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The Cutting Edge of Vibration Energy Harvesting Technology

Ruzlaini Ghoni[1,*], Mohd Tarmizi Ibrahim[1], Nik Fakhri Nek Daud[1], Ammar Husaini Hussian[1], Shaiful Rizalmee Wahid[1], Ahmad Farid Ridhwan Zakaria[1],Hamdan Azmi Abdul Aziz[1]

[1] Department of Electrical and Automation, Faculty of Engineering Technology, University College TATI, 24000 Kemaman, Terengganu, Malaysia

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ABSTRACT

Energy harvesting has been around for more than a decade, with continual research tackling the issues of charging and powering up electronic gadgets. Because of its multiple advantages, such as greater mobility and a longer lifespan, the notion of energy harvesting has acquired broad popularity. Researchers are investigating methods to harness the energy created by vibrations from various materials and transducers as part of the energy conservation movement. This paper examines major advancements in vibration energy collecting during the last 15 years. It focuses on the many processes used to collect vibration energy, such as piezoelectric, electromagnetic, electrostatic generators, and MEMs techniques, as well as power management circuits, to enhance various elements of vibration energy harvesting devices from diverse sources. While the research on vibration energy harvesting has grown significantly, this work summarises significant achievements in the subject over the last 15 years and updates prior review publications.

1. Introduction

With the threat of energy crises, one of the most critical challenges to sustainable development is the quest for renewable energy supplies. As a sort of ordinary mechanical wave, vibration happens everywhere in a variety of forms and on a wide range of scales, from human movement to the operation of domestic appliances and machinery in enterprises. Over the last decade, it has emerged as an appealing concept in energy harvesting as a viable low-power source alternative to battery-powered devices.

The technique of gathering energy from one or more surrounding energy sources is known as energy harvesting. Energy scavenging is the process of accumulating and conserving energy for future use. Current advancements in wireless and MEMs technology have shown that energy storage may be an alternative to traditional batteries. Ultra low power portable electronics and wireless sensors use normal batteries as power sources. However, the battery life is limited and relatively short compared to the device's working life. Battery replacement or recharging is inefficient and frequently

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[*] *Ruzlaini Ghoni.*
E-mail address: ruzlaini@uctati.edu.my

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difficult. Energy harvesting methods have also received much attention as a self-powered source for portable devices or wireless network sensor systems.

Transductions based on piezoelectric, electromagnetic, electrostatic, and magnetostrictive techniques are used in current vibration energy harvesting equipment. This article examined the history of vibration energy harvesting and self-powered sensing during the previous 15 years and contemporary developments. It also discusses the field's difficulties as well as potential research objectives. A vibration energy collecting system based on piezoelectrics has been thoroughly examined [1-4]. Aside from piezoelectric materials, several novel strategies for improving material characteristics, transducer architectures, electrical interfaces, and predictive models of vibration energy harvesting devices have been created. As a result, this page seeks to provide a concise summary of the most prominent researchers in the topic and a discussion of the many transduction processes involved.

2. Methods for Harvesting Vibration Energy

Three distinct transduction processes are intensively investigated in vibration energy harvesting: piezoelectric, electromagnetic, and electrostatic transductions. This section will look at how methodologies and MEMs-based structures have evolved over the last 15 years and conversion processes and efficiency.

2.1 Mechanisms of Transduction Based on Piezoelectrics

Because the piezoelectric material can convert ambient vibrations into electrical energy, it is the most prominent energy harvesting material for self-powered wireless network sensor devices. The transduction rate is the most important consideration when choosing a piezoelectric material. The direct and inverse effects are two separate modes of operation for piezoelectric materials. The direct effect is the piezoelectric property of various crystalline minerals (Figure 1), such as quartz, Rochelle salt, tourmaline, and barium titanate, which produces electricity when pressure is applied is employed as a sensor or energy transducer. However, when crystals deform in the presence of an electric field, this is known as the converse effect and is utilised as an actuator. Hooke's law may be used to describe the electrical behaviour of piezoelectric materials, which is expressed as Eq. (1)

Fig. 1. Piezoelectric Crystal [1]

$$D = \varepsilon E \tag{1}$$

Where D is the displacement of charge density, ε is permittivity, and E is the applied electric field’s strength Hooke’s law also states as Eq. (2)

$$S = sT \tag{2}$$

Where S is the strain, s is the compliance, and T is the stress. With the recent proliferation of microscale devices, piezoelectric-based power production will provide a handy alternative to conventional power sources used to power certain types of sensors, actuators, telemetry, and MEMs devices.

