

Energy Harvesting from Piezoelectric Cantilever Beam with Different Shapes

R Amna, M R Sarker, R Mohamed

Abstract: This paper reviews the piezoelectric energy harvesting from mechanical vibration. The recent development in the microelectronic devices and wireless sensor networks (WSNs) requires continuous power source for better performance. Many researchers have been done to develop a permanent portable power source for microelectronic devices. Micro energy harvesting (MEH) consists of two basic elements; freely available energy and transducer. Energy is everywhere around us in different forms. The energy conversion ability of piezoelectric energy harvester is high among different MEH techniques. A cantilever type piezoelectric energy harvester under different shapes is mostly studied in the last few years. The output of piezoelectric harvester depends upon the deflection produced, more deflection led to more electrical output. The deflection in cantilever beam under different shapes is different. This review paper presents a comparison of different piezoelectric cantilever beam shapes and output generated analyzed in the last decade.

Key Words: Piezoelectric cantilever beam, micro energy harvesting, resonant frequency.

I. INTRODUCTION

Energy harvesting (EH) is the process of capturing energy on micro scale from the sources freely available in our surroundings, transform them and store them for later use [1][2][3][4]. EH is also known as energy scavenging or power harvesting. With the recent developments in wireless sensor networks (WSNs) and micro electromechanical systems, EH got so much attention and considered as best replacement of conventional batteries[5][6][7]. These devices use the batteries as their power sources and their performance is limited due to the problems associated with batteries e.g. life time and periodic maintenance of the batteries[8][9][10]. The recharging and replacement of these batteries is a big problem when the devices are installed in remote locations.

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R Amna*, Centre for Intergrated Systems Engineering and Advanced Technologies (INTEGRA), Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia (UKM), 43600, Bangi, Malaysia

M R Sarker, Centre for Intergrated Systems Engineering and Advanced Technologies (INTEGRA), Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia (UKM), 43600, Bangi, Malaysia

R Mohamed, Centre for Intergrated Systems Engineering and Advanced Technologies (INTEGRA), Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia (UKM), 43600, Bangi, Malaysia

© The Authors. Published by Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP). This is an <u>open access</u> article under the CC-BY-NC-ND license <u>http://creativecommons.org/licenses/by-nc-nd/4.0/</u> Many researches have been done to overcome this problem and design an independent power source with life time more than conventional batteries.

From ancient times humans have been using EH in the forms of watermills, windmills etc. Nowaday's renewable energy got so much attention and considered to be the future of the power source due to the decay of fossil fuels and nuclear power instabilities [11][12][13]. The renewable energy power plants generating capacity is in the range of kW to mW, it is known as macro energy harvesting (MEH) technology[14][15][16]. On the flip side, a MEH technology utilizes free form of energy from our surroundings and their generating capacity is in the range of μ w to mw[17][18][19].

This MEH is the best alternative of batteries. For vibrational EH three mechanisms are available: electromagnetic, electrostatic and piezoelectric [20][21][22]. Piezoelectric EH is considered as independent power source for wireless sensor network systems due to their high capability of converting mechanical vibration into electrical energy with a very simple harvester structure [23]. Piezoelectric micro electromechanical systems (MEMS devices) present the advantages of (i) High energy density of piezoelectric material even the film thickness is reduced (ii) low power requirement of piezoelectric actuators (iii) capable of interfacing of electrical and mechanical components (iv) higher frequency and temperature stability of resonant devices[24][25][26].

In the middle of eighteen century two scientists, Carlous Linnaeus and Franz Aepinus first observed the special properties of some materials. The authors found that crystals and some ceramics generate electric charges as a reaction of temperature change. Piezoelectricity as a research field of crystal physics was first studied by two famous brothers Jacqus Curies(1856-1941) and Pieree Curie (1859-1906)[27]. It was also observed that the unusual behavior of some crystalline minerals like quartz, tourmaline, topaz, rochelle salt and cane sugar. Jacqus Curies and Pieree Curie found that voltages generated by the application of tension and compression opposite in polarities and directly proportional to the applied load. This was called piezoelectric effect by Hankel[28]. The piezoelectricity comes from the Greek word "Piezo" means pressure.

