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# Considering Factors in Fabricating MEMS Vibration Energy Harvester as an Alternative Energy for Wireless Sensor

[1,2,3]A.W. Khairul Adly, [1]M.S. Ali Yeon, [2]W. Yufridin, [2]M. Mazlee

[1]*Center of Excellence for Advance Sensor Technology, Universiti Malaysia Perlis, 01000 Jejawi, Perlis, Malaysia.*
[2]*Advanced MEMS Based Integrated Electronics NCER Centre of Excellence, School of Microelectronic, Universiti Malaysia Perlis, 02000 Kuala Perlis, Perlis, Malaysia.*
[3]*Mechanical Engineering Department, Politeknik Sultan Abdul Halim Mu'adzam Shah, 06000 Jitra, Kedah, Malaysia.*

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**ABSTRACT**

The growth of interest using wireless device for monitoring, sensing and tracking has increasing such as in detecting formation of crack on aircraft, controlling temperature and light in the energy efficient building or in manufacturing process equipment. Currently, wireless sensor device use battery that has to replace periodically. Large increase in the number of wireless device (node) use in the wireless network or node placed in the area, which is difficult to access, is not favorable for battery replacement. It is advantageous for a device to be capable of extracting energy from the environment, making them self-powered, self-sustaining and lowering overall cost of the wireless network. This paper discussing on the factors to consider in designing proper MEMS Vibration Energy Harvester (MVEH) by using piezoelectric cantilever based design toward powering battery less Wireless Sensor Network (WSN) node.



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## INTRODUCTION

The widespread of interest of world community has arises recently in using Wireless Sensor Network (WSN) technology. This technology has been used as means for activity of sensing, monitoring and tracking in various application such as in environment monitoring (e.g. air, temperature and water quality control in smart building), in conditional monitoring (e.g. formation of crack in bridges and airplanes or in industrial equipment), in health monitoring of human body and also in robotic exploration (Akyildiz IF, *et al.*, 2002; M. Marzenki, *et al.*, 2005). The interest in using WSN technology is due to low power consumption in current sensor nodes, which manages to consume between µW and mW power level cause by the advance in VLSI design and CMOS fabrication (J.M. Rabaey, *et al*., 2000).

Typical WSN architecture technology consists of a numbers of sensor nodes scattered around in the monitored environment or structure and connected together with the control terminal. Each sensor node consists of wireless or RF communication module, microcontroller, memory, sensor, energy storage unit and also energy or power source (S. P. Beeby, *et al.*, 2006 ; M. Marzenki, *et al.*, 2005).

Over the year, the increase of the number of wireless sensor nodes used in network has create another problem regarding the electrochemical or dry battery which currently used by sensor node as energy source; problem in the replacement of the battery. The battery has limited energy and need to be replaced periodically. This problem is a major concern in the situation when it is involves huge number of sensor nodes in WSN or in the situation when the battery replacement requires special equipment or in the situation when the sensor nodes located in remote or difficult area to access.

Requirement to replace the battery has increase the operating cost and downtime of the WSN. In addition, the disposal of the unusable battery if not properly treated will cause the harmful effect to the environment and human health. The usage of the battery also will increase tremendously the overall size of the sensor node that tends to be bulky and heavy (H.A. Sodano, *et al.*, 2004).

In order to overcome this problem, the researchers venturing into the ideas of introducing the energy harvesting element as the energy source of the sensor nodes instead of battery. Energy harvesting or energy scavenging is the term used referring to the process of converting environment or ambient waste energy such as solar, thermal, wind and vibration into usable electrical energy by using suitable transduction mechanism (P.D.

**Corresponding Author:** A.W. Khairul Adly, Department of Mechanical Engineering, Politeknik Sultan Abdul Halim Mu'adzam Shah, 06000 Jitra, Kedah, Malaysia.
E-mail: geekeddy@yahoo.com

Mitcheson, *et al.*, 2004; R. Vullers, *et al.*, 2010; D. Shen, 2009; N.G. Stephen, 2006; S. Roundy, *et al.*, 2003; J.A. Paradiso, T. Starner, 2005).

Among those available energy sources, converting energy from vibration to the usable electric energy is the one of the popular choice among researcher in energy harvesting research (C.-N. Xu, *et al.*, 1998; P. Glynne-Jones, *et al.*, 2001; G.K. Ottman, *et al.*, 2002; C. Keawboonchuay, T.G. Engel, 2003; S. Roundy, P.K. Wright, 2004; C.D. Richards, *et al.*, 2004). The popularity of vibration is due to the availability of this kind of energy in almost everywhere from residential to industrial area (S. Roundy, *et al.*, 2003; S. Roundy, *et al.*, 2004). The attention of this paper is to list down factors which should be aware of by researchers who intend to venture in harvesting energy of vibration by using piezoelectric cantilever based Micro Electromechanical System (MEMS).