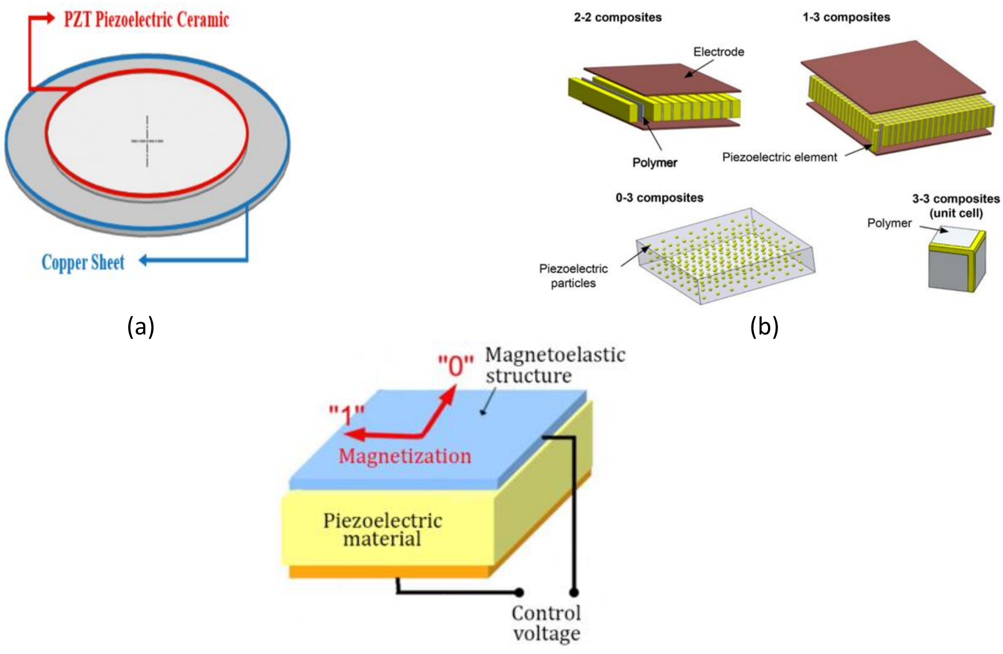
As shown in Figure 2, piezoelectric materials are piezoceramics, piezopolymers, and piezomagnetoelastic. Piezoceramics have excellent energy transfer efficiency and large electromechanical coupling constants, but they are too brittle to be employed as a universal energy transducer. On the other hand, Piezopolymers have lower electromechanical coupling constants but are more stable than piezoceramics. This section will describe the advancement of piezoelectric-based transducers for vibration energy collecting.

Much of the research has emphasised using lead zirconate titanate (PZT) piezoceramics materials in vibration energy harvesting since 2005. It is a piezoelectric material based on metallic oxide developed by scientists at the Tokyo Institute of Technology in 1952. Most of the research has been on detecting the extracted vibration energy using PZT-based piezoelectric transducers such as a circular diaphragm and a bimorph cantilever [5-7]. Meanwhile, [8] used a cantilever beam of aluminium nitride (AlN) as a piezoelectric vibration energy harvester and obtained greater output power within the frequency range of 50Hz – 600Hz with the same piezoceramic.

Bedekar *et al.,* [9] created bimorph cantilever PZT-PZN and PZT-PNN piezoceramics, whereas Harigai *et al.,* [10] created unimorph cantilever PZT-Si piezoceramics, PZT-PZN and PZT-PNN. In contrast, [11] described the use of spring steel cantilever PZT-Mn lead-based piezoceramics. Lead-based piezoceramics were inefficient in producing maximum output power from vibration compared to typical PZT piezoceramics.

Piezoelectric polymer actuators are polymer-based devices that generate significant forces when actuated, particularly in the case of thick polymeric piezoelectric films, with PVDF ferroelectric polymer being a typical material. Many investigations on the application of MFC-Piezoelectric and PVDF [7], [12,13] have been reported.

In studies done between 2005 and 2016, PZT piezopolymer transducers outperformed other piezoelectric transducers in performance efficiency throughout a low-frequency range of 50Hz-150Hz.



(a) (b)

(c)

Fig. 2. Piezoelectric materials include (a) ceramics [14], (b) piezopolymers [15], and (c) piezomagnetoelastic [16]

This section will examine and compare the developments and advancements in the piezoelectric transduction mechanism over the last several years. We would look at the most recent technique, both power production and frequency protection. Table 1 summarizes the use of piezoelectric based transduction.

Table 1
Summary of piezoelectric-based transducers' collection of vibration energy

Author	Year	Generator material	Transducer type	Frequency (Hz)	Output power (mW)	Types of Piezoelectric Materials
[2]	2011	PZT	Diaphragm	150	28	Piezoceramics
[3]	2012	PZT	Diaphragm	113	12	Piezoceramics
[4]	2005	PZT	Bimorph cantilever	50	-	Piezoceramics
[17]	2009	AlN-Piezoelectric	Cantilever beam	572	0.006	Piezoceramics
[5]	2010	PZT-Si	Unimorph cantilever	2.45k	0.1	Lead-based Piezoceramics
[6]	2010	PZT-Mn	Spring steel cantilever	79	0.0112	Lead-based Piezoceramics
[7]	2010	PZT-ZNN	Bimorph cantilever	197.25	0.0491	Lead-based Piezoceramics
[6]	2010	PMN–25PT	Spring steel cantilever	88	0.0126	Single Crystal
[4]	2005	QP-Piezoelectric	Bimorph cantilever	32	-	-
[4]	2005	MFC-Piezoelectric	Bimorph cantilever	108	-	Piezopolymers
[8]	2010	MFC-Piezoelectric	Bimorph cantilever	-	-	Piezopolymers
[9]	2009	MFC-Piezoelectric	Bimorph cantilever	first natural frequency	0.1516	Piezopolymers
[10]	2013	PVDF	Photonic crystal	510	42.1 mV	Piezopolymers
[11]	2016	PZT PMN-PT PZN-PT	Unimorph cantilever	39.5 38 37.5	0.11 0.257 0.43	Piezoceramics Lead-based Piezoceramics Lead-based Piezoceramics
[12]	2018	PZT	Cantilever beam	35	3.65V	Piezoceramics
[13]	2020	PZT	Bimorph cantilever	145	57	Piezoceramics
[18]	2016	Piezoelectric	cymbals		0.016/asphalt	Piezoceramics
[19]	2017	ScAlN-Piezoelectric	Cantilever beam with tip proof mass	86.8	0.00021	Piezoceramics
[15]	2019	LN-Piezoelectric	Spring steel cantilever	32.2	1.54 kV/g	Piezoceramics
[16]	2016	ZnO Nanowire Arrays	Cantilever beam	208	~100 mV	Piezopolymers
[20]	2016	Polypropylene (PP) PVDF				Piezopolymers

