A REVIEW ON PIEZOELECTRIC MATERIALS AS A SOURCE OF GREEN ENERGY

[1]Adlinge P.N, [2]Patil R. M., [3]Nagane D.R., [4]Aradhye A.S.

[1.2.3] Student, [4].Asst. Prof

[1-4]Department of Mechanical Engineering,

[1-4]SKN, Sinhgad College of Engineering, Korti, Pandharpur, India

Abstract: Day by day need of energy has been increasing so energy harvesting has become need of hour and demand of different energy harvesting techniques has been the prime area of research. Out of different techniques, the main focus is on green energy harvesting, piezoelectric energy being pollution free can fulfill these energy requirements. Piezoelectric materials have ability of energy transition from mechanical vibrations. The undesired mechanical vibrations can be utilized by the piezoelectric materials for energy harvesting. As described these materials are used in microelectromechanical systems (MEMS) like microgenerators and many other devices. Piezoelectric Harvesters (PEH) placed in wheels of vehicles, roadways and pavements has become the energy source. This paper reviews the various applications of Piezoelectric Materials as a source of energy; by the reference of various experimental and analytical studies.

***Index Terms–*Piezoelectric Material, MEMS, PEH.**

I. INTRODUCTION

All electrical and electronic gadgets require an energy supply for their function. This appliances acquires that power from the battery source. Batteries supply energy but have some limitations, as it replace after the use or it should be recharge again and again. Hence, there should be interruption in the functioning of the appliances. Therefore, many researches are carries to find out the non-renewable energy sources. Solar energy, wind energy, hydro energy, tidal energy are the non-renewable energy sources. But these sources are unsuitable in case of many appliances. For such appliances, piezoelectric materials are the source of energy. The piezoelectric effect was discovered by Jacques and Pierre Curie in 1880.The word piezoelectric is formed from Greek word 'piezo' means pressure and 'electric' means electrical energy. The piezoelectric materials are having ability to convert mechanical force, stress or vibrations into electrical energy which is direct piezoelectric effect. The converse piezoelectric effect is that when the electric field is given to the piezoelectric material it undergoes deformation. This is electromechanical behavior of material like lead-zirconate, lead-titanate, barium-zirconate which are having crystalline nature. These materials having high strength, high load resistance, high toughness and high resistance to repeated shocks. Hence, the energy by these sources is efficiently used for the wireless electric sensors. Also, the piezoelectric harvester or pre-embedded piezoceramic material are used in vehicle wheels, pavements, shoe and many other applications.

II. LITERATURE REVIEW

The experiment for energy harvesting from PZT is done by Elvin [1]. From the model of cantilever beam. The beam can provide the self-power source of strain energy sensor. The two ring type piezoelectric stack having one pair of bow shaped elastic plates and one shaft that pre compresses them is provided by Li et al [2].Observing that flex compressive mode of the piezoelectric transducer has tendency to generate more electric output voltage as compared to the conventional flex–tensional mode. Camblestructure can produce a large in-plane strain under a transverse external force which is used in micro energy harvesting. Yoon et al [4] forms a curved piezoceramic due to which charge on the piezoceramic increases, as mechanical strain increase. The analytic model was proposed by them which is based on shell theory and linear piezoelectric constitutive equation. By this they develop a charge generation expression for piezoelectric material, using pneumatic shock machine, he investigated a ring shaped PZT-5A element is faced to gun fire shock.

By considering the work cycle analysis, Flynn and Sander investigates limits on the electromechanical energy conversion capacity of piezoelectric transformer. Piezoelectric transformers produce maximum electric field strength, maximum surface charge density, and maximum stress & strain efficiently within the fundamental limits. They suggest that in effective case mechanical stress limit is main constraint in PZT material. Work cycle indicates that the PZT-5H material can handle 330 W/cm^3 at 100 kHz. The investigation also suggest that, magnetic components does not requires in soft switching drive and control circuit.

Series of vibrational energy harvesting devices are presented by Wright et al [3]. He suggested that low-level vibrations mainly seen in household and office environments as a potential power source for the capacitive MEMS and piezoelectric converters. They do the theoretical analysis of cantilever piezoelectric generator which shows the result that power harvesting using piezoelectric conversion is significantly higher. The cantilever based devices made up from the piezoelectric material that acquire power from the low-level ambient vibration source is made by them. They present design configuration for enhancing power harvesting capacity. The axially compressed piezoelectric bimorph is used to decrease resonance frequency up to 24%. They observed that power output to be 65-90% of the nominal value at frequency 19-24% below the unload resonance frequency.

