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Research Paper

A Review on Vibration Based Piezoelectric Energy Harvesters

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Abstract

This article reviews the mechanics of energy harvesting from various mechanical vibrations. Contemporary approach in hand-held electronic gadgets and low power sensors for wireless networks require a continuous or long battery life for uninturupted performance. Hence, there is a need for permanent and compact power supplies for advanced electronic devices. The most important part of the transducer is energy harvester which converts mechanical vibrations into electrical energy. Piezoelectric materials are important for energy conversion from mechanical vibrations. There has been a lot of research work to establish simple, clean and energy-efficient vibration-harvesting devices using piezoelectric materials. These piezoelectric substances are generally classified into piezoelectric ceramics and piezoelectric polymers. This review article discusses various piezoelectric materials and reviews some important device configurations for piezo-electric energy harvesters.

Keywords:piezo electrics, energy harvesters, piezo-electric polymers, cantilevers.

1 Introduction

Energy harvesting is a technique of extracting energy from various environmental energy sources such as ambient vibrations and motion of biological systems. The various environmental energy sources which are usable for harvesting small amount of energy for portable devices are ambient radio frequency, ambient light (artificial and natural light for photovoltaics), mechanical sources and thermal sources. Energy harvesting is also called as power harvesting or energy scavenging. With current advances in smart systems such as wireless sensors etc, the need for portable devices and wireless sensors is growing rapidly. Since these devices are portable, it is desirable that they are self-powered. Currently, in most cases the portable smart systems are powered by batteries. Batteries are generally undesirable because of the need for recharging or replacement. Therefore, considerable research effort has been directed for technology in energy harvesting for the evolution of self-powered sources for portable devices and wireless sensor system.

Microscale energy harvesting technology is targeted as the substitute for the conventional battery, and is based primarily on mechanical vibrations. In addition, most of these devices lack the energy source to be able to operate both indoors and outdoors, largely unaffected by ambient conditions of temperature and humidity. In this regard, vibrations associated with the body motions become attractive energy options for self-powering small electronic devices.

There are diverse mechanisms to convert mechanical energy from vibrating or moving objects into electricity needed by electronic devices, which include electromagnetic induction, electrostatic storage, and piezoelectric generation. Compared to electrostatic and electromagnetic methods, energy collection with piezoelectric materials provides relatively higher energy efficiency, and most importantly, better flexibility in portable electronic systems. Since piezoelectric material can change mechanical vibrations into electricity with very elementary structures, piezoelectric power conversions for portable systems such as wireless sensor networks are significant [1,2]. Further, while electromagnetic (EM) generators are suitable for generating energy at high frequencies, piezoelectric harvesters can give better performance than electromagnetic generators at relatively low frequencies. In addition, the volume occupied by the piezoelectric harvester is smaller than that of the EM generators for a given power density. Hence, piezoelectric transformation is a superior choice to yield energy at frequencies in the range 100-1000 Hz.

Piezoelectricity represents generation of charge or voltage in a piezoelectric material with the application of pressure. When a time alternating pressure is applied, then a time varying voltage will be generated at the two opposite surfaces of the piezoelectric material. Certain crystalline materials like tourmaline, quartz, Rochelle salt, and barium titanate and certain polymers like Poly(vinyldene fluoride-co-trifluoroethylene) P(VDF-TrFE) develop electricity when pressure is applied [3]. This is termed as the direct piezoelectric effect. Additionally, these crystals experience deformity when electricity is supplied, which is described as the inverse piezoelectric effect. While direct piezoelectric effect can be appiled as a energy transducer, the converse piezoelectric effect can be utilized as an actuator. During the last few years P(VDF-TrFE) has become an attractive piezoelectric material for development of energy harvesters due to its low elastic stiffness which enables the design of resonators with fundamental mode of vibration in the range 100-1000Hz. The energy harvesters so developed can be integrated with smart systems like wireless sensors for in-vitro function such as monitoring patient health like heart beat [4-7]. However, the in-vivo applications are challenging due to bio-compatibility issues of energy harvesters. This paper gives a brief review of vibration based energy harvesters using piezoelectric materials such as PZT and P(VDF-TrFE) [8-11].

2 Piezoelectric Materials

Based on their structural characteristics, piezoelectric materials can be classified into four different categories: ceramics, composites, polymers, and single crystals. In single crystal materials, positive and negative ions are organized in a periodic lattice throughout the entire single crystal. The solid solution of lead magnesium niobate-lead titanate (PMN-PT) is one of the widely used piezoelectric single crystals. In comparison, ceramics are polycrystalline materials which are comprised of many single crystal “grains” that possess the same chemical composition; ions in individual grains can orient differently from one another and the spacing between the ions also can be slightly different. Polymers on the other hand are carbon based materials composed of long polymer chains which have many repeated structural units called “monomers”. These materials are much more flexible than ceramics and single crystals. For applications requiring properties in between ceramics and polymers, engineered ceramic-polymer composites with desirable properties are achievable [12].

