Vibration Based Piezoelectric Energy Harvesting - A Review

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Abstract: In this digital race, electronic equipment has been integrated into human beings as a part of their body. Some electronic equipment is connected by wires, while some are self-powered by batteries. Today the ultra-low-power smart electronic gadgets and smart wireless sensor devices need an unlimited battery for enhancing the performance. In remote areas such as forests and hill areas, conventional charging methods of batteries by wire is not possible. Supplying power through wires is difficult. To overcome this, a sustainable solution is energy harvesting. The renewable sources for energy harvesting are light, heat, wind, tidal, motion, and vibration. Researchers have more interest in harvesting energy through mechanical vibration due to its abundant availability. This paper reviews the work about piezoelectric crystals and their role in energy harvesting, simulation software used, energy harvesting circuits and storage devices.

Keyword: Energy Harvesting; Piezoelectric materials; Simulation software; Harvesting circuit; Storage unit

1. Introduction

The process of collecting functioning or unwanted energy from the sources of natural and human-made things from the environment could be called energy harvesting. This system is used to charge batteries for self-powered portable devices or wireless sensor networks [1]. Non-renewable energy has a great impact on the environment, but piezoelectric material is renewable. The piezoelectric material could convert mechanical energy into electrical energy. It received the most attention of researchers due to the direct conversion of applied stress into electricity. Due to the compactness and smartness of piezoelectric material, it has a major role in portable electronic applications. The applications are power generation in a highway [2] and human bodies are to monitor breathing, blood flow and power pacemaker [3,4]. The portable devices such as wireless sensor networks in automotive, railways, aerospace, temperature and humidity sensing systems can be powered using piezoelectric materials [5]. This paper focuses on the review of literature related to piezoelectric materials and their role in energy harvesting, simulation software used, energy harvesting circuits and storage devices [6].

1.1 Sources of Energy Harvesting

Harvesting of energy can be broadly classified into two types, Micro and Macro energy harvesting. In micro harvesting the generation of power in m/μ volts, but in macro harvesting the production of power in kilo/mega volts [7, 8, 9]. The energy sources for micro harvesting are vibration, motion, heat, etc. The energy sources for macro harvesting are light, heat, wind.
sources for Macro harvesting are windmills, solar farms, tidal, etc. Table 1 shows a detailed summary of the sources of energy harvesting [7,8].

### Table 1. Sources of energy harvesting

| Type of energy harvesting | Energy source          | Conversion mechanism       | Energy level          |
|---------------------------|------------------------|---------------------------|-----------------------|
| Micro energy harvesting   | Vibration              | Piezoelectric, Electromagnetic, Electrostatic | 100-330µW/cm³        |
|                           | Ambient radiation      | Electromagnetic            | 1µW/cm²               |
|                           | Ambient light          | Photovoltaic               | 100 µ-100 mW/cm²      |
|                           | Thermal                | Thermo-electric           | 60 µ W/cm²            |
|                           | Fluid flow             | Small size Turbines        | 100-500 mW/cm³       |
| Macro energy harvesting   | Windmills              | Alternator                 | 1-10 kW               |
|                           | Tidal                  | Alternator                 | 1kW-1.2 MW            |
|                           | Solar farms            | Photovoltaic, Large scale Turbines | 10 kW – 500 MW |

2. Power Generation Through Piezoelectric Configuration

2.1 Piezoelectric Effect

In 1880 Pierre Curie and Jacques discovered the direct piezoelectric effect. When the mechanical strain is applied to a piezoelectric material, it tends to electrically polarize. The applied strain was proportional to polarization. Later in 1881 Jacques and Curies discovered inverse piezoelectric effect, in which applied polarization to the piezoelectric material can deform its size. [10] Figure 1 illustrates the direct and inverse piezoelectric effects. Figure 1. (a) Shows the piezoelectric material under no-load conditions. If an external force compresses the piezoelectric material then there is a change in dipole moment, which causes the same polarity poling voltage to appear between the two nodes as shown in Figure 1 (b). If the material is stretched, then piezoelectric material will produce the opposite polarity as shown in Figure 1 (c). When the opposite polarity of poling voltage is applied to the piezoelectric material then it will shorten as shown in Figure 1 (d). When the same polarity of poling voltage is applied to the piezoelectric material then it will expand as shown in Figure 1 (e). The piezoelectric material will expand and shorten by applying the alternative voltage and the frequency of material is based on the applying voltage as shown in Figure 1 (f).
2.2 Sources of Mechanical Vibration

