Review Paper

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Piezoelectric Energy Harvesting: A Comprehensive Review and Applications

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Abstract

This paper presents an overall review of Piezoelectric Energy Harvesting, starting with the importance of the abundance of mechanical energy that can be harvested into electrical energy, and how piezoelectric materials can be part of this achievement. A clear description of the piezoelectric phenomenon is intended to be described, with the different structural configuration that piezoelectric energy harvesting gives. An elaborate information about the different piezoelectric materials that we can find nowadays is covered, intending to present a wide overview about the actual status of piezoelectric materials. The many applications that piezoelectric energy harvesting can have are considered in almost all possible fields, giving a clear perspective of the present and future areas where mechanical energy can be harvested by piezoelectric materials. This work reviews recent literature in the field of power harvesting and provides the current status of energy harvesting and the multiples options where this can be applied.

CONTENTS

I. INTRODUCTION

Energy harvesting technology is a promising solution for energy crisis of non-renewable sources. Different types of renewable energy coming from the ambient environment, such as electromagnetic radiation in the form of light, vibrations, heat, wind, and even water, can be harvested into electrical energy that can be used in many applications[1,2]. Lately, harvesting energy from vibrations with the help of piezoelectric materials has been a major topic of research, combining with the big advancements in wireless communication, low-power integrated circuits, and some mobile electronics where these require a relative low power demand in consumption[2,3]. Mechanical energy is the most omnipresent energy that can be harvested into electrical power, while piezoelectric materials are one of the most convenient materials classes for the harvesting of energy from vibrations, since the piezoelectric effect is based only on the intrinsic polarization of the material. Because of that, compared to other mechanical energy harvesting methods, piezoelectric generators are durable[1], more

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sensitive to small strains, and exhibit higher density power output and high voltage output[4,5]. In addition, piezoelectric materials can be flexible and stretchable devices, and for some devices can be easy to work on the nanoscale, which give us the opportunity to expand the field of applications[2,6]. Normally, an energy harvesting system contain 3 parts: the energy source, the harvesting mechanism, and the load (the consumption or storage of the electrical output energy)[8,9]. One example of the many mechanical energy sources that we have in the nature, is human body, which provides a variety of systems where mechanical energy is implied, allowing for some energy harvester to be integrated into daily human activities. Some examples of human power that can be harvested are the approximate 10 mW that can be obtained from the motion of the upper limbs, 1 mW from typing motion, and walking can go up to 1 W[10]. In figure 1 we can observe a schematic representation of some examples of mechanical energy sources, where a harvesting method can be applied to obtain electrical energy. This electrical energy can be used to power devices in current or future applications, where some devices can consume less power and the use of energy harvesting will become more ubiquitous.

The efficiency of energy harvesting can be calculated by the ratio between the power consumed on the external load resistance and the total input mechanical power. Mechanical energy E_m, electrical energy E_e, and energy conversion efficiency $E\%$ are defined with the equations:

$$E_m = \int_0^{\Delta t} F d(t)\, dt \tag{1}$$

$$E_e = P\Delta t = \frac{V^2}{R}\Delta t \tag{2}$$

$$E_{\%} = \frac{E_e}{E_m} \tag{3}$$

where F is the applied force, d the distance of the movement induced by the applied force, Δt is the time in which the motion is generated, P is the output power, V the output voltage, and R is the resistive load that is applied to the harvester[8,11].

In this work, we are going to provide a comprehensive review of the state of piezoelectric energy harvesting technology, aimed to discuss and compile the recent literature about materials and applications of piezoelectronic systems. Starting with the general description of mechanical energy harvesting and the analysis of the phenomena behind piezoelectricity, described in section II. Next, detailed information about the different piezoelectric materials that we can find are going to be covered in section III, where we will discuss the different properties of having organic, inorganic, composite and bio-inspired piezoelectric materials. Important applications are discussed in section IV and we conclude with some conclusion and remarks.

