Piezoelectric power harvesting devices: An overview

Ashok K. Batra
Almuatasim Alomari
Ashwith Chilvery
Alak Bandyopadhyay
Kunal Grover
Henry Ford Health System, kgrover2@hfhs.org

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Piezoelectric Power Harvesting Devices: An Overview

Ashok K. Batra1,∗, Almuatasim Alomari1, Ashwith K. Chilvery2, Alak Bandyopadhyay3, and Kunal Grover4

1 Department of Physics, Chemistry and Mathematics (Materials Science Group), Alabama Agricultural and Mechanical University, Normal, Alabama 35762, USA
2 Department of Physics and Dual Engineering, Xavier University of Louisiana, New Orleans, Louisiana 70125, USA
3 Department of Electrical Engineering and Computer Science, Alabama Agricultural and Mechanical University, Normal, Alabama 35762, USA
4 Henry Ford Health System, Detroit, Michigan 48202, USA

This article reviews the fundamental behavior of piezoelectric for applications in sensors and energy harvesting technologies. In fact, many devices and applications are evolving day-to-day depending on smart materials technology such as, scanning probe microscope (SPM) and cigarette lighters. Today, vibration based energy harvesting via piezoelectric materials has become one of the most prominent ways to provide a limited energy for self-powered wireless sensor and low power electronics. This review provides an insight that involves mathematical modeling of constitutive equations, lumped parameter model, mechanisms of piezoelectric energy conversion, and operating principle of a piezoelectric energy harvesting system. This article also focuses on the dielectric, piezoelectric, mechanical, and pyroelectric properties of piezoelectric and pyroelectric materials open to use from single crystal such as PMN-PT through ceramics PZT and polymers such as PVDF. Recent important literature is also reviewed along with energy harvesting devices proposed for use in industrial and biomedical applications.

Keywords: Piezoelectric, Pyroelectric, Vibration Based Energy Harvesting, Constitutive Equations, Pyroelectric Energy Harvesting.

1. INTRODUCTION

Energy harvesting remains a topic of intense interest in academic and industrial settings since it provides a route for the realization of autonomous and self-powered low-power electronic devices. Energy harvesting or power harvesting or energy scavenging is defined as capturing a small amount of energy from one or more of the surrounding energy sources, accumulating and then, storing them for later use. The ability to deliver sustainable electric power to micro electromechanical systems (MEMS) or a wireless system network by energy harvesting is attractive not only because of the cost of batteries but it also removes the additional time and cost that is necessary to replace and maintain the batteries including installation of complex wired systems. This is in particular, relevant to the installation of sensor nodes in areas that are hostile or difficult to reach. These are safety monitoring devices, structure-embedded micro-sensors, and medical implants. Furthermore, there are also environmental benefits associated with limiting or eliminating the disposal of batteries. Thus, energy harvesting devices provide a ‘battery-less’ solution by scavenging energy from ambient energy sources such as light,
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Ashok K. Batra holds a Masters of Technology and Ph.D. from the Indian Institute of Technology, Delhi. With more than 23 years of experience in the diverse areas of solid-state physics/materials and their applications, he is presently a Professor of Physics. His research experience and interests encompass ferroelectric, pyroelectric, piezoelectric materials and their applications, design, fabrication and characterization of pyroelectric, piezoelectric, photo-thermal and photovoltaic devices, nonlinear optical crystals, organic semiconductors, crystal growth from solution and melt, microgravity materials research, nanocomposites and chemical sensors. Currently, Professor Batra is engaged in research related to the development of ambient energy harvesting and storage devices, nanoparticles-based chemical sensors and organic photovoltaic solar cells. He has obtained various research grants as the principal or co-investigator from the U. S. Army/SMD, NSF, DHS, NASA. The NASA grant was related to the International Microgravity Laboratory-1 experiment flown aboard the Space Shuttle Discovery. Receiver of a NASA Group Achievement award and the Alabama A&M University School of Arts and Sciences Researcher of the Year award, he has published over 120 publications including a book, book chapters, proceedings, review articles and NASA TMs. Professor Batra is a member of SPIE, MRS, AES and AAS.

Almuatasim Alomari was born in Irbid, Jordan, 1985. He received a B.Sc. degree in physics from the Yarmouk University, Jordan in 2007 and a M.Sc. in applied physics from the Jordan University of Science and Technology, Jordan in 2011. He is currently a Ph.D. student in physics/material science at Alabama A&M University, USA. His research interests include dielectrics, piezoelectric materials, piezoelectric composites, and smart systems. He enjoys playing soccer, snooker, and chess.