When energy hits a medium, it can cause vibrations, the common sources of vibration are drilling machine, milling machine, bearing bed testing machine, automotive, household things, public transports, etc. [11]. Table 2 shows the sources of vibration with their acceleration and frequency levels [12,13].

| Vibration source     | Equipment          | Acceleration (m/s²) | Frequency (HZ) |
|----------------------|--------------------|---------------------|----------------|
| Industries           | Base of machine tool | 10                  | 70             |
|                      | Drilling machine   | 0.93                | 178            |
|                      | Lathe              | 1.36                | 68             |
| Household things     | Washing machine    | 0.82                | 62             |
|                      | Dryer              | 3.5                 | 121            |
|                      | Microwave oven     | 0.49                | 40             |
|                      | Refrigerator       | 0.14                | 110            |
| Automotive           | Car engine         | 12                  | 200            |
|                      | Truck engine       | 1.98                | 37             |
|                      | A/C Compressor     | 2.14                | 59             |
|                      | Car instrument panel | 3                | 13             |
| Public places        | Door frame         | 3                   | 125            |
|                      | Windows to near busy road | 0.7           | 100            |
|                      | HVAC vents in office buildings | 0.2-1.6 | 62 |

2.3 Piezoelectric Materials

Piezoelectric materials can be obtained from the natural and synthetic method. The material is available in the form of crystal, ceramics and polymers. The naturally occurring crystals are Quartz, Sugarcane, Rochelle salt, Topaz, Tourmaline Group Minerals, Berlinite (AlP04), and dry bone. The man-
made ceramics include Barium titanate (BaTiO₃), Lead titanate (PbTiO₃), Lead zirconate titanate (PZT), Lithium tantalate (LiTaO₃), Lithium niobate (LiNbO₃), Sodium tungstate (Na₂WO₄), Potassium niobate (KNbO₃), Ba₂NaNb₅O₁₅, Pb₂KNb₅O₁₅. An excellent example of Polymer is Polyvinylidene fluoride (PVDF) [14]. Anton and Sodano suggested that piezoelectric materials can be arranged in different ways through altering the electrode pattern, stress direction, changing the direction of poling and varying the piezoelectric materials [15]. They also reviewed that the selection of materials has a major influence on harvesting functions and performance. PZT is highly brittle and PVDF is flexible. Lee et al. investigated Monolithic PZT and concluded that it is vulnerable to fatigue failure during continuous load. The PVDF film coated with electrodes can withstand the fatigue crack damage to the electrode [16]. Sodano et al. investigated that Micro Fiber Composite (MFC) and Quick Pack (QP) Interdigitated Electrode (IDE) are low capacitance devices for energy harvesting. The Monolithic PZT, MFC, QP has greater flexibility for energy harvesting [17]. Sarker et al. developed a MEMS-based energy harvester using COMSOL Multiphysics software. The comparison between PZT and PVDF was done by varying the size of the micro cantilever beam. The generated voltage for PZT is 0.4V and for PVDF is 0.2V. From the simulation results, they have concluded that an increase in the length of a cantilever beam can decrease the resonant frequency [18]. Hassan et al. converted ultra-low sound frequency into electrical energy using a piezoelectric material. In this experiment, PZT was used to harvest energy from a loudspeaker at different distances and then converted into electrical energy. They have found that 27mV was produced at 80 dB of sound at the frequency of 62 Hz at 100 mm distance using coupling mode 31. Using coupling mode 33, authors obtained a generation of 90 mV at 103 dB of sound at 374 Hz. Finally, they concluded that an increase in the distance could lead to decrease in voltage generation [19]. Cook-Chennault et al. 2008 reviewed that generative and non-generative power supply systems for Microelectromechanical system (MEMS), by using piezoelectric energy harvesting system and found that PZT performance is not significantly influenced by temperature [20]. M.Taware and Deshmukh reviewed that PZT with a thickness of 0.28mm on the length of 11 mm beam with proof mass at the end can produce 375 μW at 120Hz. The generated power is used to demonstrate a radio transceiver [21]. [22,23] The summary of various piezoelectric materials is shown in Table 3.

