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Review Study on Piezoelectric Energy Harvesters and Their Applications

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Abstract:- To minimize the requirement of external power source and maintenance for electric devices such as wireless sensor networks, the energy harvesting technique based on vibrations has been a dynamic field of studying interest over past years. This presents a challenge for the researchers to optimize the energy output of piezoelectric energy harvesters, due to the relatively high elastic moduli of piezoelectric materials used to date. This paper reviews the current state of research on piezoelectric energy harvesting devices for low frequency (0–100Hz) applications. Various key aspects that contribute to the overall performance of a piezoelectric energy harvester are discussed.

***Keywords*:-** Piezoelectric, power sources, optimize energy harvester, Wireless sensor networks.

I. INTRODUCTION

The continuous improvement of semiconductor manufacturing technologies has led to tremendous technological advancements in small electronic devices, such as portable electronics, sensors, and transmitters in the last three decades. In some applications, such as sensors deployed in remote locations or inside the human body, however, replacement of the battery at the end of its service life can be challenging or even unpractical. Therefore, the need for harvesting ambient energy to power the electronic devices in these situations arises. Examples of ambient energy sources include wind, solar, mechanical vibration, and movement of the human body. For small electronic devices, the level of power consumption usually lies in mW or μW range and the size of the powering unit needs to be small in order to accompany the host device.

There are various methods to convert mechanical energy from vibrating or moving objects into electrical energy needed by electronic devices, including electromagnetic induction, electrostatic induction, and the piezoelectric effect. Compared with electromagnetic and electrostatic methods, energy harvesting with piezoelectric materials provides higher energy density and higher flexibility of being integrated into a system and thus has been the most widely studied [1, 2].

II. PIEZOELECTRIC HARVESTERS

In most cases of piezoelectric energy harvesting, the vibration or mechanical energy sources either have low motion frequencies or low acceleration. Cantilever geometry is one of the most used structures in piezoelectric energy harvesters, especially for mechanical energy harvesting from vibrations, as large mechanical strain can be produced within the piezoelectric during vibration, and construction of piezoelectric cantilevers is relatively simple.

Choi et al. [3] developed a thin-film PZT based MEMS power generating device with a high power density. The cantilever-based device has a PZT/Sinx bimorph structure with a proof mass added to the end. From the base-shaking experiment with this device, it was found that the cantilever with a 170×260 μm size can generate 1 μW of continuous electrical power to a 5.2 MΩ resistive load at 2.4 V DC.

Shen et al [4, 5] developed a multilayer PZT cantilever energy harvest device shown in figure 1. The whole structure was based on an SOI wafer, and some Si at the free end was used as the proof mass to reduce the resonant frequency. Low-frequency vibration energy was harvested using the cantilever-based energy generator. The average power and power density at the same measurement conditions were 0.32 μW and 416 μW/cm^3, respectively, when the cantilever was excited at 7.36 m/s^2 acceleration amplitude with a frequency of 183.8 Hz.

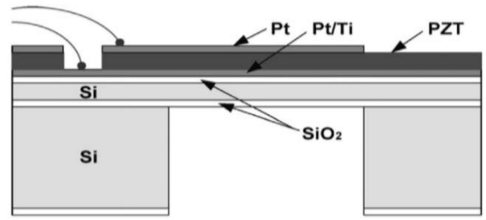

Figure 1: The schematic of piezoelectric energy harvesting cantilever based on an SOI wafer [4]

Roundy et al. [1, 6] designed a two-layer bender mounted as a cantilever beam with a mass placed on the free end, as illustrated in Fig. 2. It was found that the bending elements operated in '31' mode in their model. The design would be capable of generating power with a density of 250 μW/cm^3 at and acceleration of 2.5 m/s^2 with 120 Hz.

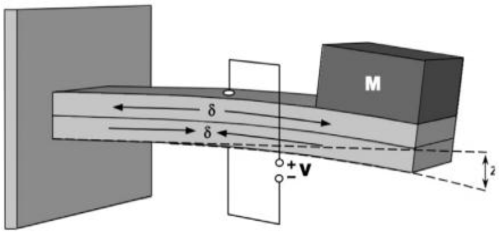

Figure 2: A two-layer bender mounted as a cantilever [6]

Leland and Wright [7] designed a simply supported piezoelectric bimorph vibration energy scavenger, which consists of a brass center shim coated on either side with a layer of lead zirconate titanate (PZT) piezoelectric ceramic. With the axial preload, the resonant frequency of the energy scavenger can be reduced. The prototype of this was developed and the power output of 300–400μW was produced at driving frequencies between 200 and 250 Hz.

DuToit et al. [8, 9] also developed a cantilever-based piezoelectric generator which was composed of the beam structure, piezoelectric elements, electrodes and a proof mass at the end, as illustrated in Fig. 3. The modal analysis for a base-excitation on the cantilever beam was conducted and an actuation model of a typical bimorph was developed. In their model, some assumptions including the Rayleigh-Ritz procedure, Euler-Bernoulli beam theory and the electrical field across the piezoelectric were introduced.

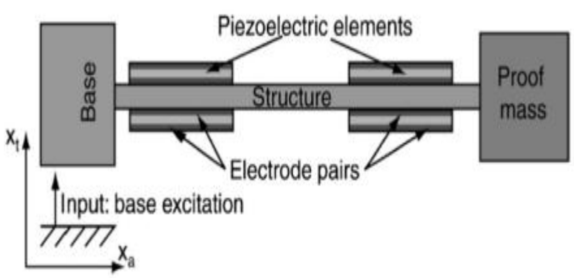

Figure 3. Cantilever bimorph configuration [9]

Erturk et al. [10, 11, 12, 13] derived the electromechanical models for the unimorph and bimorph cantilevered piezoelectric energy harvesters under translational and small rotational base motions. It was found that the closed-from single mode frequency response functions are capable of predicting the system dynamics for a wide range of electrical load resistance. Also, based on analytical modeling of cantilever-based piezoelectric energy harvesters, Erturk and Inman [14] proposed some corrections and necessary clarifications for the existing electromechanical models developed by the previous researchers (Fig. 4).

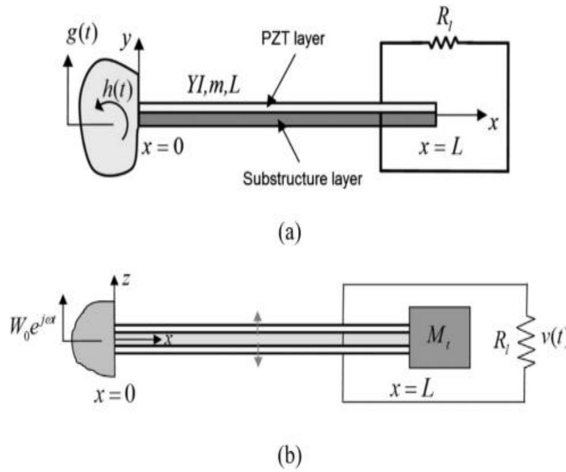

Figure 4. (a) Unimorph piezoelectric energy harvester, (b) Bimorph piezoelectric energy harvester [14]

Roundy et al. [15] developed PZT as a rectangular cantilever and found the triangular trapezoidal profile can distribute more evenly, and the trapezoidal geometry can supply more than twice the energy than the rectangular cantilever, and thus the size and cost of the bimorph can be reduced. Normally, the resonant frequencies of the conventional cantilevered beams are not close to each other.