This section will examine and compare the developments and advancements in the piezoelectric transduction mechanism over the last several years. We would look at the most recent technique, both power production and frequency protection.

In contrast, research [9,11,21] found that energy harvesters made of single crystals PMN-PT and PZN-PT outperformed those made of PZT ceramics. Increased output power was seen with the novel PZT pattern at low frequency [21-23]. Meanwhile, [24] utilised ScAlN-Piezoelectric at a lower frequency than [9], resulting in less electrical output. Lower frequency utilisation of lead-based piezoceramics of PMN-PT and PZN-PT [21] yielded better results than prior investigations [9-11].

Lead-free piezoceramics, lead-based piezoceramics, and single-crystal piezoceramic materials are the three types of piezoceramic materials [25]. Lead-free piezoceramic is non-toxic but has a lower transduction efficiency than materials based on BaTi3, Bismuth Sodium Titanate (BNT-BKT), and Potassium Sodium Niobate (KNN). On the other hand, lead-based piezoceramics are polycrystalline materials with perovskite crystal structures that have a high piezoelectric effect and low dielectric loss. The fabrication procedure is straightforward and compatible with MEMs manufacturing. They are, however, extremely poisonous due to the presence of lead. Lead-based piezoceramics include Lead Magnesium Niobate-PZT (PMN-PZT), PZT 5A, and Zinc Oxide enhanced PZT (PZT-ZnO).

On the other hand, single-crystal piezoceramics are monocrystals vertically produced on a substrate using the Bridgeman or Flux process with exceptional piezoelectric capabilities that were predominantly employed in sensors and actuators applications. Depending on the growth processes utilised, they may have varied nanostructure shapes. On the other hand, Piezoelectric cymbals extracted the most electrical power from asphalt, giving up to 16 W per asphalt [24].

The most recent piezoceramic-based transducer researchers claimed better findings than the previous ten years and demonstrated a good usage of the piezoceramic-based harvester as an alternative for vibration energy harvesting. The current study indicates an improvement in terms of output power performance. In addition to cymbals (Figure 4), stacks (Figure 5), diaphragms (Figure 6), spring steel, and photonic crystal, most piezoelectric transducers used cantilever beam structures, as indicated in Figure 3.

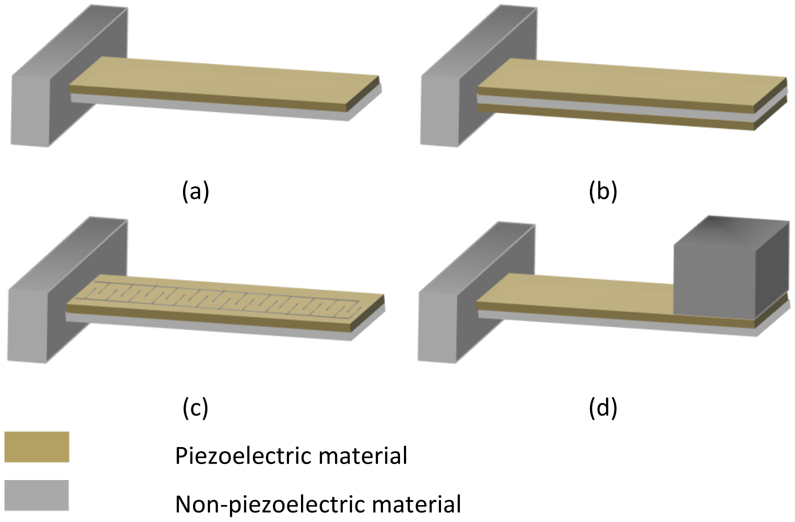


Fig. 3. Various piezoelectric cantilever beam transducer types (a) unimorph; (b) bimorph; (c) piezoelectric cantilever with interdigitated electrodes; (d) piezoelectric cantilever with proof mass at its free end

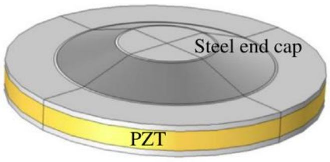


Fig. 4. Cymbal transducers [21]

Fig. 5. Stack piezoelectric transducer [22]

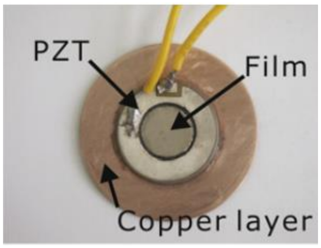


Fig. 6. Circular diaphragm transducer [23]