Piezoelectric ceramics and crystals show much better piezoelectric properties than piezoelectric polymers due to strong polarizations in their crystalline structures. However, compared with piezoelectric polymers, piezoelectric ceramics and crystals have the disadvantages of being rigid and brittle. Therefore, the preference of a particular piezoelectric material for specific energy harvesting operation depends not only on piezoelectric properties, but also on the specific requirements of the design of the energy harvesting unit, such as available volume, frequency and the form in which the mechanical energy that is delivered into the system. From the materials perspective however, for energy harvesting utilizations the important piezoelectric material properties are: piezoelectric strain constant ‘d’ (induced strain/unit electric field applied or induced polarization/unit stress applied), piezoelectric voltage constant ‘g’ (induced electric field/unit stress applied), electromechanical coupling factor ‘k’ (square root of the mechanical-electrical energy transformation efficiency), mechanical factor ‘Q’ which is degree of damping (lower value indicates higher damping), and dielectric constant ‘ε’ which is the capability of the material to accumulate charge. Table 1 shows typical values of above parameters for piezoelectric ceramics, crystals, polymers and composites. As can be seen in the table, for piezoelectric ceramics and crystals the equivalent of k, d and ε are much greater than those of piezoelectric polymers. On the other hand, ‘g’ constants of polymers are greater due to their much lower dielectric constants in comparison to those of the ceramics and crystals as $g = d/\varepsilon$. Further, considering that the intention of energy harvesting is to convert input mechanical energy into electrical energy, while selecting a piezoelectric material for an energy harvesting utilization, one has to select a material with greater electro-mechanical coupling factor ‘k’.

It is important to note that the piezoelectric energy harvester has to operate at its resonant frequency if it has to extract the maximum amount of power. However, in most cases, it is impractical to match the resonance frequency of the piezo device with the input frequency of host structure due to the volume constraints of the device. This is particularly common for lower frequency applications, since a lower resonant frequency usually requires a larger piezoelectric element. Obviously, in such a situation, the piezoelectric device must operate in off-resonance.

2.1 Piezoelectric Ceramics

As explained earlier, piezoelectric ceramics are polycrystalline materials comprised of many single crystal ‘grains’ with ions in the individual grains that are oriented differently from each other and the spacing between the ions can be slightly different as well. These polycrystalline ceramics belong to the following families with crystal structure known as perovskites: Barium titanate ($BaTiO_3$), Lead titanate ($PbTiO_3$), Lead zirconate titanate ($Pb[Zr_xTi_{1-x}]O_3$) ($0 \leq x \leq 1$) - which is generally called as PZT, Potassium niobate ($KNbO_3$), Lithium niobate ($LiNbO_3$), Lithium tantalate ($LiTaO_3$), and other lead-free piezoceramics. The general chemical formula of perovskite crystal structure is ABO_3, where A is a bigger metal ion, usually lead (Pb) or barium (Ba), and B is a smaller metal ion, usually titanium (T_i) or zirconium (Zr). Above a certain critical temperature known as the Curie temperature (T_c), each perovskite crystal ceramic element shows a simple cubic symmetry without any dipole moment; it is called as the paraelectric phase of a crystal which is as shown in Figure 1(a). Further, at temperatures below the Curie temperature (T_c), every crystal shows a rhombohedral or tetragonal symmetry

Table 1: Properties of selected piezoelectric single crystals, ceramics, polymers and PZT-polymer composites.

	PMN-32PT with <001> orientation (single crystal)	PZT-5H (ceramic)	PVDF (polymer)	PZT polymer composite with 30 vol. % PZT
Density (g/cm^3)	8.10	7.65	1.78	3.08
Dielectric constant ϵ_r	7000	3250	6.0	380
Young's modulus Y_{33} (GPa)	20.3	71.4	2	
Mechanical quality factor (Q_m)		32	10	
Piezoelectric charge constant d_{33} (pC/N)	1620	590	25	375
Piezoelectric charge constant d_{31} (pC/N)	-760	-270	12-23	
Electro-mechanical coupling factor k_{33}	0.93	0.75	0.22	

leading to a dipole moment; this phase of the crystal is called ferroelectric phase as shown in Figure 1(b).