To solve this problem, Erturk et al. [16] developed an electromechanical model with an L-shaped structure with a combination of one horizontal and one vertical thin beam with two lumped masses. The substructure and piezoceramic layers were geometrically uniform along their longitudinal directions. In this way, the structure can be tuned to have the first two resonant frequencies relatively close to each other, which contributes to a broader band energy harvesting performance.

Elfrink et al. [17] designed a series of piezoelectric device wafers with different dimensions to cover a broad frequency range from 200 Hz to 1200 Hz. The aluminum nitride was chosen as a piezoelectric material because of its easy processing property compared with PZT. For the unpacked devices with different dimensions, a maximum output power of 60μW was measured at an acceleration of 2.0g and resonance frequency of 572 Hz.

Chen et al. [18] proposed an electricity generator with a novel structure which uses one-dimensional phononic piezoelectric cantilever beams (PPCBs). It was found that the width of the vibration band gap can be increased with the mass. Also, it was shown that sticking some PZT patches on those cells could improve the efficiency of broad vibration energy harvesting (Figs. 12 and 13).

Roundy et al. [15] used a multi-degree-of-freedom bimorph system which consists of a piezoelectric beam with three masses and four springs. Using the system, the bandwidth of the scavenger was improved from 6 Hz to 24 Hz, and it was also shown that the total energy output would increase because no power of the tuning actuator is needed once the frequency is tuned.

Wang et al. [19] developed a piezoelectric circular diaphragm array which consisted of four plates with parallel connection. Compared with the single plate, it was shown that the array in parallel connection through 4 separate rectifier circuits can achieve much more energy. The experiment results showed that a power of 27.2 mW was obtained at 150 Hz across an 11 kN optimal resistor under a pre-stress of 0.8 N force and an acceleration of 9.8 m/s^2.

Ericka et al. [20] designed a unimorph membrane transducer to harvest energy from mechanical vibrations in a dynamic environment. The piezoelectric membrane consisted of multiple layers but only a bottom non-active layer and an active layer of piezoelectric material attached to the upper side of the non-active layer were used. With the experiment using the piezoelectric actuator moving a macroscopic 25 mm diameter piezoelectric membrane, a power of 0.65 mW was generated at 1.71 kHz across a 5.6 kΩ optimal resistive load for an 80 N force [21].

Clark and Mo [22] presented a general pressure-loaded piezoelectric unimorph diaphragm plate including a piezoelectric layer bonded to a substrate. The piezoelectric layer was assumed to be covered on the top and bottom with an electrode. The expressions of generated energy were derived with specific boundary conditions, piezoelectric coverage conditions, and electrode conditions. For a diaphragm plate with 1.27 cm diameter, it can provide more than 10 mW power for the sensor device.

Rezaeisaray et al. [23] designed a multi-degree of the micro-energy harvester, in which the proof mass of the structure was suspended by two beams to the device frame with a rectangular shape (Fig. 5). With this structure, the piezoelectric element can have large deflections for a given base excitation, and also the first three resonant frequencies of the vibration were in the low ambient vibration frequency range. With the experiment on ambient vibration energy harvesting, a maximum power output of 136 nW for a load resistance of 2 MΩ was found that can be achieved for a base excitation of 0.2 g at 97 Hz.

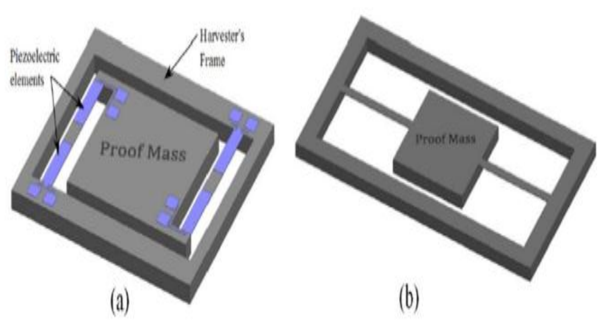

Figure 5: Rectangular fixed beam the energy harvesters [23]

Moreover, the MIT Media Lab [24] introduced a laminate of piezoelectric foil shaped into an elongated hexagon. It was a bimorph structure consisting of a central 2-mm flexible plastic substrate and 8- layer stacks of 28 µm polyvinylidene fluoride (PVDF) sheets sandwiched atop and below. The objective of designing such a transducer with a hexagon was to conform to the footprint and bending distribution of a standard shoe sole when the bimorph stave was mounted under the shoe insole. With the bending of the stave, the PVDF sheets could produce voltage through the dominant '31' longitudinal mode. For the 0.9 Hz walking pace at a 250 kΩ load, it was shown that the PVDF stave could produce an average power of 1.3 mW [25].

Xu et al. [26] presented a cantilever beam and cymbal transducer combined structure as shown in Figure 6. This study combined the flexibility of cantilever beams and the force amplification of the cymbal structures in order to obtain high power output at a low frequency. A prototype, constructed with 25 x 5 x 1 PMN-PT element, a 35-mm copper cantilever, and a 4.2-g tip mass, generated a maximum power of 3.7 mW under a harmonic excitation of 3.2 g at 102 Hz.

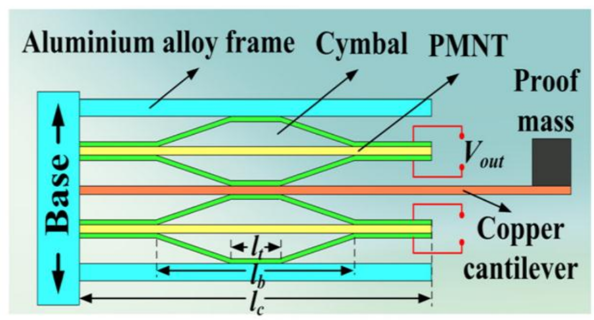

Figure 6. A cantilever driving low-frequency [26]

In 2017, Zou et al. [27] explored a combined structure of cantilever and flextensional transducers and introduced a nonlinear magnetic force into the system. As shown in Figure 7, the proposed harvester consists of a cantilever beam coupled with flextensional transducers using magnets. The working bandwidth is significantly extended by the introduced nonlinear magnetic interaction. A prototype (40 x 10 x 1 mm^3 PZT-5H) generated a maximum power of 387 mW under a harmonic excitation of 0.4 g at 9.9 Hz.