Ashwith K. Chilvery is employed as an Assistant Professor in the Department of Physics and Engineering at Xavier University of Louisiana. He has a Ph.D. in Applied Physics from Alabama A&M University, and M.S. in Electrical Engineering from University of South Alabama. His research interests are in the areas of photovoltaics, smart materials for energy harvesting, chemical and biological sensors and detectors. Prior to joining Xavier University of Louisiana, he was employed as Assistant Professor and Coordinator of Physics in the Division of Natural Sciences and Mathematics at Talladega College for 2.5 years. During his tenure, he served as the Co-PI/Site Coordinator for the Alabama Louis Stokes Alliance for Minority Participation (ALSAMP) at Talladega College and played a vital role in enhancing the STEM recruitment and retention procedures. He is also affiliated with scientific societies such as International Society for Optics and Photonics (SPIE), Material Research Society (MRS) and Optical Society of America (OSA). Currently, Dr. Chilvery has over 25 peer-reviewed publications.

Alak Bandyopadhyay is an Associate Professor of Computer Science at Alabama A&M University. Dr. Bandyopadhyay has more than 25 years of research experience in algorithm development, numerical methods, modeling and simulation of fluid dynamics and Multiphysics problems. Dr. Bandyopadhyay has a Ph.D. in Mechanical Engineering from University of Minnesota, Minneapolis and Masters in Mechanical Engineering from Indian Institute of Technology, Kanpur. Dr. Bandyopadhyay has vast experience in aerospace propulsion, process modeling, laminar and turbulent incompressible and compressible flow, and other areas of computational mechanics. Dr. Bandyopadhyay has more than 30 research publications including journal and conferences.

Reduced power consumption. Energy storage solutions are also improving such as development of super-capacitors and even structural power that will ultimately lead to successful energy harvesting products and systems.1 In this aim power efficiency and
article, we provide a list of number of excellent publication reviews and papers in the areas of piezoelectric energy harvesting and surveys of potential devices. The objective of this article is to provide an overview of energy harvesting technologies, potential devices and associated ‘piezoelectric’ materials.

2. PIEZOELECTRICITY AND POWER HARVESTING

2.1. Fundamentals of Piezoelectricity

Many materials, both natural and synthetic, exhibit piezoelectricity. Crystals which acquire a charge when compressed, twisted, or distorted are said to be piezoelectric. This provides a convenient transducer effect between electrical and mechanical oscillations. The generation of an electric charge in certain non-conducting materials, such as quartz crystals and ceramics, when they are subjected to mechanical stress (such as pressure or vibration), or the generation of vibrations in such materials when they are subjected to an electric field. Piezoelectric materials exposed to a fairly constant electric field tend to vibrate at a precise frequency with very little variation. The nature of the piezoelectric effect is closely related to the occurrence of electric dipole moments in solids. Of decisive importance for the piezoelectric effect is the change of polarization ($\vec{P}$) when applying a mechanical stress. This might either be caused by a re-configuration of the dipole-inducing surrounding or by re-orientation of molecular dipole moments under the influence of the external stress. Piezoelectricity may then manifest in a variation of the polarization strength, its direction or both, with the details depending on (i) the orientation of $\vec{P}$ within the crystal, (ii) crystal symmetry and (iii) the applied mechanical stress.

The change in $\vec{P}$ appears as a variation of surface charge density upon the crystal faces, i.e., as a variation of the electrical field extending between the faces caused by a change in dipole density in the bulk. For example, a 1-centimeter cube of quartz with 2 kN (500 lb) of correctly applied force can produce a voltage of 12,500 V. Piezoelectric materials also show the opposite effect, called converse piezoelectric effect, where the application of an electrical field creates mechanical deformation in the crystal. Piezoelectric materials exhibit both a direct and a reverse piezoelectric effect. Figure 1 indicates conversion of vibration/mechanical energy into electrical energy and vice versa. The direct effect produces an electrical charge when a mechanical vibration or shock is applied to the material, while the reverse effect creates a mechanical vibration or shock when electricity is applied. Any spatially separated charge will result in an electric field, and therefore an electric potential. In a piezoelectric device, mechanical stress, instead of an externally applied voltage, causes the charge separation in the individual atoms of the material. Figure 1 indicates generation of piezoelectricity for polar crystals, for which $\vec{P} \neq 0$ holds without applying a mechanical load, the piezoelectric effect manifests itself by changing the magnitude or the direction of $\vec{P}$ or both. For the non-polar, but piezoelectric crystals, on the other hand, a polarization $\vec{P}$ different from zero is only elicited by applying a mechanical load. For them the stress can be imagined to transform the material from a non-polar crystal class ($\vec{P} = 0$) to a polar one, having $\vec{P} \neq 0$. Figure 2 describes the mechanism of a piezoelectric effect in quartz crystal.