II. MECHANICAL ENERGY HARVESTING

In our environment, several sources of energies are available that can be scavenged (e.g., vibration, wind, solar, radio frequency, etc) and generate electrical power through different harvesting mechanism, which differ depending of the energy source[12]. There are many sources of mechanical energy in the environment, and that is the reason why the number of Mechanical Energy Harvesting (MEH) systems has increased in the past years[12,13]. In general, MEH are commonly classified according to their transduction type, applications and structures[14]. The harvested power density is related mainly to the motion frequency and its magnitude, described by[15]:

$$P_{res} = 4\pi^3 m f_{res}^3\, Z_{max} A \tag{4}$$

where m and Z_{max} are the inertial mass of the harvester and its maximum displacement respectively, f_{res} is the resonance frequency, and y is the amplitude vibration. The resonance frequency is the natural frequency of the system, where at this frequency the object will oscillate at the highest amplitude. This frequency depends on the material composition, shape, volume, and even the addition of a mass, therefore is a parameter that can be controlled[16]. Different activities like walking/running and other human motion can generate mechanical energy at a rate of 5 - 15 Hz, automobiles vibrations 50 Hz, and other elements even more[17]. There are three main transduction mechanism for mechanical energy harvesting: Piezoelectric, electromagnetic, and electrostatic[18]. In this

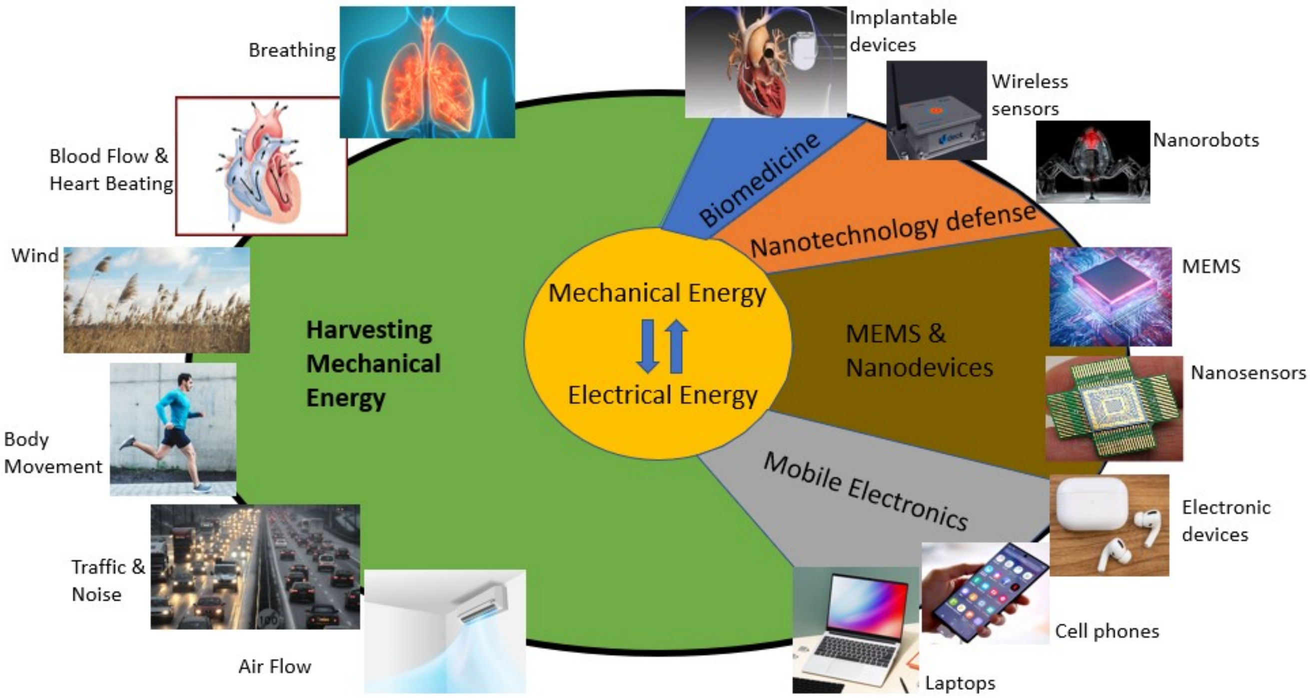

FIG. 1. Example of some mechanical energy sources that can be harvested by piezoelectric materials and used in some potential applications. Figure adapted from[7].

work we aim to give a general review of the piezoelectric effect, described below.