| Author                        | Material                        | Dimensions          | Power/voltage | Application       | Advantages/Disadvantages                      |
|-------------------------------|--------------------------------|---------------------|---------------|------------------|-----------------------------------------------|
| K A Cook Chennault et al (2008) | PZT Rectangular structure      | 1 x 1 x 1.8 cm³    | 4.8 mW        | Knee implant     | Stacked PZT can produce more power            |
| [24] Mohammadi et al (2003)   | Piezofiber Composite           | 34 x 11 x 5.85 mm  | 120 mW        | MEMS             | Increased flexibility                         |
| Sodano et al (2004)           | Composite of MFC & QP IDE      | -                  | -             | Recharging of batteries | PZT proved 6.8 % more efficient for vibration excitation |
| K A Cook Chennault et al (2008) | PVDF bimorph windmill         | 60 x 20 x 0.5 mm³ | 10.2 mW       | Windmill         | 33- mode have higher oscillating frequencies  |
| Lee et al (2005)              | Monolithic PZT                 | -                  | -             | To power transducers | Most commonly used. Fatigue crack during continuous loading |
2.4 Coupling Modes

The coupling modes of piezoelectric material with a substrate could affect the performance of energy harvester. Several authors investigated [15, 26-28] that 33 mode and 31 mode are the most influencing coupling modes if piezoelectric material in energy harvesting. When the applied force is perpendicular to the poling direction then it is called as mode 31. When the applied force is same as the poling direction then it is called as mode 33. Figure 2. Shows the coupling modes of piezoelectric materials. Mode 31 is commonly employed in the harvesting of energy because, a small force at lower vibration levels, it can produce efficient results than mode 33.

2.5 Various Geometries of Energy Harvester

Energy harvesting through a piezoelectric material can improve by optimization of piezoelectric geometry. The rectangular cantilever beam is the most commonly used geometrical configurations. Mateu and Moll analytically compared the rectangular and triangular (the small end is free and the large end is clamped) cantilever beams. It was proven that the triangular cantilever beam can produce a maximum deflection and higher strain equated to a rectangular cantilever beam with the same base and height [29]. When a piezoelectric material is subjected to higher strain and deflection, the output generated is also high. The authors concluded that the rectangular cantilever beam produces less compared triangular cantilever beam. S. Roundy and Wright suggested that the strain in a trapezoidal based cantilever beam is uniformly
distributed, whereas it's non-uniform in a rectangular cantilever beam [30-32]. They also presented that the trapezoidal beam was able to generate twice the energy as that of a rectangular cantilever beam. Baker 2005 proved that the triangular trapezoidal cantilever beam generated 30% more energy than the rectangular cantilever beam, through experimental studies [33]. Rami Reddy et al. modelled and experimentally compared the rectangular beam with and without a cavity. The cavity of the substrate tends to shift the neutral axis of energy harvester away from the surface which increases the strain and voltage [34]. They found that the beam with a cavity can produce 75% more voltage than the beam without a cavity. Reddy et al. experimentally compared the trapezoidal and rectangular cavity beam with the conventional rectangular beam. From the analytical and experimental model, they found that the trapezoidal cavity beam produces 97.5% and 108% more voltage compared with the rectangular cavity beam and the beam without cavity [35]. Usharani et al. designed a wideband energy harvester which can vary the resonant frequency range by varying the length of the beam by introducing step section in the beam. From the experiment, they concluded that step thickness of 2 mm beam reach resonance condition at 5.52 Hz while the beam without step section reach resonance at 21.24 Hz and the voltage is also 4.55 times higher compared to the beam without step section [36]. J. Park et al. designed the piezoelectric energy harvester which can be vibrated by any rotary motion of mechanical devices. From the experiment, authors conclude that their design can produce 160% more power than the tapered beam [37]. S P Matova et al. numerically and experimentally analyzed the effect of size of tapered beams. From their study, they showed that the beam with long and slender taper has a positive effect on power performance and the beam with short and wide does not affect power generation [38]. Hosseini and Hamedi developed the formula to calculate the resonance frequency of V-shaped trapezoidal beam using the Rayleigh-Ritz method and they validate their work using ABAQUS simulation [39]. Goldschmidtboeing and Woias considered the different beam shapes and sizes for piezoelectric energy harvester using the RK method and they validate the result experimentally. Finally, the authors conclude that the shapes have an only small influence on energy but have more effect on excitation amplitude and the triangular shaped with a tip mass performed well compared to rectangular beam [40]. Salmani et al. have developed and proved the mathematical modelling for exponentially tapered piezoelectric energy harvester. While tapering the beam, the natural frequency of the beam increases due to the thinner substrate layer and adding a tip mass at the free end. Table 4 shows a summary of several piezoelectric geometries investigated [41].