2.2. Piezoelectric Coefficients

This section reviews the physical meaning of piezoelectric coefficients.

2.2.1. Piezoelectric Charge Coefficient ($d_{ij}$)

The “$d$” coefficients, also known as the strain constant, relate the mechanical strain produced by an applied electric field. It is defined as the ratio of the electric charge...
generated per unit area to an applied force. This charge coefficient is usually important in the use of transducers and the piezoelectric material’s ability to perform as an actuator. The units are usually coulombs per newton.3

2.2.2. Piezoelectric Voltage Coefficient \((g_{ij})\)

The piezoelectric voltage coefficient “\(g\)” is defined as the ratio of the electric field produced to the mechanical stress applied. High “\(g\)” coefficients are a result of producing large output voltages, which are necessary for sensor applications. Its units are volts per newton.

2.2.3. Dielectric Constant \((\varepsilon_{ij})\)

The relative dielectric constant is defined as the ratio of the permittivity of the material \((\varepsilon_{ij})\) to the permittivity of free space \((\varepsilon_0)\). This is generally measured well below mechanical resonance. This variable is dimensionless.4

2.2.4. Coupling Coefficient \((k_{ij})\)

The electromechanical coupling coefficient “\(k\)” is defined as the ratio of the mechanical energy stored, to the electrical energy applied or vice versa. Since this coefficient uses the relationship of energy ratios, the units are dimensionless.5 In equation form:

\[
\begin{align*}
    d_{ij} &= \left(\frac{\partial D_i}{\partial T_j}\right)_E = \left(\frac{\partial S_i}{\partial E_j}\right)_T \\
    g_{ij} &= -\left(\frac{\partial E_i}{\partial S_j}\right)_D = \left(\frac{\partial D_i}{\partial S_j}\right)_T \\
    e_{ij} &= \left(\frac{\partial D_i}{\partial S_j}\right)_S = -\left(\frac{\partial T_i}{\partial E_j}\right)_S \\
    h_{ij} &= -\left(\frac{\partial E_i}{\partial S_j}\right)_D = -\left(\frac{\partial T_i}{\partial D_j}\right)_S
\end{align*}
\]

where the first set of 4 terms correspond to the direct piezoelectric effect and the second set of 4 terms correspond to the converse piezoelectric effect. Related to each other as follows:

\[
\begin{align*}
    d_{ij} &= \varepsilon_{ik}g_{kj} \\
    g_{ij} &= d_{ij}/\varepsilon_{ik} \\
    e_{ij} &= d_{ij}e_i^E \\
    h_{ij} &= g_{ij}s^D_{ij}
\end{align*}
\]

The electromechanical coupling factor can be written in terms of piezoelectric coefficients as:

\[
K_{ij}^2 = \frac{U_{\text{electrical}}}{U_{\text{mechanical}}} = \frac{e_{ij}^2}{\varepsilon_{ik}g_{kj}}
\]

2.2.5. Efficiency of Energy Conversion

The efficiency of energy conversion, \(\eta\), is described, at resonance, as follows:

\[
\eta = \frac{k^2/(2(1-k^2))}{1/Q + k^2/(2(1-k^2))}
\]

Where, \(k\) is the coupling factor as defined in Eq. (9).

2.2.6. Piezoelectric Constitutive Equations

In this section we will explain the basics equations which cover electromechanical properties of piezoelectric materials. When a poled piezoelectric material is mechanically strained it results a variation of a polarization strength, the changing in polarization appears as an electric charge on the surface of the material. This property is called the “direct piezoelectric effect” and it is the basis operation for sensors. Furthermore, if electrodes are attached to the surfaces of the material, the generated electric charge can be collected and used. This property is particularly utilized in piezoelectric shunt damping applications.5 The general constitutive equations commonly used to describe

---

Figure 2. Mechanism of piezoelectric effect in quartz.
the linear behavior of piezoelectric materials are derived from basic thermodynamics principles.\(^6,7\)

\[
S_p = s^p_{pq} T_q + d^p_{pq} E_k \\
D_i = d_{ik} T_k + s^i_{pq} E_k
\]

where, \(s^p_{pq}\) is elastic compliance tensor at constant electric field \((m^2/N)\), \(d^p_{pq}\) is dielectric constant tensor under constant stress, \(d_{ik}\) is piezoelectric constant tensor \((m/V)\), \(S_p\) is the mechanical strain in \(p\) direction \((m/m)\), \(D_i\) is an electric displacement in \(i\) direction \((C/m^2)\), \(T_k\) is mechanical stress in \(q\) direction \((N/m^2)\), and \(E_k\) is an electric field in \(k\) direction \((V/m)\).