A. Piezoelectric Effect

In 1880 Pierre and Jacques Curie discovered the piezoelectric effect, where piezoelectricity is a word with Greek origin, which means "press or squeeze"[19]. It is defined as the ability of specific materials to transform an applied mechanical stress into electric potential[20]. There are two types of piezoelectric effect: direct piezoelectric effect and converse piezoelectric effect. The former generates electric charge under the effect of applied pressure, the latter induces mechanical strain due to an applied electric field[21,22]. Depending the applications, both effects are very useful, for example the direct effect is used for sensors and energy transducers, while the converse effect is used in actuator[5,23]. The equations that describe direct and converse piezoelectric effects are:

$$D = dT + \varepsilon E \quad \text{(Direct effect)} \tag{5}$$

$$X = sT + dE \quad \text{(Converse effect)} \tag{6}$$

where D corresponds to the electrical displacement, d piezoelectric coefficient, s the mechanical compliance, ε is the permittivity of the material, E the electric field, X the strain, and T is the stress[23]. With the equations defined above, we can talk about the figure of merit (FoM) of piezoelectric energy harvesting system, where FoM is proportional to the square of the piezoelectric coefficient d^2 and inversely proportional to the dielectric permittivity ε[24]. The crystalline orientation makes the parameters mentioned above have different components, because these parameters act as vectors and tensors. In general, piezoelectric materials for energy harvesting are crystals that present a well-defined polar axis and, therefore, the energy harvesting performance the direction of the applied stress relative to the polar axis[25]. The polar axis is referred as the "3" direction and, due to symmetry, other directions at right angles to the polar axis can be referred to the "1" directions. In these directions the stress is applied, resulting in two common Piezoelectric energy harvesting (PEH) configurations, 33-mode and 31-mode[26]. In figure 2 we can observe a schematic representation of the 33-mode and 31-mode.

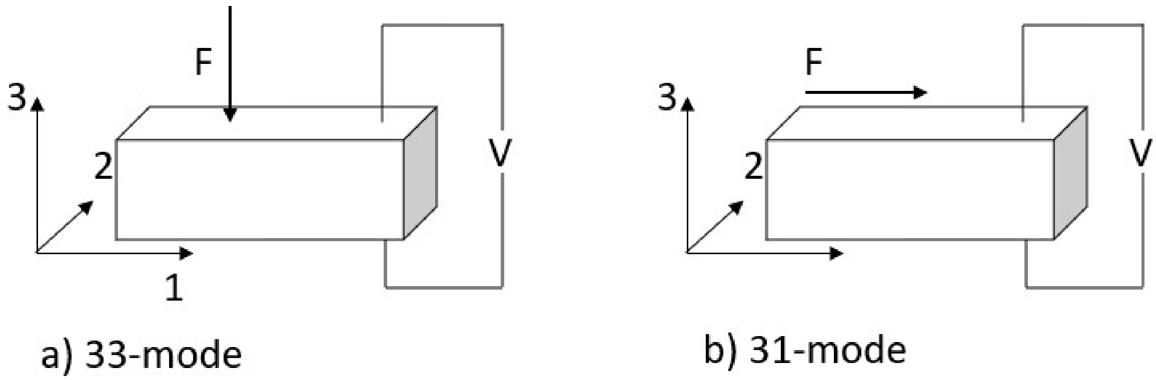

FIG. 2. Piezoelectric vibrational modes. Figure adapted from[27].