Table 4. Summary of several piezoelectric geometries investigated

| Author                  | Piezoelectric configuration                          | Advantages / Disadvantages                                                                 |
|-------------------------|------------------------------------------------------|-------------------------------------------------------------------------------------------|
| Mateu and Moll (2005)   | Rectangle and triangle beam                          | Triangle beam produces more strain and power compared to rectangle beam                    |
| Roundy et al (2005)     | Trapezoidal cantilever beam                          | Trapezoidal cantilever beam can produce more energy than rectangular beam.                 |
| Baker et al (2005)      | Rectangular and trapezoidal cantilever beam          | Rectangle beam produce 30% less power                                                     |
| A R Reddy and et al     | Rectangular beam with and without cavity             | Beam with cavity has produce 75% more power.                                              |
| R Usharani and et al    | Introduction of step section in the beam             | The beam with step section can produce 4.55% more voltage than the beam without step section.|
| J park and et al        | Variable geometry                                    | Their design can produce 160% more power that the taper beam                                |
| S P Matova and et al    | The ratio of length and width on tapered beams       | The beam with long and slender taper have positive effect on power performance and the beam.|
| A R Reddy and et al     | Rectangular cantilever beam with trapezoidal cavity  | Trapezoidal cavity beam can produce 97.5% and 108% more voltage compared with the rectangular cavity beam and the beam without cavity|
3. Various Simulation Software used in Energy Harvesting

Saadon and Sidek designed and reviewed the different types of cantilever beam excited at various resonance frequencies. The geometry of the cantilever beam, vibration frequency, and centre level of resonance frequency was simulated using ANSYS [28]. Sarker et al. developed a micro cantilever beam using C0SM0L Multiphysics. From the various analysis, they found the optimum placement of PZT and silicon mass on the beam [18]. Diyana et al. modelled and simulated comb-shaped piezoelectric beam structure using C0MS0L Multiphysics. The piezoelectric patches and structure were modelled in C0MS0L Multiphysics, MATLAB was used to make mathematical works. The natural frequency of beams was compared using both software. The power output of piezo with and without tip mass was simulated using C0MS0L Multiphysics [44]. Boban et al. optimized energy harvesting by piezo transduction mechanism. NI-PXI workstation was interlinked with LabVIEW software to measure and monitor the output voltage. They have harvested noise and converted it into electrical energy [45]. Prabhakar and Krishna analyzed rectangular cantilever beams at different conditions using Modal analysis in ANSYS. The comparison of resonant frequency for different beam mounting methods was made, and the results had only slight variations compared to experimental work [46]. Motter et al. developed non-controlled rectifier circuits for energy harvesting using a piezoelectric transducer. All tests are performed using MATLAB Simulink setup. The use of the software is to ensure the accuracy of numerical simulations and experimental verifications [47]. Nandish and Hosamani used Multisim software to simulate and analyze the results of the hardware circuit. The simulated result has a close agreement with experimental work [48]. Kundu and Nemade developed a mathematical model using MATLAB and FEM model using C0MS0L Multiphysics. Finally, the short circuit resonance frequency for C0MS0L Multiphysics and MATLAB are 100.0 Hz and 99.80Hz [48,49]. E.L.Pradeesh & S.Udhayakumar used C0SM0L Multiphysics to analysis the optimal location of piezoelectric material over the length of the beam. The effect of proof mass material and shapes were also analyzed. From the numerical analysis, they observed that piezoelectric material located near to the fixed produced more power compared to other locations [50].

