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# Review of Piezoelectric Energy Harvesting based on Vibration

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*Abstract:* **Energy has been an integral part of people's life. With the exponential increment of energy requirement, we are bound to look for various non-conventional energy sources. This paper explores energy harvesting technology from mechanical vibration. Recent growth on low power portable electronic devices and wireless sensor network require infinite battery life for better result. People are always on the lookout for alternative sources with very low battery consumption. Energy is everywhere around us and the most important part in energy harvesting is the energy transducer. Piezoelectric materials have very high energy transition ability from mechanical vibration. A significant amount of research has been instrumental to develop non-complex and optimal energy harvesting devices from vibration with the use of piezoelectric materials. This paper discusses the various types of piezoelectric materials and their applications. It also reviews integral ideas and performances of the reported piezoelectric energy harvested from vibration.**

## 1. INTRODUCTION

Energy harvesting is defined as capturing minute amounts of energy from one or more of the surrounding energy sources, accumulating them and storing them for later use. Energy harvesting is also called as power harvesting or energy scavenging.

With recent advances on wireless and MEMS technology, energy harvesting is highlighted as the alternatives of the conventional battery. Ultra low power portable electronics and wireless sensors use the conventional batteries as their power sources, but the life of the battery is limited and very short compared to the working life of the devices. The replacement or recharging of the battery is inefficient and sometimes impossible. Therefore, a great amount of researches have been conducted about the energy harvesting technology as a self-power source of portable devices or wireless sensor network system. In the view point of energy conversion, human beings have already used energy harvesting technology in the form of windmill, watermill, geothermal and solar energy. The energy came from natural sources, called renewable energy, is emerged as future power source due to limited fossil fuel and nuclear power instability such as Fukusima nuclear crisis. Since the renewable energy harvesting plants generate kW or MW level power, it is called macro energy harvesting technology. On the contrast, micro energy harvesting technology is focused on the alternatives of the conventional battery. Micro energy harvesting technology is based on mechanical vibration, mechanical stress and strain, thermal energy from furnace, heaters and friction sources, sun light or roomlight, human body, chemical or biological sources, which can generate mW or μW level power. In this paper, the energy harvesting is limited to micro energy harvesting. Since piezoelectric material can convert mechanical vibration into electrical energy with very simple structure, piezoelectric energy harvesting is highlighted as a self-power source of wireless sensor network system. Piezoelectricity represents pressure electricity and is a property of certain crystalline materials such as quartz, Rochelle salt, tourmaline, and barium titanate that develop electricity when pressure is applied. This is called the direct effect. On the other hand, these crystals undergo deformation when an electric field is applied, which is termed as the converse effect. Converse effect can be used as an actuator and direct effect can be used as a sensor or energy transducer. The coupled electro-mechanical behavior of piezoelectric materials can be modeled by two linearized constitutive equations.

Direct piezoelectric effect:

$$D = e_{ik} E_{l} + d_{imn} \sigma_{m}$$

Converse piezoelectric effect:

$$\varepsilon_{k} = d_{ik} E_{l} + S^{E}_{km} \sigma_{m}$$

| Coefficient | PZT-5H | PZT-8 | PVDF |
|---|---|---|---|
| $d_{31}$ | $-274 \times 10^{-12}$ m/V | −97 | 18–24 |
| $d_{32}$ | $-274 \times 10^{-12}$ m/V | −97 | 2.5–3 |
| $d_{33}$ | $593 \times 10^{-12}$ m/V | 225 | −33 |
| $d_{15}$ | $741 \times 10^{-12}$ m/V | 330 | —— |
| Relative permittivity $e_{33}$ | 3400 | 1000 | —— |
| Free-strain range | −250 to +850 | $\mu\varepsilon$ | —— |
| Poling field dc | 12 kV/cm | 5.5 | —— |
| Depoling field ac | 7 kV/cm | 15 | —— |
| Curie temperature | 193°C | 300 | —— |
| Dielectric breakdown | 20 kV/cm | —— | —— |
| Density | 7500 kg/m$^3$ | 7600 | —— |
| Open circuit stiffness $E_{11}$ | 62 GPa | 87 | —— |
| Open circuit stiffness $E_{33}$ | 48 GPa | 74 | —— |
| Compressive strength (static) | >517 MPa | >517 | —— |
| Compressive depoling limit | 30 MPa | 150 | —— |
| Tensile strength (static) | 75.8 | 75.8 | —— |
| Tensile strength (dynamic) | 27.6 MPa | 34.5 | —— |

**Table 1: Piezoelectric characteristics**

## 2. ENERGY HARVESTING WITH PIEZOCERAMICS

In this section, vibrational energy harvesting with piezoceramics are reviewed. Various types of vibration devices, single crystal piezoelectric materials and mathematical modeling of vibrational energy harvestings are described in the followings.