***2. Transducing Mechanism:***

Converting vibration into electric energy can be done by using several transducing mechanisms, which are either piezolectric, electrostatic, electromagnetic or magnetoelectric (S. P. Beeby, *et al.*, 2006; Jin Yang, *et al.*, 2011). There are a lot of research has been done regarding piezoelectric as transducing mechanism (C. B. Williams and R. B. Yates, 1996; R. K. Sood, 2003; S.Roundy, *et al.*, 2005; Y. C. Shu, I.C. Lien, 2006; H. B. Fang, *et al.*, 2006; R. X. Gao, Y. Cui, 2005; S.M. Shahruz, *2006;* M. Ferrari, *et al.*, 2008; *J. Q. Liu, et al.*, 2008; H.A.Sodano, *et al.*, 2004; S.M.Shahruz, 2008; E.Lefeuvre, *et al.*, 2006; H.A. Sodano, *et al.*, 2005; G.A.Lesieutre, *et al.*, 2004). This is due to piezoelectric has three criteria which attractive to be used as transducing mechanism.

Firstly, piezoelectric has high level of energy or power density which means that for any given size or volume, its can produce high ratio of energy level over size. High value in electromechanical coupling properties of the piezoelectric has result in high-energy conversion from vibration to electricity. Secondly, the ability to directly converting strain induced to the electricity without requires any external voltage introduce the simplification of the structure and the flexibility in dimensioning. Thirdly, the easy fabrication of piezoelectric with the current MEMS technology is an attractive feature to be integrating in the sensor node that has very limited volume in size (S. Roundy, *et al.*, 2003; S.Roundy, *et al.*, 2005; M. Renaud, *et al.*, 2008; Y.C. Shu, I.C. Lien, 2006; S. Saadon and O. Sidek, 2011; D.F. Berdy, *et al.*, 2009

***3. Transducing Material:***

One of the popular material uses in the MEMS vibration energy harvester (MVEH) is the $Pb(Zr,Ti)O_3$ or Lead Zirconate Titanate (PZT). PZT has high coupling coefficient for higher potential for energy conversion from mechanical to electrical energy (S. Roundy, *et al., 2004*). However, PZT is a lead based material, which is harmful to the environment and human health. Besides, fabrication of MVEH requires extra safety measurement due to poisonous properties and needs special poling treatment that leads to extra manufacturing cost (F. Stoppel, *et al.*, 2011; Isaku Kanno, *et al.*, 2012; Seung-Hyun Kim, *et al.*, 2012; Robert Andosca, *et al.*, 2012).

There are several lead free piezoelectric materials available for MVEH as shown in Table 1 (except sol gel PZT). R. Andosca *et al*. (Robert Andosca, *et al.*, 2012) demonstrates that higher value in voltage material coefficient and power material coefficient are factors to consider in the selection of MVEH material, which are Aluminium Nitrate (AlN), and Zinc Oxide (ZnO) as in Table 1. Other material, such as sodium potassium niobate [$(K,Na)NbO_3$, KNN] based ceramics (Isaku Kanno, *et al.*, 2012) and sodium potassium niobate tantalate $(Na,K)(Nb,Ta)O_3$ (NKNT) (Seung-Hyun Kim, *et al.*, 2012) are also possible alternative toward lead free MVEH.

Other important properties to consider in the selection of transducing material are dielectric constant and Young's modulus or elastic modulus. High dielectric constant is important for lowering impedance to avoid high voltage and low current output while Young's modulus affecting the stiffness of the material although the stiffness can be designate by altering the dimension (S. Roundy, *et al., 2004*). High Young's modulus also means the material will capable to strain more before its break.