Rewriting the above equations in the following form:

\[
T_p = S^D_{pq} \sigma_q + g_{pq} D_k \\
E_i = g_{iq} T_q + \beta_{pq}^T D_k
\]

where, indices \(p, q = 1, 2, \ldots, 6\), indexes \(i, k = 1, 2, 3\) refer to different directions within the material coordinate system. \(g_{pq}\) is the piezoelectric constant \((m^2/N)\), and \(\beta_{pq}^T\) is impermitivity component tensor at constant stress \((m/F)\) which is the inverse of the permittivity matrix as well. Furthermore, the subscripts \(D\), \(E\), and \(T\) represent measurements taken at constant electric displacement, constant electric field and constant stress, respectively.

Equations (11) and (12) express the converse piezoelectric effect, which describe the situation when the device is being used as an actuator. Conversely, Eqs. (13) and (14) express the direct piezoelectric effect, which deals with the case when the transducer is being used as a sensor. The converse effect is often used to determine the piezoelectric coefficients.

2.2.7. Electromechanical Properties of Piezoelectric Materials

Currently, there are over 200 different piezoelectric ceramics that are commercially available, and amongst them PZT, BaTiO\(_3\), PMN-PT and PVDF are predominantly used. Its properties were described in the forgoing section and its constitutive equations in the matrix form can be written as:\(^8\)

\[
\begin{bmatrix}
S_1 \\
S_2 \\
S_3 \\
S_4 \\
S_5 \\
S_6
\end{bmatrix} =
\begin{bmatrix}
s_{11} & s_{12} & s_{13} & s_{14} & s_{15} & s_{16} \\
s_{21} & s_{22} & s_{23} & s_{24} & s_{25} & s_{26} \\
s_{31} & s_{32} & s_{33} & s_{34} & s_{35} & s_{36} \\
s_{41} & s_{42} & s_{43} & s_{44} & s_{45} & s_{46} \\
s_{51} & s_{52} & s_{53} & s_{54} & s_{55} & s_{56} \\
s_{61} & s_{62} & s_{63} & s_{64} & s_{65} & s_{66}
\end{bmatrix}
\begin{bmatrix}
T_1 \\
T_2 \\
T_3 \\
T_4 \\
T_5 \\
T_6
\end{bmatrix} +
\begin{bmatrix}
d_{11} & d_{12} & d_{13} \\
d_{21} & d_{22} & d_{23} \\
d_{31} & d_{32} & d_{33} \\
d_{41} & d_{42} & d_{43} \\
d_{51} & d_{52} & d_{53} \\
d_{61} & d_{62} & d_{63}
\end{bmatrix}
\begin{bmatrix}
E_1 \\
E_2 \\
E_3
\end{bmatrix}
\]

(15)

3. MECHANICAL VIBRATIONS BASED ENERGY HARVESTING

Nowadays, vibration based energy harvesting is one of the most growing technologies due to decreased power consumption of low power electronics, such as wireless sensor networks (WSN). In general, the simplest figure of vibration based energy harvesting can be modeled as a cantilever beam, one or more layers of piezoelectric and substrate material, and seismic mass as shown in Figure 3(a). The equivalent lumped parameters model of Figure 3(a) can be represented as mass, spring, and damper system as shown in Figure 3(b).

The governor equation of simple model in Figure 3 can be written as:\(^10,11\)

\[
m_{eq} \ddot{x} + c_{eq} \dot{x} + k_{eq} x = -m_{eq} \ddot{u}
\]

(17)

The total electric power of the system can be obtained as:

\[
P = \frac{m_{eq} \xi \tilde{u}^2 \omega^2}{[1 - \xi \omega^2/\omega_n]^2 + \xi \omega^2/(\omega_n)^2]
\]

(18)

where \(u = x(t) - y(t)\) is the displacement response of the mass relative to the base, \(m_{eq}\) is the equivalent mass, \(\omega_n = \sqrt{k_{eq}/m_{eq}}\) is the natural frequency, \(\xi = c_{eq}/(2m_{eq}\omega_n)\) is the damping ratio and \(c_{eq}\) is the damping coefficient, and \(A\) is the amplitude of base acceleration.