B. Geometrical Configuration of Piezoelectric Energy Harvesting

There are different types of piezoelectric transducers: Cantilever Beam, Circular Diaphragm, Cymbal type, and Stack type. Each one present their own features and advantages for a specific scenario[28]. In the same way, disadvantages are visible and always present for each type of harvester. For example, normally for vibration energy harvesting one of the most studied piezoelectric structures are unimorph and bimorph cantilever configurations, obtaining high power efficiency[28,29]. A schematic representation of the cantilever beam configurations can be observed in figure 3. The cantilever beam configuration is one of the most common due to the high mechanical strain during vibration. A cantilever made of a thin layer of piezoelectric material, bonded to a non-piezoelectric layer that act as a conductor for the produced charge[30]. Figure 3a shows a unimorph device, whereas 3b contain two layers of piezoelectric material and is known as bimorph structure. Unimorph generates highest power at low load resistances and excitation frequencies, while bimorph devices generates higher power at medium and high load resistances and frequencies[31]. The bimorph structure doubles the energy capacity without a significant increase in volume of the device, therefore, this latter type is more used for some piezoelectric energy harvesting systems[26]. A proof mass is normally attached to a free end of the cantilever (Figure 3c)), in order to adjust the resonant frequency of the system, giving rise to the fact that the energy output mainly depends on the proof mass subjected to the mechanical stress[32,33] As the stress applied for a 31-mode configuration is not along the polar axis, the 33-mode is, therefore, larger for a given material. Therefore if we use an interdigitated electrode (Figure 3d)) in 33-mode, a higher energy production can be achieved[34]. In this design, alternate layers of positive and negative electrodes are placed on the surface of the piezoelectric layer. These electrodes direct the electric field laterally in the layer, making the layer polarized in the lateral direction, such that the stress that is applied to the layer is parallel to the polar axis of the piezoelectric, enabling the primary charge constant 33-mode[30,32].

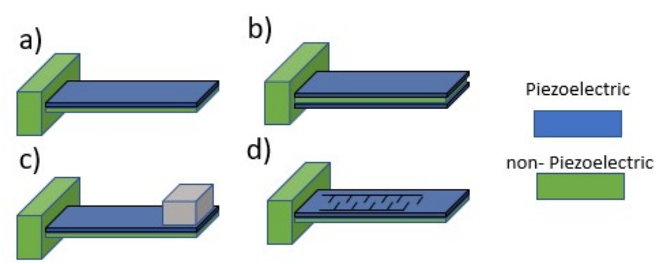

FIG. 3. Example of cantilever beam transducer. a) unimorph cantilever; b) bimorph; c) cantilever with mass at its free end; d) cantilever with interdigitated electrodes. Figure adapted from[35].

III. PIEZOELECTRIC MATERIALS

The performance of a PEH system is mostly influenced by the type of material selected for such system. Piezoelectric materials must not have a center of symmetry, which means that when applying stress a net polarization is produced, having a voltage difference between the two surfaces of the crystal where the stress is applied[36]. A wide range of materials including organic, inorganic, composites and bio-inspired materials have been investigated for piezoelectric energy harvesting[37]. It is important to highlight that some factors that affect the properties of piezoelectric materials are the strain constant, induced polarization, voltage constant, dielectric constant, electromechanical coupling factor, among others. When choosing a piezoelectric material, we have to look not only on the properties mentioned above, but also other parameters like application frequency, design flexibility, availability[38]. Often single crystals (such quartz) present high acoustic quality, can cost more than some piezoceramic materials, which produce a larger piezoelectric response but the display limited resolution of the oscillating frequency. Nevertheless, one of the most common used material is found to be lead-based, but due to the toxicity of lead, this material has been replaced for lead-free like $BaTiO_3$[12,39]. Here, we are going to classify piezoelectric materials in four different classes: Organic materials, Inorganic materials, Composite, and bio-inspired piezoelectric materials.