II. PIEZOELECTRIC PHENOMENON

Piezoelectric materials (PMs) are classified (according to existence) into two classes: natural and man-made. The natural PMs are crystalline materials like Tourmaline (group minerals), Rochelle salt , Topaz and some organic substances like silk, wood bone, rubber etc[29][30]. Fig. 1 shows the atomic structure of Silicon Dioxide (SiO2) which

is built of oxygen atoms around a silicon atom.



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Fig. 1 Silicon Dioxide atomic structure

The distance between oxygen atoms and silicon atom is same. When stress is applied, the position of the atoms is changed and Polarization is caused as a result of net dipole movement and electricity is produced.

The man-made PMs are quartz analogs, polymers, ceramics and composites. There are 32 crystal classes divided into seven groups:

- Triclinic
- Monoclinic
- Orthorhombic
- Tetragonal
- Trigonal
- Hexagonal
- Cubic

Only 20 out of 32 classes allow piezoelectric effect. In
these 20 classes, 10 are polar and the remaining 10 are non-
polar. PMs are capable of transforming applied mechanical
force into electrical energy and this property is exhibit by
special type of materials like barium titanate, Rochelle salt,
quarts and tourmaline. The generation of electricity in these
materials is known as piezoelectric effect. Diversely, by the
application of electric field these crystals deforms
[31][32][33]. This effect is known as inverse piezoelectric
effect as shown in Fig 2 and Fig 3. The application of
piezoelectric effect is in sensors and transducers whereas
inverse piezoelectric effect is used in actuators. The
electromechanical behavior of the PMs can be expressed by
two linearized equations given below.

$$D_i = \boldsymbol{\varrho}_{ij}^{\sigma} \boldsymbol{E}_j + \boldsymbol{d}_{im}^{d} \boldsymbol{\sigma}_m \tag{1}$$

$$\varepsilon_k = d_{ik}^c E_j + S_{km}^E \sigma_m \tag{2}$$

Where D_i is represents dielectric displacement in N/m V or C/m^2 , \mathcal{E}_k is the strain vector, E_i is applied electric field in volts/meter, σ_m is stress in N/m², d_{im} , d_{jk} is piezoelectric constants in m/V or C/N, e_{ij}^{σ} is dielectric permittivity inN/V² or F/m, S_{Km}^{E} is Elastic compliance matrix in m²/N, C is inverse piezoelectric effect, d is piezoelectric effect, σ is quality measured at constant stress and E is quality measured at constant electric field.

Coefficients	PZT-5H	PZT-8	PVDF
d ₃₁	-274*10 ⁻¹² m/V	-97	18-24
d ₃₂	-274*10 ⁻¹² m/V	-97	2.5-3
d ₃₃	593*10 ⁻¹² m/V	225	-33
d ₁₅	$741*10^{-12}$ m/V	330	
Relative permittivity e ₃₃	3400	1000	
Free strain range	-250 to +850	με	
Poling field dc	12kV/cm	5.5	
Depoling field ac	7kV/cm	15	
Curie Temperature	193 [°] C	300	
Dielectric Break down	20Kv/cm		
Density	7500kg/m ³	7600	
Open circuit stiffness E ₁₁	62GPa	87	
Open circuit stiffness E ₃₃	48GPa	74	
Compressive strength(static)	>517MPa	>517	
Compressive depoling limit	30MPa	150	
Tensile strength (static)	75.8	75.8	
Tensile strength (dynamic)	27.6MPa	34.5	

Table. 1	Piezoelectric	characteristic	[26]
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Fig. 3 Piezoelectric Effect in cylindrical body of piezo ceramic(a)No load (b) compressed (c) stretched (d)shorten(e) Lengthen (f) grown or shrink [34]

On the base of their performance PMs are divided into two categories: piezo ceramics and piezo polymers. Piezo ceramics have large energy conversion rate and electromechanical coupling constant but they are too brittle to be used in different shapes. On the other hand the coupling constant of piezo polymers has smaller value but it has the advantage of being flexible and could be used in any shape easily. Fig 4 shows comparison of energy density for 3 types of vibrational energy harvesting techniques. Table 1 shows a comparison between the characteristics of piezo ceramics and piezo polymers. Many researches have been done to analyze the EH from mechanical vibration [35][36][37].