### *2.1 Cantilever type*

A cantilever type vibration energy harvesting has very simple structure and can produce a large deformation under vibration. Flynn and Sander imposed fundamental limitations on PZT (lead zirconate titanate) material and indicated that mechanical stress limit is the effective constraint in typical PZT materials. They reported that a mechanical stress-limited work cycle was 330W/cm3 at 100 kHz for PZT-5H.

Elvin et al.[1] proposed a theoretical model by using a beam element and performed experiment to harvest power from PZT material. They showed that a simple beam bending can provide the self-power source of the strain energy sensor.

Wright et al.[2] presented series of vibrational energy harvesting devices. First, they indicated low-level vibrations occurring in common household and office environments as a potential power source and investigated both capacitive MEMS and piezoelectric converters. The simulated results showed that power harvesting using piezoelectric conversion is significantly higher. They optimized a two-layer cantilever piezoelectric generator and validated by theoretical analysis (Fig. 4).They also modeled a small cantilever based devices using piezoelectric materials that can scavenge power from low-level ambient vibration sources and presented new design configuration to enhance the power harvesting capacity. It used axially compressed piezoelectric bimorph in order to decrease resonance frequency up to 24%. They found that power output to be 65–90% of the nominal value at frequencies 19–24% below the unloaded resonance frequency.

### *2.2 Cymbal type*

Cymbal structure can produce a large in-plane strain under a transverse external force, which is beneficial for the micro energy harvesting. Kim et al.[3] reported that piezoelectric energy harvesting showed a promising results under pre-stress cyclic conditions and validated the experimental results with finite element analysis. Li et al.[4] presented a two ring-type piezoelectric stacks, one pair of bow-shaped elastic plates, and one shaft that pre-compresses them (Fig. 5). The reported that flex-compressive mode piezoelectric transducer has the ability to generate more electric voltage output and power output as compared to conventional flex-tensional mode.

### *2.3 Stack type*

Stack type piezoelectric transducer can produce a large electrical energy since it uses d33 mode of piezoelectric materials and has a large capacitance because of multi-stacking of piezoelectric material layers. Adhikari et al.[5] proposed a stochastic approach using stack configuration rather than cantilever beam harmonic excitation at resonance and analyzed two cases, with inductor in the electrical circuit and without inductor. Lefeuvre proposed a synchronized switch damping (SSD) in vibrational piezoelectric energy harvesting (Fig. 6). They claimed that SSD increases the electrically converted energy resulting from the piezoelectric mechanical loading cycle. This stack type can be weak under mechanical shocks.

### *2.4 Shell type*

Since shell structure can generate larger strain than flat plate, it can improve the efficiency of piezoelectric energy harvesting. Yoon et al.[6] employed a curved piezoceramic to increase the charge because of mechanical strain (Fig. 7). They optimized the analytical model using shell theory and linear piezoelectric constitutive equations to develop a charge generation expression. Yoon investigated a ring-shaped PZT-5A element exposed to gunfire shock experimentally using pneumatic shock machine. They found dependence of piezoelectric constant on load-rate, the shock-aging of piezoelectric effect, and the dependence of energy-transfer efficiency on the change in normalized impulse. Chen et al.[7] analyzed circular piezoelectric shell of polarized ceramics under torsional vibration to harvest electric output. The proposed structure harvested electrical energy from torsional vibration.

### *2.5 New materials*

Jeong et al.[8] investigated piezoelectric ceramics with microstructure texture experimentally prepared by tape casting of slurries containing a template $SrTiO_3$ (STO), under external mechanical stress. They concluded that STO-added specimens showed excellent power over the STO-free specimen when a high stress was applied to the specimen.

Elfrink et al.[9] analyzed aluminum nitride (AlN) as a piezoelectric material for piezoelectric energy harvesters because of their high resulting voltage level. They reported a maximum output power of 60 μW for an unpackaged device at an acceleration of 2.0 g and at a resonance frequency of 572 Hz.

Tien and Goo[10] analyzed a piezocomposite composed of layers of carbon/epoxy, PZT ceramic and glass/epoxy to harvest energy (Fig. 8). They reported that piezocomposite have potential to harvest energy subjected to vibration after numerical and experimental validation.