4. OPERATING PRINCIPLE OF A PIEZOELECTRIC ENERGY HARVESTING SYSTEM

The process of acquiring the energy surrounding a system and converting into usable electric energy is termed as power harvesting or scavenging. There is a dramatic rise in the use of piezoelectric materials that provide the ability to convert mechanical strain energy (vibrations) into electric charge. The electric energy later can be stored or power small equipment with the help of power management circuit. A piezoelectric generator system consists of five major modules: mechanical energy source; mechanical...
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Piezoelectric material
Substrate material
Tip mass

Figure 3. Simple model of vibration based energy harvesting (a) piezoelectric cantilever beam with seismic mass (b) its equivalent lumped parameter model.

Transformer; piezoelectric transducer; generator electronics as well as intelligent energy and storage management sub-system as described with usual functions of components in Figure 4. The energy sources are translational, rotational, and acoustic energy. Mechanical transfers have two functions: the transformation of non-translational into translational energy and matching the mechanical impedance. Power transfer circuit consists of three essential components: rectification, filtering, and optimum power transfer electronics. An intelligent energy management and storage sub-system is required to ensure reliable energy supply. In this, controlled and reliable wake-up and sleep routines are required in accordance with the available energy.

5. PIEZOELECTRIC MATERIALS AND TECHNOLOGICAL ASPECTS

Piezoelectric materials are a set of materials that can generate charge when mechanical stress is applied. Piezoelectricity results from the motion of dipoles naturally occurred, or artificially induced in the crystalline or molecular structures of these materials. Based on their structural characteristics, piezoelectric materials can be divided into four different categories: polycrystalline ceramics, single crystals, polymers, and composites. In single crystal materials, positive and negative ions are organized in a periodic fashion throughout the entire material except for the occasional crystalline defects. One of the most widely used piezoelectric single crystals is the solid solution of lead magnesium niobate-lead titanate (PMN-PT). In contrast, ceramics, such as lead zirconate titanate (PZT) are polycrystalline materials. Namely, they are comprised of many single crystal “grains” that possess the same chemical composition. Polymers 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 and possess greater strength and flexibility. In some applications, all the above materials can be combined to form composites in order to achieve certain properties that these materials cannot individually provide on their own. Because of the strong polarizations in their crystalline structures, piezoelectric single crystals and ceramics exhibit superior piezoelectric properties than piezoelectric polymers. However, they are considered disadvantageous for being rigid.
and brittle. Therefore, the selection of a certain piezoelectric material for a specific energy harvesting application is determined not only by the piezoelectric properties but also the specific design requirements of the energy harvesting unit, such as the application frequency, the available volume, and the form in which mechanical energy is fed into the system. However, strictly from the materials perspective, the important properties of piezoelectric materials for energy harvesting applications include piezoelectric strain constant $d$ (induced polarization per unit stress applied, or induced strain per unit electric field applied), piezoelectric voltage constant $g$ (induced electric field per unit stress applied), electromechanical coupling factor $k$ (square root of the mechanical-electrical energy conversion efficiency), mechanical quality factor $Q$ (degree of damping; lower value indicates higher damping), and dielectric constant $e$ (the ability of the material storing charge). Table I shows some typical values of these parameters for piezoelectric single crystals, ceramics, composites, and polymers. The values of $d$, $k$, and $e$ for piezoelectric single crystals and ceramics are much higher than those of piezoelectric polymers. The $g$ constants of the polymers are higher because of their much lower dielectric constants compared to those of the single crystals and ceramics.

Since the goal of energy harvesting is to convert as much input mechanical energy/vibrations into electric energy, therefore selecting a piezoelectric material with high electromechanical coupling factor $k$, as the square of $k$ is the efficiency of this material converting the input mechanical energy to the output electric energy is highly desired. A piezoelectric ceramic with high $k$’s usually also has high $d$’s because under static or quasi-static conditions (i.e., at frequencies much lower than the resonance frequency), $k$ is directly related to $d$ through elastic compliance and permittivity of the material.

To extract maximum amount of power, the piezoelectric energy harvester is preferable to operate at resonant frequencies. However, in many cases, it is impractical to match the resonance frequency of the piezoelectric with the input frequency of the host structure due to the volume constraint of the device. This is especially common for low frequency applications, as it usually demands a larger piezoelectric element for energy conversion.

6. A SURVEY ON PIEZOELECTRIC ENERGY HARVESTING

Umeda et al. (1996, 1997), Xu et al. (1998), Goldfarb and Jones (1999) measured the output power efficiency of piezoelectric materials. Kymissis et al. (1998) investigated power generation from piezoelectric shoes; it was determined that the average generated power is about 1.3 mW at 0.9 Hz when the load resistance is 250 kΩ. Glynn-Jones et al. (2001) studied the electrical power of piezoelectric thick-film from harmonic excitation, it was claimed that the maximum power output was around 3 μW under a resonant frequency. Ramsay and Clark (2001) investigated the power harvesting from a 1 cm² piezoelectric plate, it was observed that the produced power is between microwatt to milliWatt which can be useful in vivo bio MEMS.