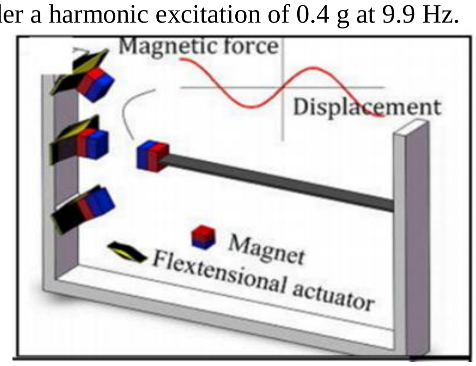

Figure 7: A nonlinear compressive-mode PEH with magnets [27].

Wu et al. [28] developed a barbell-shaped PEH with the high-temperature piezoceramic $BiScO_3$-$PbTiO_3$. Figure 8 shows the barbell-shaped structure that also employs the cantilever configuration. The structure was proposed to overcome the failure of the epoxy bounding layer and the piezoelectricity decay of conventional cantilever PEHs in high-temperature and large amplitude-vibration circumstances. A prototype was made of a ring piezo stack (inner diameter 8 mm; outer diameter 21 mm; thickness 20 mm), a 125-mm long steel shaft, and a tip mass of 100 g. The experimental data demonstrated that under a harmonic excitation with a peak-peak amplitude of 1 g, the prototype generated a maximum power of 4.76 mW at room temperature, and the power output was doubled in a high-temperature range (150 ^{0}C–250 ^{0}C).

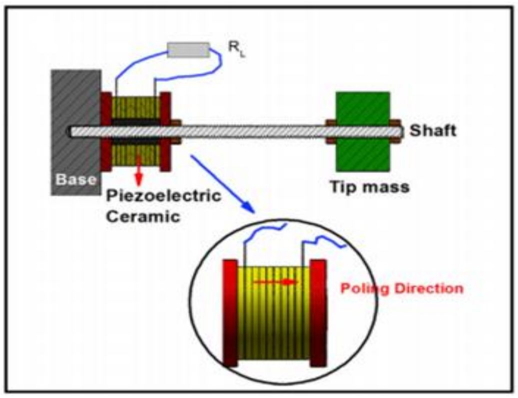

Figure 8. Barbell-shaped high-temperature PEH [28].

Yang et al. [29, 30] developed a high-performance compressive-mode energy harvester, the proposed harvester consists of a pair of elastic beams, two mass blocks, two bow-shaped plates, and a center piezoelectric plate. While working, the base vibration is first transferred through the elastic beams and absorbed by the mass blocks at the center. The compressive mode was therefore suggested for designing high-performance energy harvesters. A prototype was fabricated with a PZT-5H plate of 40 x 15 x 0.5 mm^3 and a mass of 100g. Under a harmonic excitation with an amplitude of 0.3 g at 22.7 Hz, the prototype108 produced a maximum power of 30 mW, corresponding to an average power of 15 mW as shown in figure 9.

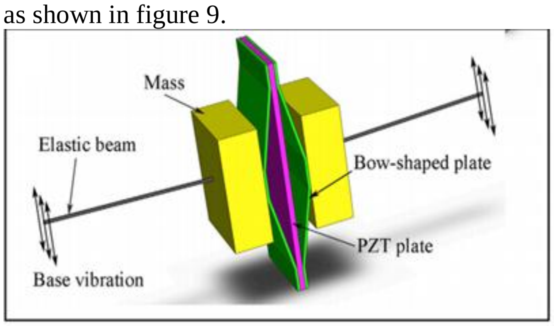

Figure 9: High-performance compressive-mode piezoelectric energy harvester (HC-PEH) [29].

To improve power output, Wang et al. [31] proposed a flex-compressive PEH that can be sustained under heavy loads of thousands of newtons (Figure 10). The bow-shaped center shell amplifies and transfers the applied load force to the symmetrically arranged piezoelectric stacks. Under a 4-Hz harmonic excitation with a 600-N amplitude, a maximum power output 17.8 mW was generated by a prototype (piezo stack: 20 x 20 x 36 mm^3).

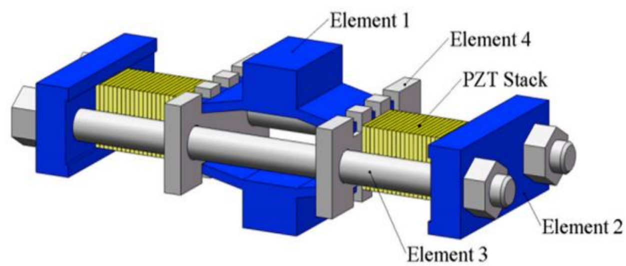

Figure 10. Stack-based flex-compressive PEH [31].

Xu et al. [32] developed a hybrid PEH using the flexure force amplification mechanism (Figure 11). The proposed structure resembles the conventional flextensional transducer but was modified with two outside curved piezo stacks. While a force is applied, the outside curved piezo stacks are compressed (d33); by contrast, the center piezo stack is stretched (d31). It is thus called a hybrid transducer system. A 35.5 x 25 x 10 mm^3 prototype generated 76.6 mW power under a direct normal force excitation of 15 N at 345 Hz, and a 26% energy conversion efficiency was claimed. The ultra-high power output and efficiency are mainly contributed by the flexure force amplification mechanism and the fact that almost all inactive materials have been eliminated in the newly designed structure.

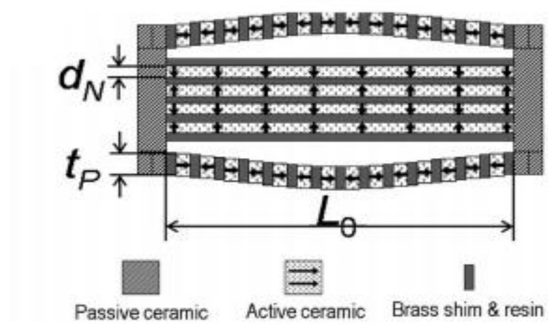

Figure 11. Bending and compressive hybrid PEH [32].

III. Application Based Harvesters

PEHs have been explored in a variety of fields in the past decade, including wearable devices, medical implants, vehicles, and wireless sensor networks. Here we mainly review four specific most widely studied applications: shoes, pacemakers, tire pressure monitoring system (TPMS), and building and bridge monitoring systems.

A. Shoes

In 2014, Zhao and You [33] developed a 1-mW shoe-embedded PVDF energy harvester. In the design, to attain a high power output the authors stacked eight layers of PVDF films together and sandwiched them between two wavy surfaces. As shown in Figure 12, the stacked PVDF film (50 x 80 mm^2) was fixed on the lower plate at both ends, and the upper movable plate was activated by the foot. Once the upper plate was moved down, the PVDF film would be stretched and fit in the wavy surface. Figure 12 shows the irregular response curves of the prototype. Under brisk walking at 1 Hz, the prototype generated a peak-to-peak voltage of 136 V, a peak power of 4 mW, and an average power of 1 mW.