A. Organic Materials

Organic materials are characterized for their abilities of being flexible, durable and easy to process[40]. Normally, organic piezoelectric materials are classified into organic piezoelectric and traditional piezoelectric polymers. In general, organic piezoelectric materials present a good number of advantages, such as a relative easy synthesis process, structural diversity, dipolar orientation, intrinsic dipole moment, improved biodegradability, which give an improved electromechanical behavior[41]. Although the piezoelectric coefficient d in polymers is lower than for some ferroelectric ceramics, polymers present a relative low permittivity, which makes them to have an acceptable FoM to work with[42]. One of the most studied piezoelectric polymer material, include poly(vinylidene fluoride) (PVDF). These organic piezoelectric polymers present two main types, semicrystalline (the majority) and amorphous polymers[43]. Amorphous polymer chains present a glass transition property that may affect d_{ij}, making these polymer chains responsible for the piezoelectric effect[44]. In the case of organic piezoelectric materials, they are attractive due to their light-weight nature, low-cost, mechanical flexibility, and environmental friendly, which can be used for flexible and sensor-electronic device[45].

B. Inorganic Materials

Many natural materials like quartz, exhibit a specific crystalline structure that favours the piezoelectricity effect[1]. Perovskite structures are one of the most commonly system that posses piezoelectric effect, which present a prominent piezoceramic crystal structure with very good performance. In this structure, there are various ferroelectrically-active non-cubic phases due to the fact that a cubic phase at a low temperature can be easily distorted and present highly symmetrically distributed atoms that allow the deformation of the unit cell easily, which does not contain an inversion center, and therefore can be highly piezoelectric.[46,47]. In the 20^{th} century, the first piezoelectric ceramic, $BaTiO_3$ (BT) was discovered[48]. After observing that the polycrystalline material can hold permanently piezoelectric behaviour after applying an electric field, several efforts were devoted to fabricating high-performance piezoelectric generators[49]. Takahashi et al.[50] fabricated high-density and nano-domain BT that presented a dielectric constant of 4200, and piezoelectric constant d_{33} = 350 pC/N[51].

C. Composite Materials

Composite piezoelectronic materials are developed to overcome pure ceramic and polymer materials limitations[52]. Piezoelectric ceramics present an outstanding performance, but their intrinsic brittleness limits their application when we need flexible devices. On the other hand, piezoelectric polymers present high flexibility but poor piezoelectric properties which limits the applications in high energy density[53,54]. For example, lead zirconate-lead titanate (PTZ) present a high performance in piezoelectric characteristics, with high charge coefficient in the 33-mode, but the applications are very limited due to the stiffness of the material[55]. However, a composite of PZT/PVDF present similar flexibility than a pure PVDF but a greater piezoelectric coefficient than the natural PVDF[56]. Siddiqui et al.[57] developed a piezoelectric nanocomposite based on BT nanoparticles that are embedded into a highly crystalline PVDF-PTrFE. The highly crystalline properties of the composite was because of the polymer, and the high piezoelectricity because of the BT nanoparticles, reaching an output voltage of 9.8 V and output power density of 13.5 $\mu W/cm^2$. A general review of piezoelectric composites for energy harvesting applications can be observed by Mishra et al.[26]

D. Bio-inspired Materials

Natural biological materials like sugar cane, cellulose, collagen fibrils, bones, hair, etc. can present piezoelectric properties[2]. Besides this, biomaterials generally present a non-toxic, biodegradable and biocompatible nature, which make bio-inspired piezoelectric materials an optimistic alternative for harvesting energy[58]. A large natural polymer that exhibits high piezoelectric coefficient (26-60 pC/N) is cellulose, which also present biocompatible and biodegradable characteristics[59]. Another example is a bio-waste eggshell membrane that was proposed as a piezoelectric material by Karan et al.[60], which exhibit a piezoelectric coefficient of 23.7 pC/N. This piezoelectric nanogenerator has an output voltage of 26.4 V, converting 63% of the energy. The system can be enhanced by the series and parallel connection of five nanogenerators that can light up to 90 LEDs.