4. Energy Harvesting Circuit

The piezoelectric materials can produce AC voltage as an output [51]. The generation of AC voltage is about in μ / m volts, so the AC has to be changed into DC for storage or direct use of electronic equipment [23, 52-55]. Figure 3. Shows a Full wave bridge rectifier circuit, which is used to convert AC to DC.

![Figure 3: Full Wave Bridge Rectifier Circuit](image)

The basic circuit of energy harvesting is shown in Figure 4, ambient vibration is caused by surrounding environments and a piezoelectric element which is used to harvest the energy from vibration [56]. Step up circuit is used to boost the power of piezoelectric [57]. The signal conditioning circuit consists of several Dedicated Integrated Chips to provide a regulated voltage for the storage of power in the storage unit [58].
Yamuna. M. B et al. investigated that the voltage generated from piezoelectric has some ripples, this could be avoided using rectification and filtering. Rectifier circuit converts AC to DC and the regulator circuit removes ripples and maintains the same value of DC. They use MCP73862 charge management controllers used to charge Lithium-ion batteries [59]. Linear Corporation Technology of USA developed a device LTC 3588 series for standalone energy harvesting which is shown in Figure 5. It is completely optimized energy harvesting solution for high impedance sources of piezoelectric elements. It can be interfaced with a piezoelectric element, storage device, load and microcontroller. By using this unit the rectifier circuit, step-up circuit and signal conditioning unit can be eliminated. This unit can also be used to operate ultra-low-power electronic equipment without batteries [60].

![Figure 4: Basic Energy Harvesting Circuit](image)

![Figure 5: Standalone Energy Harvester Circuit](image)

5. Storage Devices

Storage devices are used to store and power the electronic equipments, the storage devices are a capacitor [61,62] and the battery. Typically, batteries are in different types, Nickel Metal Hydride battery (NiMH) and Lithium-Ion battery (Li-ion) are used in piezoelectric harvesting. Sodano et al. compared Nickel Metal Hydride battery and a capacitor for storage of power from PZT. They found that the charging and discharging rates of the capacitor are quick and the capacitor can't store much power like batteries.
Sodano et al. use a Nickel Metal Hydride battery instead of Lithium-Ion batteries because NiMH has a high current charge density and Li-ion batteries need a voltage regulator or charge controller [17]. Guan and Liao investigated that the super capacitor has high efficiency of 95 %, while Li-ion batteries have 92 % of efficiency and NiMH batteries have only 65% of efficiency. The lifecycle of the super capacitor is unlimited, but batteries can withstand only 300-1000 life cycles. The self-discharge rate of Lithium-ion batteries about 95 % in 30 days. The Nickel Metal Hydride battery has a self-discharge rate of 70% in 30 days and super capacitor can withstand only 65% in 30 days [63]. The conclusion was that a super capacitor can perform better than the batteries in the terms of longer lifetime, charging and discharging efficiencies, but it has poor withstand capacity compared to batteries.

6. Conclusion
Vibration based piezoelectric energy harvesting was reviewed in this paper. It is one of the lasting power source solutions for transportable microelectronic devices by harvesting vibration. The piezoelectric energy harvester is clean and greener technologies can protect the environment. This system is less maintenance and cost-efficient to generate power. However, the real application of energy harvester is still limited and it does not use commercially by consumer electronic equipment. The limitation can overcome by improving geometric configuration, selection of multiple piezoelectric patches, development of efficient smart circuits and selection of better storage devices. Vibration is everywhere around us and we look forward that self-powered smart devices will exist in our life shortly.

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