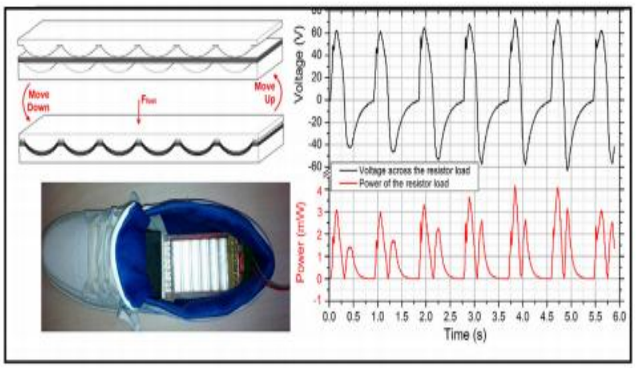

Figure 12. PVDF wavy surfaces and the electrical responses under strike [33].

In 2015, Jung et al. [34] proposed a curved PVDF energy harvester. Figure 13 illustrates the proposed energy harvester. Two 0.1-mm thick PVDF films were attached on each side of an arc-shaped polyimide (PI) (0.2 mm thick) substrate. A pair of such arc PVDF-PI composites were assembled together back to back. A prototype, fabricated with four 70 x 40 mm^2 PVDF films, generated an averaged open-circuit voltage of 25 V and an averaged short-circuit current of 20 mA, during walking at 0.5 Hz.

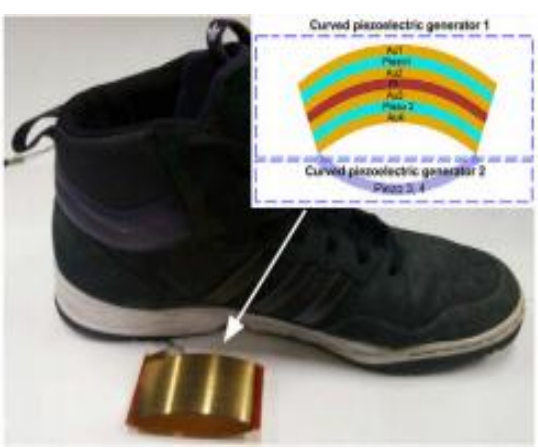

Figure 13. Curved PVDF stack [34].

In 2013, Daniels et al. [35] used a rectangular flextensional transducer to harvest energy from the relative motion between foot and ground during walking (Figure 14). The harvester prototype was placed under the sole of a boot. It generated an averaged power of 2.5 mW under 760 N at 1.4 Hz and was able to power a wireless sensor module independently.

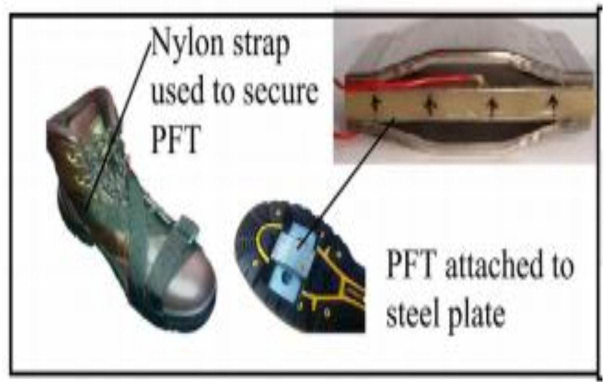

Figure 14. PZT flex transducer [35].

In 2014, Xie and Cai [36] proposed a novel structure, consisting of an amplification mechanism and a stack of piezoceramic bimorphs, as shown in Figure 15. A foot strike applies an impact force on the V-shaped slider in the vertical direction and then causes a movement of the symmetric H-shaped sliders in the horizontal direction. The harvester has four springs that connect the static framework and two clampers to restore the V-shaped slider. A prototype, 105 g in total, was fabricated with 20 PZT-5H bimorphs (30 x 15 x 0.2 mm^3). The prototype was embedded in the heel of a shoe and excited by a user of 68 kg. The maximum RMS power is 18.6 mW at 1 Hz (regular walking pace), and the corresponding power density over the whole volume is about 0.41mW cm^3, which is higher than that in some electromagnetic harvesters [37].

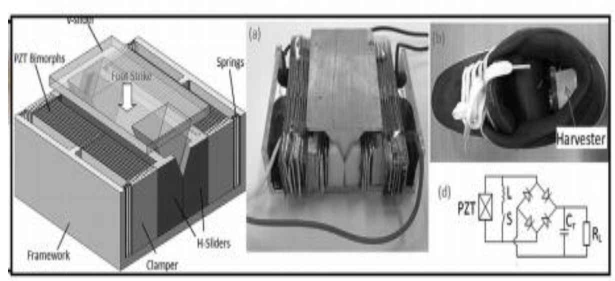

Figure 15. PZT with an amplification mechanism [36]

B. Pacemakers

The wide diffusion of implantable medical devices has been raising the quality of life and life expectancy. As microelectronics develop rapidly, implantable devices require increasingly less energy. Table 1 lists the power consumptions of five medical implants. Most of them require power less than 1 mW, and the artificial cardiac pacemaker only consumes 5–10 mW.

Table 1: Application Devices and their power requirements

Device	Power Requirement
Pacemaker	5-10 μW
Cochlear implant	100-2000 μW
Drug pump	400 μW
Retinal Stimulator	250 mW
Neural Recording	1-10 mW

In 2017 Ansari and Karami [38] proposed a fan-folded structure that consists of bimorph beams folding on top of each other. A 1-cm^3 prototype was constructed with three bimorph beams (PZT-5A layer: 20 x 5 x 0.19 mm^3) and a tip mass of 18.4 g. The prototype was excited by a normal heartbeat waveform from a feedback controlled shaker and generated 16 mW power on average.

Dagdeviren et al. [39] proposed a strain-based harvester for conformal energy harvesting from the contraction and relaxation motions of the heart. Thin PZT ribbons (500 nm in thickness) were sandwiched between metal electrodes, fixed on a thin spin-cast PI substrate layer, and encapsulated with biocompatible materials. The thin-film harvester generated a maximum open-circuit voltage of 4–5 V, and its maximum power density could reach 1.2 mW cm^2 when using multilayer stacks.

Hwang et al. [40] proposed a flexible energy harvester using the high-efficiency single-crystal PMNPT. They optimized the stress-controlled exfoliating process, [43] which transferred a PMN-PT thin film from a bulk substrate onto a flexible substrate. The PMN-PT thin film had an area of 17 x 17 mm^2 and was 8.4 mm thick. It was bonded on a polyurethane (PU)-coated polyethylene terephthalate (PET) substrate. Excited by a linear motor for a strain of 0.36% at a strain rate of 2.3% s^{-1}, the thin film harvester generated a maximum open-circuit voltage of 8.2 V and short-circuit current of 145 mA.