## 3. ENERGY HARVESTING WITH PIEZOPOLYMERS

Mateu and Moll analyzed several bending beam structures using piezo films suitable for shoe inserts and walking-type excitation, and obtained the resulting strain for each type in function of geometrical parameters and material properties. By comparing the energy harvested, the optimum configuration can be determined. They developed piezoelectric film inserts inside a shoe based on their first work. In this paper, they analyzed different factors, such as piezoelectric type, magnitude of excitation, required energy and voltage, and magnitude of the capacitor, to find an appropriate choice of storage capacitor and voltage intervals.

Farinholt developed a novel energy harvesting backpack that can generate electrical energy from the differential forces between the wearer and the backpack by using PVDF. They also proposed an energy harvesting comparison of PVDF and the ionically conductive ionic polymer transducer to examine the effectiveness of electro-mechanical conversion properties. Analytical models using spring-mass-damper for each material assuming axial loading and simulation results were compared with experimental results.

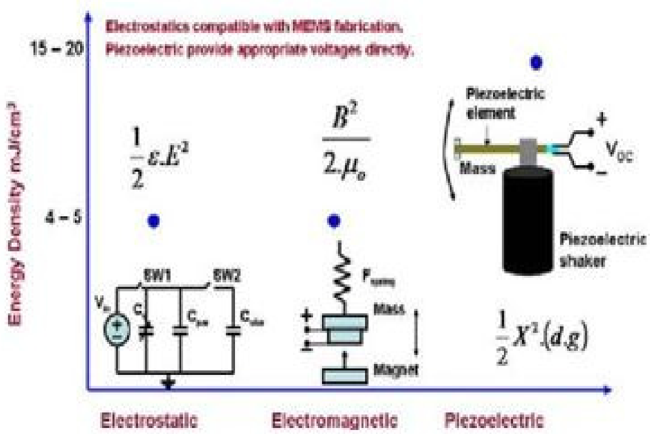


**Fig.1: Comparison of the energy density for the three types of mechanical to electrical energy converters [9].**

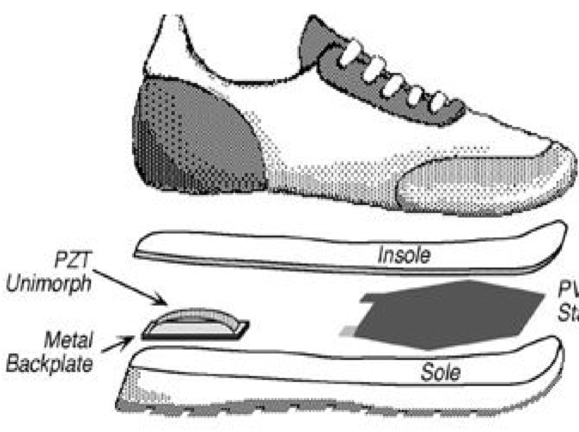


**Fig. 2: Exploded view showing integration of piezo shoe[10]**

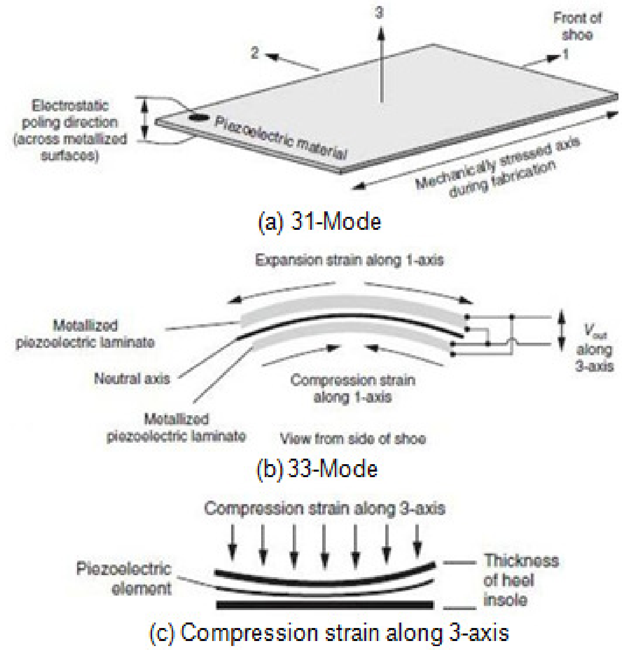


**Fig. 3: Conventional axis definition for a PZT material[11].**

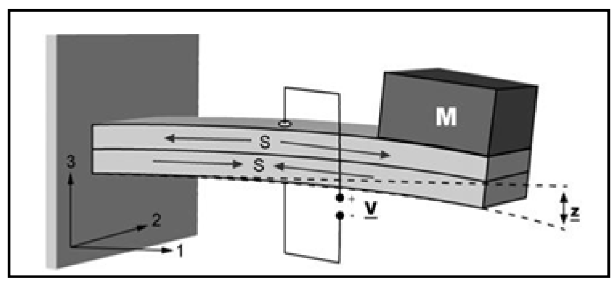


**Fig. 4: A two-layer bender mounted as a cantilever[15].**

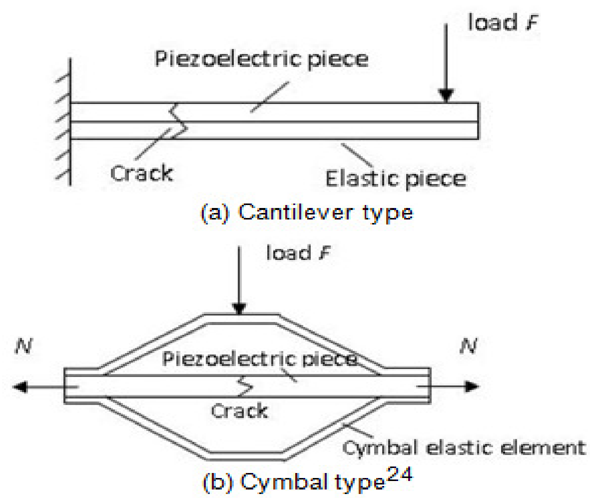


