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Review

Rotational Piezoelectric Energy Harvesting: A Comprehensive Review on Excitation Elements, Designs, and Performances

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Abstract: Rotational Piezoelectric Energy Harvesting (RPZTEH) is widely used due to mechanical rotational input power availability in industrial and natural environments. This paper reviews the recent studies and research in RPZTEH based on its excitation elements and design and their influence on performance. It presents different groups for comparison according to their mechanical inputs and applications, such as fluid (air or water) movement, human motion, rotational vehicle tires, and other rotational operational principal including gears. The work emphasises the discussion of different types of excitations elements, such as mass weight, magnetic force, gravity force, centrifugal force, gears teeth, and impact force, to show their effect on enhancing output power. It revealed that a small compact design with the use of magnetic, gravity, and centrifugal forces as excitation elements and a fixed piezoelectric to avoid a slip ring had a good influence on output power optimisation. One of the interesting designs that future works should focus on is using gear for frequency up-conversion to enhance output power density and keep the design simple and compact.

Keywords: piezoelectric; rotational energy harvesting; energy harvester excitation elements; rotational energy harvester design; factors affecting energy harvester performance

Citation: Chilabi, H.J.; Salleh, H.; Al-Ashtari, W.; Supeni, E.E.; Abdullah, L.C.; As'arry, A.B.; Rezali, K.A.M.; Azwan, M.K. Rotational Piezoelectric Energy Harvesting: A Comprehensive Review on Excitation Elements, Designs, and Performances. *Energies* **2021**, *14*, 3098. https://doi.org/10.3390/en14113098

Academic Editor: Abdessattar Abdelkefi

Received: 3 April 2021
Accepted: 10 May 2021
Published: 26 May 2021

1. Introduction

Energy harvesting is defined as the process of converting mechanical energy such as distortion energy, vibration, or other kinetic energy into electrical energy [1]. Fast development in wireless sensor networks (WSN), and storage power with better efficiency solutions will finally increase using of self-power devices in health care, monitoring of the environment, and automotive applications [2]. However, limitation of power source and batteries, such as volume, weight, and short lifetime, which is much less than the WSN life, changing the batteries frequently, and devices in hard reach area [3]. All these limitations make the powering of microdevices and WSNs using energy harvester considering a feasible approach in our environment due to its small size, low power consumption, and special working environment [4,5].

Piezoelectric energy harvesting is one of the innovative approaches that has been evolved and implemented for harvesting power for microdevices using different types of mechanical power sources [6]. Piezoelectricity is the electric charge accumulated in certain solid materials (Piezoelectric) such as crystals, ceramics, and Polyvinylidene Fluoride PVDF in response to applied mechanical stress [7]. Depending on the application, and the availableness of the mechanical power sources, various types of energy harvesting are obtainable most of the time. Mechanical energies, such as vibration, fluid-flow, human motion, etc., are energies of changeable frequencies and amplitude, which could be named random energies that available everywhere [8].

Rotational mechanical energy is one of the significant power sources for piezoelectric energy harvesting. Various types of rotational power sources have been used in the past few years for piezoelectric energy harvesting, such as rotational machines [9–18], vehicle tire [19–23], human motion [24–28], and even wind [29–36] and fluids [31,32,37–41]. They have been applied in various applications, such as tire pressure monitoring system TPMS [42–44], WSNs in any rotary machine [11,45,46], wearable device and medical implants [47–51], and others.

The Rotational Piezoelectric Energy Harvesting (RPZTEH) operation principle is based on the plucking of piezoelectric for excitation, which results in piezoelectric vibration, bending, or pressing, and thus voltage is generated. This plucking could be done using different excitation elements. Researchers have used various excitation elements in RPZTEH such as magnetic [52–54], mass weight [44,49], gravitational force [55–57] centrifugal force [58,59], and gears teeth force [60,61], or a compilation of these elements [42,62,63]. They have utilised these elements for frequency up-conversion of rotational frequency, which is considered lower in general than the piezoelectric resonant frequency [9,62,64], or widen the broadband range [20,65,66].

Most of the previously published review papers mentioned rotational piezoelectric energy harvesting partly and focused mainly on frequency up-conversion or bandwidth widening [2,67–72]. However, frequency up-conversion methods continue to be enhanced. Hence, rotational power sources, especially wind, human motion, some rotary machines, and some vehicle tires, are generally considered as low frequencies, compared to piezoelectric frequency. In some cases, the wiring for output power transfer is still an issue because the piezoelectric is rotating with the system and thus a slip ring or any other wireless transfer is needed, and the device has become even more complicated [4,43,45,72,73] The rapid repetitive bending and impact on the piezoelectric with the direct excitation contact can also be considered an issue because it will reduce its lifetime; however, this can be avoided in different ways and suitable excitation elements [37]. Besides choosing suitable excitation elements, the compact, simple, and right-size design for the suggested application is quite important [43,72]. Using gear (and gear teeth) as a rotational mechanical input for piezoelectric energy harvesting excitation has been considered a good and new method. Only a few works have been accomplished using the gear as input in rotational piezoelectric energy harvesting.

This paper aims to present a comprehensive review of RPZTEH from the mechanical input method concept and applications. To the authors' knowledge, there is no such review specifically for rotational energy harvesters. This paper's originality is mainly on comparing various designs and excitation elements and their influence on performance. It also focuses on past work performance and key design comparison perspectives on the various mechanical inputs and applications, such as fluids (air, water) movement, rotational vehicle tires, human motion, and other rotational operational principals. Various excitation elements such as mass (the mass weight work as a force), magnetic, centrifugal force, gravity, gears, or others were discussed. Each mechanical input study is examined in-depth, including working principles and main findings. Each of the above four mechanical inputs has been subdivided into comparison of different designs and excitation elements and the influence of excitation elements and design on performance (challenges and issues). This review summarises several important aspects of the previous energy harvesting studies including methods, materials type, polarity, rotational speed, output power, power density, and wiring. The comparison tables and graphs of performances are also included in this paper. The advantage or disadvantage of each mechanical input study was identified, and future research recommendations were discussed.

2. Methodology

In the present review, the comparisons of excitation elements, design and their influence on performance are divided into four types according to mechanical inputs: fluids (air, water) movement, human motion, rotational vehicle tires, and other rotational operational principals. For each one, mechanical inputs, excitation type, design, methodology, and wiring have been characterised and thoroughly reviewed. The type of excitation has been subdivided according to excitation elements, such as mass, gear, magnetic, spring, centrifugal, gravity and impact forces. Each group may contain one or more of the excitation elements to conclude which group has the maximum influence on rotational piezoelectric energy harvesting enhancement. The design comparison also discusses the piezoelectric rotation, which may affect the type of wiring for output power transfer. The fixed piezoelectric cantilever uses direct wiring, while a rotating one requires either a slip ring or Arduino and Bluetooth for output power transfer. For each of the following section. At the end of each section, a summary table was made by the author with full detail and calculated power density for related previous works, as in Tables 1–4. A plot has also been made by the authors for all the designs, due to rpm and output power density, to give a clear idea about the best excitation elements and which one has the highest power density, and as in Figures 5, 9, 13, and 18, respectively. Figure 1 show the methodology schematic diagram.

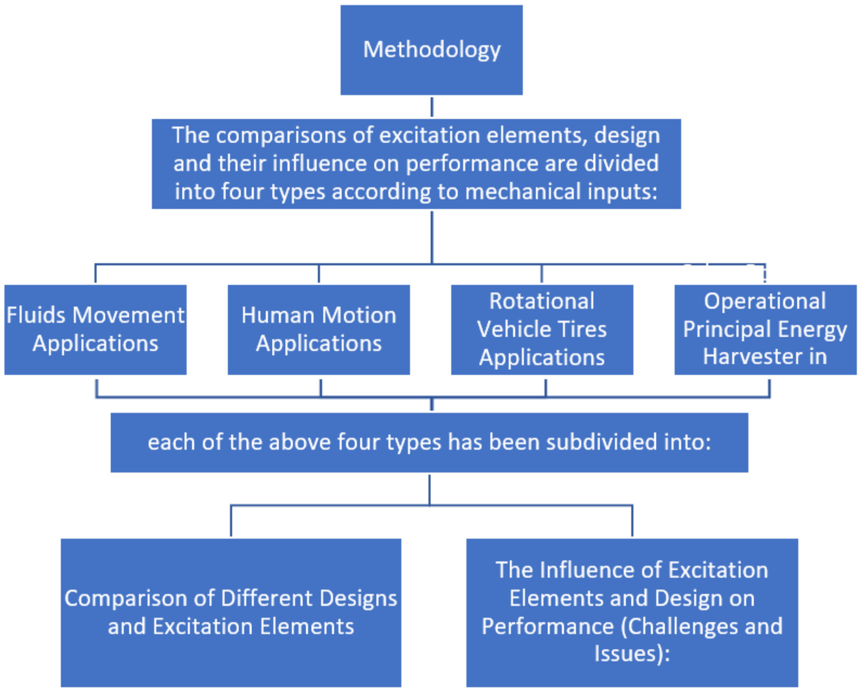


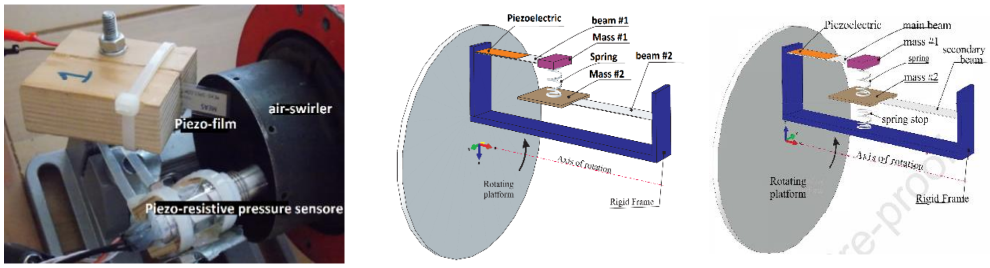
Figure 1. Methodology schematic diagram.

3. Fluids Movement Applications

In this section, a comparison has been made on the studies that have used fluid including wind (or air), and water (or rain) as a mechanical input source for RPZTEH. Each of these two groups is divided according to excitation elements. Their design, methodology, and power density have been reported for each study.

3.1. Comparison of Different Designs and Excitation Elements

Firstly, the studies that use air (wind) as a mechanical input source for RPZTEH have been reported. Using air only as an excitation element, Stamatellou & Kalfas [29] utilised air swirled to create a turbulent flow field and harvest energy, as shown in Figure 2a. The piezoelectric mounting mode allows for varying the orientation and position of piezoelectric to optimise output power. A power density of 0.031 μW/mm^3 was harvested in a collection time of 20 s cycle duration from 37 mm PZT at a 300 rpm, without using a slip ring or any output power transfer since the PZT does not rotate with the system.



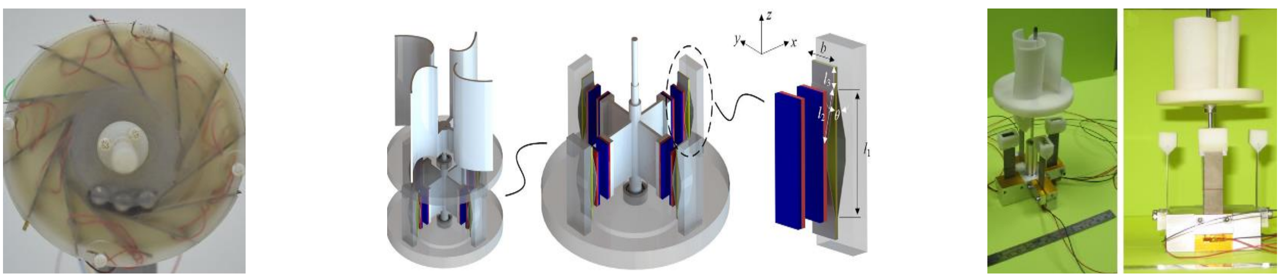
(**a**) (**b**) (**c**)

Figure 2. (**a**) Simultaneous measurement of the pressure and piezoelectric film output voltage [29]; (**b**) View of rotating energy harvesting system [55]; (**c**) View of enhanced energy harvester [74].

