Fundamentals of Piezoelectric Energy Harvesting

Ashwani Kumar[1] Deepak Chhabra[2]
[1]P.G. Student [2]Assistant Professor
[1,2]Department of Mechanical Engineering
[1,2]University Institute of Engineering &Technology, Maharshi Dayanand University, Rohtak, Haryana, India

Abstract— The field of science and technology is focused and concentrating on a single word 'Energy'. All our advanced devices seems to be dealing with converting one type of energy into another one and providing the desired form of work. Energy is available everywhere in our surrounding in various forms (wind energy, solar energy, geothermal energy, vibrational energy etc). Main aim is to focus on extracting the energy from such sources which are available everywhere and never ending. Energy harvesting or energy scavenging from mechanical (vibrational) energy is a significant step in this direction. There are basically three vibrational energy harvesting techniques: piezoelectric, electrostatic and electromagnetic harvesters. This paper puts light on basics of piezoelectric energy harvesting which is one of the most efficient method of micro-mechanical energy harvesting.

Key words: Energy Harvesting, Piezoelectric Materials tabase

I. INTRODUCTION

In our world we are surrounded by a number of untapped energy sources like: electromagnetic fields, solar energy field, waste heat and thermal energy field, air field, sound, vibrational energy and even our body movements and motions all have the potential to be harvested in order to provide the power to wireless sensors and other portable electronic devices. Energy harvesting or energy scavenging or power harvesting can be defined as the process of collecting the minute amount of energy that would otherwise be lost and go waste as light, sound, heat, vibrations or movements, from one or more surrounding energy sources, accumulating and storing them for later use. Generally we use conventional batteries to power our electronic devices and wireless sensors but it is not reliable to use batteries due to their periodical recharging requirements and limited life span. So the researchers are entering into the field of energy harvesting in order to develop such technologies which can be used as self power source for portable devices and wireless sensor network system.

We have already used energy harvesting in the form of solar energy, watermill, windmill and the technologies based on long established principles such as the thermoelectric effects, photovoltaic and electro-dynamic. The renewable energy is that which came from the natural sources and is emerging as the future source of power due to limited quantity of fossil fuel and instability of nuclear power like Fukusima nuclear crisis. Dhingra et al.(2014) performed a significant analysis to improve the yield from Jatropha-based biodiesel (an alternative of fossil fuels) and optimized the energy harvesting process using design of experiment approach. Renewable energy harvesting plants generate energy at micro level within the range of kW or MW. Energy harvesting at micro level is based on mechanical vibrations, mechanical stress and strain, sun light or room light, human body, chemical or biological sources, thermal energy from various heat sources like furnace and frictional sources, which can generate power at mW or µW level for providing alternative of conventional battery. In this paper we reviewed the micro level energy harvesting from mechanical vibrations using piezoelectric materials.

In this paper we have covered some important issues to which we have to understand to become familiar with the field of vibrational energy harvesting. We will also cover energy harvesting techniques from different type of piezoelectric materials like: piezoceramica, piezopolymers and some other modified materials.

II. FUNDAMENTALS OF PIEZOELECTRICITY

Piezoelectric materials have received most attention due to their ability to directly convert the strain energy into electric energy and the ease with which they can be attached into a system. A piezoelectric material is one that can produce an electric charge when mechanical stress is applied on it, this is known as direct effect. On the other hand they undergo deformation when an electric field is applied, which is termed as converse effect. Direct effect can be used for sensor applications and inverse effect can be used for actuator applications. Piezoelectricity can be termed as pressure electricity and is a property of certain crystalline materials such as tourmaline, barium titanate, Rochelle salt, quartz, berlinite, topaz, sucrose etc. To produce piezoelectric effect piezocrystal is heated above curie temperature under the effect of strong electric field. Due to this dipoles inside the crystal get oriented in a proper fashion facing in the same direction. Energy conversion takes place due to local charge separation because when strain energy is applied, deformation of the dipole and formation of a charge takes place that can be removed from the material to power various devices. Once the material is poled an electric field can be applied across the surface of the material in order to induce expansion or contraction in the material. Potentially different magnitude of stress, strain can be produced in the piezo material by applying the electric field along its different surfaces. Hence to facilitate the ability to apply electric potential in three directions, piezoelectric properties must contain a sign convention. To under this in a simple way piezoelectric materials can be generalized into two cases, one is stack configuration which operates in the -33 mode and another is bender configuration which operates in -31 mode. Assumption of sign convention is that poling is always in "3" direction. In the -33 mode , electric field is applied in "3" direction and material is strained in poling or "3" direction. In -31 mode electric field is applied in "3" direction and material is strained in the "1" direction or perpendicular to the poling direction. Chopra (2002) explained the coupled electromechanical behavior of piezoelectric materials using following two linearized constitutive equations:

Direct piezoelectric effect:

$$D_i = e^{\sigma}_{ij} E_j + d^{d}_{im} \sigma_m$$

Converse piezoelectric effect:

$$\varepsilon_k = d^{c}_{jk} E_j + S^{E}_{km} \sigma_m$$

where vector D_i is the dielectric displacement in N/mV or C/m ^{2}, ε_k is the strain vector, E_j is the applied electric field vector in volts/meter, and σ_m is stress vector in N/m ^{2}.The piezoelectric constants are the piezoelectric coefficients d^{d}_{im} and d^{c}_{jk} in m/V or C/N, the dielectric permittivity e^{σ}_{ij} in N/V ^{2} or F/m, and S^{E}_{km} is the elastic compliance matrix in m ^{2} /N. The superscripts c and d refer to the converse and direct effects, respectively, and the superscript σ and E indicate that the quantity is measured at constant stress and constant electric field, respectively.

Piezoelectric materials can be broadly divided into two categories: piezoceramics and piezopolymers. Piezoceramics are too brittle in nature and have high electro-mechanical coupling constants, hence they are used as actuators. Piezoploymers are flexible in nature and have smaller electro-mechanical coupling constants, hence can be used as shape energy transducer. Figure (1) shows the general classification model of piezoelectric materials.

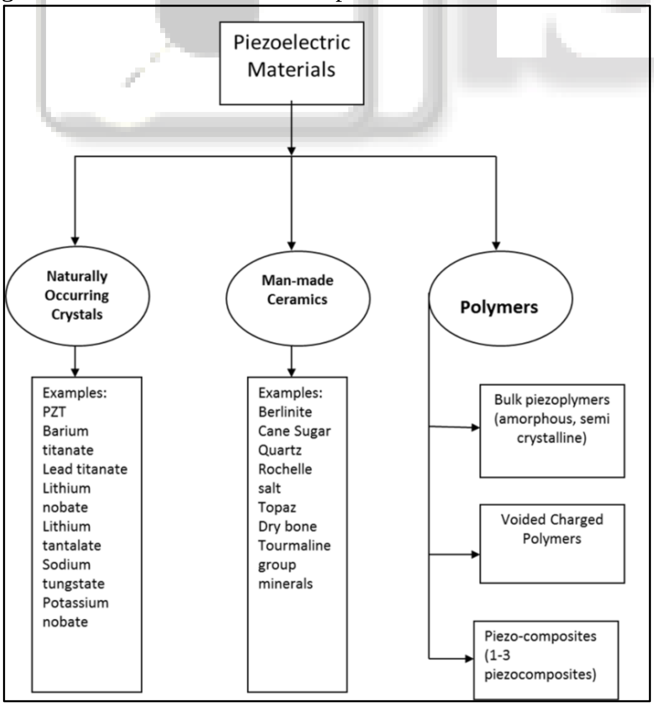

Fig. 1: Classification of Piezoelectric Materials

1.Naturally occurring crystals: Berlinite (AlPO4), Cane sugar, Quartz, Rochelle salt, Topaz, Tourmaline Group Minerals, and dry bone (apatite crystals). 2 Man-made ceramics: Barium titanate (BaTiO3), Lead titanate (PbTiO3), Lead zirconate titanate (Pb[ZrxTi1-x]O3 0<x<1) - More commonly known as PZT, Potassium niobate (KNbO3), Lithium niobate (LiNbO3), Lithium tantalate (LiTaO3), Sodium tungstate (NaxWO3). 3 Polymer: Polyvinyledene fluoride (PVDF).