Fig. 4 Comparison of energy density for 3 types of vibrational energy harvesting techniques.

In this section different types of vibration devices, single crystals piezoelectric materials and mathematical modeling of piezoceramic vibrational energy harvesters is reviewed.

Retrieval Number: D5116118419/2019©BEIESP DOI:10.35940/ijrte.D5116.118419 Journal Website: <u>www.ijrte.org</u> In[38] the study is presented review of piezoelectric low profile transducers. According to her theoretical calculations, the energy density of electromagnetic and electrostatic devices is 3-5 times less than the piezoelectric EH devices (fig.4). In [39] the study proposed the piezoelectric EH from shoes which can broadcast digital radio frequency identification (RFID).

III. PIEZOELECTRIC CANTILEVER BEAM

The piezoelectric energy harvester is customarily used in cantilever form with one end fixed and other end free to move [40][41]. The cantilever structures have the advantages of (i) generating larger strain (ii) ease of fabrication (iii) lower fundamental frequencies to match with mechanical sources [42]. The quality factor of piezoelectric beam is high and the operating frequency of the piezoelectric cantilever is relatively low. Generally piezoelectric cantilever is not able to produce high voltage at small frequency range. The piezoelectric cantilever generates small amount of energy when the frequency of vibration of the beam is far from its natural frequency. The small amount of energy is insufficient to energize low powered electronic devices. So the resonance frequency needs to be tuned and characterized to match the frequency of vibration. After tuning, piezoelectric cantilever beam generates optimum energy [43].

The piezoelectric cantilever harvester consists of piezoelectric ceramic, elastic body and a proof mass. This structure produces large deformation and hence collects electric output from piezoelectric element. Harvesting energy from piezoelectric cantilever structure with proof mass requires careful selection of beam characteristics i.e. shape length, height and thickness to achieve desired output voltage level. The output of piezoelectric energy harvesting system (PEHS) is sensitive to these beam characteristics [44].

One disadvantage of the piezoelectric cantilever beam structure is its gradient strain distribution i.e. piezoelectric element is not fully utilized. To overcome this problem, PEHS under different shapes is designed and analyzed [32, 33]. Mostly the performance of piezoelectric harvester is compared in terms of their power density (output power per harvester volume, Wcm⁻³) which is measured at given acceleration and frequency of vibration. The power density values for piezoelectric EH are reported in the range of μ Wcm⁻³ to few mWcm⁻³[45].

It is proved practically that the geometry of the cantilever beam affects the harvested power directly. Different piezoelectric EH have been proposed and investigated to power up wireless devices. The conventional EH systems have many difficulties in practical application as there power efficiency is not stable. To overcome these problems the researchers proposed different improvements techniques such as multimodal system, self-tuning, frequency pumping, wide-band width transducers and mechanical tuning [46].



IV. RECTANGULAR BEAM

The cantilever beam is the most studied form of piezoelectric EH. The simplest shape of cantilever beam is rectangular that is frequently studied and analyzed as shown in Fig 5[47]. The harvester consists of a piezo ceramic with elastic body and proof mass. This simple form of piezoelectric EH produces deflection to generate noticeable electrical output. The performance of the harvester depends upon its length, area, mass etc. (physical parameters). These factors can be optimized to get maximum electrical output.



Fig. 5 Piezoelectric Cantilever Beam [47]

The series of experiments are performed with different beam aspect ratios and analyzed their power generation performance at constant acceleration and frequency of vibration and found that the output power density of the harvester is enhanced when beam shape is closed to square with constant bending stiffness and beam area. The values of beam's volume was 0.89 cm³, 0.86 cm³, 1.19 cm³, 2.12 cm³, 0.58 cm³, 2.99 cm³ and the output power density observed values were 5.25mWcm⁻³, 10.71 mWcm⁻³, 13.47 mWcm⁻³, 12.87 mWcm⁻³, 7.92 mWcm⁻³ to 12.15 mWcm⁻³. It's clear from the observations that the maximum power density is 13.47 mWcm⁻³ at 1.19 cm³ volume of the beam, if the volume is further increased the output power density is reduced.