In 2008, Potlay and Brooks [41] designed a PVDF cuff surrounding arterial blood vessels. A small 28 x 8 x 0.028-mm^3 PVDF film was embedded inside a 0.25-cm^3 self-curling silicone cuff. The harvester was tested on a mock artery (latex tubing). On average, 6 nW power was generated from 80 mmHg blood pressure variation through the Φ 12.7-mm latex tubing. In 2015,

Zhang et al. [42] tested a PVDF harvester on the ascending aorta of a pig heart. Similar to Potlay's work, they first evaluated the performance of the flexible PVDF harvester on a latex tube. A 25 x 56 x 0.2-mm^3 prototype showed a maximum output power of 681 nW and a maximum voltage of 10.3 V, respectively, under a pressure variation of 80 mmHg, 160 beats per minute. The implanted harvester is able to charge a 1-mF capacitor to 1.0 V within 40 s. It is roughly estimated that the average power output is about 12.5 nW.

Overall the energy-harvesting technology holds great potential to prolong the lifespan of existing implantable devices with more functions, and support the emergence of new therapies.

C. *Tire Pressure Monitoring System*

The automotive industry has a great interest in small-scale sensors for control and safety applications. To address the power source issue, researchers have started to exploit on-site wasted energy in vehicles. Bowen et al. [43] and Kubba et al. [44] have presented excellent reviews on tire pressure sensors and energy harvesters for TPMS application broadly via the electromagnetic, piezoelectric, electrostatic, and thermal effects.

D. Vibration energy

In 2013, Mak et al. [45] added a bump stop to the cantilever energy harvester to protect the structure from large deformations (Figure 16). A theoretical model was developed to estimate the dynamic responses of cantilever energy harvesters under different conditions. The model estimated that a bimorph with PZT elements of 11 x 5 x 0.18 mm^3 is able to generate an RMS power of 178 mW with a bump stop and 298 mW without a bump stop, respectively, at a driving speed of 64.4 km hr^{-1} .

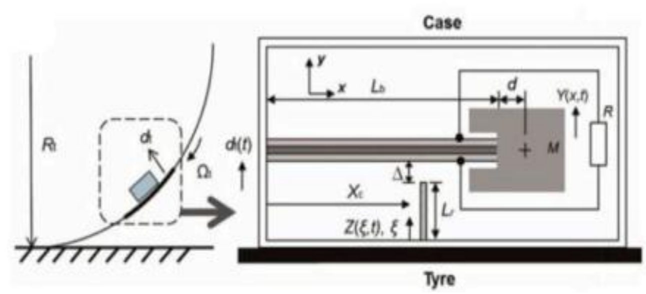

Figure 16. Cantilever harvester with a bump stop [45]

Elfrink et al. [46, 47] fabricated a MEMS cantilever harvester as shown in Figure 17. Under a harmonic excitation of 4.5 g and 1,011 Hz, the 3 x 3 x 1.7-mm^3 AlN unimorph prototype generated a maximum power of 489 mW. When mounted on the tread wall and tested on the road at 70 km hr^{-1} driving speed, the prototype generated a power of 30 mW on average.

Figure 17. MEMS cantilever harvester [46].

Zhang et al. [48] proposed an asymmetric air-gaped piezoelectric cantilever for harvesting energy from tires. As shown in Figure 18, they deliberately introduced a gap into the cantilever to increase the distance between the piezoelectric element and the stress-neutral plane, and thus increased the voltage induced on the piezoelectric element. At a driving speed of 50 mph, the prototype used 35 s to charge a 32-mF capacitor to 8 V and the maximum power was 47 mW.

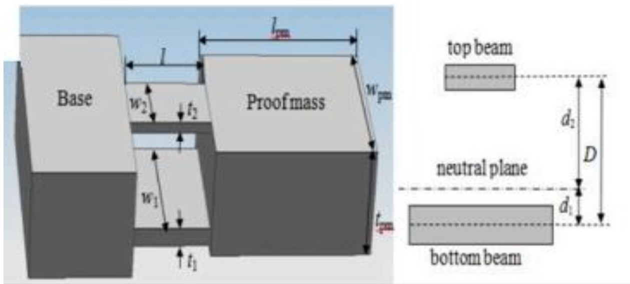

Figure 18. Asymmetric air-gaped piezoelectric cantilever [48].

Sadeqi et al. [49] considered the vibrations caused by the gravitational field in a rotating wheel and ignored the centrifugal effect in the analysis. The prototype was fixed on the rim, consisting of a piezoelectric bimorph supported by four springs at each corner. The resonant frequency of the energy harvester can be tuned by adjusting either the mass on the bimorph or the stiffness of the springs. In-lab tests using a DC motor showed that two response peaks exist around 50 Hz and 70 Hz, and the maximum response voltage is only about 4 V.

Zhu et al. [50] set the cantilever harvester perpendicular to the tread wall surface on the rim to harness vibration energy from the tangential acceleration variation. A prototype was made of a 70 x 7 x 0.32-mm PZT-5H unimorph and a tip mass of 11 g and tested on the outside of a rim. It produced a peak power of 500 mW and an average power of 140 mW at a driving speed of 50 km hr^{-1}. This proposed design faces a serious installation problem. It is difficult to install a vertical piezo beam inside an inflated tire and at the same time keep it from impacts while driving.

Jousimaa et al. [51] fixed a piezoelectric disc on a base with a mass attached at the center. It mainly utilizes the periodic radial acceleration variation of a rolling tire due to the tire radius change in each rotation, as well as the periodic and random vibrations from the tire-road interaction. The prototype was made of a PZT unimorph disc of diameter 32.77 mm (Thunder TH-5C) and assembled with a circuit and a housing. The whole assembly is 35 x 35 x 25 mm^3 and weighs 65 g. The prototype produced 88 mW power on average at the excitation speed of 60 km hr^{-1}.

Wu et al. [52] proposed structure was constructed with a pair of PVDF cantilevers, a seesaw beam, and two magnets at each end. The structure was fixed on a rolling wheel rim and coupled once per round with a permanent magnet fixed on the stationary brake caliper. The swing of the seesaw structure driven by the magnetic repulsive force from the stationary magnet imposes an impulsive force on the PVDF cantilevers. It was claimed that the centrifugal force has no influence on the seesaw structure, and the harvester can work efficiently independent of the rotating speed as shown in figure 19. Excited by a motor rotating at 750 rpm (90 km hr^{-1}), a prototype with a 25 x 12 x 0.1-mm^3 PVDF generated a power of 5.6 mW.

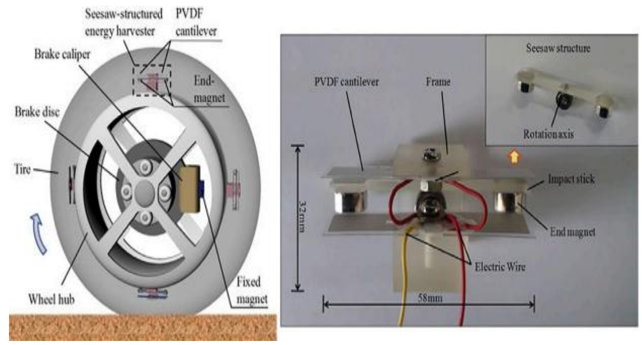

Figure 19. Seesaw-structured energy harvester [59].