***4. Design Configuration:***

There are few common designs for vibration energy harvesting using piezoelectric material which are in form of straight cantilever (Y.C. Shu and I.C. Lien, 2006; S. Saadon, O. Sidek , 2011; D.F. Berdy, *et al.*, 2009; F. Stoppel, *et al.*, 2011; Isaku Kanno, *et al.*, 2012; Seung-Hyun Kim, *et al.*, 2012; Robert Andosca, *et al.*, 2012; Ioan Alexandru Ivan, *et al.*, 2012), meandered cantilever (D.F. Berdy, *et al.*, 2012; Huicong Liu, *et al.*, 2012), simply supported (M. OuledChtiba, *et al.*, 2010), corrugated (R.L. Harne, 2012), wire based (B. Kumar and S. W. Kim, 2012; G. Murillo, *et al.*, 2011; X. Wang , 2012; C. Falconi, *et al.*, 2012), wall based (C. Falconi, *et al.*, 2012), fiber based (J. Chang, *et al.*, 2012), helically curved (K. Monri and S. Maruo, *2012*), shell (B. Yang and K. S. Yun, 2012) and diaphragm ( I. Kuehne, *et al.*, 2008; X. R. Chen, *et al.*, 2012, Z. Shen, *et al.*, 2013).

The interest of using MVEH for WSN is more on cantilever design configuration due to the abundance availability of low-level vibration in the environment and easy integration with the MEMS fabrication. This design can achieve relatively low resonance frequency and relatively high average strain for a given force input (S.Roundy, *et al*., 2005). This means that for low-level vibration input, which is ubiquitous in the environment, the cantilever design can produce large power output.

### *5. Nanomaterial:*

Toward implementing MEMS fabrication in MVEH, the piezoelectric material should be in form of film, nanowire, nanowall or nanofiber. Film and nanofiber piezoelectric nanomaterial need a structure as support (substrate such as silicon, SUS etc.) while others type of nanomaterial can be stand alone without requires any structure to operate but requires some kind of contact to pick up the energy generated such as AFM tip and zig zag electrode (X. Wang, 2012).

Among the nanomaterials type currently available, film form nanomaterial is usually associated with the cantilever design configuration in MVEH (R. Xu, *et al.*, 2012; Isaku Kanno, *et al.*, 2012; S. H. Kim, *et al.*, 2012, M. Baù, *et al.*, 2011; Y. Wakasa, *et al*., 2011; H. Liu, *et al.* , 2010; T. Zawada, *et al.*, 2010; P. Wang, *et al*. 2012; T. Suzuki, *et al.*, 2006; I. Kanno, *et al.*, 2003; E. Cattan, *et al.*, 1999). One of the reasons is that the combination of cantilever design with the piezoelectric film nanomaterial provides simplicity in preparation and fabrication of the MVEH.

There are two types of film that are thin film and thick film. Thin film as name suggests has a thickness less than ten of micrometer while the thick film can be several ten up to hundred micrometers. Among those two, MVEH is more suitable to use thick film due to the lack of optimal thickness offered by thin film and filling the gap of performance as offered by bulk piezoelectric material (S.-H. Kim, *et al*., 2011; T. Zawada, *et al.*, 2010).

The film can be deposit on the substrate by using a few deposition methods such as screen printing, sol-gel spin on, sputtering and chemical vapor deposition (CVD). Screen printing technique is one of the most associated deposition methods for thick film due the ability to deposit the thick film at low cost, cover wide area, simple and flexible (T.H. Shin, *et al.*, 2013; R. Xu, *et al*., 2012; M. Baù, *et al*., 2011; S. H. Kim, *et al*., 2011; T. Zawada, *et al.*, 2010; C.G. Hindrichsen, *et al*., 2010; K. Yao, *et al.*, 2005). However, using screen-printing alone tends to produce low-density film, which due to availability of a lot pores. This problem can be treated by pressure (T.H. Shin, *et al.*, 2013; T. Zawada, *et al.*, 2010; C.G. Hindrichsen, *et al*., 2010), chemical solution infiltration (S. H. Kim, *et al*., 2011) or by heat treatment (K. Yao, *et al.*, 2005)

**Table 1:** List of piezoelectric material (Robert Andosca, *et al*., 2012).

| Material | Piezoelectric coupling coefficient $d_{31}$ ( pC/N) | Young's modulus $E_p$ (GPa) | Dielectric constant $K_p$ | Density ρ (g/cc) | Voltage material coefficients* $\lvert(d_{31}(E_p)^{3/4}/K_p)\ \rho^{1/4}\rvert$ | Power material coefficients** $[(d_{31}^2(E_p)^{3/2}/K_p^2)\rho^{1/2}]$ |
|---|---|---|---|---|---|---|
| Sol–gel lead zirconate titanate (sol–gel PZT) | -44 | 100 | 1700 | 7.55 | 1.00 | 1.00 |
| Single crystal barium titanate (BaTiO3) | -34.5 | 67 | 10000 | 6.02 | 0.09 | 0.01 |
| Polyvinylidene fluoride (PVDF) | 20 | 3 | 12 | 1.78 | 1.85 | 3.41 |
| Lithium niobate (LiNbO3) | -1 | 181.6 | 29 | 4.644 | 3.23 | 10.46 |
| Aluminum nitride (AlN) | -2 | 340 | 9 | 3.26 | 17.43 | 303.68 |
| Zinc oxide (ZnO) | -5.43 | 124 | 10.5 | 5.68 | 21.87 | 478.13 |

* Normalized to PZT.
** 1st order approximation.