2.2 Electromagnetic as Vibration Energy Harvesting Transducer

The relative motion of a conductor mass in a magnetic field supplied by a permanent magnet is the basis for electromagnetic vibration energy harvesting. In a coil, the coiled mass often forms an inductor. According to Faraday's law, the AC voltage is created by the relative motion of the mass and the pick-up coil.

$$\varepsilon_v = -\frac{d\phi_B}{dt} \tag{3}$$

where ε_v is the voltage induced and ϕ_B is the magnetic flux. Magnetic field-based vibration energy harvesters include magnetoelectric, magnetostriction, and the Halbach series. The magnetoelectric effect refers to any interaction between a material's magnetic and electric characteristics, whereas magnetostriction is a magnetic material attribute that causes a change in form or dimensions during the magnetization process. As the magnetization of materials varies owing to the applied magnetic field, the magnetostrictive tension rises. On the other hand, A Halbach array is a one-of-a-kind arrangement of permanent magnets that augments the magnetic field on one side of the array while cancelling it to near zero on the other [26]. This configuration was made possible by using a magnetization pattern that rotates spatially.

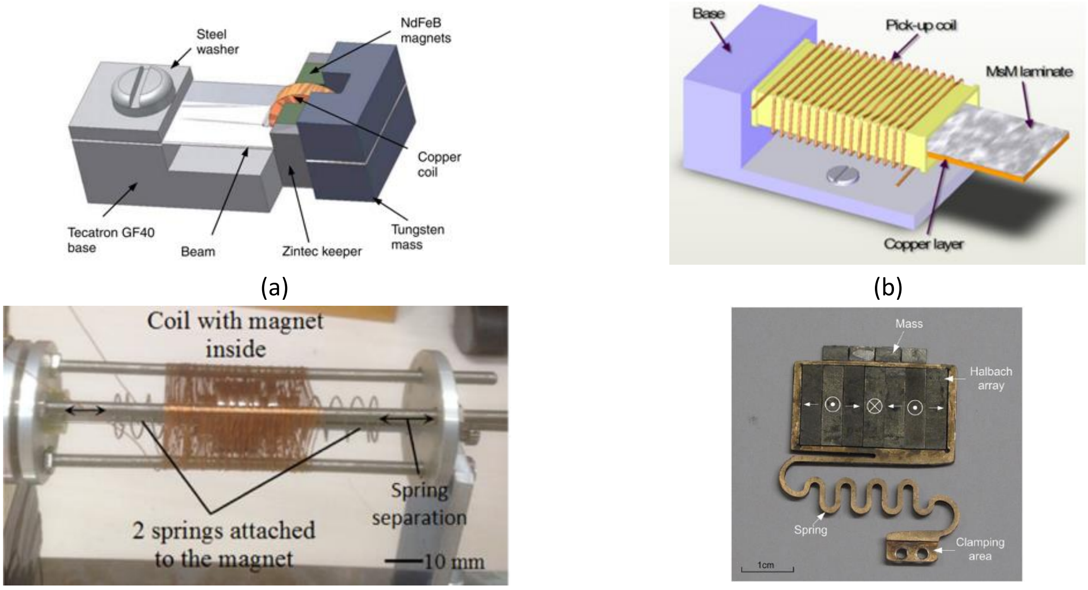
From 2007 until the present, much of the current work on vibration energy harvesting utilising electromagnetic processes has focused on optimising output power from low ambient frequency. A substantial quantity of literature has been published on electromagnetic vibration energy harvesting with the capability of harnessing larger output power [27-34] at a considerably lower frequency [27,28,33,35,36], which led to the vibration energy harvester's improved performance.

Few studies [27-29] reported using an electromagnetic vibration energy storage system with a high power density and a wide bandwidth at low frequencies. An electromagnetic micro-generator customised to function at frequencies ranging from 43 Hz to 109 Hz from an air compressor was tested. Zhang *et al.,* [30] created a 96 W electromagnetic energy harvester comprised of four magnets and three coils. The Halbach array of vibration energy harvesting was researched for its potential to reduce electromagnetic on a large scale. Beepy *et al.,* [37], on the other hand, employed micro electromagnetic at a low frequency. Table 2 summarizes the vibration energy harvesting using electromagnetic transducers.

Table 2
Summary of vibration energy harvesting by electromagnetic materials

Author	Year	Generator material	Transducer type	Frequency (Hz)	Output power (mW)
[20]	2015	Electromagnetic	Coil	10	350
[16]	2013	Electromagnetic	Tip mass	4	11
[38]	2009	Rotary Electromagnetic microgenerator	Cantilever and proof mass	normal walking	0.4166
[39]	2014	Microelectromagnetic	Spring cantilever	65	263
[27]	2007	Microelectromagnetic	Etched cantilever	52	0.046
[28]	2010	Magnetoelectric	Cantilever		
[24]	2008	Magnetostrictive material (MsM)	Coil	58	0.2
[25]	2014	Magnetostrictive material (MsM)	Coil	first natural frequency	9.8
[40]	2012	Halbach array	Coil	45	0.15
[41]	2020	Electromagnetic	-	-	-
[42]	2016	Magnetoelectric	Spring	3.2	0.04498
[29]	2016	Magnetic levitation for a multi-degree of freedom (MDOF)	Coil	4.6–14.5	20.2
[30]	2019	Hybrid (Magnetic levitation and Magnetoelectric)	Coil	1.9	1.46