When an electric field of about $10^4 Vcm^{-1}$ is applied to the ferroelectric material below Curie temperature, spontaneous polarization develops; all polarization vectors are aligned in a nearly uniform direction. This process is known as poling or generation of a macroscopic net polarization. Before application of the electric field there exists a uniform distribution in all direction, which is without any macroscopic net polarization [13].

Piezoelectric ceramic materials are commonly used as piezoelectric elements in energy harvesting devices because of their good piezoelectric properties, low cost, and also ease of fabrication as energy harvesting devices. Amongst all the piezoelectric ceramics, PZT is important because of its excellent piezoelectric properties and high Curie temperature. Because of the wide range of excellent piezoelectric properties, during the last few years, the use of PZT has expanded very significantly by tailoring its properties with modification of its chemical composition or fabrication processes. PZT-5H and PZT-5A are some of the more frequently used composite materials. Furthermore, piezoelectric ceramics can be tailored in different configurations depending upon the characteristics of the mechanical energy source. Piezoelectric ceramic thin films, thick films, and plates are usually preferred for vibration based energy harvesters because they can be readily incorporated in a cantilever structure. In order to harvest energy from mechanical vibrations, multilayered stacks of piezoelectric ceramic materials can be used for energy conversion.

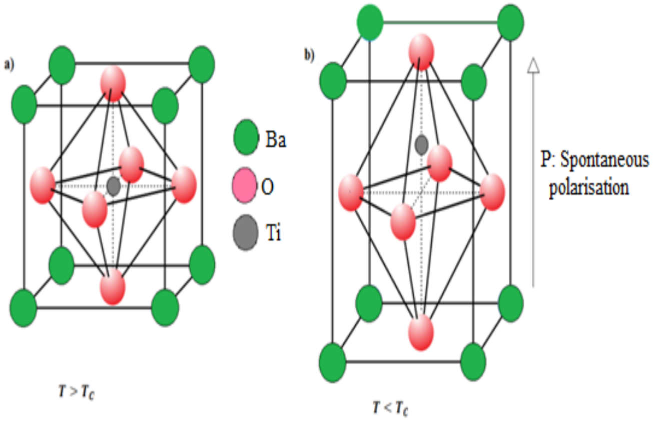

Figure 1: Crystal structure of a piezoelectric ceramic ($BaTiO_3$) (a) above curie temperature and (b) below curie temperature.

A PZT bimorph cantilever was used by Roundy et al [14] as an energy harvesting device to harvest energy from low level vibrations to power wireless sensor networks. In this study, a PZT cantilever was made using PZT-5A ceramic and a steel center shim. The length of the cantilever was 1.75cm. A proof mass was attached to the tip of the cantilever to lower its resonance frequency. The device was driven at 100 Hz, matching the natural frequency of the cantilever energy harvester, and the driving acceleration was 2.25 m/s^2. The authors achieved 60 μW of power when the load resistance was set at the optimum value ($\sim$220 kΩ). Following this first experiment, Roundy et al fabricated and investigated two cantilevers using PZT-5H ceramic with two lengths 1.5 cm and 3 cm. These cantilevers accomplished power yields of around 200μW and 380μW at their ideal working conditions.

In 2003, Sodano et al. fabricated a wide PZT-5H cantilever with dimensions of 63.5 × 60.3 × 0.27 mm^3. This cantilever, driven on an electromagnetic shaker at 50 Hz, the resonance frequency of the cantilever, was able to charge a 1000 mAh NiMH rechargeable battery to 90% of its capacity within 22 h [15]. A trapezoidal PZT cantilever was investigated by Yuan et al [15] to find the energy harvesting performance. The thickness of the PZT layer on each side of the metal layer was 0.3 mm and the length and width of the cantilevers were 45mm and 20 mm, respectively. A power of 24.2 mW was obtained, when the cantilever was driven at the resonance frequency under an optimal resistive load.

In another experiment, the energy harvesting capability of a cymbal transducer was reported by Kim et al in 2004 [16]. The cymbal transducer was 29 mm in diameter and had a PZT disc with a thickness of 1 mm. Three different PZT ceramics were evaluated for comparison: a soft PZT, a PZT with a high 'g' and a hard PZT. The PZT with a high g constant showed the highest output voltage $\approx$ 100V under a force of 7.8 N with a 100 Hz frequency. High-g PZT cymbal transducer was able to deliver an output power of 39 mW when an optimal resistive load was used. The transducer's power generating capability under higher force conditions was further explored by Kim et al who used a cymbal transducer with thicker steel end caps and the same high-g PZT ceramic with the same thickness as the previous experiment. They obtained a maximum power of 52 mW under an AC force of 70 N at 100 Hz when the steel cap thickness was 0.4 mm. In vibration based energy harvesting studies, the resonant frequency can be reduced below 1 kHz using piezoelectric ceramics in the form of thin layers. Multilayer stacks of piezoelectric ceramic materials can be used for energy conversion to harvest energy from mechanical impacts.