One way to improve the efficiency of energy harvesting systems is the impedance matching between a piezoelectric energy harvester and electrical circuit configuration. Kasyap et al. (2002) developed a converter circuit with an impedance that could be matched to that of a piezoelectric energy harvester. Ottman et al. (2002) investigated adding an adaptive control dc–dc converter to maximize the output power from piezoelectric energy harvester revealed that the output power could be enhanced by over 400% as compared without using dc–dc converter. Meninger et al. (2001) added an extra capacitor to provide the maximum energy transfer, which modified the transmission process. Richards et al. (2004) and Shu et al. (2006) developed an analytic formula to predict the energy conversion efficiency of piezoelectric energy harvesters in case of AC power output. Guan et al. (2007) studied the efficiencies of energy harvesting circuits considering the storage device voltages.

Recently, piezoelectric cantilevered beams (PCB’s) under base or ambient excitation have gained increased

<table>
<thead>
<tr>
<th>Material</th>
<th>GaN</th>
<th>AlN</th>
<th>CdS</th>
<th>ZnO</th>
<th>BaTiO₃</th>
<th>PZT-4</th>
<th>PZT-5H</th>
<th>PMN-PT</th>
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Piezoelectric Power Harvesting Devices: An Overview

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attention due to their ability to display high amounts of strain. Ambient vibrations suitable for energy harvesting can be found in various aspects of human experience, such as buildings, bridges, trains and etc. Many researchers and scientists in both field of science and engineering have studied the linear effect of PCB’s under base excitation experimentally and theoretically. Sodano et al. (2003, 2004) developed a model based on Rayleigh-Ritz discrete formulation to predict the amount of power generated from a piezoelectric cantilever beam.27,28 Similarly, Lu et al. (2004) developed a model for a cantilever type piezoelectric generator; the output power was analyzed and its applications in MEMS were discussed.29 A three dimensional analyses of a parallel piezoelectric bimorph and triple layer piezoelectric actuators were also done in recent years by Lim et al., (2001), Lim and He (2004), and Sodano et al., (2004).30–32 A 1-D electromechanically coupled piezoelectric generator model was presented by DuToit et al. (2005).33,34 Stephen (2006) and Daqaq et al. (2007) discussed the maximum power generation and the effect of mechanical damping using the same SDOF relation.35,36 Ajitsaria et al. (2007) employed the SDOF relation for predicting the voltage output analytically.37 Erturk and Inman (2008) reviewed and discussed the general solution of the base excitation problem for transverse vibrations of a cantilevered Euler–Bernoulli beam and predicted the output voltage and power. Furthermore, multimodal energy harvesters were investigated and designed.38 Tadesse et al. (2009) presented a design of multimodal energy harvesting beam employing both electromagnetic and piezoelectric transduction mechanisms, each of which was efficient for a specific mode.39 Ou et al. (2012) presented a two-degrees-of-freedom (2-DOFs) system using a two-mass cantilever beam.40 Also, a novel compact piezoelectric energy harvester using two vibration modes was developed by Wu et al. (2013). The compact design efficiently utilizes the cantilever beam by generating significant power output from both the main and secondary beams. An experiment and simulation were carried out using (2-DOFs) and, the results showed that the proposed novel method is more adaptive and functional in practical vibrational circumstances.41 In order to enhance the maximum output power of piezoelectric cantilever beams as well, researchers have developed a variety of techniques based on, varying shape of structure beam using an L-shaped flexible structure,42–44 using dual-mass systems,45 changing the cross-section of a dynamic magnifier46 and using an energy harvester with a dynamic magnifier (EHDAM).47–50

Although the piezoelectric constitutive equations are nonlinear, most of the current analyses consider only the linearized form of these equations. Yet, the nonlinear behavior of piezoelectric cantilever beams has been considered for the actuation purpose.51–56 Recently, nonlinear modeling of piezoelectric energy harvesters from base excitations has gained some attention. Triplett and Quinn (2009) included a nonlinear electromechanical coefficient term in lumped model. It was demonstrated that the nonlinearities in an electromechanical coupling could increase the output electrical power.57 Daqaq et al. (2009) studied energy harvesting using a parametric excitation. In their approach, the dynamic response of the system was investigated using a lumped-parameter model.58 Stanton et al. (2010) identified the nonlinear coefficients based on a nonlinear least-squares optimization algorithm that utilizes an approximate analytical solution obtained by the method of harmonic balance.59 Masana and Daqaq (2011) developed an electromechanical model of a clamped–clamped energy harvester subjected to transverse excitations based on the nonlinear Euler-Bernoulli beam theory.60 Abdelkefi (2012) performed and developed global nonlinear analyses for piezoelectric energy harvesters from ambient and aeroelastic vibrations.61