IV. APPLICATIONS

The continuous progress in the research of nanomaterials, allowed to develop a large number of piezoelectric generators, which can be designed according the necessity on the field, from materials with high flexibility, durability, stretch-ability, high performance, biocompatibility, etc.[61]. In this section, we are going to give a general overview of the application of piezoelectric energy harvesting, covering a wide area of studies of energy harvesting at nano and mesoscale, allowing to work in applications at nanoscale like nanosensors or in mesoscale like roads which can give a large amount of energy harvested. Many areas like transportation, in water applications, aerial applications, biomedicals, wearable, implantable electronic and others are going to be discussed to give a broad scope of the application of piezoelectric generators.

A. Transportation

When we talk about transportation, there exist several areas where piezoelectric materials can work for the harvesting of energy. For example, Li et al.[61] tested the piezoelectricity generating capacity of road pavement, with a tracking wheel-pressure. He found that a voltage of 65 V can be achieved, 0.8 kW/h electric capacity can be produced and this would be sufficient to power some traffic signal lights or others. In Israel, Innowattech company uses piezoelectric elements on asphalt, to harvest the ambient vibrational energy from the traffic[62]. Regarding the application in pavements, the analysis has been divided into mathematical analysis[63], laboratory test[64], numerical simulations[65], and field tests[66]. In the same way, there exist many other areas where mechanical energy can be absorbed and converted into electrical energy such as rails, speed bump, bridges, and of course vehicles that contain several parts[67].

Rail Ways

A piezoelectric generator to harvest rail-borne energy of rail system, has been considered by Gao et al.[68]. In the experiment, they simulated the normal conditions of the rail system, achieving a 4.9 mW output power and 22.1 V output voltage with a 100 kΩ load impedance. There are several works related to the research on energy harvesting in railway systems using piezoelectric technology[69].

Bridges

When vehicles pass through a bridge, there is vibrational energy that can be converted into electrical power by energy harvesters. Karimi et al.[70] developed a cantilever beam type to harvest energy from bridge vibrations. It was found that the optimal load resistance at 13.5 Hz as the frequency of the generator, was 200 kΩ, which gives a maximum power of around 35 μW. It was determined that the generated power output using piezoelectric energy harvesters, is usually low for a individual piezoelectric transducer when one vehicle goes through the bridge, therefore to have a reliable and efficient methodology, multiple sensor arrays must be arranged under repeated traffic loading[71].

Speed Bumps

Piezoelectric energy harvester can be installed inside speed bumps to convert the kinetic energy generated by the traffic passing over the speed bump. Chen et al.[72] installed a harvester inside of a speed bump, consisting of 48 piezoelectric unimorph cantilevers, a platform with 48 bar, 3 springs, and a spring substrate (e). The efficiency of the energy harvesting circuit was 74%. A general overview of energy harvesting implying speed bumps can be observed by Castillo-Garcia et al.[73].

B. Vehicles

There is a big portion of the fuel energy that is lost in the form of heat and mechanical energy when a car is overcoming the resistance from friction and air[67]. This mechanical energy can be extracted from many parts such tires, engine, suspensions, and converting it into electrical energy that could power sensors improving the autonomy and efficiency of the vehicle, and at the same time decreasing economic and enviromental cost[74].

Engine

Internal combustion engines produce torsional vibration that can be harvested by piezoelectric generators and produce electric power. From a cantilever beam attached to the surface of a rotating shaft can generate around 14 μW electrical power, having the possibility to power wireless transducer or sensors[75].

Tires

The necessity of having a sensor mounted on a tire is gradually increasing since tires are one of the most important components for driving safety[76]. Esmaeeli et al.[77] used a rainbow-shaped piezoelectric energy harvester on the inner layer of a pneumatic tire, powering a tire pressure monitoring system, therefore overcoming associated problems to the use of batteries for powering this sensors. Lee et al.[78] developed a energy harvesting system in the tire of a car using piezoelectric material. They applied the system to a Hyundai motor, generating 380.2 μJ and storing 34.5 μJ, which correspond to a storage efficiency of 9.07%. The power obtained from the energy harvester proposed in the study was 1.37 μW/mm^3, which has been optimized and can be improved by the reduce of leakage of capacitors, impedance matching and others[79].