The possibility of embedding three PZT stacks within a total knee replacement (TKR) implant was explored by Plattet et al. The PZT stacks were used to power the encapsulated sensors which were capable of monitoring the health and working status of the TKR implant [17]. TKR implants had three rectangular PZT stacks as the energy harvesting elements, each having the dimensions of $1.0 \times 1.0 \times 2.0 cm^3$. and consisted of $\sim$145 PZT layers connected in parallel. The PZT stacks were Placed inside a TKR implant and were designed to be subjected to axial force applied by the human body. Under a 900 N load at a frequency of 1 Hz, it was observed that the maximum power output per PZT stack was $\sim$1.6 mW with a matched resistive load, implying 4.8 mW for the entire energy harvesting device, which was able to continuously power a low-power microprocessor.

It can be seen from the reports described above, that for a piezoelectric ceramic energy harvester to have a reasonably small size, the resonance frequency of the piezoelectric element is usually in the range of tens of Hz or higher. However, in many vibration based energy harvesting applications it is challenging for the ceramic element to adapt to the motion of the host when both the frequency and amplitude of the host structure are very low. Renaud et al. attempted to solve this problem, by designing a new piezoelectric generator that converts small motions of the host structure into the movement of a moving mass. The mass is designed to deliver impact to the piezoelectric ceramic element [17]. Two piezoelectric cantilevers positioned on the two ends of the device housing were connected in this design, with a guiding channel which guides a moving steel "projectile" (mass = 4 g) having an oblong shape. As the steel "projectile" bounces between the two piezoelectric beams, providing impact, mechanical energy of small vibrations or rotory motion of the host structure converts into electrical energy. The prototype harvester having a volume of 25 cm^3 and a weight of 60 g, generated average power output of 47 μW at a frequency of 1 Hz.

2.2 Piezoelectric Polymers

Polyvinylidene difluoride (PVDF) and their copolymers are the most regularly used piezoelectric polymers. PVDF is a semi-crystalline polymer having repeating units of (CH_2-CF_2) and it consists of approximately 50% crystals which are embedded in an amorphous matrix. It is a ferroelectric polymer, showing piezoelectric and pyroelectric properties. The effect of piezoelectricity was first observed in the polymer PVDF in 1969 [18] and subsequently observed in co-polymers of trifluoroethylene(TrFE), vinyl acetate, vinyl-cyanide, vinyl idene fluoride and nylons along with numerous bio-polymers [18]. PVDF is a light-weight, hard engineering polymer which can be used in a vast range of thicknesses and large areas. It has piezoelectric property due to the strong molecular dipoles within the polymer chain leading to piezoelectric charge coefficients (d) in the range of 10-40 pC/N. Shortcomings of PVDF ploymer are weak electro-mechanical coupling in comparision to ceramics and thermal stability, which restricts the operation at temperatures below 100°C. However, new copolymers of PVDF which evolved recently and have extended the operating temperature range to 135°C.

Using the piezo films, a few bending beam structures which are appropriate for shoe embeds and walking type excitation were analyzed by Mateu and Moll [19]; and they obtained the subsequent strain for each sort as function of geometrical parameters and material properties. They created piezoelectric film embeds inside a shoe in view of their first work [20]; they explored various parts such as piezoelectric sort, extent of excitation, required energy and voltage, and magnitude of the capacitor, to locate a proper choice of storage capacitor and voltage intervals. Granstrom et al. [21] established a new backpack for energy harvesting, which can provide electrical energy from the differential forces between the backpack and the user by means of PVDF polymer. In order to obtain the efficiency of electro-mechanical conversion properties, they also suggested an energy harvesting comparison of PVDF and the ionically conductive ionic polymer transducer [22]. Lallart et al. [23] estimated the energy harvesting capacity of composite terpolymer polyvinylidene-trifluoroethylene-chlorofluoroethylene fluoride (P(VDF-TrFECFE)) filled with 1% by volume of carbon black. They found that the carbon-filled terpolymer has superior properties as compared to other similar compositions. By theoretical and experimental investigation, they have demonstrated that an energy harvesting module with AC to DC conversion utilizing a bias voltage of 0.01 kVμm$_{-1}$ and 0.2% of transverse electric field is more powerful than other piezo-based energy harvesters. A comparision of micro power procured by energy harvesters using PZT, PVDF and the polypropylene was done by Shah et al. [24]. Further, the authors have evaluated the voltage reaction of polymer based piezoelectric strips, PVDF, and ceramic based piezoelectric fiber composites (PFCs), regulated to different water drops and wind speeds to study the potential for generation of power from these two characteristic natural sustainable power sources for usage in low power electronic gadgets. They demonstrated that piezoelectric polymer materials can create a higher voltage and power than ceramic based piezoelectric materials, and it was desirable to deliver energy from sustainable sources, such as rain drops and wind by the utilization of piezoelectric polymer materials.