Piezoelectric cantilevered beam with an effect of magnetic field has been the topic of many researchers both experimentally and theoretically, where the results exhibited increased bandwidth and superior efficiencies of electric output power. Tang and Yang (2012) proposed a magnetic coupled piezoelectric energy harvester, in which the magnetic interaction is introduced by a magnetic oscillator. In their experiment, the bandwidth was increased by 100% and the magnitude of output power increased by 41%.62 Su et al. (2013) designed and developed a dual-cantilever structure that consists of an outer and inner beams with magnets attached to the tips. The magnets generate nonlinear repulsive force between the two beams and make the structure bistable. The new design showed a significant improvement in the bandwidth.63 Wakeel Al-Ashtari et al. studied a design of piezoelectric bimorph cantilevers configurations under the influence of two permanent magnets. Theoretical and experimental results show that magnetically stiffened harvesters have important advantages over conventional set-ups with and without tip mass. It was also observed that they generate more power with a slight increase in the deflection of a piezoelectric harvester and can be tuned across a wide range of excitation frequencies.64

Piezoelectric energy harvesting from aeroelastic vibration has received growing interests in the last few years as well. The aim of an aeroelastic vibration is to convert airflow energy into electricity for aircraft sensors and wireless electronic devices using high wind.65 Vortex-induced vibration, flutter, buffeting, and galloping are examples of some of these aerodynamics phenomena that can be used as a source of harvesting energy. Recently, Erturk et al. (2008) investigated energy harvesting from a flow-excited morphing airfoil. In their study, the experimental results showed that the maximum root mean square (RMS) level of the harvested power is about 7 μW and was obtained when the angle of attack was set equal
to 20 degrees with and for an electrical load resistance equal to 98 kΩ at a flow velocity of 15 m/s. The device was designed to capture otherwise wasted mechanical loading and convert to electrical power.

7. PIEZOELECTRIC POWER HARVESTING DEVICES

Piezoelectric power generation devices can be divided into two categories:

(a) self-energizing devices (self-powered solely from static or dynamic movement of piezoelectric devices, and

(b) energy-harvesting devices that are attached to existing structures that vibrate during operation of the structure.

7.1. Flexible Piezoelectric Energy Harvesting from Jaw Movements

Delnavaz and Voix developed and tested a prototype of jaw movement energy harvester and compared its performance to the analytical model predictions. It consists of a flexible piezoelectric element made of flexible composite (PFC) that fits below the chin and is attached to a head-mounted device by two elastic rubber straps. The head-mounted devices could also have been used as tactical helmets, sports helmets, or headphones. The person wearing the device must adjust the strap assembly to a snug fit to keep the strap under tension. Opening the mouth further stretches the side strap and causes: distributed force stress in the PFC contact surface and tensile stress in PFC cross-section. Electric charge is accumulated in the PFC electrodes are from tensile stress and the electric charge flows through the resistive load and generates the electric current in the circuit. By closing the mouth, the system returns to its initial position and a reverse current of same magnitude is generated. Under optimum conditions, they could obtain the maximum power transfer of about 7 μW.

7.2. Piezo-Wind Generators

Piezoelectric power generation devices are self-energizing devices that are powered solely from static or dynamic movement and convert to electrical energy. The wind energy can be converted to electrical energy via integrating piezoelectric material on leaves or converting rotary energy to linear energy to bend piezoelectric materials (PE) or PE materials can be directly utilized on rotary motion.

Li et al., proposed a novel vertical-stalk L-type design to harvest more energy which is composed of a poled PVDF stalk, a plastic hinge and polymer leaf. Oja et al., made a tree shaped design to harvest energy by embedding PVDF’s on leaves and PZT’s on trunk part of the tree where the bending can be realized by strong wind. There have been studied rotary to linear motion wind generators. Priya et al., designed a piezoelectric wind mill with ten piezoelectric bimorphs in the cantilever form. It was observed that at 10 mph speed, power of 7.5 mW had been obtained across optimum load of 6.7 kOhms. In the research work performed by Bryant et al., two degrees of freedom is utilized by deflection of beam and a rotation of a flap about bearing joint which allows a
modal to flutter response for energy harvesting.\textsuperscript{81} Ting et al., proposed a nozzle accelerator to increase the wind speed by five times and consistently increase the drag force in order to vibrate the piezoelectric bimorph for maximum energy harvesting.\textsuperscript{82} Robbins et al. reported on the harvested energy by using flag-like membrane with piezoelectric materials which is attached to an anchor rod. Wind leads flapping of the membrane and periodic stress occur on bimorph generates voltage across electrodes.\textsuperscript{83} Recently Karthikeyan et al., describes the vertical stalk-horizontal leaf and horizontal leaf-horizontal stalk arrangement, Piezo tree, and the ways to harvesting then energy generated and places it can be erected. They used PVDF for fabricating stalk.\textsuperscript{84} Readers are referred to Ref. [85] for details of wind power harnessing.\textsuperscript{85}