Takuya Tsukamoto et al [6] demonstrated that the bending stiffness can be adjusted by changing the line spacing of meshed-core structure, in the FEM analysis section. By inclined photolithography and a simple bonding process they showed the fabrication process of the 3 D meshed-core PVEH. The maximum attained electrical output, 24.6 μW, is suitable for powering sensor nodes in wireless sensor networks. Lastly without any change in the material, device size, and basic fabrication process they proposed a method for improving the output power and lowering the resonance frequency.

III. PIEZOELECTRIC MATERIAL

3.1 Polycrystalline Piezoelectric Ceramics

PZT solid solution with morphotropic phase boundary (MPB) was discovered in 1950. It has been dominating the piezoelectric industry. MPB is an intrinsic region of a phase diagram where two or more phases coexist. The MPB contained solid solution of piezoelectric material shows enhanced piezoelectric & dielectric properties of their phase boundary. There are always fixed number of equivalent polar axes in a particular crystallographic symmetry in which the dipoles can be switched. The Zirconium-rich side of MPB, PZT with rhombohedra symmetry possess 8 equivalent directions as polar axes whereas, Ti- rich side MPB in PZT possess the tetragonal crystal symmetry with 6 equivalent directions as polar axes. The switching of polar axes in PZT has 14 available directions under applied electric fields, at MPB two different phases coexist. This is the phenomenon that was considered to be responsible for giving rise to high piezoelectric response at MPB.

The monoclinic phase between tetragonal & rhombohedra phases around MPB of PZT were discarded by Noheda et al , some of the piezoelectric materials well known for having MPB are $(1-x)$ Pb $(Mn_{1/3} Nb_{2/3})O_3$- $xPbTiO_3$, $(1-x)$ Pb $(Zn_{1/3}Nb_{2/3})$ O_3-$xPbTiO_3$ and $(Na_{0.5}Bi_{0.5})$ TiO_3-$BaTiO_3$. [5]

One of the important methods to achieve a high piezoelectric response is finding MPB in a solid solution of piezoelectric material. It has been shown that the presence of miniaturized ferroelectric domains with high mobility can be related to the enhanced piezoelectric effect. A miniature domain structure in $BaTiO_3$ single crystal was synthesized by 'Wada et al' by applying electric field along non polar directions. The enhanced piezoelectric response in non-polar directions was believed to originate from broadening of domain walls. The broadening of these domain walls under applied electric field was correlated with the enhanced piezoelectric response in the specimen with miniaturized domains and this was confirmed by Rao and Wang by performing theoretical calculations. Further to enhance the piezoelectric response the doping of various soft and hard elements in PZT is done.

The soft PZTs (e.g. PZT-5) were obtained by doping Nb^{5+} or Ta^{5+} (donor) elements and hard PZTs (e.g. PZT-8) were obtained by doping of elements like Fe^{3+} or Sc^{3+} (i.e. acceptor type dopant). Due to the presence of doping-induced oxygen vacancies the hard PZT behaviour has been attributed to the pinning of domain wall motion. The hard PZTs have low piezoelectric response but high mechanical quality factor. While the hard PZTs are suitable for non-resonance applications, soft PZTs should be used for off-resonance applications.

3.2 Single crystal piezoelectric ceramics

Over the last 15 years the Relaxer-based ferroelectric single crystals such as Pb $(Mg_{1/3}Nb_{2/3})$ O_3-$PbTiO_3$ (PMN-PT) and Pb $(Zn_{1/3}Nb_{2/3})$ O_3-$PbTiO_3$ (PZN-PT) have attracted extensive attention using ultrahigh piezoelectric properties. By placing suitable elements on the desired lattice sites and selecting the suitable MPB composition the piezoelectric response is improved and it depends on the crystallographic orientation of single crystals.

Table 1. Piezoelectric and dielectric properties of various PZT ceramics [5].

Properties EM coupling factor	Soft PZT-5H	Semihard PZT-4	Hard PZT-8
k_p	0.65	0.58	0.51
k_{31}	0.39	0.33	0.30
k_{33}	0.75	0.70	0.64
k_{15} piezoelectric constant	0.68	0.71	0.55
$d_{31}(\times 10^{-12}m/V)$	-274	-122	-97
d_{33}	593	285	225
d_{15}	741	495	330
$g_{31}(\times 10^{-3}Vm/N)$	-9.1	-10.6	-11.0
g_{33}	19.7	24.9	25.4
g_{15} Permittivity	26.8	38.0	28.9
$\varepsilon^X_{33/\varepsilon_0}$	3400	1300	1000
$\varepsilon^X_{11/\varepsilon_0}$	3130	1475	1290
Dielectric loss (tan d) (%)	2.00	0.40	0.40
Mechanical quality factor(Q_M)	65	500	1000