The electromagnetic 1-D displayed three coaxial permanent cylindrical magnets that generated an electromotive force (EMF) in one or more of its surrounding coils [43]. Abed *et al.,* [33] used arrays of levitated magnets to gather vibration energy in a narrow working frequency range of 4.6–14.5 Hz to address magnetic nonlinearity and electromagnetic damping. Figure 7 depicts many kinds of electromagnetic transducers. [36] created a dual excitation using a nonlinear magnet electrical frame and a magnet levitation mechanism. Lin *et al.,* [35] created a nonlinear magnetoelectric generator using three-dimensional magnets (3D) and spring force for wide operating bandwidth.



(a) (b)

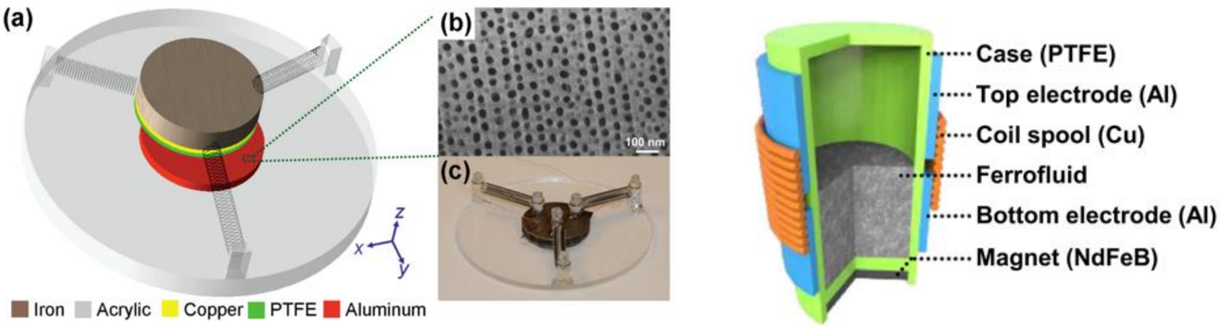
(c) (d)

Fig. 7. Electromagnetic transducer types (a) Microcantilever generator [37,44] MsM energy collecting device (c) Electromagnetic energy harvester with free impact [28] (d) Halbach array resonator [45]

Magnetostrictive materials (MsM) are a form of metallic compound used to gather vibration energy. It employs the Villari effect, also known as the magneto-mechanical effect, in which friction results in MsM deformation and, as a result, a change in the magnetization of the item. According to Faraday's rule, this magnetization transition is transformed into electrical energy by a pick-up coil circling the magnetostrictive layer under dynamic or cyclic loading. With the progress of these materials over the last decade, they have become more often employed as actuators and sensors in various intelligent constructions. However, only a few recent attempts, such as those in [31,44], have been attempted to include MsM into energy harvesting.

2.3 Electrostatic as Vibration Energy Harvesting Transducer

The basis for electrostatic energy harvesting is the changing capacitance between two surfaces of a charged capacitor, which has movable electrodes separated by a dielectric to create a capacitor. The conversion to electrical energy is accomplished by spinning the linked electrodes, resulting in mechanical motion. As seen in Figure 8, electrostatic energy harvesting is the triboelectric approach. Table 3 summarizes the vibration energy harvesting via electrostatic transduction.



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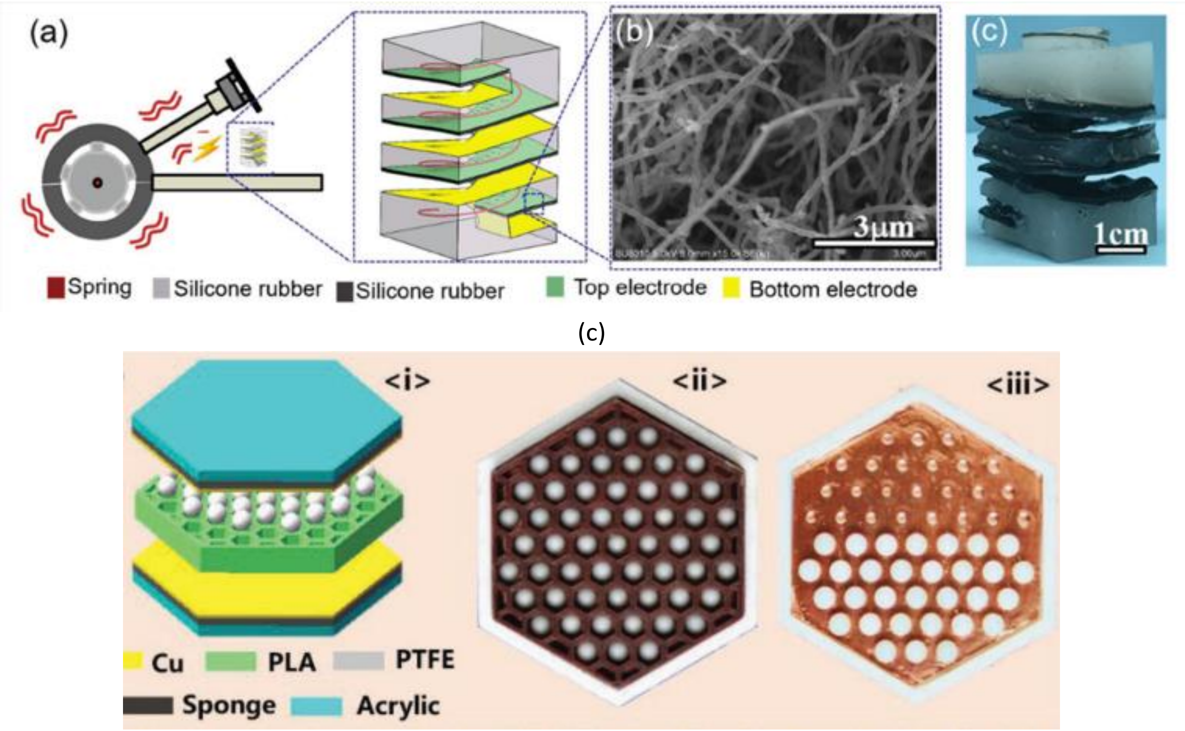