Similarly, Febbo et al. [55] performed a novel design alternative to a simple PZT beam that fixed the beam to a hub, by utilising a beam, spring, gravity, centrifugal forces, and two masses as excitation elements, as shown in Figure 2b. The power density ranges from 0.079–0.32 μW/mm^3. The power transfer using an acquisition system (Arduino) to avoid slip rings. Future work may use two PZT since they have two beams to get more power, and a durability test will be useful to extend the harvester lifetime.

The same authors enhanced their model [74] by adding a single side spring stop, in addition to the two-flexible beam, and the spring that joined the two dense masses, as shown in Figure 2c. This design generates more power than the previous one, and the rectified output power density is 0.31–2.59 μW/mm^3 at 50–150 rpm. The novelty of this device is that the contact force was maximum at the lowest rotation speed. Thus, it proposed as an alternative solution for generated power at the low excitation frequency.

However, Y. Yang et al. [30] have used impact-induced resonant to have piezoelectric beam effective excitation vibration mode. The harvester-based knowledge designed is that; an impact could excite resonance beneath any operating conditions. A configuration has been made of twelve PZT beams and a seven ball, as shown in Figure 3a. The harvester power density at a speed of 200 rpm and across 20,000 ohms was 1.3 μW/mm^3. This power can be stored in a capacitor and used in WSN; however, this WSN must rotate with the system or add a slip ring or other output transfer device.



(**a**) (**b**) (**c**)

Figure 3. (**a**) Piezoelectric windmill diagram shows piezoelectric bimorphs arrangement [30]; (**b**) Schematic illustration and working mechanism of the investigated Magnetically Coupled Piezoelectric Wind Energy Harvester (MPWEH). The symmetrical opposite magnetic arrangements [75]; (**c**) Prototypes of nonlinear wind harvester: configuration of tangential design and configuration of radial design [52].

Furthermore, Bai & Havr [66] studied an air-flow energy harvester by combining two piezoelectric beams with a composition of free-standing bi-morph thick film, and a windmill with a free-spinning fan; all have been fabricated and assembled. The maximum power density is 0.058 μW/mm^3 at a fan rotation speed of 750.6 rpm and 87 Hz magnetic force frequency. Further optimisation can be done by designing the harvester to be more compact and miniaturised, which is considered essential for the conventional wind turbine.

Rezaei-Hosseinabadi et al. [65] also designed a wide-band piezoelectric energy harvester and optimised it to get the maximum energy using mass and magnetic as excitation forces. The prototype consists of PZT that vibrates due to the interactions between permeant magnetics in the small turbine and the magnetic attached to the piezoelectric beam. It was found that the optimum output power density was 0.59 $\mu W/mm^3$, and no need for a slip ring for output power transfer; typical wiring was used since the PZT does not rotate.

Alternatively, Zhao et al. [75] presented an innovative method for RPZTEH with wind and use mechanisms of force amplification and magnetic coupling as excitation only. By arranging the magnetic in a symmetrical opposite way, they maximised the effective force and significantly reduced the resistance torque, as in Figure 3b. The experimental results show that it can work continuously for more than 12,000 s with wind speed from 3–10 m/s, and the maximum power density was 3.3 $\mu W/mm^3$. This device could describe as a wide speed range of wind energy harvester and better robustness.

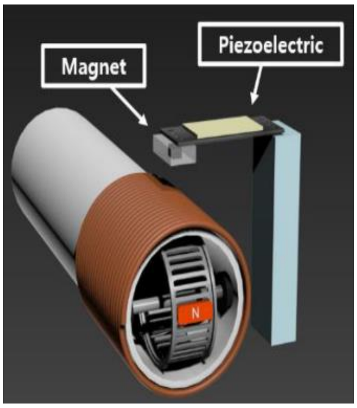
Moreover, using magnetic force for excitation, Çelik et al. [54] present a configuration consisting of a PZT layer of 70 × 32 × 1.5 mm dimensions and a harvester of 30 cm length from propeller to the tail end with 16 cm propeller diameter. The system's maximum power density in dynamical regime simulation is 4.76 $\mu W/mm^3$ at 600 rpm. This study confirmed that a piezoelectric harvester with a magnet at its tip could harvest chaotic and regular dynamics on different rotation speeds.

Additionally, a built-in wind generator has been designed to supply sensor nodes with power in hard reach or remote locations from low wind speed by Karami et al. [52] using magnetic only as excitation. Two configurations have been made: a tangential and a radial one, as in Figure 3c. The measuring maximum output power density is 15.5 $\mu W/mm^3$ in 200 rpm, 16 Hz, and a magnetic gap of 25 mm. This work presents a novel nonlinear PZT wind turbine, whose wind speed startup is low and harvests enough power for the operation of a common WSN.

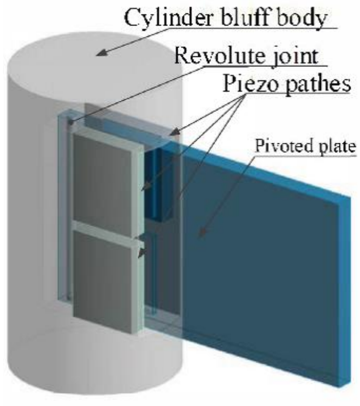
Alternatively, an energy harvester mathematical modelling using mass, gravity, and centrifugal forces for excitation has been presented by Nezami et al. [76]. The harvester can convert the slow mechanical rotation into PZT vibration by using two magnets and a small desk for large applications, such as wind turbine blades. In the range of 35–45 rpm, the output power becomes significant, where the disk motion is chaotic by switching between bouncing and passing. The power density is 2.83 $\mu W/mm^3$, and a slip ring was used to transfer it since the PZT rotates with the system.

The studies that use water as a mechanical input source for RPZTEH, have been reported below. Another approach for energy harvesting from raindrops besides the direct impact; is an indirect one using a PZT turbine or watermill and magnetic force for excitation. Since raindrop's maximum speed is reached far before hitting the ground, raindrops' kinetic power is related to the square of the raindrops' speed. So, there is no difference in the harvested power from rainfall on higher elevation or ground level. Moreover, raindrops can be collected using a water tank at a higher platform. The rainwater with gravitational energy could be released into the PZT turbine arm [39,40]. This will rotate the turbine, and thus the PZT will be bend and harvest energy. This way gives a higher force on PZT than a single raindrop at each time, and thus it will harvest more power. The estimated output average energy from this harvester is 10 W/cm^3 to 100 W/cm^3 [40].

Furthermore, a piezoelectric energy harvester and hydro-electromagnetic have been designed to give power to the smart type of water meter system using water flow and magnetic force for excitation by Cho et al. [37]. A stainless-steel turn-buckle water wheel of 90 mm diameter and two magnets was proposed in this work, as shown in Figure 4a. Output power density maximum root mean square for the piezoelectric harvester was 0.6222 $\mu W/mm^3$ at 10 kΩ. The power harvested by piezoelectric will be used for the warning system of water leakage as a water leakage detector. Further work on the threshold voltage detector as a key issue can be investigated as future work.



(a)



(b)

Figure 4. (**a**) Pipe-flow energy harvester system using magnets and with no contact [37]; (**b**) A general view for a vortex-induced piezoelectric energy harvester [32].

Conversely, in the An et al. study, a novel vortex-induced PZT energy converter (VIPEC) is proposed to harvest the ocean's kinetic energy in the underwater environment [32]. The harvester consists of a storage circuit, PZT patches, cylinder, and a pivoted plate attached to its tail, as shown in Figure 4b. The maximum output power density reaches 0.035 $\mu W/m^3$ with a resistance of 10 kΩ. The VIPEC simple structure makes it quite suitable for underwater mooring cables or other Underwater Mooring Platforms (UMPs).

Similarly, Cellini et al. [77] assessed energy harvesting feasibility from the mechanical buckling of Ionic Polymer-Metal Composites (IPMC) induced by a steady flow of fluid. The harvester consists of a slider-crank mechanism, two (IPMC) fixed at both ends, and a paddlewheel. Experimental results demonstrate that IPMC output power range from 1 pW–1 nW as the flow speed varies from 0.23–0.54 m/s, and the shunting resistance different from 1–1000 Ω. The design is unique; however, the output power needs to be enhanced and make the design more compact.

3.2. The Influence of Excitation Elements and Design on Performance (Challenges and Issues)

As shown in Table 1, a comparison has been made between variable factors, divided into input, output, and comments. In general frequency (rpm), Piezoelectric size, dimension, and material type, resistance, and whether the Piezoelectric rotate or not, using a slip ring or not, all these elements affect piezoelectric energy harvesting output power, as shown in Table 1. Output power and power density are also included in this table. Although, excitation elements affect the design, however, as shown in Table 1, for the same excitation elements, the output power density is different depending on the design. The materials used in the RPZTEH were mainly PZT; however some researchers used PVDF and PZT composite.

Table 1. Summary comparison for rotational piezoelectric energy harvesting studies with detailed information.

Number	Ref.	Input							Output			Comments		
		Excitation Elements	**Volume (mm$_3$)**	**Piezo Dimension (mm)**	**Polarisation Mode**	**Material Type Use**	**rpm**	**Frequency (Hz)**	**Optimal Resistance (Ω)**	**Power (μW)**	**Power Density (μW/mm^3)**	**Mechanical Power Source**	**PZT Rotate or Not**	**Wiring**
1	[29]	air swirler	96.2	37 × 13 × 0.2	/	PVDF	300	6	47	3	0.03	Air	Not	Normal wiring
2	[55]	M + Sp + Gr	328	50.8 × 25.4 × 0.254	d31	PZT 5A	150	13.1	10 k	105	0.32	Air	Yes	storage rotates with the system
3	[74]	Sp + M + Gr	326.5	50.8 × 25.4 × 0.254	d31	QP16N	150	2.5	5×10^5	845	2.588	Air	Yes	Bluetooth
4	[30]	imp	470	(47 × 20 × 0.5)	/	PZT	200	3.33	20 k	613	1.3	Air	Yes	supercapacitor
5	[66]	M + Mg	4.26	16 × 3.5 × 0.076	/	PZT-bimorph	751	12.5	200 k	0.25	0.06	Air	Not	fixed piezo
6	[65]	M + Mg	115	31.8 × 7.12 × 0.508	d31	Q220-A4–303YB	3696	61.6	3300	/	0.59	Air	Not	the application within the rotation area
7	[75]	Mg	400	40 × 10 × 1	/	(PZT-5H)	546	9.1	3×10^5	1320	3.3	Air	Not	/
8	[54]	Mg	3360	70 × 32 × 1.5	/	PZT layer	600	10	8000 k	16000	4.76	Air	Not	Normal wiring
9	[52]	Mg	323	(50 × 12.7 × 0.127) × 4	d31	PZT-5A	200	16	247 k	5000	15.5	Air	Not	Normal wiring
10	[76]	M + Gr + Mg	776	40.2 × 25.4 × 0.76	d31	(PPA-2011)	30	34	25 k	2200	2.835	Air	Yes	slip ring
11	[37]	Mg	315	45 × 35 × 0.2	d31	PZT-ceramic	120	/	10 k	196	0.6222	Wat	Not	/
12	[32]	vortex-induced	/	/	d31	PZT	/	16.49	1×10^5	/	0.035 1E + 09	Wat	Not	/
13	[77]	Water flow + slide-crank	166.4	52 × 16 × 0.2	/	ionic polymer metal composites	372.4	1	50	1×10^9		Wat	Not	/

M for mass, Mg for magnetic, Gr for gravity, Sp for spring, Wat for water, air for air, imp for impact force, and / for no information from the authors.

In Figure 5, all the above studies have been plotted with rpm and output power density to have a clear idea about the best excitation elements with the highest power density. As shown in the figure, the studies that use magnetic force as an excitation element get an excellent output power density [52,54]. Both of them use only magnets for excitation and able to harvest excellent output power. However, Karami et al. [52] have an added advantage: their output power density is higher and has a lower rotational speed. Additionally, using air only as an excitation gives the lowest output power. Yet, the feasibility of energy harvesting from a swirling flow using a piezoelectric beam has been examined.