3.3 Textured Piezoelectric Ceramics

Due to high cost of fabrication the single crystals have been facing challenges in their deployment. Moreover the other challenging task is obtaining large-size single crystals with required chemical homogeneity. These single crystals yet being expensive have been used in medical imaging applications, where performance is more important than the material cost. Classification of high performance piezoelectric ceramics based on their synthesis is done as: one is to explore a new phase diagram and another is to tailor the microstructures of known materials. From the material with anisotropic properties the synthesis of grain-oriented materials can be done and it has been proven to be an effective method to obtain the best performance. Including alumina structural ceramics, TE oxide ceramics and piezoelectric ceramics have been successfully synthesized by textured materials.

In the figure below a schematic diagram of the texturing process and resulting microstructural development is shown. Using the tape-casting method, micro sized template crystals are aligned in the ceramic matrix powder, in order to obtain textured ceramics.

Giving rise to the textured grains, epitaxial growth occurs on the template speed during high temperature processing. To give a high degree of texturing, anisotropically shaped template seeds should have a smaller (<15%) lattice mismatch with the matrix phase. Using the topochemical microstructural conversion process the anisotropically shaped $BaTiO_3$ (BT) templates were synthesized. These templates were used to fabricate various highly textured piezoelectric materials with excellent properties.
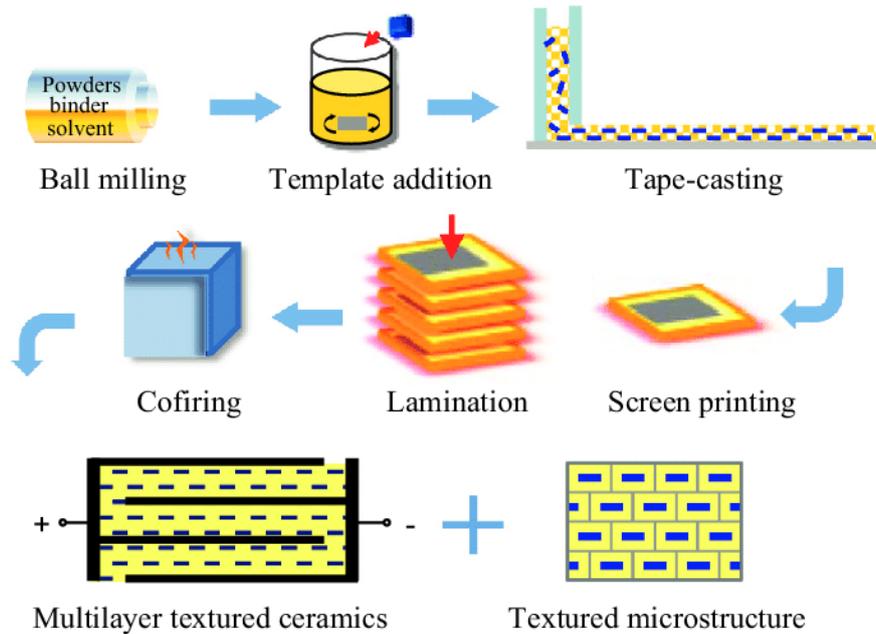

Figure-2: Schematic diagram of TGG process.

IV. VIBRATIONAL ENERGY HARVESTING

Vibration is the conversion of kinetic energy into mechanical energy. Vibrations are produced in the human motions, civil structures, railway tracks, pumps and vehicles etc. These vibrations are used to produce electrical energy. Many researches are carried out on energy harvesting sources. According to researchers, it is found that there is significant growth in energy harvesting sources, but at the same time energy consumption of micro-electric component is going on decreasing. So, there is an opportunity to develop 'self-power devices' using these vibrations in piezoelectric materials.