Table 1 shows the general characteristics of some commonly studied piezoceramics (PZT-5H,PZT-8) and piezopolymers (PVDF).

Coefficients	PZT-5H 8	PZT-	PVD F
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	3400	1000	-
Free-strain range	-2500 to 850	$\mu \in$	-
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	-
Compressive strength(static)	〉 517MPa	〉 517MPa	-
Compressive depoling strength	30MPa	150	-
Tensile strength(static)	75.8	75.8	-
Tensile strength(dynamic)	27.6MPa	34.5	-

Table 1: Piezoelectric Characteristics, Chopra (2002)

Tanvi et al.(2010) proposed that piezoelectricity can be best alternative to power portable electronic devices than conventional batteries and explained the techniques of energy harvesting from piezoelectric windmill and increased bandwidth piezoelectric crystal. Figure (2) shows the utilization of direct effect for energy harvesting. Figure (3) shows the structure of piezoelectric component that can be used for energy harvesting.

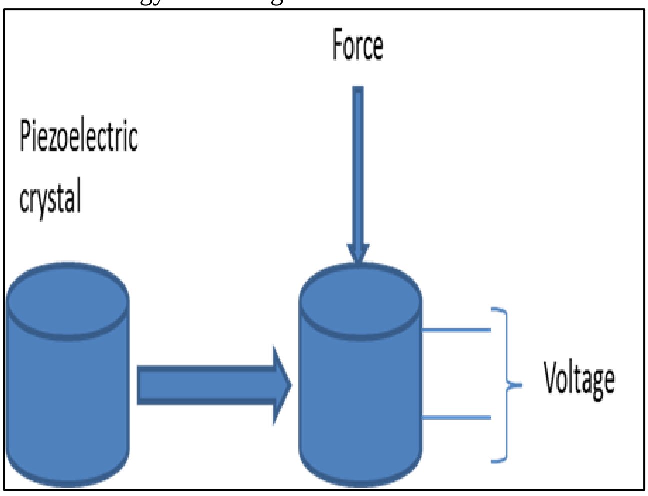

Fig. 2: Principle of direct piezoelectric effect Tanvi et al.(2010)

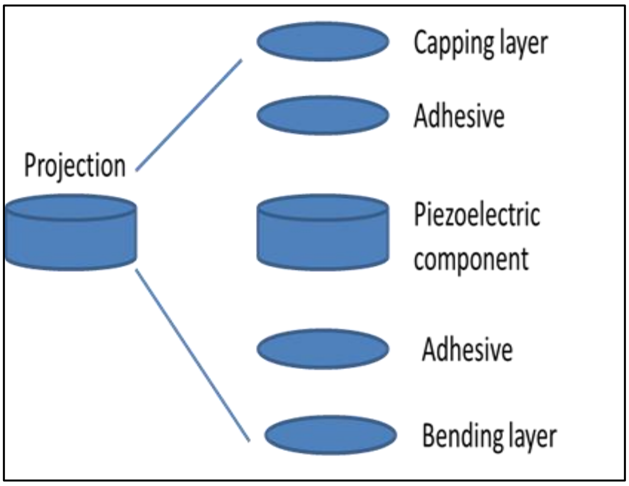

Fig. 3: Structure of piezoelectric componenet Tanvi et al.(2010)

III. ENERGY HARVESTING USING DIFFERENT PIEZOELECTRIC MATERIALS

As we know that piezoelectric materials can be broadly classified into two catogeries: piezoceramics and piezopolymers. Both have different kind of properties and hence their applications are also different in the area of energy harvesting. In this section we have reviewed the utilization of different piezoelectric materials in energy harvesting applications.

A. *Via Piezoceramics*

Kymissis et al.(1998) worked on the concept of harvesting the energy from the piezoelectric shoes of a walker and used the piezoceramic material strip and PVDF foil stave for the purpose. Shenck et al.(2001) used the flexible piezoelectric materials to harvest the energy from wearable shoe structure. Inman et al.(2008) performed the experiments to analyze the shunt damping performance and power generation capacities of single crystal piezoceramic lead magnesium niobate-lead zirconate titnate(PMN-PZT). Inman et al.(2011) proposed best design for light weight devices under low power applications after analyzing the different configurations of PZT-5H monolithic ceramics, single crystal PMN-PZT and polycrystalline PZT-5A in a unimorph cantilevered beam.