In 2014, Roundy and Tola [53] also developed a tube-type energy harvester and exploited the nonlinear dynamic characteristics of an offset pendulum to increase the working bandwidth. A model was developed and predicted a power output of10 mW at 10 mph. In the on-road tests, a prototype was assembled into a TPMS module that consumes 6.25 mW on average to make one transmission per minute. The on-road tests were performed from 10 to 155 km hr^{-1}, and the developed harvester could achieve more than one RF transmission per minute in the speed range.

In summary, the power output of the developed energy harvesters ranges from10 mW to 1 mW in on-road tests. The harvester prototypes have been able to power TPMS for more than one RF transmission per minute. PZT, PVDF, and piezoelectric composites have been utilized in different forms to harvest energy from vibrations in tangential and radial directions, and strain energy on the tread wall. Furthermore, attaching piezoelectric patches on a soft tire causes trouble during maintenance and also alters the elastic characteristics of the tire, which may lead to some unknown problems. In addition to reliability issues, current energy harvesters also face problems including low efficiency, poor environmental adaptability, and short lifespan.

E. Bridges and Buildings

One of the main applications for the wireless sensor networks (WSNs) is civil infrastructure systems such as bridges and buildings. In 2011, Erturk [54] presented a theoretical analysis of energy harvesters in civil infrastructures using two types of excitations: vibrations and surface strain fluctuations. A rosette strain gauge was used to measure the dynamic response of a steel multi-girder bridge (span length: 33 m). The recorded data after a fast Fourier transform analysis indicated that the major harmonic strain component lies at 22.6 Hz and the strain fluctuation amplitude is about 20 microstrain. Under such a harmonic strain fluctuation, the developed model estimated that a maximum power output of 0.13 mW can be achieved by a 30 x 30 x 0.2-mm^3 PZT-5A patch.

Zhang et al. [55] presented a finite element model of a concrete slab-on-girder bridge for simulating the harvester performance with one passing vehicle and a continuous vehicle flow. Xie et al. [56] presented a distributed model similar to that in the work of Erturk [54] for a cantilever energy harvester on tall buildings.

Cahill et al. [57] also discussed the dynamic response of a bridge traversed by trains via a finite element model. Karimi et al. [58] proposed a distributed-parameter model whereby passing vehicles on a bridge were considered as a concentrated point mass and distributed mass. Bhaskaran et al. [59] numerically analyzed an array of cantilever energy harvesters with different resonant frequencies via the finite element method in order to achieve broadband energy harvesting on bridges.

Maruccio et al. [60] proposed a cantilever energy harvester made of electrospinning PVDF nanofibers. They first analyzed the vibration recording of a cable-stayed bridge and identified the excitation source with an RMS acceleration of 5.87 x 104 –0.0108 g and frequency of 0.92–6.39 Hz and RMS voltage of 1.7–15.6 V can be generated by the harvester at different locations of the cable-stayed bridge

In 2013, Peigney and Siegert [61] tested a cantilever energy harvester in situ on a bridge. The spectral analysis of the recorded signals reveals that the main frequency components are around 4 Hz and 14.5 Hz. A cantilever harvester prototype was made of two PZT bimorphs (46 x 33 x 0.76 mm), a steel plate of 220 x 40 x 0.8 mm^3, and a proof mass of 12g. The prototype was mounted at the fixture of a water pipe under the bridge and generated a maximum power of 30 mW.

In 2009, Lee et al. [62] designed a segmented-type PEH for capture energy from the random vibration of the HVAC (heating, ventilation, air conditioning) system in a building. The power spectrum of the measured data from an HVAC system indicated that the vibration is randomly distributed between 0 Hz and 150 Hz with two peaks about 0.2 g at 39 Hz and 0.1 g at 110 Hz, respectively.

In 2013, Zhang et al. [64] proposed a multi-impact energy harvester for low-frequency vibration applications, such as bridges. It is composed of a metal frame, two vertical piezoelectric cantilever beams, and a mass-spring system. The two cantilever beams were manufactured with a triangle bulge at each tip and installed symmetrically on each side of the hung mass on the metal frame. In this manner, the low-frequency vibration (2.71 Hz) of the spring-mass system triggers vibrations of the cantilevers around the resonant frequency (120Hz). It is reported that a prototype, made of 50 x 30 x 0.2-mm^3 PZT plates, generated a maximum power of 7.7 mW under and sinusoidal excitation of 0.29g, 2.71 Hz.

The power output of the developed PEHs ranges from several microwatts to several milliwatts. Most research focuses on the theoretical analysis of cantilever energy harvesters in bridges and buildings under different conditions. There are a few studies that report experimental data, and thus more in situ experiments on bridges and buildings are expected. Furthermore, although there is no strict limitation to size, new methods to scale down energy harvesters are always desirable so that harvesters can be embedded inside bridges and buildings.

IV. CONCLUSION

This paper is devoted to reviewing state-of-the-art research aimed at high-performance piezoelectric energy harvesting. We have comprehensively analyzed different designs, nonlinear methods, optimization techniques, and materials that were explored to achieve high power output and broad frequency bandwidth. A systematic performance comparison has been conducted on recently proposed representative energy harvesters. We found that it is not appropriate to compare different designs by one figure of merit due to the complexity in dynamics, structures, and electromechanical coupling of energy-harvesting systems. Therefore, we propose to evaluate the performance of different energy harvesters using a set of metrics useful to end users, instead of one universal metric. We think performance evaluations and optimization are more appropriately conducted within specific application conditions. Here we have identified four promising applications: shoes, artificial pacemakers, TPMSs, and bridge and building monitoring systems. The excitation characteristics of each application are analyzed and corresponding energy-harvesting methods discussed. Although energy-harvesting technology has been intensively studied for decades, there is still a considerable gap between the achieved performance and the expected performance. Most energy harvesters are developed for a general purpose and tested under simplified harmonic excitations. This approach provides technology that is far from ready to be used in the potential applications. Even though some application-oriented harvesters have been tested in situ, their reliability, stability, and compatibility have not been well examined. More research is expected to deal with these challenges. Likewise, more system-level investigations are warranted, whereby energy harvesters are integrated with power conditioning circuits, energy storage elements, sensors, and control circuits. Such research will facilitate in turning decades of research efforts on energy harvesting into tangible benefits in our daily life. Overall, we have witnessed significant progress in energy-harvesting technology in the last decade. It continues to approach the goal of self-powered autonomous operations of wearable electronics, medical devices, automotive sensors, and wireless sensor monitoring systems.

REFERENCE

[1]. S. Roundy and P. K. Wright, Smart Mater. Struct. 13(5), 1131–1142 (2004).

[2]. S. R. Anton and H. A. Sodano, Smart Mater. Struct. 16(3), R1–R21 (2007)

[3]. Choi WJ, Jeon Y, Jeong JH, Sood R, Kim SG. Energy harvesting MEMS device based on thin film piezoelectric cantilevers. J Electroceram 2006;17(2–4):543–8.