Suspension

Suspension system is one of the most important components for traveling on vehicles, if you want the minimum disturbance generated by road irregularities, braking and accelerating forces, centrifugal forces on turns and others[80]. Xie and Wang[74] worked on a mathematical model for a piezoelectric bar generator that absorbs vibration and motion energy from the suspension system. The output power that the model can reach is up to 738 W, with a piezoelectric bar of 1.5 cm and 10 cm of width and height respectively.

C. Aerial Applications

Wind is a good source of energy supply for many characteristics, like clean and environmentally preferable[81]. Many of the energy that can be harvested from wind, can be found in low scale for self-power some electronic devices, or in big scale taking advantage of the environment[82]. Wu et al.[83] used an effective wind energy cantilever subjected for harvesting cross wind, obtaining an energy output up to 2 W by manipulating the resonant frequency of the harvester with mass on the tip. Xie et al.[84] worked on a piezoelectric energy harvester in high-rise buildings, taking advantage of the large vibrations produced by wind, reaching to a power up to 432.2 MW. Petrini and Gkoumas[85] developed a piezoelectric generator that harvested energy from flow-induced vibrations inside of a heating, ventilation and air conditioning system. The material was capable to power a humidity and temperature sensor, and depending of the aerodynamics of the fin, the output power that are in the range of 200-400 μW, which is sufficient to power the temperature sensor. Several methods of piezoelectric wind energy harvesting and applications are discussed by Zhao and Yang[86].

D. In-water Applications

We know that the majority of the earth's surface is covered by water, which makes energy harvesting from fluid an attractive field. Wang et al.[87] have studied a hydraulic pressure system that works with fluctuations as sources of energy for harvesting with piezoelectric materials. The ocean provides a continuous flows of large mass of water, which the breaking wave force can be harvested by piezoelectric materials, and is predicted to provide around 885 TWh of electrical power[88]. Another in-water application is fish-tags, which can study the migration patterns and movements of some fish species, by implanting a sensor tag, which will be wireless communicated and powered by the energy harvesting of the fish swimming[89].

Viet et al.[90] designed a model to harvest energy from water waves with a floating energy harvester using piezoelectric effect. Their simulation showed that for a 2 m wave amplitude and 6 s period, the power harvested can be up to 103 W.

E. Smart Home

Nowadays, there is more and more implementation of technology at houses or buildings, in order to achieve a smart environment that can make the place more efficient. A clear example can be harvesting energy from steps by inserting piezoelectric generators into the floor. Puscasu et al.[91] harvested energy from steps by piezoelectric generators. They used a 50 x 50 cm^2 energy-harvesting tile, which generates 2.4 mJ energy per step, even having an outstanding 10 million compression cycles before any decay in the performance. Heel-strike energy harvesting showed that a person walking at a 2 steps per second, generates 67 W of power, which can be harvested as electrical power of 5 W[92]. Kim et al.[93] developed a floor tile that exhibited an output voltage of 42 V and a current of 52 μA, which successfully operated a wireless transmitter sensor node.

F. Body movement

Generally, human body movements can result in two kinds of mechanical energy that can be scavenged. One is the continuous activities such as breathing and heart beating, while the other is related to discontinuous movements, like walking and joint movements[94]. An advantage of using piezoelectric materials, is that they have the ability to directly convert mechanical energy from human motion, into electrical signals without any external input[95]. Body joints contain high motion amplitude, large impulse force, fast angular velocity, and high frequency that are used daily in human activities[96]. The knee is one of the joint that produces the highest biomechanical energy since it has the largest torque in comparison to other joints, and a plucking-based harvester, can scavenge rotational energy from the knee during a normal walk, achieving output power of 17 mW[97]. The recent advances in piezoelectric energy harvesting, have allowed to start applications of harvesting energy from the movement of the human body, that can power autonomous wearable devices[98]. The human body is full of movements that involve mechanical energy, attaching piezoelectric generators to different part of the body. Kim et al.[99] designed a piezoelectric generator that can produce a peak output voltage and output power of 22 V and 40 μW respectively, under periodic mechanical push force. Depending of the area where the device is attached, and the different human movements, it generates different quantities of energy, for instance on the foot can generate 2.5 V, 1.98 V on the elbow, and 1.05 V on the knee.