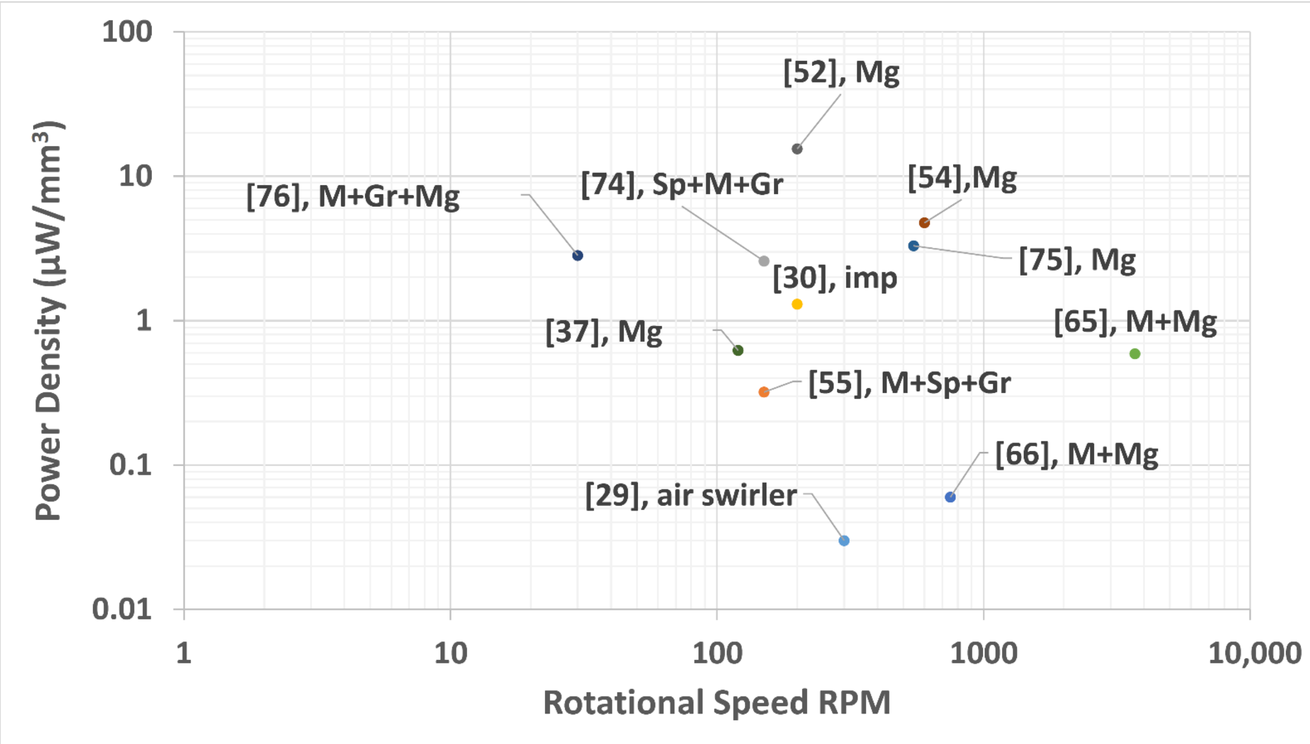


Figure 5. Power density comparison for different studies on rotational piezoelectric energy harvesting for fluid input mechanical power source with different excitation elements and as follows: M for Mass, Mg for magnetic, Gr for gravity, Sp for spring, and air swirler for air swirler.

Regarding the design aspect, Zhao et al. [75] and Karami et al. [52] present a design with an innovative method and a novel PZT cantilever and harvest good output power. Both authors used magnetic only for excitation, and their prototypes are small and compact. Karami et al. [52] have one more advantage: the PZT in his design does not rotate with the system and thus no-slip ring or any other device is needed for output power transfer. Then again, Y. Yang et al. [30] and Nezami et al. [76] are both able to harvest enough power; however, both prototypes are bulky and larger. In general, Karami et al. [52] have the highest output power density with only one excitation element to be less complicated, and it comes with a small compact design. One of the interesting designs that future works should focus on is applying magnetic and gravity forces as excitation elements but with a small compact design to achieve maximum output power density.

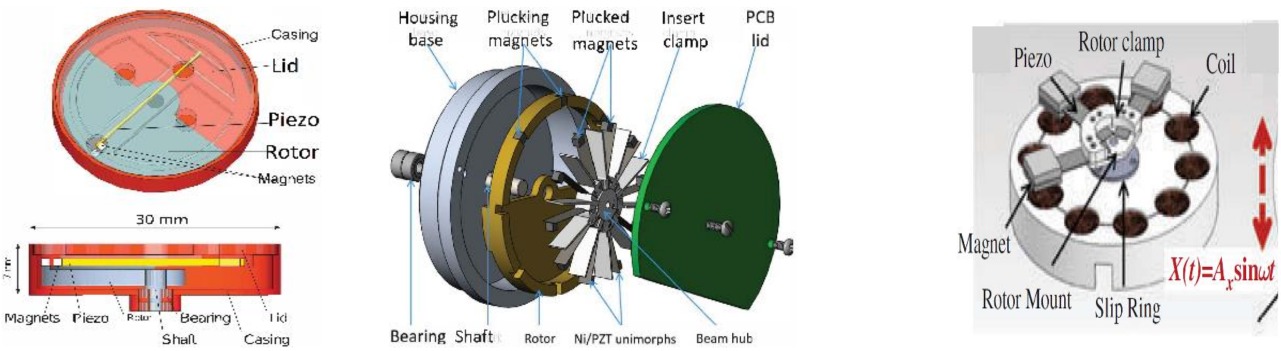
4. Human Motion Applications

In most human motion applications, the harvester needs a frequency up-conversion so that its frequency will be near or at the piezoelectric resonant frequency to get maximum output power. This section has made a comparison for different designs and excitation elements on the studies that used human motion as a rotational input mechanical power source. It has been subdivided into groups according to excitation elements, such as (mass, magnetic, and gravitational Forces), (mass and magnetic force), (magnetic force only), (mass), and (magnetic and gravity). The design and excitation elements influence on output power density have been reported as well.

4.1. Comparison of Different Designs and Excitation Elements

Balancing between excitation elements and design is quite essential to produce a simple device with sufficient output power. Sometimes, using the same excitation element can produce different output power due to their implementation in the design.

One of the challenges of human motion energy harvesting is random excitation and low frequency. Pillatsch et al. [64] used a successful frequency up-conversion strategy: introducing an inertial device containing PZT beam buckling principle using the magnetic coupling of two permanent magnets and a rotating mass in half disk shape with a gravitational force as excitation elements, as shown in Figure 6a. This device can work from 0.5 to 4 Hz, and its maximum power density was 0.023 μW/ mm^3 at 2 Hz (120 rpm). The device is quite simple, has fewer component numbers, is wear-reducing, and avoids physical contact.



(**a**) (**b**) (**c**)

Figure 6. (**a**) Harvester prototype isometric view and section view [64]. (**b**) Diagram structure of the wrist driven rotational energy harvester using magnetically plucked PZT [78]; (**c**) The energy harvester diagram [72].

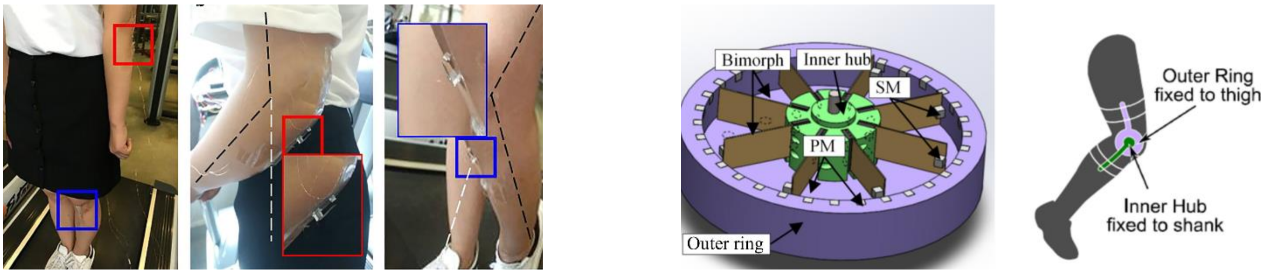
Halim et al. [78] fabricated a wrist-worn rotational energy harvester using plucked piezoelectric for wearable applications that use mass and magnetic force as excitation and without gravity. It is made of an eccentric rotor consisting of multiple magnets and piezoelectric clamped to the hub centre, and a magnet at each beam tip, as in Figure 6b. This device can harvest a more power density 0.3461 μW/mm^3 at 1.25 Hz only. Its design is compactable, light, and small, and the configuration allows the arrangement of multiple magnets in terms of number, size, and gap to tune the system.

Furthermore, using the same excitation elements, Fan et al. [24] proposed a multi-purpose harvester containing a ferromagnetic ball with 14 mm diameter and four PZT beams. The prototype has been fabricated and tested, and it was found that, for the rotational motion, it can harvest a power density of 1.91 μW/mm^3 at the rotating frequency of 1 Hz (60 rpm), which is more than the previous device and with less Hz. This method is promising for low-power devices implementing self-sustained power.

Moreover, a novel hybrid multimodal device was presented by Larkin et al. [72] using mass and magnetic force as excitation also. A configuration has been made of an unbalanced rotary-disk, three PZT-beams, and two permanent magnets that act as a proof mass at each PZT end, as in Figure 6c. This device can harvest more power density (4.18 μW/mm^3) and has been suggested for several applications, such as worn on an ankle or bicycle. However, this device needs to be scaled down and use a slip ring, and it also works in a much higher frequency range 20.2 Hz (1212 rpm).

On the other hand, using magnetic force only as the excitation, Sriyuttakra et al. [79] introduced a practical optimisation test to the RPZTEH for low-frequency applications like wearable devices. When the rotor is driven, a pushing force is applied from the two magnets' magnetic force attached at the PZT far end in the stator and on the rotor's rotational disk. The harvested power density ranges from 0.06–2.259 μW/mm^3, at 10–100 rpm (0.167–1.667 Hz) respectively. The harvested power is quite good, has a wider frequency range, and the harvester size is small and compact.

Moreover, a novel wearable energy harvester that converts the low frequency of human limb into high frequency has been proposed in this study by Li, Keli, et al. [25]. Micromachined nickel cantilever and NdFeB magnet were glued and fixed on a poly-dimethylsiloxane (PDMS) film, as shown in Figure 7a. The generated power density at 300 rpm (5 Hz) is 2.91 μW/mm^3. The packaging technique of flexible devices needs to be improved, and the device needs to be weaved into the structures of tissue.



(**a**) (**b**)

Figure 7. (**a**) Photos show wearable applications where two flexible harvesters are fixed on a human elbow and knee with Close views [25]; (**b**) Piezoelectric knee-joint energy harvester with frequency up-conversion by magnetic plucking [48].

Additionally, Kuang et al [48] produce a Knee-Joint Energy Harvester (KEH). A prototype has been made of eight PZT mounted on the inner hub, an outer ring of 88 mm inner diameter, and 64 slots are equally positioned all around the outer ring inner edge. Each slit allows one primary magnetic (pm) to be fixed and a secondary magnetic (sm) is fixed in the tip of the piezoelectric beam, as in Figure 7b. The output power increased with the gap decreasing between pm & sm and increasing rotational speed. The maximum power density is 3.94 μW/mm^3 at 32 PMs, and uses eight piezoelectrics and a 1.5 mm gap between the pm and sm at a rotating speed of 0.9 Hz (54 rpm). This study makes fair use of magnetic force without any signs of performance decreasing.

However, in this study, Mohamad Hanif et al. [49] was utilised only the mass concept for excitation. They have designed a prototype consists of PZT cantilever, a rotor with a pole on it for PZT plucking, and aluminium proof mass, as in Figure 8a. The power density is 6.5 μW/mm^3 at a frequency of 18 Hz (1080 rpm) which is much powerful than the previous technique. This device's advantage is to generate enough electricity to power electronic devices, only by using the low-frequency vibration of human motion, without relying on external power.