[4]. Shen D, Park J-H, Noh JH, Choe S-Y, Kim S-H, Wikle Iii HC, et al. Micromachined PZT cantilever based on SOI structure for low-frequency vibration energy harvesting. Sens Actuators A: Phys 2009;154(1):103–8.

[5]. Dongna S, Jung-Hyun P, Jyoti A, Song-Yul C, Howard, III CW, Dong-Joo K. The design, fabrication, and evaluation of a MEMS PZT cantilever with an integrated Si proof mass for vibration energy harvesting. J Micromech Microeng 2008;18(5):055017.

[6]. Roundy S, Wright PK, Rabaey J. A study of low level vibrations as a power source for wireless sensor nodes. Comput Commun 2003; 26(11):1131–44.

[7]. Eli SL, Paul KW. Resonance tuning of piezoelectric vibration energy scavenging generators using compressive axial preload. Smart Mater Struct 2006; 15(5):1413.

[8]. DuToit NE, Wardle BL. Experimental verification of models for microfabricated piezoelectric vibration energy harvesters. AIAA J 2007; 45(5):1126–37.

[9]. Dutoit NE, Wardle BL, Kim S-G. Design considerations for mems-scale piezoelectric mechanical vibration energy harvesters. Integr Ferroelectr 2005; 71(1):121–60.

[10]. Erturk A. Electromechanical modeling of piezoelectric energy harvesters. Blacksburg: Virginia Polytechnic Institute and State University; 2009.

[11]. Erturk A, Inman DJ. A distributed parameter electromechanical model for cantilevered piezoelectric energy harvesters. J Vib Acoust 2008; 130(4), [41002].

[12]. Erturk A, Inman DJ. On the mechanical modeling of cantilevered piezoelectric vibration energy harvesters. J Intell Mater Syst Struct 2008;19:15.

[13]. Erturk A, Inman DJ. An experimentally validated bimorph cantilever model for piezoelectric energy harvesting from base excitations. Smart Mater Struct 2009;18(2):025009.

[14]. Erturk A, Inman DJ. Issues in mathematical modeling of piezoelectric energy harvesters. Smart Mater Struct 2008;17(6):065016.

[15]. Roundy S, Leland ES, Baker J, Carleton E, Reilly E, Lai E, et al. Improving power output for vibration-based energy scavengers. Pervas Comput IEEE 2005;4(1):28–36.

[16]. Elfrink R, Kamel TM, Goedbloed M, Matova S, Hohlfeld D, Andel Yv, et al. Vibration energy harvesting with aluminum nitride-based piezoelectric devices. J Micromech Microeng 2009;19 (9):094005.

[17]. Chen Z, Yang Y, Lu Z, Luo Y. Broadband characteristics of vibration energy harvesting using one-dimensional phononic piezoelectric cantilever beams. Physica B: Condens Matter 2013;410:5–12.

[18]. Wei W, Tongqing Y, Xurui C, Xi Y, Qifa Z. Vibration energy harvesting using piezoelectric circular diaphragm array. In: Applications of Ferroelectrics (ISAF/ PFM), 2011 international symposium on and 2011 international symposium on piezoresponse force microscopy and nanoscale phenomena in polar materials. 2011.

[19]. Ericka M, Vasic D, Costa F, Poulin G, Tliba S. Energy harvesting from vibration using a piezoelectric membrane. In: J de Phys IV (Proceedings). EDP Sciences. 2005.

[20]. Minazara E, Vasic D, Costa F, Poulin G. piezoelectric diaphragm for vibration energy harvesting. Ultrasonics 2006; 44(Supplement):Se699–Se703.

[21]. Clark W, Mo C. Piezoelectric energy harvesting for bio-MEMS applications. In: Priya S, Inman D, editors. Energy harvesting technologies. US: Springer; 2009. p. 405–30.

[22]. Sodano HA, Park G, Inman DJ. An investigation into the performance of microfiber composites for sensing and structural vibration applications. Mech Syst Signal Process 2004;18(3):683–97.

[23]. Rezaeisaray M, Gowini ME, Sameoto D, Raboud D, Moussa W. Low-frequency piezoelectric energy harvesting at multi vibration mode shapes. Sens Actuators A: Phys 2015;228:104–11.

[24]. Kymissis J, Kendall C, Paradiso J, Gershenfeld N. Parasitic power harvesting in shoes. In: Wearable computers, 1998. Digest of papers. Second international symposium on. 1998.

[25]. Shenck NS, Paradiso JA. Energy scavenging with shoe-mounted piezoelectrics. Micro IEEE 2001;21(3):30–42.

[26]. 102. Xu, C.D., Ren, B., Di, W.N., Liang, Z., Jiao, J., Li, L.Y., Li, L., Zhao, X.Y., Luo, H.S., and Wang, D. (2012). Cantilever driving low-frequency piezoelectric energy harvester using single crystal material 0.71 Pb(Mg1/3Nb2/3)O3-0.29PbTiO3. Appl. Phys. Lett. 101, 033502.

[27]. Zou, H.-X., Zhang, W.-M., Li, W.-B., Hu, K.-M., Wei, K.-X., Peng, Z.-K., and Meng, G. (2017). A broadband compressive-mode vibration energy harvester enhanced by magnetic force intervention approach. Appl. Phys. Lett. 110, 163904.

[28]. Wu, J., Chen, X., Chu, Z., Shi, W., Yu, Y., and Dong, S. (2016). A barbell-shaped high-temperature piezoelectric vibration energy harvester based on BiScO3-PbTiO3 ceramic. Appl. Phys. Lett. 109, 173901.

[29]. Yang, Z., and Zu, J. (2014). High-efficiency compressive-mode energy harvester enhanced by a multi-stage force amplification mechanism. Energy. Convers. Manag. 88, 829–833.

[30]. Yang, Z., Zhu, Y., and Zu, J. (2015). Theoretical and experimental investigation of a nonlinear compressive-mode energy harvester with a high power output under weak excitations. Smart Mater. Struct. 24, 025028.

[31]. Wang, X., Shi, Z., Wang, J., and Xiang, H. (2016). A stack-based flex-compressive piezoelectric energy harvesting cell for large quasi-static loads. Smart Mater. Struct. 25, 055005.

[32]. Xu, T.-B., Jiang, X., and Su, J. (2011). A piezoelectric multilayer-stacked hybrid actuation/transduction system. Appl. Phys. Lett. 98, 243503.

[33]. 189. Zhao, J., and You, Z. (2014). A shoe embedded piezoelectric energy harvester for wearable sensors. Sensors 14, 12497–12510.

[34]. Jung, W.-S., Lee, M.-J., Kang, M.-G., Moon, H.G., Yoon, S.-J., Baek, S.-H., and Kang, C.-Y. (2015). Powerful curved piezoelectric generator for wearable applications. Nano Energy 13, 174–181.

[35]. Daniels, A., Zhu, M., and Tiwari, A. (2013). Design, analysis, and testing of a piezoelectric flex transducer for harvesting bio-kinetic energy. J. Phys. Conf. Ser. 476, 012047.