(c)

(d)

Fig. 8. Triboelectric nanogenerator (a) 3D triboelectric nanogenerator [31] (b) ferrofluid-based triboelectric-electromagnetic [32] (c) spring based triboelectric nanogenerator [33] (d) honeycomb structure inspired triboelectric nanogenerator [34]

Table 3
Summary of vibration energy harvesting by electrostatic materials

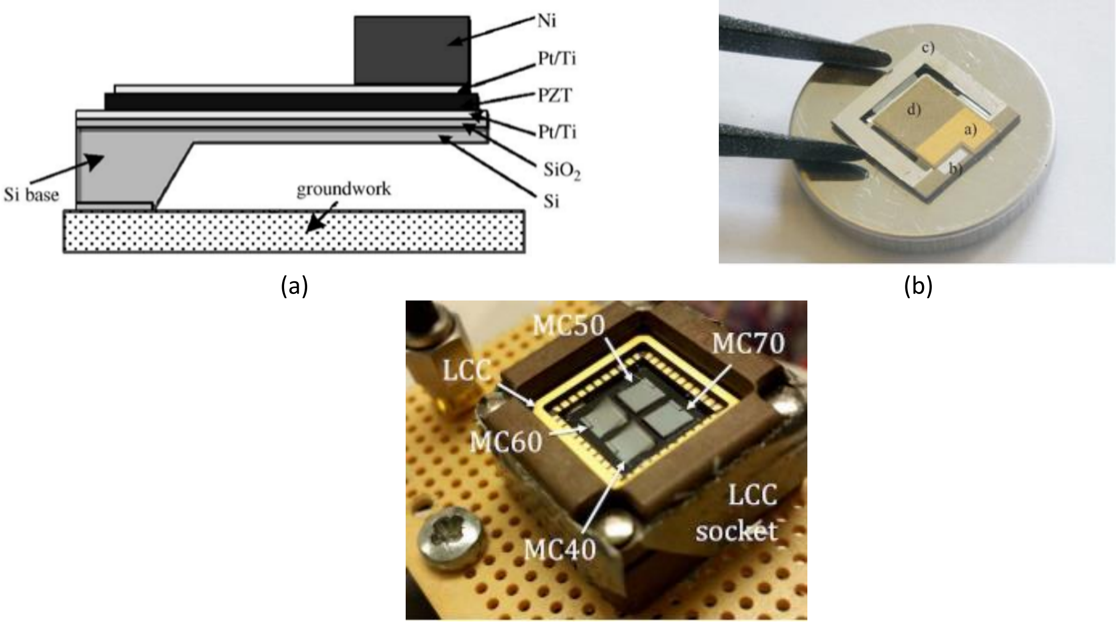
Author	Year	Generator material	Frequency (Hz)	Output power (mW)
[35]	2013	3D spiral triboelectric nanogenerator (TENG)	30	2760
[31]	2014	3D triboelectric nanogenerator (3D-TENG)	75	1350
[36]	2014	3D triboelectric nanogenerator (3D-TENG)	20	0.00128
[37]	2014	Contact-mode triboelectric nanogenerator (CF_TENG)	15	17
[44]	2017	Spring-based amplifier with triboelectric nanogenerator	-	
[32]	2017	Ferrofluid tribo- electric-electromagnetic (FF-TEEM) device	7	-
[45]	2018	Triboelectric-piezoelectric-electromagnetic	20	122
[33]	2018	Spring based TENG (S-TENG)	16 (vertical resonance vibration) 8.5 (horizontal resonance vibration)	240 45
[46]	2018	Floating buoy-based triboelectric nanogenerator (FB-TENG)	1.7	0.036
[34]	2019	Honeycomb structure - triboelectric nanogenerator (HSI-TENG)	33	-
[47]	2020	Spherical triboelectric nanogenerator	8	0.0000109

A triboelectric nanogenerator is an energy harvesting system that uses the triboelectric effect and electrostatic induction to transform external mechanical energy into electricity. Triboelectric nanogenerator (TENG) as a power source and self-powered sensors have made tremendous development in recent years [47-49]. TENG improvisation has been reported in the literature employing contact mode [50], floating buoy-based floating [51], honeycomb design [52], spring-based [49,52], and spherical structure [55]. Although the improved technology could run at a lower frequency, it had a substantially lower output capacity than TENG. Meanwhile, [51] presented a TENG combination of piezoelectric and electromagnetic with a frequency of 20 Hz and output power of 122mW, which compromises the piezoelectric and electromagnetic.