7.4. Rotary Knee-Joint Harvester
Piezoelectric harvesters have been conceptualized, designed and fabricated for energy harvesting from joint motion of human body, including knee-joints.\textsuperscript{86}

7.5. Piezoelectric Prosthetic Leg Energy Harvesters
Pechrach et al. reported an energy harvesting system using smart materials for self-power generation of upper and lower prosthetic legs.\textsuperscript{87} The smart material used for energy harvesting is piezoelectric PZT (Lead Zirconium Titanate). The bimorph structured PZT material produced a maximum peak voltage of 1.8 volts and maximum peak power of 12.5 \( \mu \)W. The first arm of the piezoelectric produces a downward movement, which provides an angle for the movement amplification of the second arm.

7.6. Piezoelectric Pacemaker
A group led by John Rogers at the University of Illinois at Urbana–Champaign has developed a flexible, piezoelectric patch that harvests the mechanical energy of a beating heart.\textsuperscript{88} The implant contains a film made of 500 nm thick ribbons of lead zirconate titanate (PZT) surrounded by gold and platinum electrodes. PZT is piezoelectric, meaning a voltage develops across it when it is bent. The output voltage is used to charge a tiny battery integrated into the device, and the whole thing is encased in a layer of polymide to make it biocompatible. They found that, when stitched at the optimal orientation onto the right ventricle, their device generated up to 0.18 \( \mu \)W/cm\(^2\) power. State-of-the-art pacemakers can run on as little as 0.3 \( \mu \)W-a power output the team achieved by stacking multiple piezoelectric layers on top of one another.

7.7. Piezoelectric Railways
Israel’s Innowattech has engineered piezoelectric materials for railways. An array of piezoelectric disks was installed beneath the rail tracks to transform mechanical stresses into electrical output.\textsuperscript{89} It was observed that a railway track with traffic of 10 to 20 car trains an hour could harvest as much as 120 kWh, which could be used to power infrastructural elements such as signaling lights or can be uploaded to the grid. In addition we can determine the impact of number of wheels, weight of each wheel, the wheel’s capitation, wheel perimeter position, wheel diameter, and the speed of the train.

7.8. Piezoelectric Roads and Highways
Recently, the California Energy Commission is investigating the viability of deploying piezoelectric materials in California roadways for the purpose of harvesting electrical energy. It assessed the value of piezoelectric-based energy-harvesting technology to determine if the early results from prototype demonstrations warrant a more detailed demonstration in California. It was estimated that the cost range of the piezoelectric system to be between $0.08–$0.18/kWh. The railway application implies the use of a thinner unit for two reasons:
(1) the geometry of the installation requires a thin unit, and
(2) there are less inelastic forces in action in this application and fewer discs are needed per unit to harvest useful energy.

There are a number of cost-saving opportunities in this installation. The unit is thinner, so it requires fewer piezoelectric discs, thus lowering its capital costs.\textsuperscript{90}

7.9. Flexible Wearable Harvester
A flexible energy harvesters with a piezoelectric polymer PVDF in-shell structure that can generate high power from slow motion have been proposed.\textsuperscript{91–95}

8. SUMMARY AND OUTLOOK
This article presents a fundamental review of piezoelectric materials for applications in energy harvesting technology. The Piezoelectric and Pyroelectric coefficients of some important and common materials are described for ready reference. A mathematical background of constitutive equations, a lumped parameter model, piezoelectric theory is mentioned in this review paper. Since there are a very wide range of piezoelectric materials open to use from single crystal such as PMN-PT through polymers such as PVDF, dielectric, piezoelectric, mechanical, and pyroelectric properties of some important piezoelectric materials are considered. Furthermore, piezoelectric energy harvesting based on vibration and mechanical waves is still limited for only low power electronics devices such as wireless sensor networks (WSN). However, a few piezoelectric commercial devices such as an electric switch etc. are available in the market. In future, piezoelectric energy harvesting technology will play a prominent role as more ultra-low power devices are available along with stringent rules to protect the environment.
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References and Notes

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