The sol-gel spin on (H. B. Fang, *et al*., 2006; Seung-Hyun Kim, *et al.*, 2012; M. A. Dubois and P. Muralt, 1999; D. J. Kim, *et al.*, 2008) and sputtering (E. Iborra, *et al.*, 2004; K. Kano, *et al.*, 2006) are mostly associated with the thin film, although the introduction of the hybrid technique can be used to modify this technique to produce thick film instead of thin film as demonstrate by Zhong-xia Duan, *et al*. (2011), Z. Wang, *et al*., (2007) and S.A. Rocks, *et al*. (2009) .

### *6. Band Of Frequency:*

A good MVEH is capable to produce steady supply of required energy to the load or wireless sensor and able to operate in the wide frequency range. The challenge to achieve that is due to a using of single structure of MVEH for example a single cantilever based MVEH which only capable to produce enough energy as required by load within narrow frequency range only which is unpractical to commercialize. The reason is that each structure only vibrates in the maximum amplitude that gives maximum energy when its vibrating frequency is same as the vibration in the ambient (resonant frequency) but the environment has non-periodic value of vibration, which has different value in frequency and amplitude in different area.

A few researcher has propose different techniques to address the problem regarding cantilever based MVEH. The techniques such as multi array of cantilever sorting in parallel (M. Ferrari, *et al*., 2008; J. Q. Liu, *et al*., 2008), two-layered cantilever which has different thickness in each layer (S. J. Jeong, *et al.*, 2008), bistability by using ferromagnetic substrate cantilever placed in front of permanent magnet (M. Ferrari, *et al*., 2011), folding of piezoelectric cantilever equally to smaller width for reducing mechanical damping and frequency up conversion (FUC) .

FUC is a method, which uses low resonant frequency cantilever (LRF) to initiate the deflection of high resonant frequency (HRF) cantilever that can be either double cantilever beam combination (Huicong Liu, *et al.*, 2011*;* Huicong Liu, *et al.*, 2012) as illustrate in Fig. 1 or triple cantilever beam combination (M. Ferrari, *et al.*, 2012).

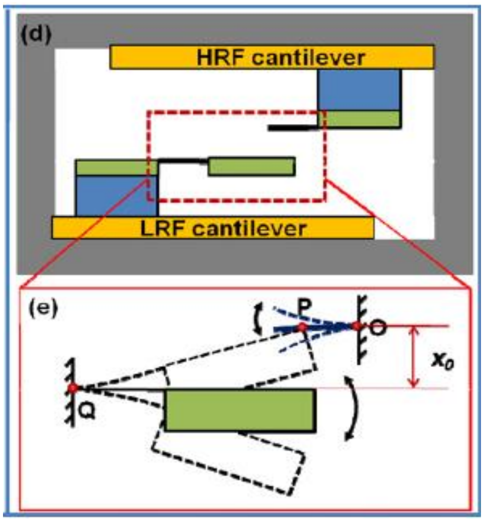


**Fig. 1:** Arrangement and illustration of behavior of FUC (Huicong Liu, *et al.*, 2011).

### *7. Mode Of Operation:*

Generally MVEH used in two different modes that are 33 mode and 31 mode. Direction is identified by using three axes, labeled 1, 2 and 3 as shown in Fig. 2. The polar or 3-axis is chosen parallel to the direction of polarization. In term application of the cantilever based MVEH, 33 mode meaning that both the voltage and strain act in the 3 direction while in 31 mode meaning that the voltage act in the 3 direction and strain act in the direction 1.

Electromechanical coupling in 33 mode is higher compare to 31 mode. However, MVEH is more favorable to be operated in 31 mode as its can produce larger strain for smaller input forces and low resonant frequency (S. Roundy, *et al.*, 2004). L. Zhou *et al*. (L. Zhou, *et al.*, 2012) recently reported that by using MVEH in 15 mode or shear mode, electromechanical coupling produces by this mode is much higher compare to 31 or 33 mode and at the same time maintaining low resonant frequency.