Walking activity

The process of walking can produce the largest amount of power in comparison with other human motions, a 68 kg man is able to generate 67 W when walking at a speed of two steps per seconds[100,101]. Qian et al.[102] developed a a two-stage force-amplification mechanism, which was able to achieve an average output power of 11.0 mW for a frequency of 1.0 Hz. The peak of the output power was 31.7 mW.

Upper limb movements

The upper limb is an attractive location to generate energy for fast battery charging needs or self-power devices. Upper limb are involved in many activities like housekeeping, playing instruments, sports or even working with computers[100]. During normal walk, the arms generally swing back and forth, with a certain bending which suggest that it generates high mechanical energy. Li et al.[103] designed a wearable vertical vibration device, to generate electricity from the joint in the elbow. The joint rotation allowed the release and pull cycle, where the ultra low frequency limb movements, can result in high resonance up to hundreds of Hz. A peak voltage of 7.5 V and a maximum output power of 0.457 μW were obtained at maximum movement conditions.

Composite materials are one of the most used materials to achieve high power density for harvester from the hand and wrist. Polymers with good flexibility are more suited to harvest on the arm and shoulder, because they allow a larger range of stretching motions[104].

G. Self-Powered Biomedical Devices

Biomedical devices are increasingly needed due to advances in technology and the many applications they can have, which can serve as diagnostic tools or treatments for any health issues, improving human life quality[105]. Recent innovations has lead to develop biomedical devices like cardiac pacemakers, cardiac monitors, cardioverter defibrillators, artificial retinas, and cochlear implants[106]. Piezoelectric energy harvesting is an ideal alternative when we talk about the use of this biomedical devices, because the major inconvenient of these devices are the limited battery life, which can be solved by implementing self-powered biomedical devices, reducing physical and financial problems to the patient, avoiding extra surgeries for the replacement of the battery or any associated problem[107,108].

For example, cardiac energy harvesting have been developed in power pacemakers in order to replace the batteries[106]. Heartbeat vibrations can power a pacemaker using a fan-folded piezoelectric structure, having several piezoelectric beams stacked, generating more than 10 μW of power, sufficient to power the pacemaker[109]. Likewise, Zhang et al.[107] developed a pulsating energy of ascending aorta using a piezoelectric generator based on PVDF film. The generator could reach a maximum output voltage of 1.5 V and current of 300 nA with a blood pressure of 160/105 mmHg, which is sufficient to charge a 1 μF capacitor to 1.0 V. An updated review about the state of energy harvesters for wearable electronics and biomedical devices can be seen by Hasan et al.[110].

V. CONCLUDING REMARKS

In this paper, we presented a general overview of the status of piezoelectric energy harvesting, reviewing the principles of the piezoelectric effect, the characteristics of different system configurations energy harvesting, and different applications. Piezoelectric materials provide a ubiquitous alternative to other forms of energy harvesting from the environment. In general, organic, inorganic and composite materials are employed with the different structure configurations presented here, being the 33-mode with cantilever beam structure one of the most used. Current progress in this field, allow to the development of new energy harvesting techniques, involving new materials, methodology and applications. The continuous research on piezoelectric materials, will enable a new generation of energy harvesters, that take advantage from a large variety of sources from vibration nature, factories or transportation means, to the human body, being the latter one of the most interesting source of mechanical energy to harvest.

Many of the literature used in this review, was selected with the intention of cover a general aspect of the energy harvesting by piezoelectric materials, and where is the current status of the application in the different areas such as transportation, body movement or smart home.

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