2.4 Electrostatic as Vibration Energy Harvesting Transducer

Microelectromechanical systems (MEMs) are micrometre-scale mechanical transducers incorporated by cantilevers, combs, membranes, or logic circuit channels. MEMs transducers can operate as sensors, receive environmental data, and act as actuators in response to a control system's environmental change decision (Figure 9).

Previous research has previously coupled MEMs with piezoelectric-based transducers [53] employing epitaxial PZT thin film [43], unimorph [54], and bimorph [54,55] cantilevers, whereas [56] compared d31 and d33 piezoelectric. Meanwhile, additional publications [57]combined a silicon-based frame and silicon proof mass. Jia *et al.,* [58] explored the ideal proof-mass-to-cantilever ratio, whereas [53] created a single proof mass multi-layered using Al/ AlN/ Mo films and [59] created a nickel-metal mass composite cantilever whereas [43] created electret-based MEMs. Table 4 summarizes the use of MEMs to harvest vibration energy.



(a) (b)

(c)

Fig. 9. Various MEMs transducers (a) MEMS-based piezoelectric [48] (b) Screen printed PZT/PZT thick film bimorph MEMS [49] (c) MEMS chip consisting of the 4 uncoupled micro-cantilevers with varying end mass [50]

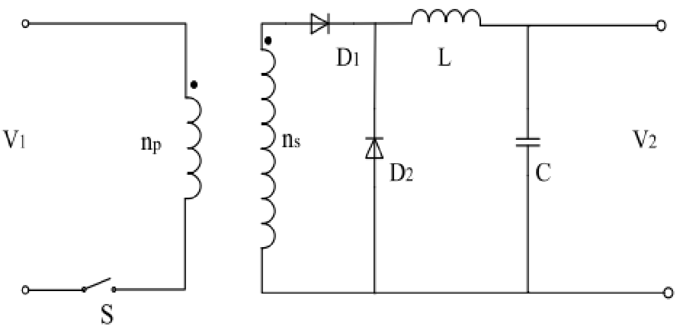
Table 4
Summary of vibration energy harvesting by MEMs

Author	Year	MEMs	Transducer type	Frequency (Hz)	Output power (mW)
[48]	2008	Array thick-film piezoelectric	Cantilever	226–234	3.98
[55]	2006	Nickel metal mass	Cantilever	608	0.00216
[58]	2006	Silicon based frame	Cantilever		0.00115
[56]	2008	Si proof mass	Unimorph cantilever and Si proof mass	461.15	0.00215
[60]	2011	Epitaxial piezoelectric thin fil	Cantilevers	2.3 k	0.013
[49]	2012	PZT/PZT thick film	Bimorph cantilever	344	0.0332
[51]	2013	d31 and d33 piezoelectric	Cantilever		0.0088-0.02
[52]	2015	Al/ AlN/ Mo multilayer films	Cantilever	230.4	0.000935 (series) 0.003315 (parallel)
[59]	2016	Metal-based	Bimorph cantilever	140.8	0.423 (parallel) 0.413 (series)
[50]	2016	End mass cantilever	End mass cantilever	210	0.00178 – 0.0205
[53]	2017	ScAlN	cantilever	37.4	0.0013
[61]	2017	Electret	-	12	0.00495

3. Power Management Circuit

Because the power delivered by the vibration transducer is frequently in the micro and milliwatt ranges and fluctuates, it cannot be transferred directly to the load without being rectified, necessitating the installation of an AC to DC converter capable of pulling additional power from the transducer. The emphasis was on converting AC to DC or DC to DC. However, other academics concentrate their study on maximum power point tracking (MPPT). From 2005 through 2021, this section compares technique variants employed in the vibration energy harvesting conditioning circuit.

Few studies on conditioning circuits focus on improving the efficiency of power harvesting using an AC to DC rectifier [54,62-64] (Figure 10), with others focusing on improving low-vibration harvesters [65], lowering the voltage drop from the conventional forward voltage diode and the reverse current from the output capacitor to the input source [66], and modelling parasitic loss [43]. Meanwhile, McCullagh *et al.,* [67] suggested non-periodic bridge vibration passive diode switching, which saves power and allows for lower turn-off voltage.