It can be seen from the reports described above, the use of piezoelectric polymers for vibration based piezoelectric energy harvesters is beneficial because piezoelectric polymers are flexible, supple to shock, deformable and light weight. The utilization of piezoelectric polymer based energy harvesters for backpack, shoe-inserts etc indicate their feasibility in real life applications. Newly created piezo-paper based on cellulose may be one more example for piezoelectric polymer based energy harvesters [25].

3 Energy harvesting techniques

In most cases of piezoelectric energy harvesting, the vibrational or mechanical energy sources have either low frequencies or low acceleration. A thin and flat form factor permits a piezoelectric element to easily respond to the movement of the vibrating device. In addition, this kind of form factor is advantageous in decreasing the overall dimensions and weight of the energy harvesting device. Therefore, most of the piezoelectric materials used have configurations or geometric shapes of a thin-layer.

3.1 Cantilever form

The cantilever configuration is among the widely used structures in piezoelectric energy harvesters, specifically for mechanical energy harvesting from vibrations. This is due to the fact that a huge mechanical strain could be generated in the piezoelectric material during vibration and also due to the fact that the construction of piezoelectric cantilevers is comparatively easy. Equally important, the resonant frequencies of the primary flexural modes of thin cantilevers are quite low which enable extraction of energy from generally available vibration energy sources. Therefore, a majority of the piezoelectric power harvesting devices reported involves a unimorph or bimorph cantilever design.

A thin layer of piezoelectric material may be built as cantilever by anchoring one end to a non-piezoelectric or metallic layer as shown in the Figure 2(a). Such a configuration is called “unimorph” in which one active piezoelectric layer is used in this structure. A cantilever also can be designed by bonding two thin layers of piezoelectric material to the metallic layer to increase the power output of the unit, as shown in Figure 2(b). This shape is called as “bimorph”, where two active layers are used. Bimorph structures are most commonly utilized in studies of piezoelectric energy harvesting because these systems double the output energy of the energy harvester without substantially increasing the complexity of the device.

In a piezoelectric cantilever, the poled directions related to piezoelectric layers are normally perpendicular to the planar direction of the piezoelectric layers, when they are fabricated; this technique is most advantageous to polarize piezoelectric sheets. The piezoelectric cantilevers operating in the above mode is said to be operating in the ‘31 mode’, where in ‘3’ denotes the direction of polarization of the piezoelectric material and ‘1’ denotes the stress direction of the cantilever. The 31 mode uses the d_{31} charge constant , the induced polarization in the poled direction (“3”) of the piezoelectric material per unit strain implemented in direction “1.” For a given piezoelectric material, d_{31} is, in reality, smaller than d_{33} due to the fact that in 31 mode stress is not always applied along the polar axis of the piezoelectric material. Therefore, to utilize a piezoelectric sheet that is in the “d_{33}” mode for higher power output, an interdigitated electrode layout can be used as shown the Figure 2(c). In this electrode design, an array of narrow negative and positive inter digitated electrodes is located alternatively on top of a piezoelectric sheet when it is fabricated. During poling treatment of the sheet, the interdigitated electrodes direct the electric field in laterally inside the sheet so that the sheet is polarized in the lateral direction rather than in the conventional vertical direction. In this way, if the sheet is subjected to bending, the stress direction is parallel to the poled direction of the piezoelectric sheet, which permits the usage of the piezoelectric charge constant d_{33}. Figure 2(d) shows a cantilever with proof mass which reduces the resonance frequency of the cantilever.