Pillatsch et al. [47] discovered a method of wirelessly actuating a rotor inside of a formerly presented rotational PZT harvester by using magnetic and gravity forces as excitation. A prototype has been made of the internal rotor, PZT beam, and magnetic, as shown in Figure 8b. The maximum output power density is 13.6 μW/mm^3, at 25 Hz. This harvester can charge the capacitor, even if there is no movement from the person, so, it could be a valuable addition to the already existing motion energy harvester, get red the primary concern of failure at rest.

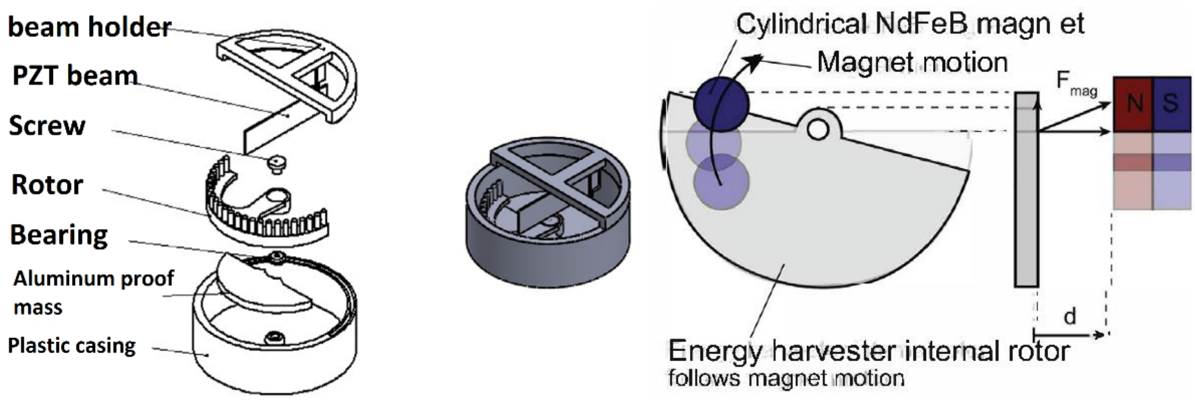


Figure 8. (**a**) Exploded view of the rotational motion energy harvester device [49]; (**b**) The harvester rotor design with the motion of magnetic and internal rotor [47].

4.2. The Influence of Excitation Elements and Design on Performance (Challenges and Issues)

Table 2 summarises different variables, divided into input, output, and comments. Excitation elements greatly affect the shape of the design and make it suitable for certain applications and help harvest sufficient output power. However, as shown in the Table, for the same excitation elements, the output power density is changing, and this is due to design change and its effect on output power.

Figure 9 compares all these study designs according to rpm and the output power density to have a clear idea about the best excitation elements based on power density. As indicated in the figure, almost all the studies used magnets as an essential element for excitation. However, Pillatsch et al. [47] can harvest the highest output power with added gravity force to the magnetic force as an excitation element at 25 Hz. In contrast, Pillatsch et al. [64] used the same excitation elements (magnetic and gravity forces) and added mass to them but failed to get as high as Pillatsch et al. [47]; however, its frequency was much lower which is 2 Hz only. These revealed that using the same excitation elements with the right better design gives a better result; however, achieving good power at very low frequency is also important especially in human motion applications where the frequency is low and irregular.

Regarding the design of the prototype, Mohamad Hanif et al. [49] and Pillatsch et al. [47] both have the best simple design with the best output power. Mohamad Hanif et al. [49] used a straightforward design with only mass for excitation and harvest a good output power in less frequency compared to Pillatsch et al. [47] which used magnetic force with mass for excitation. However, Pillatsch et al. [47] have discovered a method using the coupling reluctance of a magnetic to an outer rotor with at less one permanent magnetic and gravitational force. This method can charge the capacitor, even if there is no movement from the user.

On the other hand, Fan et al. [24] and Larkin et al. [72] can harvest sufficient output power but with a more complicated bulky design. In general, Pillatsch et al. [47] present the best simple, small, and compact design with higher output power. It could also be a valuable addition to the existing motion energy harvester and get red the primary concern of failure at rest. One of the interesting designs that future works should focused on is applying gravity and magnetic forces as excitation elements but with compact and small design to achieve maximum output power density.

Table 2. Summary Comparison for rotational piezoelectric energy harvesting studies with detailed information.

INPUT									Output			Comments		
©	**Ref.**	**Excitation Elements**	**Volume (mm_3)**	**Piezo Dimension (mm)**	**Polarisation Mode**	**Material Type Use**	**rpm**	**Frequency (Hz)**	**Optimal Resistance (Ω)**	**Power (μW)**	**Power Density ($\mu W/mm^3$)**	**Mechanical Power Source**	**PZT Rotate or Not**	**Wiring**
1	[64]	M + Mg + Gr	1850	/	/	PZT	120	4	150 k	43	0.0232	HM	Yes	/
2	[78]	M + Mg	18.06	12 × 3.5 × 0.43	/	piezo-electric M1100 ceramic	75	1.25	95 k	6.25	0.3461	HM	Not	Normal wiring
3	[24]	M + Mg	73.1	42 × 7.1 × 0.245	/	PZT-5H	60	1	80 k	140	1.92	HM	Yes	Normal wiring
4	[72]	M + Mg	1012	33 × 14 × 0.73	d31	PZT5A	1212	20.2	75	4230	4.18	HM	Yes	slip ring
5	[79]	Mg	103.8	6.4 × 31.8 × 0.51	d31	PZT-5A4E	100	1.667	/	234.5	2.259	HM	Not	Normal wiring
6	[25]	Mg	1.2	5 × 4 × 0.06	d31	PZT	300	5	40 k	3.5	2.92	HM	Yes	/
7	[48]	Mg	1471	38.1 × 12.7 × 0.38	/	PZT bimorph 5H	54	0.9	15 k	5800	3.94	HM	Yes	/
8	[49]	M	200	40 × 10 × 0.5	/	PZT5H)	1080	18	12 k	1300	6.5	HM	Yes	Normal wiring
9	[47]	Mg + Gr	7.22	19.5 × 1 × 0.37		PZT bimorph	1500	25	151 k	100	13.9	HM	Yes	Normal wiring

M for mass, Mg for magnetic, Gr for gravity, HM for human motion, and/for no information from the authors.

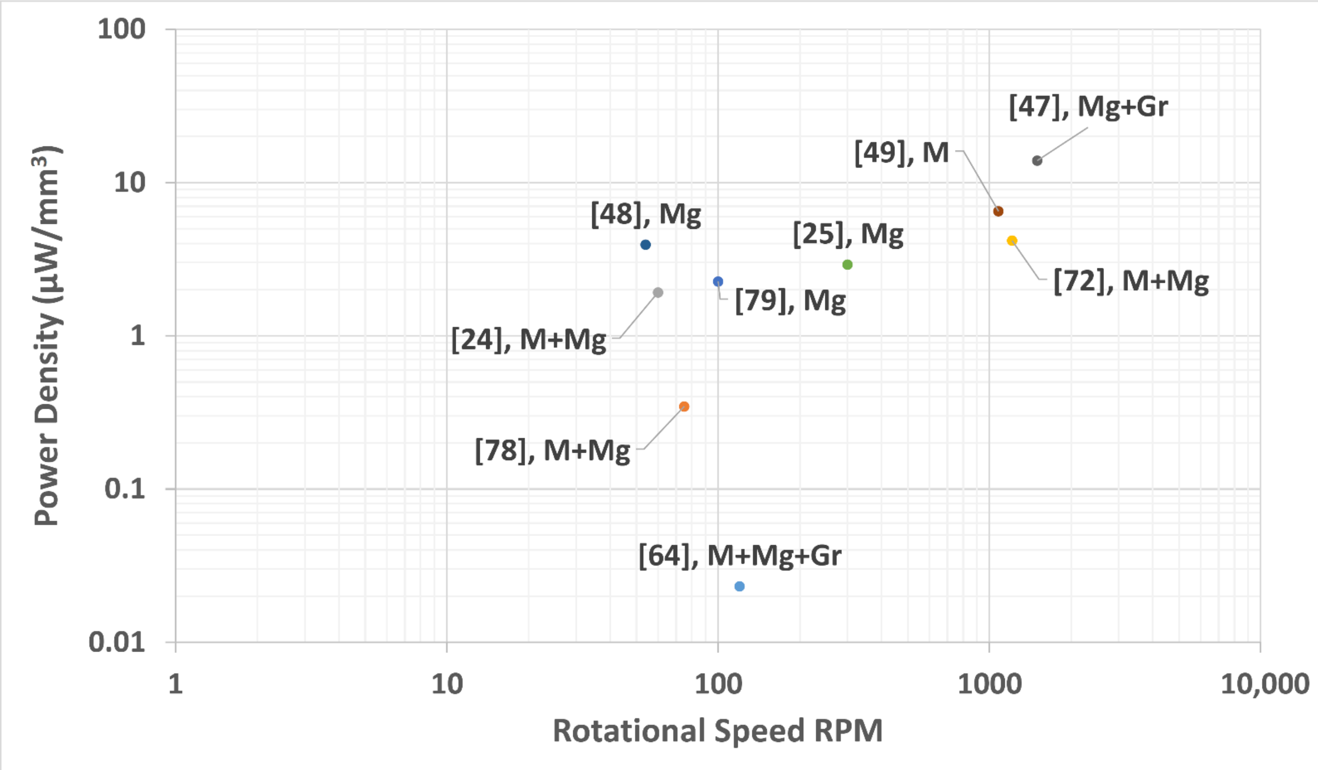


Figure 9. Rotational piezoelectric energy harvesting for human motion mechanical input with excitation elements and as follow: M for Mass, Mg for magnetic, and Gr for gravity.

5. Rotational Vehicle Tires Applications

In this part, a comparison has been made on the studies that use rotational vehicle tire as input mechanical for piezoelectric energy harvesting. It has been subdivided into groups according to the excitation elements such as mass, magnetic, gravity, and centrifugal force or a combination of them. The design, methodology, and power output density have been reported for each study as well.

5.1. Comparison of Different Designs and Excitation Elements

Xie, Kwuimy et al. [19] presented a rotational energy harvester using a PZT bistable buckled beam, with a rotating disk in low rotational speed, and magnetic force only as excitation as in Figure 10a. the Dual Attraction Magnets with Single Repulsion (DASR) can enhance the power and obtain a wide broadband frequency of 6–14 Hz (560–840 rpm) with an output power density of 0.99–1.54 µW/mm^3. The device uses a contactless method for harvesting energy; however, size needs to be reduced, and it needs to be more compatible.

Furthermore, Fu & Yeatman [20] also used magnetic coupling as excitation for frequency up-conversion in low-frequency rotational energy harvesting. A prototype consists of a piezoelectric cantilever harvester with a magnetic on its tip and a rotating magnetic on the rotating host, as shown in Figure 10b. At a rotational speed of 15–35 Hz (900–2100 rpm), the power density was 5.031 µW/mm^3. This design is simple in structure, compact, and using non-contact plucking, and can be used in various rotational energy harvester methods.