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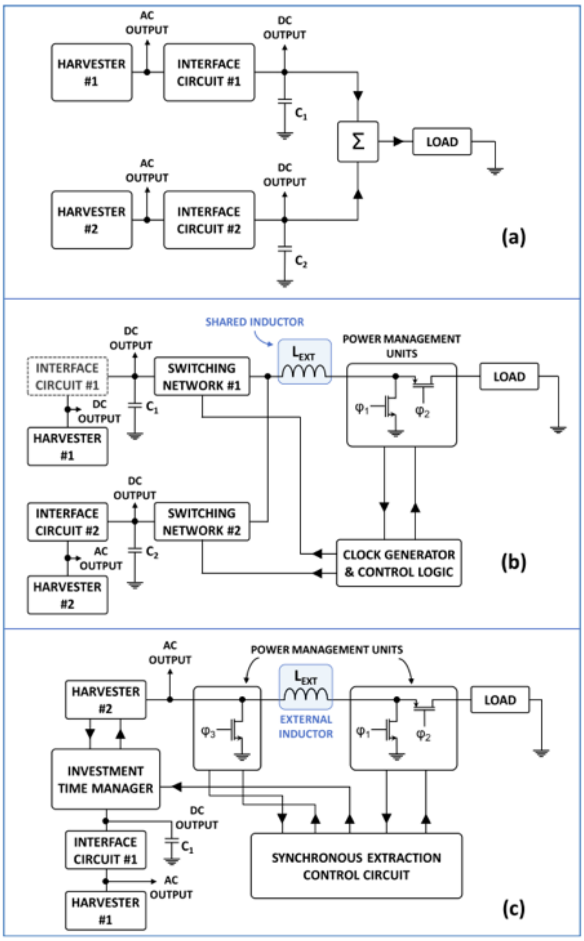

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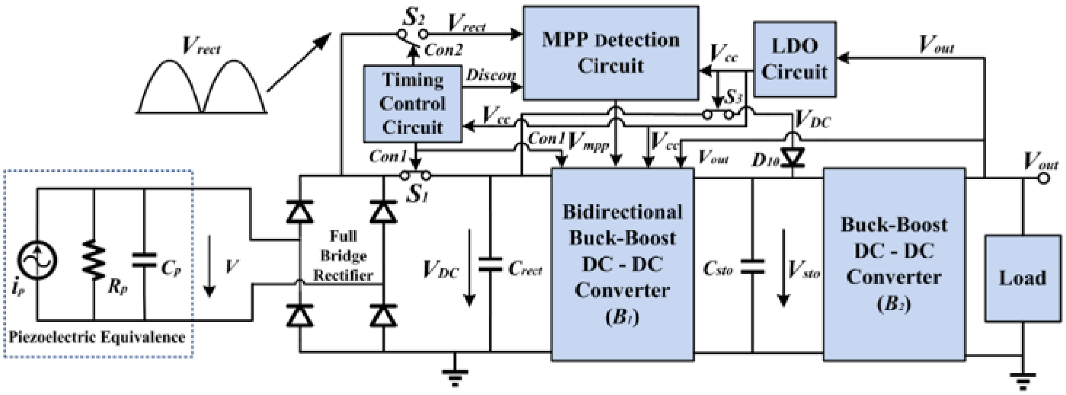

(c)

Fig. 10. Development of conditioning circuit (a) DC/DC boost converter circuit [68] (b) hybrid energy harvesting interface for electromagnetic and piezoelectric sources [54] (c) power management circuit based on quasi maximum power point tracking with bidirectional intermittent adjustment [43]

Several studies on optimising the device voltage at the point of greatest power have been conducted on the Maximum Power Point Monitoring (MPPT) of a vibration energy harvesting device, as shown in Figure 10 (c) [69-71], on the other hand, optimised the MPPT algorithm, which results in low efficiency if not properly adapted. Other signal conditioning problems studied the key causes of switching delay (SD) and the related remedy [72]. Hadas *et al.,* [73] proposed an inductor-less dynamically configured interface circuit that binds two piezoelectric materials in parallel or series by assessing the ambient excitation level regularly, and [74] investigated the use of a bridge under operating conditions with energy collection signatures against time that undergoes forced dynamical vibrations.

4. Discussion and Conclusion

This review examined various advancements in vibration energy harvesting during the last 15 years. This study focuses on the many methods utilised for harvesting vibration energy, such as piezoelectric, electromagnetic, electrostatic, and MEMs approaches, as well as power management circuits, to create various features of vibration energy harvesting devices from various sources.

Piezoelectric remains the essential choice in vibration energy collection. However, current trends in utilising non-toxic, lead-free piezoceramics have shifted. Piezoceramics and piezopolymers are the most often utilised piezoelectric forms with higher power output [23]. This new trend has shown greater output power to the conventional PZT [23] than in 2011 and 2012 [5], [6].

Within the last 15 years, several electromagnetic generator models have been used for vibration energy harvesting, including rotational electromagnetic microgenerators, micro electromagnetic, magnetoelectric, hybrid magnetic and magnetoelectric, and magnetostrictive. Compared to piezoelectric, electromagnetic transduction enables vibration harvesting at lower frequencies, which is advantageous for squandering vibration energy at lower frequencies.

Electrostatic transducers having significantly higher output power than electromagnetic transducers, on the other hand, provide enough harvest at lower frequencies. Electrostatic transduction, also known as Triboelectric Nanogenerator (TENG), has been in operation since 2013. TENG was used to reignite vibration energy collecting and self-powered sensing, especially for low-frequency vibrations like human movements, autos, machinery, and bridge vibrations.

The problem of energy conditioning is to convert the gathered valuable energy into real-world industrial use. The power delivered by the vibration transducer is frequently in the micro and milliwatt range and variable, necessitating rectification before being directly given to the load. Current trends also looked at maximum power point tracking (MPPT) to improve device voltage at the maximum power point.

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