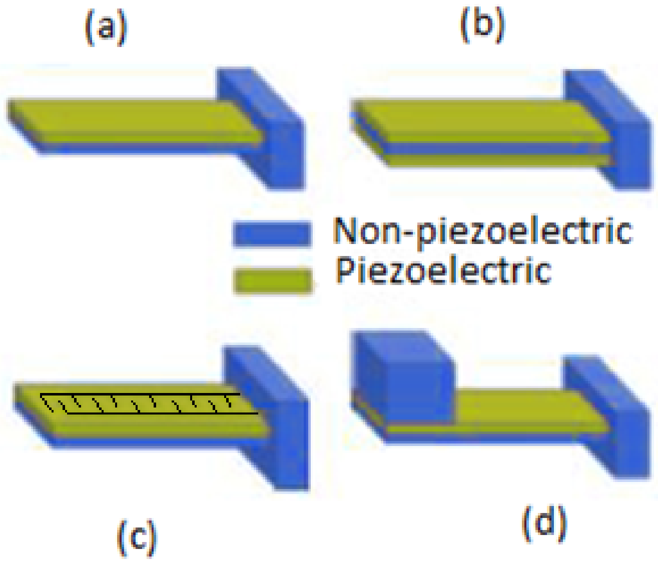

Figure 2: Configurations of piezoelectric cantilevers: (a) unimorph cantilever, (b) bimorph cantilever, c) inter digitated electrodes, (d) piezoelectric cantilever with proof mass.

An experiment performed by Elvin et al [26] to harvest energy from PZT material by using an analytical model of a beam cantilever showed that the self-power source of the strain energy sensor can be provided by a simple beam bending. A series of vibrational energy harvesting devices was studied by Roundy et al [27, 28]. They showed low-level vibrations taking place in conventional domestic and office environments as a potential energy source and studied both capacitive MEMS and piezoelectric converters [29]. The authors showed by utilising simulation results that energy harvesting by piezoelectricity is efficient. They also designed a small piezoelectric cantilever device that can harvest the energy from ambient vibration sources and demonstrated new design structure to increase the capacity of energy harvesters. A two-layer piezoelectric cantilever is shown in Figure 3.

In 2003, Sodano et al [30] examined monolithic PZT material and micro fiber composite (MFC) and studied the performance of those two materials. The authors also reviewed three types of piezoelectric energy harvesting devices namely, a monolithic PZT, micro fiber composite and bimorph Quick Pack (QP) actuator in order to analyse the efficeiency of energy harvesters. Shen et al [31] explored a Si micromachined PZT cantilever with a proof mass for a low frequency vibration energy harvesting utilization. The authors obtained average energy and energy density of about 0.32 W and 416 Wcm^{-3}, respectively. Based on thick-film piezoelectric cantilevers, Liu et al [32] examined an array of power generator to improve frequency resilience and output power and they showed that the effective electrical power output was about 3.98 mW. Using thin film PZT, Choi et al [29] fabricated a power harvesting MEMS device to enable self-supportive sensors. The effect of proof mass, beam shape and damping on the power producing efficiency has been studied in order to give direction for maximum energy harvesting from naturally attainable low frequency vibrations.

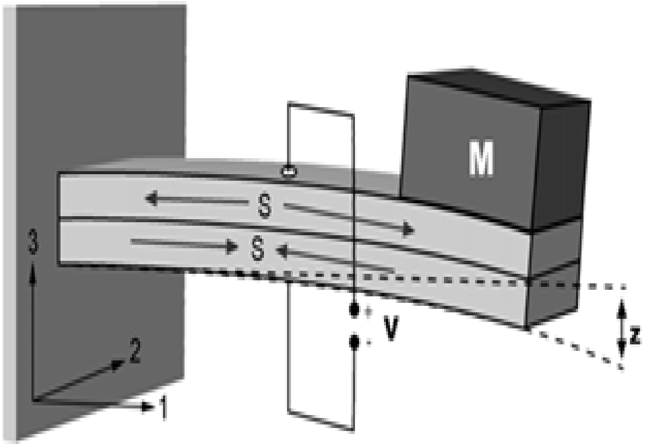

Figure 3: Schematic of a two layer piezoelectric cantilever with proof mass (M), displacement (z), voltage (V) and strain (S).

3.2 Cymbal form

Cymbal transducers were developed for applications that are having high impact forces. Under a transverse external force, this configuration can generate a large in-plane strain, which is advantageous for micro energy harvesting. Generally, this structure consists of a piezoelectric ceramic disc and a metal end cap on each side as shown in Figure 4. Li et al [33] proposed a ring-sort piezoelectric stacks, one pair of bow-formed elastic plates, and one shaft that precompresses them. They also showed that the flex-compressive form piezoelectric transducer has the potential to generate higher output voltage and electrical energy output compared to average flex-tensional form.