**Fig. 5: Conventional piezoelectric energy harvesters**

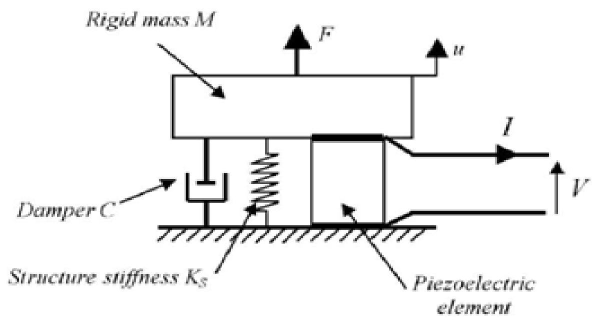


**Fig. 6: Model of a vibrating structure including a piezoelectric element**

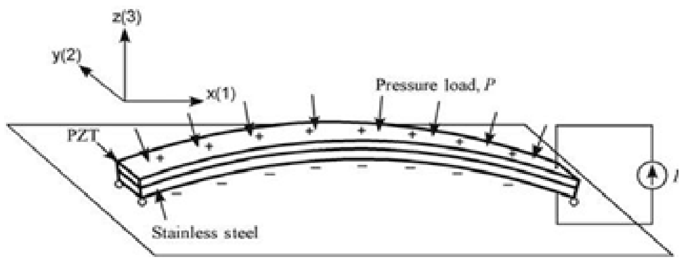


**Fig. 7: Curved PZT unimorph excited in d31-mode by a normal distributed force**

## 4. ENERGY HARVESTING CIRCUIT

The optimized method of vibrational energy harvesting with piezoelectric materials is very essential to develop a scavenging energy device. In nature, vibrational piezoelectric energy harvesting devices is based on the induced power from mechanical vibrations with varying amplitude, resulting induce output voltage with alternating current (AC) from the piezoelectric elements. Early attempt to utilize the piezoelectric energy harvester, power production must be designed with a rectifier. Many different rectifiers have been suggested and studied: e.g. vacuum tube diodes, mercury arc valves, silicon based switches and solid state diodes. However, the simplest way to rectify the alternating input is to connect the piezoelectric harvester with a P-N junction diode which can work only in half input wave. To obtain full-wave rectification of vibrating piezoelectric device, a bridge-type with 4 diodes is required. In order to improve power harvesting circuit efficiency, there are many attempts to modify the rectifying circuit. Using a buck-boost DC-DC converter which can track the power generator's dependence with acceleration and vibration frequency of piezoelectric device, the high efficiency of 84% was reported.

Also, to improve the conversion efficiency of the bridge-type rectifying circuit, the synchronized charge extraction technique with inductor was introduced, resulting the increase of the harvested power by factor 4 (Fig. 16).