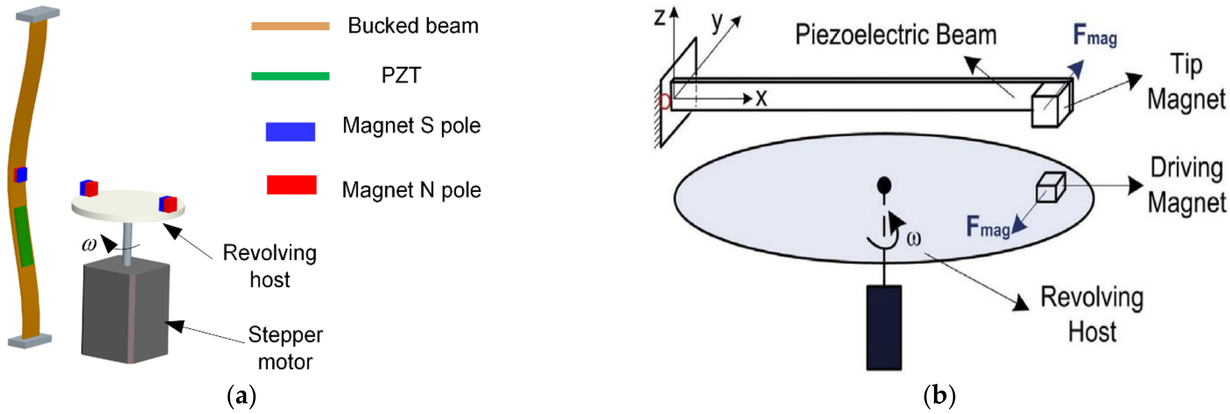


Figure 10. (**a**) Energy harvester design [19]; (**b**) Energy harvester diagram: Outline of magnetic coupling and parameters of structure [20].

Above all, Manla et al. [80] have carried out the experiment using magnetic force and centrifugal force for excitation. The harvester includes, a tube with a piezoelectric thunder fix on each end and a magnetic adhesive to each thunder. At a rotation speed from 3–5.5 rps (180–330 rpm), the output power density is from 0.0031–0.054 µW/mm^3. This design is a novel approach, low in mass, volume, and also compact. However, utilising the magnets' stiffness by changing its size or axial gap will enable the harvester to be used in other applications where different input force is applied.

Furthermore, X. Wu et al. [4] also studied a combination of centrifugal and magnetic forces and implemented them as excitation elements in a novel design of see-saw structure. This design consists of two magnetic support seesaw structure and PVDF fix below them. At 16 Hz (965 rpm and 115.4 km/h for an actual car), the power density is 1.2 µW/mm^3 using a slip ring to transfer the power. This unique design could avoid the effect of huge centrifugal force, due to its balance distinctive. In future work, different piezoelectric materials maybe test to overcome the temperature issue in high-speed.

Along with, Zhang et al. 2016 [42], presented an energy harvester using magnets, mass, and gravity force for excitation. The prototype consisted of; aluminium beam, PZT adhesive on it, two magnets, and an adjusting pole to change the distance between them, as in Figure 11a. The experiment shows that stochastic resonance will enhance the performance and that the capture power is 12-times better than using the noise excitation only and 50-times better than using gravity. The power density is 0.52 µW/mm^3 at 6 Hz, and since the harvester is attached to the wheel centre, a cable transmission can be used to power the TPMS.

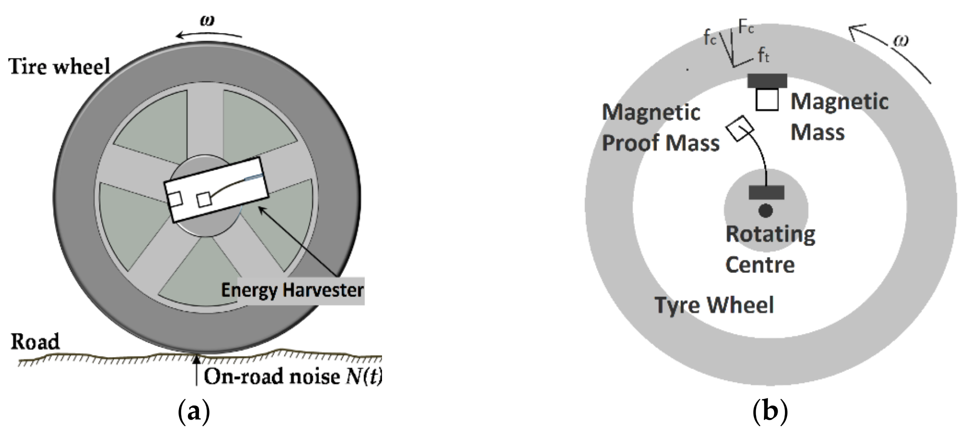


Figure 11. (**a**) Energy harvester fixed to the wheel centre [42]; (**b**) Rotating tire energy harvester model, with real one photo [63].

Similarly, mass, magnetic, but with centrifugal force, has been used as the design excitation elements by Shange et al. 2018 [63]. A prototype consists of two magnetic masses with the same polarities and a cantilever beam with piezoelectric attached to it, which is applied on a rotating energy harvester tire, as in Figure 11b. In a driving test, the rotating frequency bandwidth could be broadened from 15–25 km/h to 10–40 km/h, and the generated power density is 11.26 µW/mm^3. The advantage of this design is that it broadens the bandwidth of rotating frequency and concurrently stabilised high energy path oscillations.

Along with, Gu & Livermore 2010 [59] have presented a self-tuning energy harvester using mass and centrifugal forces as excitation. The prototype was made of a radial cantilever piezoelectric at a distance from the centre with a mass tip at its end. The output power density range 1.5–5.3 µW/mm^3, using a slip ring for output power transfer. This design showed significantly enhanced performance compared with the untuned harvester.

As well as Gu & Livermore 2012 [58] also produced a self-tuning energy harvester's rotational applications using centrifugal force only for excitation. The harvester turns into a vertical plane, and it consists of two beams: a piezoelectric cantilever and a thin driving cantilever with mass put at his end. At 15.2 Hz, the power density is 1.53 µW/mm^3, although the PVDF beam output power is less than PZT ceramic, its durability is higher, besides, using a thicker PVDF beam can increase the output power.

Furthermore, Zhu et al. [44] have made a prototype of a piezoelectric beam with one end fix and a mass on the other end, and with using mass, vibration, and centrifugal force for excitation. A road test has been done to check the energy harvester output power from the wheel vibration excitation. At 952.2 rpm, the output power density is 6.122 µW/mm^3. This device is feasible to supply power for TPMS; however, a slip ring was needed to transfer output power.

Hence, Guan & Lia [43] have used mass, spring, and gravity forces for excitation. The prototype is made of; piezoelectric mounted on a beam and fixed near the edge of a rotating frame with mass at its end, as in Figure 12. Using a slip ring for power transfer, the power density is 2.168 µW/mm^3 at 13 Hz (810 rpm). This application could be applied in TPMS, but the housing and mounting must consider as a future issue. Besides, it will not harvest energy, at a very slow speed or at rest; however, this can be solved by using a super capacitor or rechargeable battery.

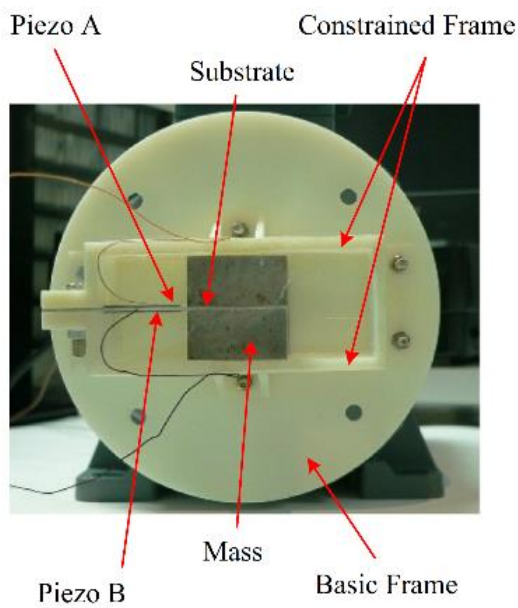


Figure 12. The prototype of the piezoelectric harvester structure fixes on the frame [43].

Moreover, Y. Wang, et al. [81] proposed a design that changes its resonance frequency with different rotational speeds. Mass and spring force have been used for excitation but with centrifugal force instead of gravity force. The design is made of a trapezoidal cantilever with a rubber plate and a tensional spring to join the trapezoidal base's. When the wheel rotates at 200–700 rpm the output power density is 1.06–2.12 μW/mm^3, and a slip ring was used. This design's novelty is its ability to change its resonance frequency with different rotational speeds.

Alternatively, Rui et al. 2019 [82] presented a piezoelectric composite fibre materials energy harvester installed in spoke for the TPMS. The gravity influence of the free end mass generates a periodic excitation during the rotation, and the structure of the safety limiting is designed. The experimental results show that the power density was 1.67 μW/mm^3. This harvester in the spokes has good application prospects and higher practicability than other harvesters installed on the tire. However, some improvements can be made to enhance output power, such as using bimorph instead of uni-morph and install more harvester, one at each spoke.

Similarly, Rui et al. 2020 [83] using mass, centrifugal, and gravity forces as excitation and proposed a PZT energy harvester to provide power for low-consumption appliances in intelligent car wheels. The harvester is implanted in the spoke and has the self-tuning ability due to centrifugal force in the rotational motion. An experimental prototype has been built with macro fibre composite, and the generated output power density ranges from 1.437–14.804 μW/mm^3 at a 40–120 kph on a real road test. The harvester passive self-tuning creates broadband to match vehicle speed.

Furthermore, applying a High-Efficiency Compressive-Mode Piezoelectric Energy Harvester (HC-PEH) in a rotational system was studied theoretically and experimentally by Wang et al. [84]. The HC-PEH is comprised of a proof mass, two elastic beams, and a centre of a flex-compressive which consists of one PZT and two bow-shape curved in metal plates. The experimental results show that the maximum output power density was 26.993 μW/mm^3 at 21.67 Hz, with an external resistor of 40 kΩ. Notably, the harvester performance in a rotational system is better than the translation one; thus, it is quite adaptable for rotational system applications.

5.2. The Influence of Excitation Elements and Design on Performance (Challenges and Issues)

As shown in Table 3, a comparison has been made between variable factors, divided into input, output, and comments. In general frequency (rpm), PZT size, dimension, and material type, resistance, and whether the PZT rotate or not, using a slip ring or not, all these elements that affect on piezoelectric energy harvesting output power has been reported in Table 1, also, both output power and power density have been reported as well in this table. Although, excitation elements greatly affect shaping the design and make it suitable for certain applications and help harvest sufficient output power. However, as clearly shown in Table 3, for the same excitation elements the output power density is changing, and this is due to design change and its effect on output power.

Figure 13 compares all these designs according to rpm and the output power density to have a clear idea about the best excitation elements. As shown in the Figure, almost 78% of the reported studies have used centrifugal force for excitation. However, this was not enough to harvest maximum output power. As shown, the prototype that adds mass as excitation alone/or with gravity force gets a very good result [44,84]. On the other hand, the applications that add a magnet to centrifugal force for excitation get the lowest results [4,80]. However, Manla et al. [80] presented a harvester that contains a tube with a piezoelectric thunder fix on each end. This design is a novel approach, having low values of mass, minimum volume, and compact. X. Wu et al. [4] also presented a see-saw structure design, this unique harvester design could avoid the effect of huge centrifugal force due to its balance distinctive.

Table 3. Summary Comparison for rotational piezoelectric energy harvesting studies with detailed information.

