey J. A study of low level vibrations as a power source for wireless sensor nodes. *Computer Communications.* 2003; 26(11): 1131–1144.
[17] Aziz M, Mounir A, El MEN, Imad EZ. Performance evaluation of energy-efficient clustering algorithms in wireless sensor networks. 2015; 83(2): 187- 194.
[18] Hu Y, Hu T, Jiang Q. On the interaction between the harvesting structure and the storage circuit of a piezoelectric energy harvester. *International Journal of Applied Electromagnetics and Mechanics.* 2008; 27(4): 297-309.
[19] Choi WJ, Jeon Y, Jeong JH, Sood R, Kim SG. Energy harvesting MEMS device based on thin film piezoelectric cantilevers. *Journal of Electroceramics*. 2006; 17(2–4): 543–548.
[20] Lee BS, Wu WJ, Shih W P, Vasic D, Costa F. Power harvesting using piezoelectric MEMS generator with interdigital electrodes," in *Proceedings of the IEEE Ultrasonics Symposium (IUS '07).* 2007; 1598–1601, New York, NY, USA, October 2007.
[21] Liu JQ, Fang HB, Xu ZY. A MEMS-based piezoelectric power generator array for vibration energy harvesting. *Microelectronics Journal*, 2008; 39(5): 802–806.
[22] Jun K., Kenji U, Shoichiro N. Dielectric and Piezoelectric Properties of 0.91Pb(Zn1/3Nb2/3)O3-0.09PbTiO3 Single Crystals. *Japanese Journal of Applied Physics,* 1982, 21:1298-1302.
[23] Park SE, Shrout TR. Ultrahigh strain and piezoelectric behavior in relaxor based ferroelectric single crystals. *Journal of Applied Physics*, 1997,82(7): 1804-1811.