In brief we can say that piezoceramic are brittle in nature and less deformable, they can't bear heavy cyclic loads but the efficiency of energy harvesting can be improved through certain modifications. Usage of single crystal piezoelectric materials is a better option in the field of energy conversion because of their high coupling coefficients.

B. *Via Piezopolymers*

Mateu and Moll(2006) investigated the factors on which the choice of storage capacitor depends by inserting the piezo-films into shoes and providing them walking excitation. Granstrom et al.(2007) used the PVDF to generate energy from the forces exerted by the wearer on its backpack. Farinholt et al.(2009) examined the energy conversion capacities of PVDF and ionically conductive ionic polymer transducer. Cao et al.(2011) analyzed the PVDF energy transducer considering the effect of air damping on the vibrations of transducer and concluded that output power was almost twice in "unpackaged in vaccum" conditions than "packaged in air conditions". Lebrun et al.(2010) worked on carbon filled terpolymer and found that energy harvesting abilities of a composite filled with 1 vol% was much better than pure form.

In brief we can say that piezoplymers are more reliable for energy harvesting in real life applications because these are light in weight, ductile, deformable, shock bearer and flexible to take various shapes.

C. *Via Modified Materials*

Lee et al.(2011) studied strontium titanate $SrTiO_3$ (STO) added piezoceramic specimen prepared by tape casting and found it better than STO free specimen. Kamel et al.(2009) used aluminum nitride as piezoelectric material and obtained a maximum power output of 60μW at resonance frequency of 572Hz for an unpackaged device at an acceleration of 2.0g. Tien and Goo(2010) validated the energy harvesting capacity of a composite made up of PZT ceramic, carbon/epoxy, glass/epoxy by numerical and experimental validation. Briand et al.(2011) worked on energy harvesting devices made up of epitaxial PZT thin films and compared the experimental and analytical results and concluded that such energy harvester can be used to generate high electric power.

IV. CONCLUSIONS

A vibration energy harvester is an energy harvesting device that pairs off a certain transduction mechanism to ambient vibration and converts mechanical energy to electrical energy. Ambient vibration includes machinery vibration, human motion and flow induced vibration.

Piezoelectric energy harvesters have the like power density to the electromagnetic energy harvesters. They take in simple structures, which makes them easy to cook up. systems.

Piezoelectric energy harvesters have the capacity to directly convert strain energy into electrical energy without any necessity of additional voltage sources and can be incorporated into any microsystem without any size event and therefore best suited for human powered applications. They possess the ability to generate a high power density to power portable electronic devices.

In this manner we have compared three different vibrational energy harvesting techniques in different views. This work helps the architects and engineers to select a particular energy harvesting technique for a particular application under different constraints.

- Piezoelectric vibration energy harvesting technology is remarked as a permanent, environmentally friendly and durable power supply source for both portable electronic devices as easily as for recharging the batteries for charge reservation.
- We have studied piezoelectric harvester can directly convert the string into electrical energy without any demand of external voltage source and also suited for any size device configuration. In malice of these attributes, output voltage produced by these harvesters is quite less and even during cyclic loading conditions with chances of equipment failure are more.
- We can create the technology of piezoelectric energy harvesting more reliable and trustful by using more

flexible piezoelectric materials with high coupling coefficients and integrating them into efficient rectifiers and storage circuits.

References

[1] Adhikari, S., M. Friswell and D. Inman. 2009. Piezoelectric energy harvesting from broadband random vibrations. Smart Materials and Structures 18(11): 115005.

[2] Bruant, I., L. Gallimard and S. Nikoukar. 2010. Optimal piezoelectric actuator and sensor location for active vibration control, using genetic algorithm. Journal of sound and vibration 329(10): 1615-1635.

[3] Bruant, I., L. Gallimard and S. Nikoukar. 2011. Optimization of piezoelectric sensors location and number using a genetic algorithm. Mechanics of Advanced Materials and Structures 18(7): 469-475.