				Input						Output		Comments		
Number	**Ref.**	**Excitation Elements**	**Volume (mm_3)**	**Piezo Dimension (mm)**	**Polarisation Mode**	**Material Type Use**	**rpm**	**Frequency (Hz)**	**Optimal Resistance (Ω)**	**Power (μW)**	**power Density (μW/mm^3)**	**Mechanical Power Source**	**PZT Rotate or No**	**Wiring**
1	[19]	Mg	42.2	22 × 8 × 0.24	/	PZT-5H	840	14	110 k	65.4	1.55	VT	No	Direct wiring
2	[20]	Mg	3.98	26.5 × 1.5 × 0.1	/	/	2100	300	/	20	5.03	VT	No	Direct wiring
3	[80]	Mg + Cn	64.5	25.4 × 12.7 × 0.2	/	PZT 5A	330	5.5	/	3.5	0.05	VT	Yes	/
4	[4]	Mg + Cn	30	25 × 12 × 0.1	D31-	PVDF	965	16	600 k	36	1.2	VT	Yes	Slip ring
5	[42]	M + Mg + Gr	22.9	22.9 × 10 × 0.1	/	PZT-ceramic	552	9.2	252 k	12	0.52	VT	/	/
6	[63]	M + Mg + Cn	21.3	22.9 × 9.3 × 0.1	/	/	365	6.08	150 k	240	11.3	VT	Yes	/
7	[58]	Cn	80	25 × 6.4 × 0.5	d31	PZT	972	16.2	/	123	1.54	VT	Yes	slip ring
8	[59]	M + Cn	130	41.3 × 6.3 × 0.5	/	PZT	792	13.2	/	700	5.38	VT	Yes	slip ring
9	[44]	Cn + M	24.5	70 × 5 × 0.07	d33	PZT-5H	952	15.9	1000 k	500	20.4	VT	Yes	slip ring
10	[43]	M + Sp + Gr	380	28.5 × 50 × 0.267	/	PSI-5A4E	810	13.5	/	825	2.17	VT	Yes	slip ring
11	[81]	M + Sp + Cn	66	22 × 6 × 0.5	D31	PVDF	700	11.7	3300 k	140	2.12	VT	Yes	slip ring
12	[82]	M + Gr + Cn	600	150 × 20 × 0.2	/	PVDF	504	/	2×10^5	1003	1.6717	VT	Yes	slip ring
13	[83]	M + Gr + Cn	424.2	101 × 20 × 0.21	/	PZT (MFC)	1008	16.79	2×10^5	6280	14.804	VT	Yes	Sd card
14	[84]	M + Gr + Cn	612	51 × 20 × 0.6	d31	PZT-5H	1300	21.67	40 k	16,520	26.993	VT	Yes	slip ring

M for mass, Mg for magnetic, Cn for centrifugal, Gr for gravity, Sp for spring, VT for vehicle tires, and/for no information from the authors.

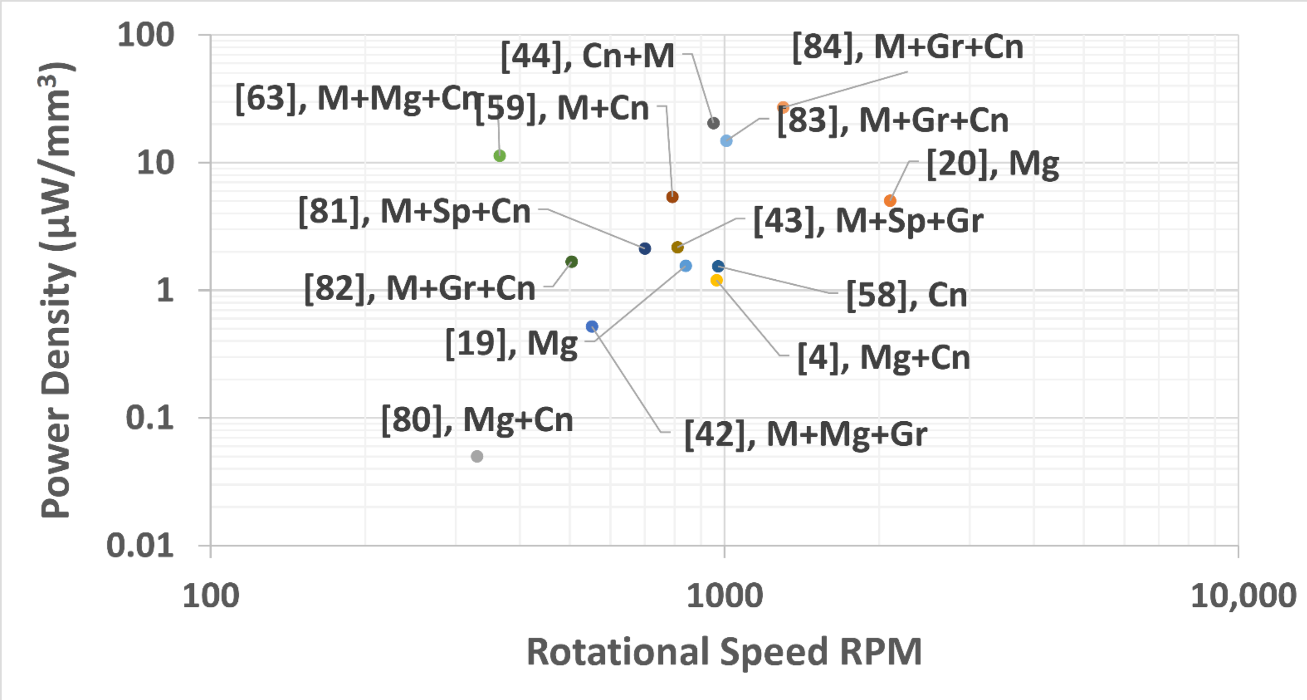


Figure 13. Rotational piezoelectric energy harvesting for vehicle tires mechanical input with excitation elements and as follow: M for mass, Mg for magnetic, Cn for centrifugal, Gr for gravity, and Sp for spring.

Now in terms of design, few studies present a very simple, small, and compact design [44,59,83]. Zhu et al. [44] design their model after several tests to wheel vibration characteristics and energy harvester test at the road. Gu & Livermore [59] have enhanced their self-tuning energy harvester by adding mass force beside centrifugal force for excitation. This design showed significantly enhanced performance comparing with the untuned harvester. Rui et al. [83] present a harvester with the ability of passive self-tuning ability by centrifugal force to create a broadband matching vehicle speed. There are some other designs that are not very compact [19,43,81]. For example, Fu & Yeatman [20] prototype needs to reduce the size and make it more compact; however, the device uses a contactless way to harvest energy.

Additionally, Guan & Lia [43] application could be applied in TPMS, but it must be considered; the housing and mounting as a future issue. Besides, it will not harvest energy, when the tire moves very slow or at rest; however, this can be solved by using a supercapacitor or rechargeable battery. The design produced by Y. Wang, et al. [81] is also a little bit complicated with many parts and excitation elements. For the output power transfer, a slip ring was used; however, the novelty of this design is that its ability to change its resonance frequency with different rotational speeds. In general, Zhu et al. [44] and Rui et al. [83] has the simplest compact design with a significantly enhanced performance. One of the interesting designs that future works should focus on is applying gravity and centrifugal forces as excitation elements but with a compact and small design fit easily in vehicle tire to achieve maximum output power density.

6. Other Rotational Operational Principal Energy Harvester in General

This section compares the studies of various authors, who have suggested that their designs can make use of any rotational machine as an input mechanical power source for rotational piezoelectric energy harvester, has been done. It has been divided into two sections: any rotational machine in general and a rotational machine using gears. Each subsection is divided into different groups according to excitation elements for each study, their design, methodology, and output power density have been reported.

6.1. Comparison of Different Designs and Excitation Elements

Firstly, in this section, the studies that have been designed to work without specific rotational mechanical input (any application) have been reported in different sections according to their excitation elements.

Grzybek and Micek et al. [85] present an investigation on piezoelectric energy harvesting using Macro Fiber Composite (MFC) which was directly glued on the rotating shaft without adding any mechanical structure, using shaft stress and rpm as excitation. At 56.17 kΩ, and 20 Hz the output power density is 2.08 μW/mm^3. This harvester can be used to supply power for WSN used in measuring shaft parameters, e.g., stress. This sensor can replace the conventional sensor that required conduits and a slip ring for output transfer.

Conversely, Ramírez et al. [73] designed a device of two cantilever beams with a mass at the free end and connected with spring as excitation elements, as shown in Figure 14a. This work's primary influence is to provide a finite element of one dimension of modelling a three-dimension rotating energy harvester. The maximum output power density is 0.0229 μW/mm^3 at 6 Hz (300 rpm), an Arduino is used to transfer the output voltage via Bluetooth to avoid slip ring mechanisms complexity. Future work may include developing a rotational energy harvester more complex to investigate the generation of power.

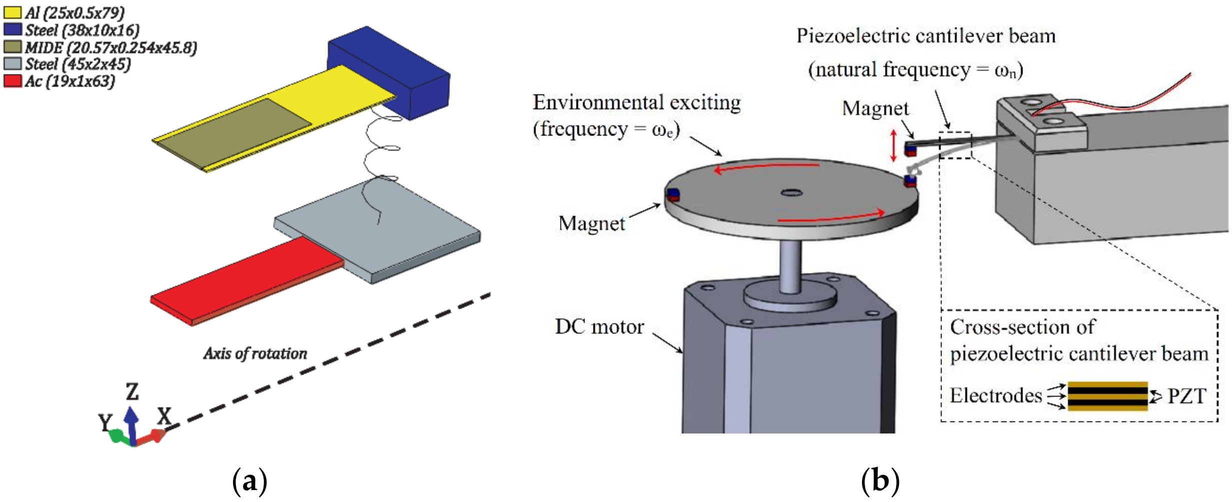


Figure 14. (**a**) piezoelectric beam using a tip mass [73]; (**b**) The harvester design, with its excitation force using magnetics [12].

W. Wu [12] has made a prototype of two piezoelectric beams connected in parallel with a magnet of 2.5 m diameter and 2 mm in height fixed on the piezoelectric beam free end and on the rotating host, respectively to provide magnetic force, as in Figure 14b. It was found that at 546 rpm, the maximum output power density is 22.82 μW/mm^3. Besides, the magnetic force will widen the PZT broadband energy harvester, and optimising the system was done by using different configurations of magnetic force.

Furthermore, Ma et al. [86] designed a hybrid energy harvester of triboelectric-electromagnetic-piezoelectric induced by a multi-function magnet. In the piezoelectric generator (PEG) unit, a PZT is put in the top shell centre beside a permanent magnet that is fixed to the end of the PZT. The attractive and repulsive forces between the passing and permanent magnets bend the PZT and therefore energy was harvested, as shown in Figure 15a. The PEG output power density is 0.4213 μW/mm^3 under 50 MΩ. This hybrid harvester shows good durability and stability and demonstrates a new energy harvester kind that can effectively harvest rotational mechanical energy.

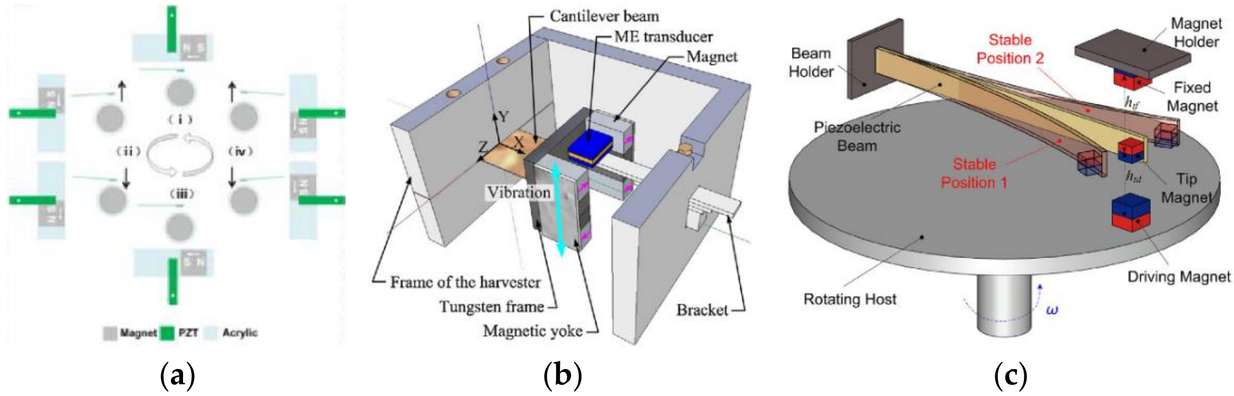


Figure 15. (**a**) Operation principle of PZT generator [86]; (**b**) the diagram of the simulated model [45]; (**c**) a schematic design showing the two magnetic and all other parts. [9].