### *8. Size Of Cantilever And Mass:*

Targeted range of frequency and overall size of MVEH required will determine the size of cantilever. The power output is inversely proportional to the frequency (S. Roundy, *et al.*, 2004). As the frequency of the system goes down, the displacement of the proof mass goes up. Lowering frequency of the design system means whether its design with longer beam, thinner beam, increase mass etc will increased overall displacement that accompanied by increase strain and produced larger power output. However, there is a limit of how much strain can be support by piezoelectric material before its fracture. The mass on the cantilever or proof mass used to change the resonant or fundamental frequency of the MVEH.

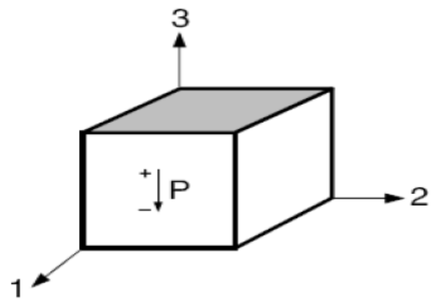


**Fig. 2:** Identified direction of axes 1, 2 and 3 (Piezosystems Inc., 1998).

***9. Shape Of Cantilever:***

Introduction of the triangular or trapezoidal profile rather than a rectangular profile in cantilever based MVEH result strain distribute more evenly which means maximum strain reach at every point in the cantilever. A trapezoidal geometry can supply more than twice energy per unit volume, reducing overall size and cost (S.Roundy, *et al*., 2005).

R.X. Gao *et al*. (2005) set up simplified static model to analyze energy extraction of two cantilever designs: triangular shaped beam and rectangular shaped beam. The triangular shaped beam features a constant stress distribution across its length, while the stress distribution for rectangular beam varies. Although structural different causing the natural frequency of the cantilever to shift, it can be adjusted by selecting different seismic mass. The triangular cantilever was able to extract over 40% more energy compared to the rectangular cantilever under same volumetric condition.

***10. Polarization Configuration:***

There are two standard polarization configurations for the bimorph (dual layer piezoelectric material) MVEH construction: either electrically connected in series or parallel. Unlike unimorph (single layer piezoelectric material), using piezoelectric with ferromagnetic based material such as PZT requires extra precaution during poling stage.

The bimorph MVEH for series operation is poled in the opposite direction, which requires two connections to the outside surfaces while bimorph MVEH for parallel operation is poled in the same direction. Series operation characterized by a lower capacitance, lower current and higher voltage as depicted in Fig. 3.As depicted in Fig. 4, the bimorph MVEH poled for parallel operation requires three electrical connections. The third connection accesses the center shim. Voltage is develops across the individual layers. The parallel operation is characterized by higher capacitance, higher current and lower voltage.

In parallel poling, current produce by each layer will add while in series poling, where layers are pole in opposite direction will add the voltage by each layer. In all cases, the potential for power conversion is same, it is only effect voltage to current ratio (S. Roundy, *et al.*, 2004).

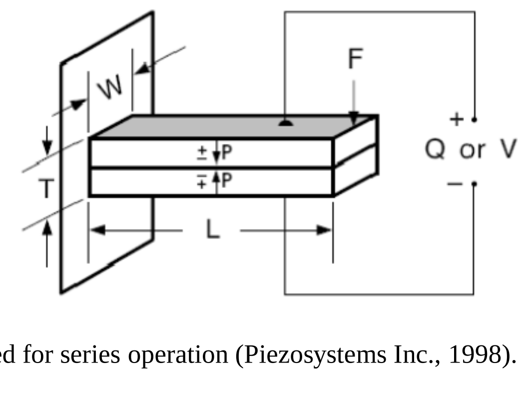


**Fig. 3:** Bimorph cantilever poled for series operation (Piezosystems Inc., 1998).

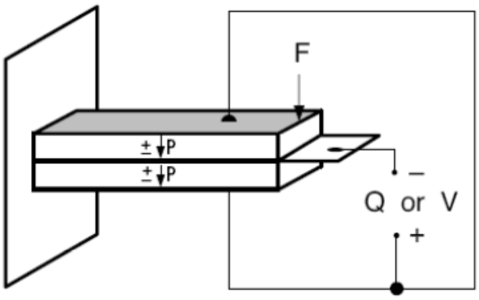


**Fig. 4:** Bimorph cantilever poled for parallel operation (Piezosystems Inc., 1998).

***Conclusion:***

The consideration factors for fabricating the MVEH have been discussed as listed in this paper by referring to recent development and experiment. The succesfull integration of the MVEH as vibration to electricity energy converter which capable to supply power will enable wireless sensor to be self-powered, self-sustaining and lowering overall cost of the wireless network which limitation for commercialization only on size required and cost involve in the design.

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