The undesired vibrations that are emitted by vehicles, structures or let it be a human body, are of no use until now. By using PEHs these vibrations are made useful.
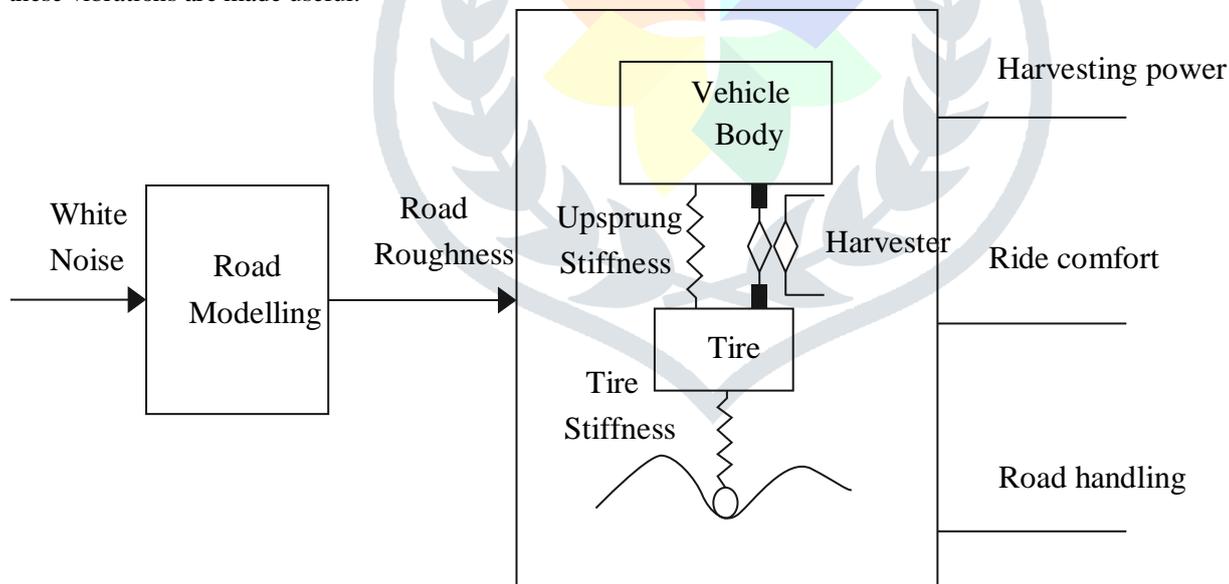

Figure-3: Integrated road-vehicle-harvester model [5]

4.1 Automobile Vibrations

It is observed that $1/5^{th}$ of energy is lost into mechanical energy. Less than half of energy is transferred to driving unit. 14-30 % energy is utilized in overcoming resistances from the road friction. Fuel efficiency can be improved by recovery of waste heat, tire energy harvesting, regenerative braking and regenerative shock absorber.

4.2 Energy harvesting from human motion

Starner and Paradiso proposed a review on an energy harvesting from various human activities. Human activities like breathing, walking, arm motion, blood pressure, fingure motion generates the small amount of electrical energy. The transducers like piezoelectric unimorph and bimorphs cymbals, microfiber composites are commonly used for the energy harvesting. Portable electronic devices and personal health-care systems uses the energy harvested from human motion. By employing electromagnetic, piezoelectric, or electrostatic transduction methods human activities are considered as energy sources. As the dominant frequency of motion (fm) reaches the resonant frequency of harvester (fr) the obtained power output is maximum. The amount of energy used by the human body per day, is 1.07×10^7 J, is the basic idea of harvesting energy from human body [7].
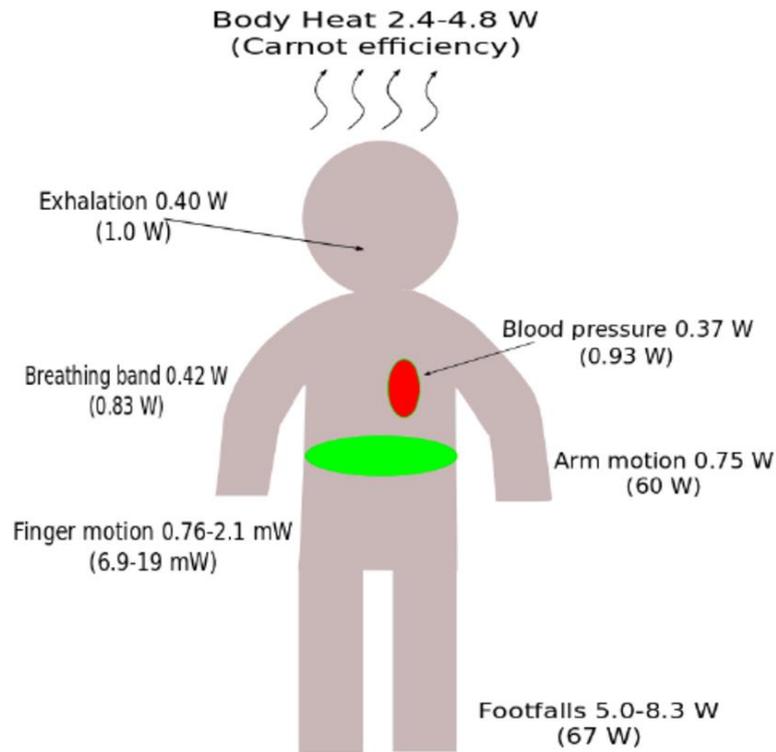
Figure 4: Energy harvesting potential from various human activities.