To avoid slip ring mechanism complexity for data transmission, an Arduino board has been implemented as a data gaining system to transfer voltage through Bluetooth by M. Li et al. [45]. The prototype consists of a magnetic circuit that fixed to the beam free end, and the cantilever is put in the magnetic circuit air gap as in Figure 15b. At a rotation speed of 588 rpm (9.8 Hz), the power density 2.73 μW/mm^3. Future work may include an investigation on the harvester radial location influence on the output power's performance and developing a MEMS-scale generator.

Fu & Yeatman [9] presented a harvester for low-power sensing applications. A prototype of mass and magnets as excitation elements for PZT were used to change kinetic energy into electric energy, as in Figure 15c. The output power density at 660 rpm is 5.2 μW/mm^3. This work presents a theoretical model and in-depth bistable frequency up-converting harvester analysing, giving basic guidance, and understanding the design of low-frequency broadband energy harvester.

Ramírez et al. [87] presented an experimental validation with numerical analysis to the novel piezoelectric rotational motion device made with E-shape multi-beams. Centrifugal force and mass have been used for excitation elements, and the harvester comprises of two E-shape multiple beams connected by a rigid beam, and as shown in Figure 16a. The maximum output power density of 0.61 μW/mm^3 achieved when running in a low-frequency from 0.5 to 3 Hz (30–180 rpm). Finally, the proposed device provides a good energy harvesting solution at a very low rotational frequency such as 30 kW wind turbines.

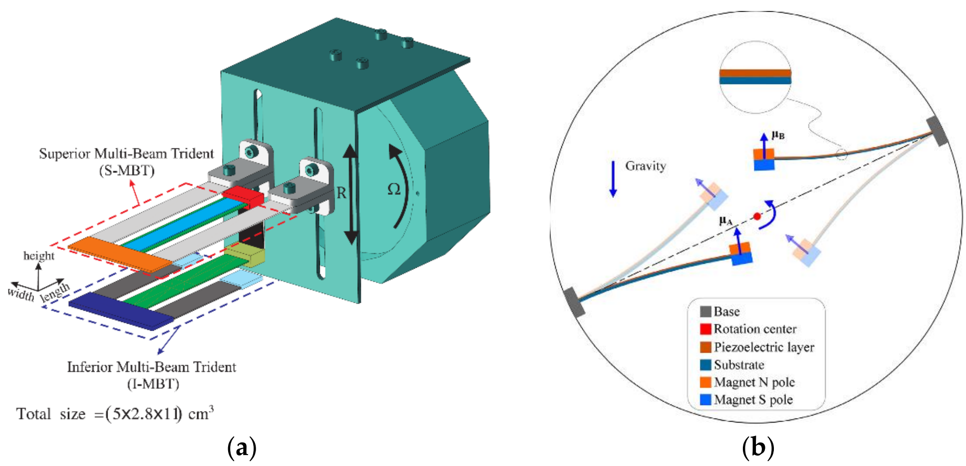


Figure 16. (**a**) Schematic illustration of rotational piezoelectric energy harvester using multi-beam [87]; (**b**) Rotational motion design using magnetic and two piezoelectric beams [10].

Furthermore, Zou et al. [10] presented a magnetically coupled design of an energy harvester using two inverted piezoelectrics and their free ends points to the rotating shaft, as in Figure 16b. The excitation elements are a combination of centrifugal and magnetic forces all alone with mass and gravity force. The obtained output power density at 420 & 550 rpm (7 & 9.17 Hz) is 14.1 & 13.3825 μW/mm^3. The results have shown that this harvester is suitable for low frequency rotational, and vibration energy can be harvested in multiple frequency bands.

F Khameneifar et al. [11] present a harvester comprises a piezoelectric beam with tip mass fixed on a rotating host, and the mass and gravity are the elements of piezoelectric excitation. At 132 rad/s and 40 kΩ, the maximum output power density can be reached to 9.16 μW/mm^3 at 1260.5 rpm (21 Hz). They have found that with the proper size and parameters, this design can harvest enough power to operate wireless sensors in rotating mechanisms like tires and turbines; however, an experimental test will be useful to utilise these results.

Similarly, using the same excitation elements, Hsu et al. [56] present a design consists of a piezoelectric beam with a tip mass fixed to a clamp which can be driven to rotate along with a machine tool spindle. The maximum output power density at optimum resistance of 400 kΩ, and 720 rpm is 18.51 μW/mm^3. Furthermore, this method flexibility in the various geometrical model building allows the procedure to be used in a more complex geometries model beam harvester, however, it is difficult to be done with the classical beam theory.

Moreover, Farbod et al. [57] have also used mass and gravity force as excitation elements to study vibration energy harvester. A design has been made of a cantilever beam with a tip mass on its end and piezoelectric ceramic mounted along the beam fixed on a rotating shaft. The output power density is 25.43 μW/mm^3 at 21.96 Hz, and it is transferred using a slip ring. Furthermore, more power can be generated by using more than one harvester; however, further experimental studies need to be made for system power generation evaluation.

Alternatively, a gear was used as a frequency up-conversion method; more frequency can be obtained and higher frequency to match the piezoelectric resonant frequency. Moreover, no need for more slip ring or any other extra device for output power transfer, normal wiring can be used since the PZT is stationary and does not need to rotate within the system.

P. Janphuang et al. [88] have tested the gear teeth impact on piezoelectric energy harvesting. A prototype consists of 16 teeth gear, with 25 rpm motor rotating speed, and gear that supply impacts force on the bimorph MEMS piezoelectric transducer. The maximum output power density is found to be 0.3 μW/mm^3 with 25 rpm and 100 μm depth tip. The output power reaches a good level to be used in applied applications, and it can be simply risen by increasing, beams number on the gear, the rotational speed, or gear teeth number.

Furthermore, Wei & Duan [61] have presented a piezoelectric rotating energy electrical harvester using gear with polygon shape along with multiple cantilever piezoelectric. The generator has accomplished a 7.14 μW/mm^3 open-circuit output power density at 300 rpm. The produced power could be used as AC and Dc power with a delivered power of about 80% (4.5 μW/mm^3) for AC and 40% (2.55 μW/mm^3) for DC. This generator's broadband feature makes it ideal for scale-scale fluid-driven power-generation systems operating with low-frequent broadband excitations.

Moreover, Park et al. [60] have demonstrated a new design based on shape optimisation, with a gear of 36 teeth as a frequency up, and different shapes of cantilevers are used to compare with the normal one. Without area constraint but with a wider tip, it was found that the output average power density is 0.874 μW/mm^3. Moreover, it concludes that the design with a wider free tip improves the output power level. Future work by making the design more practical can be done by reducing the friction by enhancing the tip excitation and selecting a material with higher durability and efficiency.

Similarly, Pattanaphong Janphuang et al. [89] carried out a compact energy harvester configuration to convert low-frequency mechanical oscillation into usable energy by using an Atomic Force Microscope (AFM) like the piezoelectric MEMS cantilever coupled to a rotational gear. It was found that at a rotating speed of 19 rps (1140 rpm), the output average power density is 3.42 $\mu W/mm^3$. Wear-less coating and materials have been investigated to reduce the problem of wearing and enhance this harvester's longevity and efficiency.

Additionally, A gullwing-structural rotational piezoelectric energy harvester using the mechanism of gear-induced oscillation is proposed by Yang et al. [90]. The prototype consists of two nonlinear blocked bridge which uses a flexible polymer substrate and a piezoelectric unit naturally buckled. The harvester can generate an output power density of 6.54 $\mu W/mm^3$ at 7.8 Hz. These results show that this approach promises self-powered sensors, specifically at low-frequency and changeable ambient, like tire pressure monitoring.

Pattanaphong Janphuang et al. [91] demonstrated a configuration realised mechanism of frequency up-conversion using piezoelectric and a rotating gear. The frequency up can be achieved using the Atomic Force Microscope (AFM), such as piezoelectric beam plucked by rotating gear teeth. They have found that the output power density at a rotational speed of 19 rps (1140 rpm) is 10 $\mu W/mm^3$. Furthermore, the performance can be enhanced by using more durable harvesting material or applying a frictionless coating while keeping the system compact and extending its lifetime.

Furthermore, Chilabi et al. [92] fabricated a frequency up-conversion energy harvester. The prototype consists of the planetary gear, interchangeable planet cover, and PZT installs on the fix ring gear, as shown in Figure 17. At a resistance of 50 kΩ, 1500 rpm, and 6.25 Hz bending frequency of the PZT the output power density was 9.59 mW/cm^3. This harvester novelty of providing the desired output power from a fixed rotational speed could be a good start for future enhancement. Additionally, the way of system rotation made an impact on PZT by planet gear teeth smother, resulting in PZT longer lifetime.

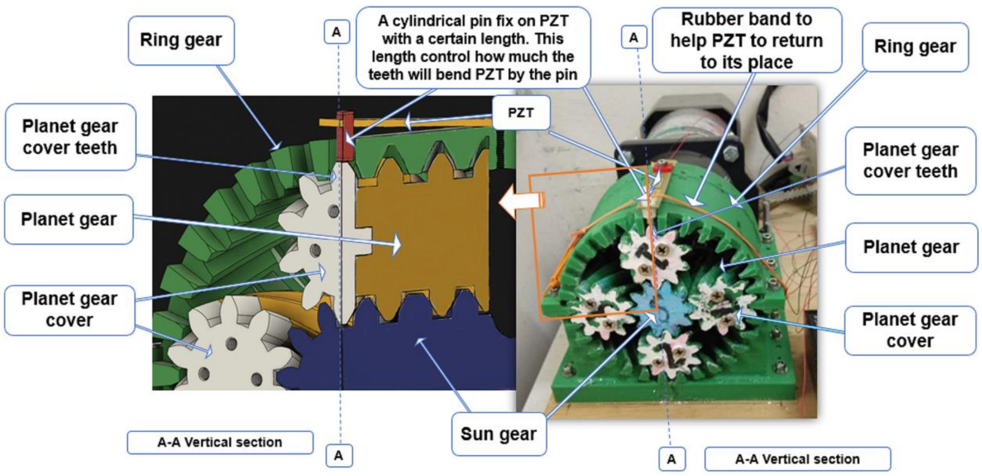


Figure 17. The harvester prototype with a section view in the A-A vertical line, and all part names [92].

6.2. The Influence of Excitation Elements and Design on Performance (Challenges and Issues)

As shown in Table 4, a comparison has been made between variable factors, divided into input, output, and comments. In general, frequency (rpm), PZT size, dimension, and material type, resistance, and whether the PZT rotate or no using a slip ring or not, all these elements that effect piezoelectric energy harvesting output power has been reported in the Table, also, both output power and power density have been reported as well in this table. Although, excitation elements greatly affect shaping the design and make it suitable for certain applications and help harvest sufficient output power. However, as clearly shown in the Table, for the same excitation elements the output power density is changing, and this is due to design change and its effect on output power.

Table 4. Summary Comparison for rotational piezoelectric energy harvesting studies with detailed information.