[36]. Xie, L., and Cai, M. (2014). Increased piezoelectric energy harvesting from human footstep motion by using an amplification mechanism. Appl. Phys. Lett. 105, 143901.

[37]. Ylli, K., Hoffmann, D., Willmann, A., Becker, P., Folkmer, B., and Manoli, Y. (2015). Energy harvesting from human motion: exploiting swing and shock excitations. Smart Mater. Struct. 24, 025029.

[38]. Ansari, M., and Karami, M.A. (2017). Experimental investigation of fan-folded piezoelectric energy harvesters for powering pacemakers. Smart Mater. Struct. 26, 065001.
[39]. Dagdeviren, C., Yang, B.D., Su, Y., Tran, P.L., Joe, P., Anderson, E., Xia, J., Doraiswamy, V., Dehdashti, B., Feng, X., et al. (2014). Conformal piezoelectric energy harvesting and storage from motions of the heart, lung, and diaphragm. Proc. Natl. Acad. Sci. USA 111, 1927–1932.
[40]. Bedell, S.W., Fogel, K., Lauro, P., Shahrjerdi, D., Ott, J.A., and Sadana, D. (2013). Layer transfer by controlled spalling. J. Phys. D 46, 152002.
[41]. Potkay, J.A., and Brooks K. An arterial cuff energy scavenger for implanted microsystems. in Bioinformatics and Biomedical Engineering, 2008. ICBBE 2008. The 2nd International Conference. 2008. IEEE.
[42]. Zhang, H., Zhang, X.-S., Cheng, X., Liu, Y., Han, M., Xue, X., Wang, S., Yang, F., Smith, A.S., Zhang, H., and Xu, Z. (2015). A flexible and implantable piezoelectric generator harvesting energy from the pulsation of the ascending aorta: in vitro and in vivo studies. Nano Energy 12, 296–304.
[43]. Bowen, C., and Arafa, M. (2015). Energy harvesting technologies for tire pressure monitoring systems. Adv. Energy Mater. 5, https://doi.org/10.1002/aenm.201401787.
[44]. Kubba, A.E., and Jiang, K. (2014). A comprehensive study on technologies of tyre monitoring systems and possible energy solutions. Sensors (Basel) 14, 10306–10345.
[45]. Mak, K.H., McWilliam, S., and Popov, A.A. (2013). Piezoelectric energy harvesting for tyre pressure measurement applications. J. Automobile Eng. 227, 842–852.
[46]. Van Schaijk, R., Elfrink, R., Oudenhoven, J., Pop, V., Wang, Z., and Renaud, M. (2013). A MEMS vibration energy harvester for automotive applications. Proc. SPIE. https:// doi.org/10.1117/12.2016916.
[47]. Elfrink, R., Matova, S., de Nooijer, C., Jambunathan, M., Goedbloed, M., van de Molengraft, J., Pop, V., Vullers, R.J.M., Renaud, M., and van Schaijk, R. (2011). Shock-induced energy harvesting with a MEMS harvester for automotive applications. In Electron Devices Meeting (IEDM), 2011 IEEE International. IEEE.
[48]. Zheng, Q., Tu, H., Agee, A., and Xu, Y. (2009). Vibration energy harvesting device based on asymmetric air-spaced cantilevers for tire pressure monitoring system. Proceedings of Power MEMS, 403–406.
[49]. Sadeqi, S., Arzanpour, S., and Hajikolaei, K.H. (2015). Broadening the frequency bandwidth of a tire-embedded piezoelectric-based energy harvesting system using coupled linear resonating structure. IEEE/ASME Trans. Mechatronics 20, 2085–2094.
[50]. Zhu, B., Han, J., Zhao, J., and Deng, W. (2017).The practical design of an energy harvester considering wheel rotation for powering intelligent tire systems. J. Electron. Mater. 46, 2483–2493.
[51]. Jousimaa, O.J., Parmar, M., and Lee, D.-W. (2016). Energy harvesting system for intelligent tyre sensors. in Intelligent Vehicles Symposium (IV), 2016 IEEE. IEEE.
[52]. Wu, X., Parmar, M., and Lee, D.-W. (2014). A seesaw-structured energy harvester with superwide bandwidth for TPMS application. IEEE/ASME Trans. Mechatronics 19, 1514–1522.
[53]. Roundy, S., and Tola, J. (2014). Energy harvester for rotating environments using offset pendulum and nonlinear dynamics. Smart Mater. Struct. 23, 105004.
[54]. Erturk, A. (2011). Piezoelectric energy harvesting for civil infrastructure system applications: moving loads and surface strain fluctuations. J. Intell. Mater. Syst. Struct. 22, 1959–1973.
[55]. Zhang, Y., Cai, S.C., and Deng, L. (2014). Piezoelectric-based energy harvesting in bridge systems. J. Intell. Mater. Syst. Struct. 25, 1414–1428.
[56]. Xie, X., Wu, N., Yuen, K.V., and Wang, Q. (2013). Energy harvesting from high-rise buildings by a piezoelectric coupled cantilever with a proof mass. Int. J. Eng. Sci. 72, 98–106.
[57]. Cahill, P., Nuallain, N.A.N., Jackson, N., Mathewson, A., Karoumi, R., and Pakrashi, V. (2014). Energy harvesting from the train-induced response in bridges. J. Bridge Eng. 19, 04014034.
[58]. Karimi, M., Karimi, A., Tikani, R., and ZiaeiRad, S. (2016). Experimental and theoretical investigations on piezoelectric-based energy harvesting from bridge vibrations under traveling vehicles. Int. J. Mech. Sci. 119, 1–11.
[59]. Bhaskaran, P.R., Rathnam, J.D., Koilmani, S., and Subramanian, K. (2017). Multiresonant frequency piezoelectric energy harvesters integrated with high sensitivity piezoelectric accelerometer for bridge health monitoring applications. Smart Mater. Res. 2017, https://doi.org/10.1155/2017/6084309.
[60]. Maruccio, C., Quaranta, G., DeLorenzis, L., and Monti, G. (2016). Energy harvesting from electrospun piezoelectric nanofibers for structural health monitoring of a cable-stayed bridge. Smart Mater. Struct. 25, 085040.
[61]. Peigney, M., and Siegert, D. (2013). Piezoelectric energy harvesting from traffic-induced bridge vibrations. Smart Mater. Struct. 22, 095019.
[62]. Lee, S., Youn, B.D., and Jung, B.C. (2009). Robust segment-type energy harvester and its application to a wireless sensor. Smart Mater. Struct. 18, 095021.
[63]. Rhimi, M., and Lajnef, N. (2012). Tunable energy harvesting from ambient vibrations in civil structures. J. Energy Eng. 138, 185–193.
[64]. Zhang, Y., Cai, C., and Zhang, W. (2014). Experimental study of a multi-impact energy harvester under low-frequency excitations. Smart Mater. Struct. 23, 055002.