[4] Cao, Z., J. Zhang and H. Kuwano. 2011. Vibration Energy Harvesting Characterization of 1 cm2 Poly (vinylidene fluoride) Generators in Vacuum. Japanese Journal of Applied Physics 50(9).

[5] Chopra, I. 2002. Review of State of Art of Smart Structures and Integrated Systems. AIAA Journal 40(11): 2145-2187.

[6] Dhingra, P., J. Biswas and S. Sukanya. 2012. Energy Harvesting using Piezoelectric Materials. International conference on electronic design and signal processing(ICEDSP)(special issue of international journal of computer applications(0975-8887)).

[7] Dhingra, S., K. K. Dubey and G. Bhushan. 2014. Enhancement in Jatropha-based biodiesel yield by process optimisation using design of experiment approach. International Journal of Sustainable Energy 33(4): 842-853.

[8] Dikshit, T., D. Shrivastava, A. Gorey, A. Gupta, P. Parandkar and S. Katiyal. 2010. Energy harvesting via piezoelectricity. Bharati Vidyapeeth's Institute of Computer Applications and Management: 265.

[9] Erturk, A., O. Bilgen and D. J. Inman. 2008. Power generation and shunt damping performance of a single crystal lead magnesium niobate-lead zirconate titanate unimorph: Analysis and experiment. Applied Physics Letters 93(22): 224102.

[10] Elfrink, R., T. Kamel, M. Goedbloed, S. Matova, D. Hohlfeld, Y. Van Andel and R. Van Schaijk. 2009. Vibration energy harvesting with aluminum nitride-based piezoelectric devices. Journal of Micromechanics and Microengineering 19(9): 094005.

[11] Farinholt, K. M., N. A. Pedrazas, D. M. Schluneker, D. W. Burt and C. R. Farrar. 2009. An energy harvesting comparison of piezoelectric and ionically conductive polymers. Journal of Intelligent Material Systems and Structures 20(5): 633-642.

[12] Granstrom, J., J. Feenstra, H. A. Sodano and K. Farinholt. 2007. Energy harvesting from a backpack instrumented with piezoelectric shoulder straps. Smart Materials and Structures 16(5): 1810.

[13] Isarakorn, D., D. Briand, P. Janphuang, A. Sambri, S. Gariglio, J. Triscone, F. Guy, J. Reiner, C. Ahn and N. De Rooij. 2011. The realization and performance of vibration energy harvesting MEMS devices based on an epitaxial piezoelectric thin film. Smart Materials and Structures 20(2): 025015.

[14] Karami, M. A., O. Bilgen, D. J. Inman and M. I. Friswell. 2011. Experimental and analytical parametric study of single-crystal unimorph beams for vibration energy harvesting. Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on 58(7): 1508-1520.

[15] Kymissis, J., C. Kendall, J. Paradiso and N. Gershenfeld. 1998. Parasitic power harvesting in shoes. Wearable Computers, 1998. Digest of Papers. Second International Symposium on.

[16] Mateu, L. and F. Moll. 2006. Appropriate charge control of the storage capacitor in a piezoelectric energy harvesting device for discontinuous load operation. Sensors and Actuators A: Physical 132(1): 302-310.

[17] Shenck, N. S. and J. A. Paradiso. 2001. Energy scavenging with shoe-mounted piezoelectrics. Ieee Micro 21(3): 30-42.

[18] Sodano, H. A., D. J. Inman and G. Park. 2004. A review of power harvesting from vibration using piezoelectric materials. Shock and Vibration Digest 36(3): 197-206.

[19] Sodano, H. A., D. J. Inman and G. Park. 2005. Comparison of piezoelectric energy harvesting devices for recharging batteries. Journal of Intelligent Material Systems and Structures 16(10): 799-807.

[20] Sodano, H. A., D. J. Inman and G. Park. 2005. Generation and storage of electricity from power harvesting devices. Journal of Intelligent Material Systems and Structures 16(1): 67-75.

[21] Tien, C. M. T. and N. S. Goo. 2010. Use of a piezocomposite generating element in energy harvesting. Journal of Intelligent Material Systems and Structures: 1045389X10381658.