							Input			Output		Comments		
Number	**Ref.**	**Excitation Eements**	**Volume (mm₃)**	**Piezo Dimension (mm)**	**Polarisation Mode**	**Material Type Use**	**rpm**	**Frequency (Hz)**	**Optimal Resistance (Ω)**	**Power (µW)**	**Power Density (µW/mm^3)**	**Mechanical Power Source**	**PZT Rotate or Not**	**Wiring**
1	[85]	Shaft stress	357	85 × 14 × 0.3	d31	PZT	1200	20	56,170	744	2.084	RM	Yes	slip ring
2	[73]	M + Sp + Gr	239	20.57 × 0.254 × 45.8	d31	QP16N	360	12.7	/	5.5	0.02	RM	Yes	Arduino
3	[12]	Mg + Sp force	53.9	35 × 2.2 × 0.7	/	PZT	546	34.1	400 k	1230	22.8	RM	Not	Normal wiring
4	[86]	Mg	15.12	21.6 × 3.5 × 0.2	/	(PZT)	45	0.75	5 × 10^5	6.37	0.4213	RM	Yes	slip ring
5	[45]	M + Mg	57.6	12 × 6 × 0.8	NA	PZT	588	9.8	3.3 M	157	2.73	RM	Yes	slip ring
6	[9]	Mg + bistable	10.1	33.5 × 2 × 0.15	d31	PZT	660	11		52.3	5.2	RM	Not	Normal wiring
7	[87]	M + Cn	327.7	50.8 × 25.4 × 0.254	d31	PZT(MFC)	180	0.5–3	1000	200	0.6102	RM	Yes	wireless data acquisition
8	[10]	M + Mg + Gr + Cn	40	20 × 10 × 0.2	d31	(PZT)	550	9.17	50 k	535	13.4	RM	Yes	/
9	[11]	M + Gr	840	50.8 × 31.8 × 0.26	d31	PZT-ceramic	1261	21	/	7700	9.17	RM	Yes	/
10	[56]	M + Gr	86.4	24 × 18 × 0.2	/	(PZT-5A)	720	12	400 k	1600	18.5	RM	Yes	slip ring
11	[57]	M + Gr	89	50.8 × 38.1 × 0.13	d31	PVDF& PZT	1318	22	400 k	6400	25.4	RM	Yes	slip ring
12	[88]	G	4.2	/	/	/	25	0.4	2.7	1.26	0.3	RMG	Not	Normal wiring
13	[61]	G	138.66	33 × 22 × 0.191	/	PZT	300	6	/	6000	2.55	RMG	Not	Normal wiring
14	[60]	G + M	4.26	152 × 0.028	/	PZT-5A	15	500	1000	3.72	0.87	RMG	Not	Normal wiring
15	[89]	G	3.5	3.5	/	/	1140	19	4700	12	3.43	RMG	Not	Normal wiring
16	[90]	Gr	61.2	10 × 18 × 0.17 × 2	/	PZT-ceramics	468	7.8	30 k	400	6.54	RMG	Not	/
17	[92]	PGr	157.8	46.4 × 6.8 × 0.25	d31	PZT 5H	1500	6.25	50,000	1566	9.59	RMG	Not	Normal wiring
18	[91]	G + M + Mg	1.2	5 × 3 × 0.08	d31	PSI5A4E,	1140	19	180 k	12	10	RMG	No	Normal wiring

M for mass, Mg for magnetic, Cn for centrifugal, Gr for gravity, Sp for spring, G for gear, Pgr for planetary gear, RMfor rotationa motion, RMGfor rotational machine (gear), and/for no information from the authors.

In Figure 18, a plot has been made for all the designs, due to rpm and output power density, to give a clear idea about the best excitation elements and which one has the highest power density. As shown in the Figure, a very good output power result has been made by Hsu et al. [56] and Farbod et al. [57] using mass and gravity and Wu [12] using magnetic and spring force and also get good results. A compilation of mass, spring force, and gravity has been used by Ramírez et al. [73] and get the lowest results. However, for Ramírez et al. [73] the primary influence is to provide a finite element of one dimension accomplished of modelling three-dimension rotating energy harvester. One of the interesting designs that future works should focus on includes developing a rotational energy harvester more complex to investigate power generation.

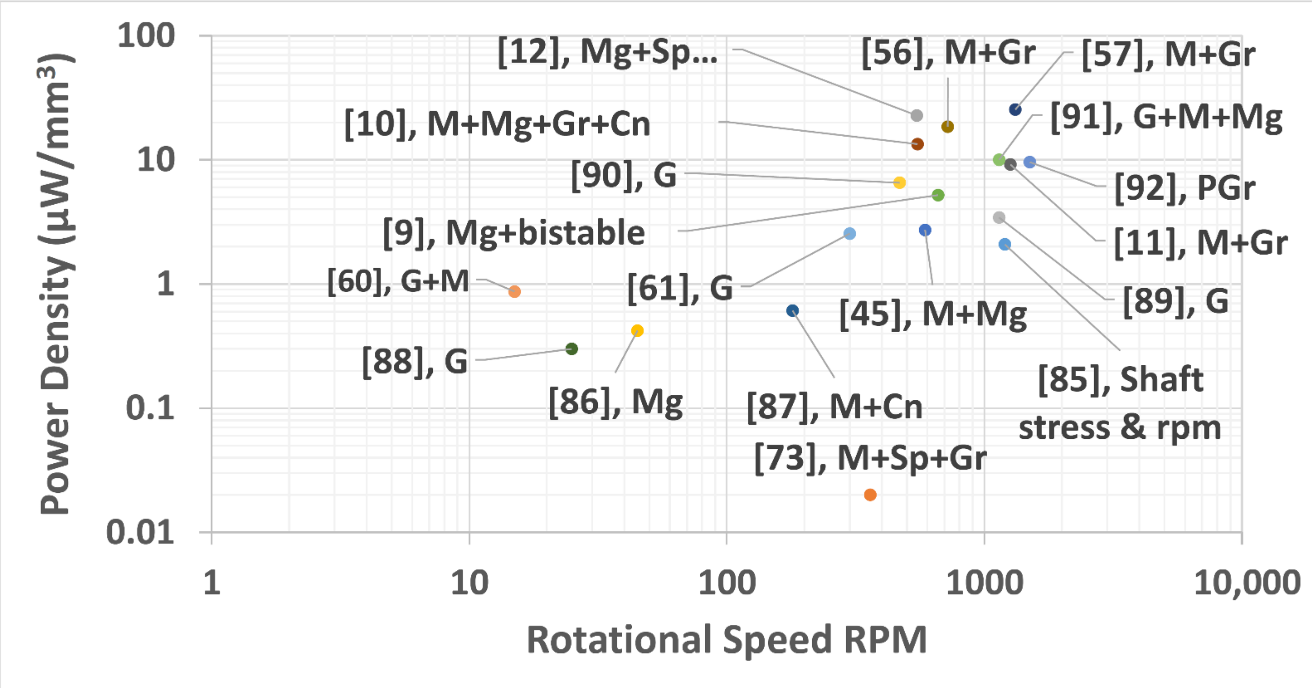


Figure 18. Rotational piezoelectric energy harvesting for rotating machine including gear with excitation elements and as follow: M for Mass, Mg for magnetic, Cn for centrifugal, Gr for gravity, Sp for spring, G for gear, PGr for planetary gear, and bistable for bistable force.

Regarding the design aspect, Wu [12], Fu & Yeatman [9], Farbod et al. [57], and Pattanaphong Janphuang [91] present; the simple, smaller size, and compact design. On the other hand, Ramírez et al. [87] and Hsu et al. [56] present a more complicated prototype. However, Ramírez et al. [87] present the novel piezoelectric rotational motion device made with E-shape multi-beams and provides a good solution for energy harvesting at low rotational frequency. Hsu et al. [56] present a method with flexibility in the various geometrical model building that allows the procedure to be used in a more complex geometries model beam harvester. This method is challenging to be done with the classical beam theory. In general Wu [12] and Farbod et al. [57] present the best prototype for the prospective of; simple excitation elements, design, and maximum power output. Similarly, Pattanaphong Janphuang [91] and Chilabi et al. [92] present a good design that its output power reaches a good level to be used in applied applications, and it can be simply risen by increasing, beams number on the gear, the rotational speed, or gear teeth number. One of the interesting designs that future works should focused on applying gravity spring, and magnetic forces as excitation elements and using gears, but with compact small design considering less friction with gears to achieve maximum output power density.

7. Conclusions

This paper reviews the recent studies and research in rotational piezoelectric energy harvesting based on its excitation elements and design and its influence on performance. Depending on the application, and the availableness of the mechanical power sources, various types of energy harvester are obtainable most of the time. The materials used in the RPZTEH were mainly PZT, however some researchers used PVDF and PZT composite. Mechanical energies such as vibration, fluid-flow, human motion, etc., are energies of changeable frequencies and amplitude, which could be named as random energies that are available everywhere. Human motion and some other rotational mechanical power source have a low rotational frequency, and thus, it will not reach the piezoelectric resonance frequency. Consequently, researchers have started to find ways of bandwidth widening techniques and frequency up-conversion methods. The comparison of excitation elements and design and their influence on performance for various mechanical Inputs are divided into four types according to mechanical inputs: fluids (air, water) movement, human motion, rotational vehicle tires, and other rotational operational principal.

The fluid power source has been divided into two sections air (wind) and water (or rain). There are some excellent works for air or wind and where various types of excitation elements have been utilised; however, no plane has been done for very high wind speed. Furthermore, more experiments can be done on more conventional available places such as the air inside the air conditioning tunnel or air conditioning air exhaust. For water flow or rain as the input power source, only a few studies have been conducted; however, the power density is small. Based on this review it was found that with a small compact design, applying magnetic and gravitational forces as excitation elements can achieve higher output power density.

Different excitation elements have been used for frequency up-conversion and output power enhancement for human motion as rotational input mechanical power sources. However, this power source's main concern is its low frequency and need for a light and compact harvester. Many studies have used different novel designs with various excitation elements to wideband the bandwidth and thus harvest more power in different speed ranges. Furthermore, more compact designs need to be fabricated using PVDF materials considering their flexibility with human body parts movements. More real-life experiments need to be done to see its feasibility in human daily use. Based on this review it was found that applying gravity and magnetic forces as excitation elements with a small compact designs can achieve higher output power density.

For using vehicle tires as mechanical input power source, different designs have been used; some of them need to have a field test on a real vehicle to see its feasibility others need to resize it so that it fits in the tire. However, our main concern is to focus on fabricating a prototype that harvests enough power in the wideband frequency range, especially at low vehicle speed. based on this review it was found that applying gravity and centrifugal forces as excitation elements with a small compact design that fit easily in vehicle tire can achieve higher output power density.

There are not many studies that use the gear as an excitation element for frequency up-conversion. However, its output power reaches a good level to be used in many applications. Besides, it can be increased by simply used more gear teeth or increasing the piezoelectric number. More studies can be done to reduce that contact between the gear teeth and piezoelctric or make it contactless (use magnetic) to increase piezoelectric lifetime and output power and make the gear harvester more compact. Based on this review it was found that with a small compact design and using gear; applying gravity spring, and magnetic forces as excitation elements can achieve higher output power density, taking into account less friction with the gear teeth.

In general, many essential factors influence the rotational piezoelectric harvester output power, which made a wide range of output power from nano to milliWatts. Design with a fixed piezoelectric cantilever is more favourable for future work. In this case, normal wiring can be used for the output power transfer, without a slip ring or any extra component that makes the design less compact. Generally, for most rotational piezoelectric energy harvesting applications, it can be said that the magnetic force had a good influence on optimising output power considering the pole direction and the number of magnets. The studies revealed that the design of a small compact prototype with a fixed piezoelectric to avoid slip ring and using magnetic, gravity, and centrifugal forces had a good influence on output power optimisation. Future work should also focus on using gear for frequency up-conversion to enhance output power density and keep the design simple and compact.

Author Contributions: Conceptualisation, H.J.C.; writing—original draft preparation, H.J.C.; writing—review and editing, H.S.; visualisation, H.J.C.; supervision, E.E.S.; project administration, H.S.; funding acquisition, E.E.S.; review and editing, A.B.A.; review and editing, K.A.M.R.; review and editing, W.A.-A.; review and editing, L.C.A.; review and editing, M.K.A. All authors have read and agreed to the published version of the manuscript.

Funding: The founder for this research is UPM Faculty of Engineering, grant number 9607500.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: A special thanks for Ahmed B. Atrah for help and guide through the work. Many thanks are also extended to Moaath Al-Rifaay and Nuradeen M. Nasidi for help and guidance.

Conflicts of Interest: There are no conflict of interest to disclose.

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