4.3 Vibration energy harvesting from Railway tracks
Huge vibrations are produced when railway moving on the track. These vibrations are used for harvesting the energy. The deflection frequency depends on the distance between two train wagons. For a train moving 25-75 mph, the frequency of track deflection is 0.6-1.8 Hz. The average power (P_{avg}) is given by,

$$P_{avg}= (NFD)/T = (FD)/ (\Delta T) \qquad (1)$$

Where,
N= no. Of wheels,
F= normal force exerted by wheel,
D= track deflection,
T= total time taken by each train to pass,
ΔT= average time taken by each wheel to pass.
 In 1.36 sec, a four wheel train wagon moves at a speed of 40 mph and having weight of 100 tonnes and length of 80 ft. The average power is 2 kW calculated from above equation. This energy can be used in powering LED signal lights, trackside health monitoring systems.

4.4 Vibration in civil Structure
Stability & reliability of civil structure depends on the vibrations, as they suffers the large amount of dynamic loading external during earthquakes, tsunamis, wind storms, human motion etc. Vibrations are used to harvest the energy & oppose the excess mechanical energy. This energy can be used to fulfill the power requirements.

V. CIRCUIT

The experiment on PZT ceramics in order to collect electrical energy and summarize the governing equation for piezoelectric is done by Ayers [4]. Capacitor and rechargeable batteries both can store the electric energy. Their feasibility and efficiency is also investigated.
The dominant factor that influences the charging and discharging is leakage resistance of energy storage devices. Researchers suggested quick test method for experimental study of charge and discharge efficiency of energy storage device. This can be done by using super-capacitors which were suitable and durable.
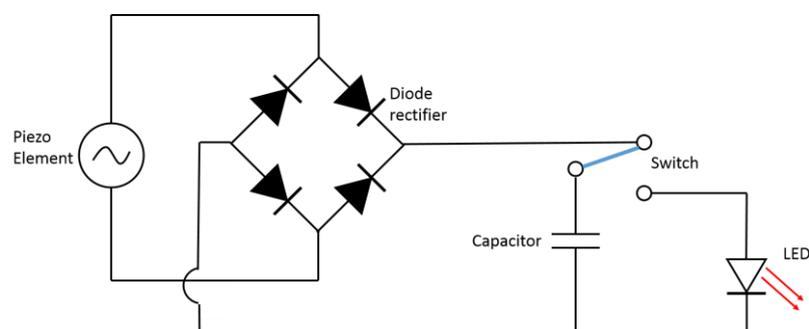

Figure 5: Circuit for piezoelectric energy harvester by using vibrations

VI. CONCLUSION

As above mentioned there are many types of undesired vibrations. These vibrations may cause defect in mechanical structure. To avoid such condition, we are using piezoelectric energy harvester which can convert vibrations efficiently. This paper also reviews on the use of energy harvesting piezoelectric materials. Classification of piezoelectric ceramics and their applications are studied. It is found that textured piezoelectric ceramics are having excellent properties as they are fabricated by using microsized templates which are made by tape-casting method.

REFERENCES

[1] Elvin, N. G., Elvin, A. A. and Spector, M., 2001, "A self-powered mechanical strain energy sensor," Smart Materials and Structures, Vol. 10, No. 2, pp. 293-299.

[2] Li, X., Guo, M. and Dong, S., 2011 "A flex-compressive-mode piezoelectric transducer for mechanical vibration/strain energy harvesting," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, Vol. 58, No. 4, pp. 698-703.

[3] Nihit Kumar Singh, Suhit Datta, 2014 "Review of Piezoelectric energy harvesting based on vibration" Vol. 1, No. 5.

[4] Yoon, S. H., Lee, Y. H., Lee, S. W. and Lee, C., 2008, "Energy harvesting characteristics of PZT-5A under gunfire shock," Materials Letters, Vol. 62, No. 21–22, pp. 3632–3635.

[5] https://www.researchgate.net/publication/274253934.

[6] Takuya Tsukamoto et al, 2018 "Bimorph piezoelectric vibration energy harvester with flexible 3D meshed-core structure for low frequency vibration" Science and Technology of Advanced Materials 2018, Vol. 19, No. 1, 660-668.

[7] Elham Maghsoudi Nia et al, 2017 "A review of walking energy harvesting using Piezoelectric Materials", IOP Conference Series: Materials Science and Engineering, Vol. 291, Conference 1.