### *4.1 Synchronized Switch Harvesting on Inductor*

Guyomer analyzed the real energy flow that lay behind several energy conversion techniques like parallel Synchronized Switch Harvesting on Inductor (SSHI) and series SSHI for piezoelectric vibration energy scavenging and introduced pyroelectric effect which extracts energy due to temperature variation. Minazara proposed energy generation using a mechanically excited unimorph piezoelectric membrane transducer under dynamic conditions and envisaged a new SSHI to enhance the power harvested by the piezoelectric transducer up to 1.7 mW which was sufficient to supply a large range of low consumption sensors.

### *4.2 Circuits and storages*

Ayers conducted experiments on PZT ceramics to collect electrical energy and summarized governing equations for piezoelectric. The energy storage using both capacitor and rechargeable batteries was also investigated and findings were made for feasibility and efficiency of battery recharging.

Guan and Liao investigated leakage resistances of the energy storage devices which are the most dominant factor that influences the charging or discharging phenomena. They proposed a quick test method to experimentally study the charge/discharge efficiencies of the energy storage devices using super capacitors which were suitable and more desirable than the rechargeable batteries.

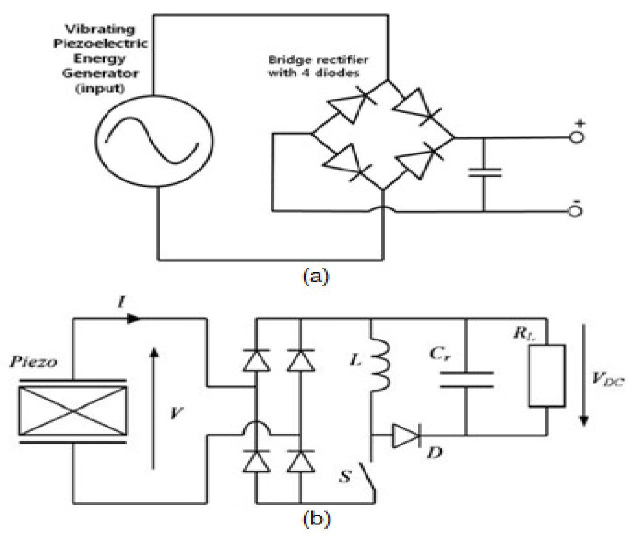


**Fig. 16: (a) Full wave-bridge type rectifying circuit for vibrational piezoelectric energy harvester, (b) Synchronous charge extraction circuit with an inductor L and a switch S26**

Recently, a rectifier free piezoelectric energy harvesting circuit has been suggested by Kim. The suggested circuit was a simple and scalable, which could reach 71% of high conversion efficiency. Very recently, for ultralow input piezoelectric voltage, Peters suggested two stage concept including passive stage and only one active diode, resulting in successful rectification of tens of mV with very high efficiency over 90%. Other approach using a bias-flip rectifier with an inductor was presented in the range of μW, which is greater than 4X power extraction compared to conventional full bridge rectifier.

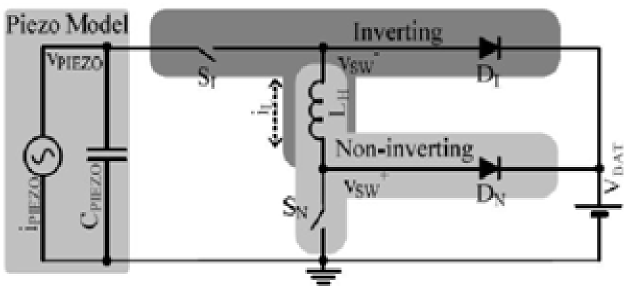


**Fig. 18: Rectifier-free piezoelectric energy harvesting circuit**

## 5. SUMMARY AND OUTLOOK

Piezoelectric energy harvesting technologies from vibration were reviewed in this paper. Principles of piezoelectric energy harvesting, various types of piezoelectric harvesting devices and piezoelectric materials were investigated. Vibration energy harvesting technology is highlighted as a permanent power source of portable electronic devices and wireless sensor network. There have been many novel ideas for vibration-based piezoelectric energy harvesters. Device ideas in conjunction with design technology are likely matured. However, real applications of the vibration-based energy harvesters are still limited. There are three issues that limit the broad technological impact of the vibration-based piezoelectric energy harvesters. Since the obtained electrical energy from vibration is small, rectification and energy storing circuits should be able to activate in such a low power condition. Vibration is everywhere, and vibration-based energy harvesters will come to our real life.

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