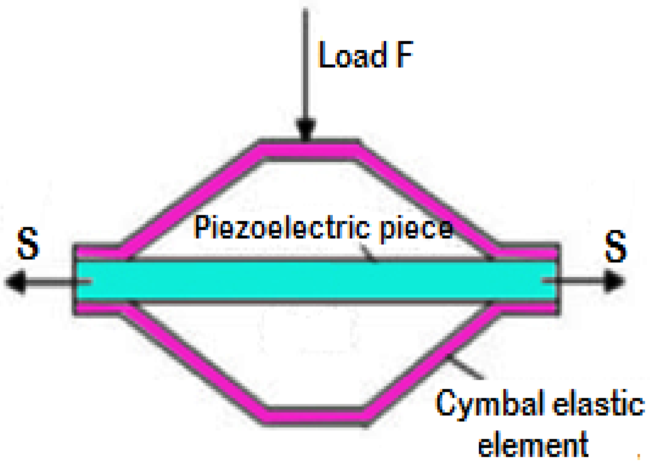

Figure 4: Schematic of cymbal type piezoelectric energy harvester.

3.3 Stack form

Stack type of piezoelectric transducer can generate a huge electric energy due to the fact that it makes use of d_{33} mode of piezoelectric materials and has a huge capacitance due to multi-stacking of piezoelectric fabric layers as shown in the Figure 5. The schematic of the stack shows 'n' layers with thickness 't' of each layer. The energy output depends upon L, W and nt. A theoretical model was proposed by Adhikari et al [34] for stack configuration in which they analyzed two versions: one with inductor within the electrical circuit and the other with no inductor.

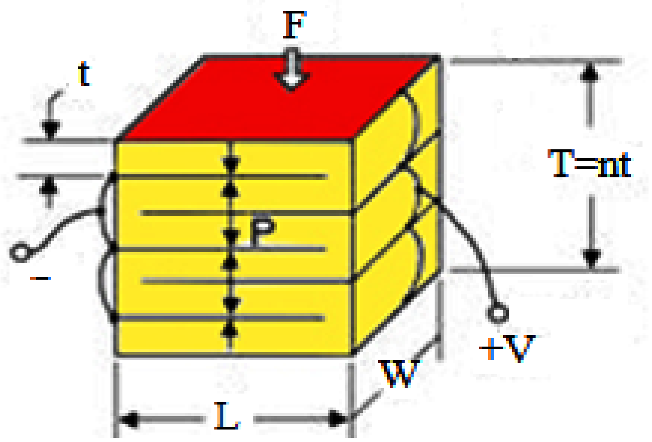

Figure 5: Stack type of piezoelectric transducer where F is the force applied and V is the voltage output. Each layer has a -ve and +ve terminal.

4 Energy Harvesting Circuits

Advanced technique of vibration based energy harvesting through piezoelectric substances is crucial to establish a energy harvesting tool. The vibrational piezoelectric energy harvesters depend on the induced energy from mechanical vibrations with fluctuating amplitude, resulting in an output voltage with AC current. To utilize the vibrational piezoelectric energy harvester, power extraction should be achieved with a rectifier. Many rectifiers have been investigated which include mercury arc valves, vacuum tube diodes, solid state diodes and silicon based switches. Nonetheless, the easiest option to rectify the alternating output is to connect the piezoelectric harvester with a diode [35, 36]. In order to acquire full wave rectification of vibrating piezoelectric device, a full wave bridge-type rectifier with four diodes is essential as shown in Figure 6(a). To increase the transfer efficiency of the bridge rectifying circuit, a synchronized charge extraction procedure with inductor has been used as shown in the Figure 6(b).