It was analyzed by [48] that the natural frequency of the two rectangular beams is 8.79Hz and 8.83Hz respectively, with peak voltages 42.6V and 57.0V and average power of 1.04mW and 1.99mW. The length of the beam was 100mm, width 40mm, thickness of the beam t_m , 0.5mm, thickness of each of the piezoelectric plates t_p ,0.5mm and mass of the block was 5g.

A rectangular piezoelectric EH designed and simulated and the results are shown below in table 2.

Table.	2 Selected	variable	parameters	and le	evels
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Length	2500µm
Width	500µm
Height	бμт
Proof mass	0.145mg
Resonant Frequency	485Hz
d ₃₁ V _{out}	2.1V
d 33 Vout	8.5V

V. TRIANGULAR BEAM

The study proved that the cantilever geometrical structure plays vital rule in the design of an EH with greater

Retrieval Number: D5116118419/2019©BEIESP DOI:10.35940/ijrte.D5116.118419 Journal Website: <u>www.ijrte.org</u> efficiency and the triangular tapered cantilever beam has been found to be most favorable design than rectangular. Because this shape achieves high output power compared to rectangular beam with width and length equal to the base and height of corresponding triangular cantilever beam with high constant strain. On the basis experimental results it is believed that the triangular beam produces output almost double than a rectangular beam [49]. Fig 6 shows triangular shape piezoelectric beam.



Fig. 6 Triangular Piezoelectric Beam [20]

Table. 3 Comparison of power density amongRectangular and Triangular beams [50]

	Rectangular shape	Triangular shape
Volume of Piezoelectric	113.41	61.30
Material(mm ³)		
Volume		
density	1.99	4.49
$(\mu W/mm^3)$		

On the basis of analytic comparison between rectangular and triangular cantilevers (the stress across the width of the cantilever assumed to be uniform) divulge that a triangular cantilever with the same beam volume as compared to a rectangular beam has a large deflection and a higher average strain for a given load.

VI. TRAPEZOIDAL BEAM

Power density of a beam can be enhanced by the application of smaller volumes and the strain distribution is more evenly in trapezoidal cantilever beam which generates the output power two times greater than a rectangular beam for a given volume. The output of trapezoidal cantilever beam can be increased by reducing the resonant frequency of the beam [51]. Fig 7 shows trapezoidal shape piezoelectric beam.



Fig. 7 Trapezoidal Piezoelectric energy harvester [51]



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VII. T-SHAPED

A harvester is designed for a specific acceleration of vibration and resonant frequency to optimize the harvested power. One of the important parameter in the design of EH is stress in the device. The maximum stress in the rectangular beam is located near clamped end. The stress and the acceleration are inversely proportional; when the stress in the device is reduced it can vibrate with greater acceleration of vibration. To reduce the stress the beam should be widened at the clamping and it spread the stress. Because widening the beam at the clamping increases the resonant frequency. Fig 8 shows T-shape piezoelectric beam[52].

The structural T-shaped piezoelectric EH beam was analyzed and made observations are listed in the table 4 [52]. It's suitable and no proof mass was used and lower resonant frequency was achieved.

Table. 4 Structural properties of T-Shaped piezoelectric beam

Beam volume	24.566*10 ⁻³ cm ³
Vibrational source	0.5g acceleration
Resonant frequency	229.25Hz
Free end displaced	2.77mm
Free end displaced with Velocity	3.29m/sec
Max. stress near fixed end	$2.39*10^8$ N/m ²



Fig. 8 T-Shaped Piezoelectric Harvester

VIII. CONCLUSIONS AND OUTLOOK

In this paper piezoelectric EH technology from mechanical vibration was reviewed and piezoelectric cantilever beam under different shapes was investigated. The vibrational EH technology is considered as permanent and reliable source of power for microelectronic devices and WSNs. The triangular configuration as compared to rectangular one is capable of higher strain and higher power generation. Also it is found that the trapezoidal configuration evenly distributes the strain and increases the efficiency of the harvester. On the basis of observations it is seen that the Trapezoidal beam produces 30% more energy than Rectangular beam.

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