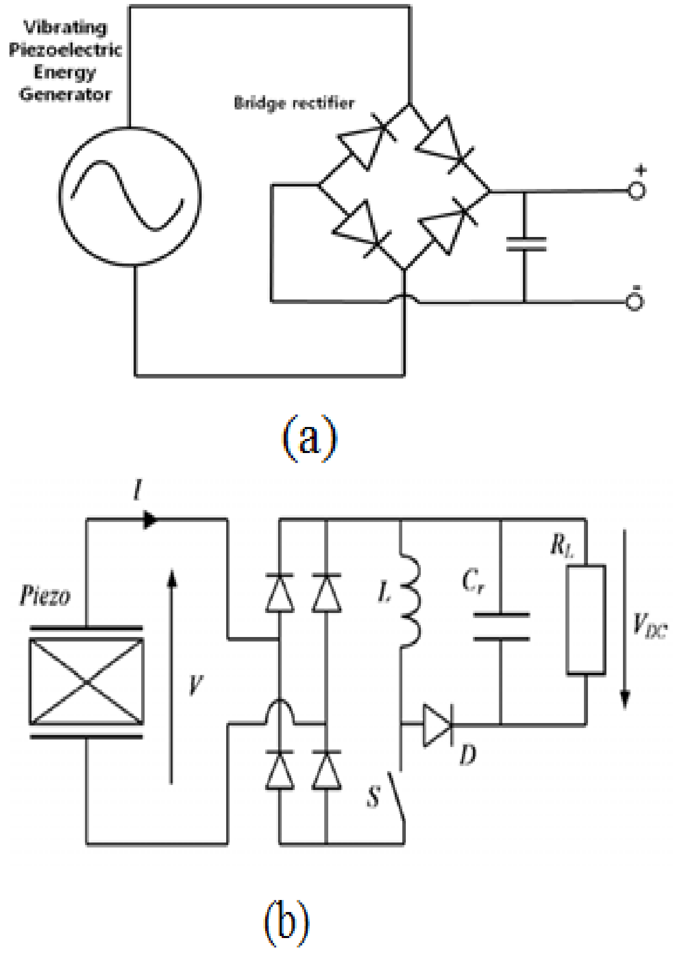

Figure 6: (a) Full wave bridge rectifier circuit for vibrational piezoelectric energy harvester, (b) Synchronous charge extraction circuit with inductor and switch.

4.1 Circuits and Storages

Experiments with PZT ceramics were carried out by Ayers et al [37] who investigated the storage of energy by means of rechargeable batteries and capacitor. Leakage resistances of the energy storage devices were explored by Guan et al.[38], which is a component that influences the charging and discharging phenomena. They proposed power storage devices with the utilization of supercapacitors which were suitable and more attractive than the rechargeable batteries. Wickenheiser et al [39] examined the results of various electro-mechanical coupling within piezoelectric energy harvesting systems subjected to base excitation by charging a storage capacitor. They studied the charging or discharging performance of the device through simulation.

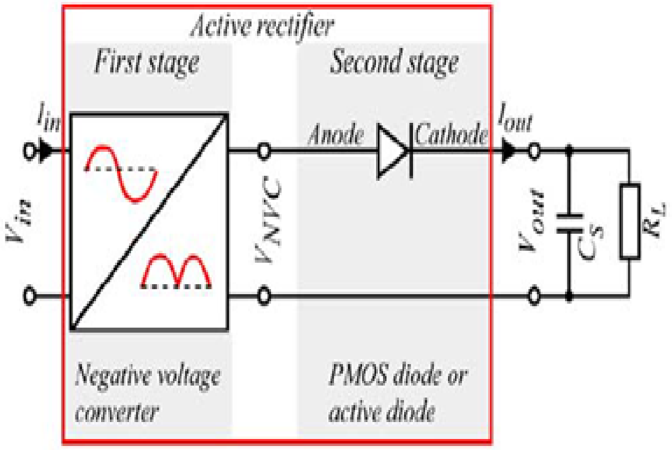

Figure 7: Two level rectifying circuit for ultra-low input piezoelectric voltage [41].

Recently, a piezoelectric power harvesting circuit without rectifier was proposed [40]. The proposed circuit was able to achieve 71% conversion performance. For ultra-low input piezoelectric voltage, Peters et al [41] proposed a circuit with two stages, the first stage comprising of passive stage and the second, is an effective stage with single diode as shown in Figure 7; this resulted in a successful rectification of voltages as low as tens of mV with high performance over 91%. At room temperature, the built-in voltages of silicon and germanium based P-N junction diodes are about 0.7 V and 0.4 V, respectively. Hence, the induced vibrational input must be greater than built-in voltage of diode to harvest the vibrational based piezoelectric output. To bound the built-in voltage and enhance the efficiency of rectifying circuit, Schottky diode with low flip-on voltage has been recommended. The utilization of piezoelectric elements in energy harvesting devices need many specifications to be streamlined to quantify the performance so that remote sensors and electronics can be self-powered.

5 Summary

Various techniques of piezoelectric energy harvesting from vibrations has been reviewed in this paper. Different types of piezoelectric materials, harvester configurations and techniques utilized to enhance the mechanical to electrical energy conversion efficiency have been examined. Cantilever structures are among the most studied configurations for vibrational based piezoelectric energy harvester todate because of their high response to small vibrations. There have been numerous methods for harvesting vibrational energy through piezoelectric mode. But the implementation of efficient piezoelectric energy harvesters is slow. The greatest difficulties in the development of efficient piezoelectric energy harvesters are: 1) the mechanical energy sources have very low input accelerations and frequencies, and it is very difficult to get piezoelectric energy harvesters to efficiently react to them, and 2) the performance efficiency of present piezoelectric materials in energy harvesting is not adequate to replace the batteries as the solitary power source. However, with the recent advancement in microelectronics and MEMS, the power requirements for most of the electronic devices have been reduced. In view of this, it is likely that more and more piezoelectric energy harvesters may find applications in these devices in the near future.

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