

Comprehensive Review on Effective Strategies and Key Factors for High-Performance Piezoelectric Energy Harvester at Low Frequency

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ABSTRACT

In the past decade, there has been rapid development in piezoelectric energy harvester due to its limited application and low output power. This paper critically reviews the strategies implemented to improve the power density for low-frequency applications. These strategies include piezoelectric material selection as well as optimisations of shape, size and structure. The review also focuses on the recent advances in multi-modal, nonlinear and multi-directional energy harvesting. Based on the comprehensive summary of the normalised power density at 1g acceleration, it was found that most works fell in the second quadrant of low frequency and high power density. The maximum value was around 1mW/mm³/g. Adding an extension of beam or spring to the conventional piezoelectric beam could enhance the normalised power density dramatically. Additionally, the multi-modal energy harvester exhibits broader bandwidth when its multiple resonance peaks get closer. The findings indicate that the anticipated performance of a piezoelectric harvester can be attained by achieving the trade-off between output power and bandwidth. To achieve high performance at low frequency, the following factors are essential: excellent material characteristics optimised geometry for high strain energy density, excellent flexibility, high excitation amplitude and broad bandwidth.

Keywords: Piezoelectric energy harvester; low frequency; renewable energy; vibration.

INTRODUCTION

Ambient energy was no longer overlooked as a viable energy source as methods have been developed to harvest energy from heat and vibration sources since many decades ago. Due to the popularity of smaller electronics applications and the increasing demand for maximising the lifespan of batteries, many researchers have been looking into the potential of vibration-based power generators. Electrical energy can be converted from kinetic energy by using piezoelectric material which generates an electrical signal when it encounters vibration (mechanical strain). The energy density of a typical piezoelectric energy harvester is at least three times larger than those of electromagnetic and electrostatic transducers [1]. Applications of piezoelectric energy harvester include a wireless medical implant that harvests energy from heartbeat to power the modern cardiac pacemaker [2], embedded sensors in buildings [3,4], transportations [5,6] and wearable [7-9] or handheld devices such as self-charging mobile phone [10]. The current research trend is the developments of micro [11] and nano power generators [12,13]. However, the main drawback of harvesting energy from piezoelectric material is low output power as

they allow vibration scavenging for a specific frequency only. Furthermore, energy is particularly most abundant at the low-frequency range. However, the low-frequency vibration sources usually have low amplitudes, for example in human motions [14,15]. Therefore, many strategies have been implemented to improve the performance of piezoelectric energy harvester at low frequency. This paper systematically reviews the works conducted, aiming to identify the effective strategies and key factors for high power density (the amount of output power per unit piezoelectric volume). The targeted frequency range is below 200Hz. The findings benefit the low-frequency applications, including but not limited to self-powered wireless sensors for health and condition monitoring such as on railway tracks [16], bridges [17] and rotating machines [18].

SELECTION OF PIEZOELECTRIC MATERIAL

Characteristics of Piezoelectric Materials

The characteristics of piezoelectric materials are determined by a set of parameters: Strain coefficient, voltage constant, dielectric constant, electromechanical coupling factor, mechanical quality factor and Curie temperature [19]. Strain coefficient is the ratio of mechanical displacement per unit electrical field applied or the ratio of short circuit charge density per unit mechanical stress applied. Voltage constant gives the amount of mechanical strain experienced by material per unit charge density applied or the value of open-circuit electrical field generated per unit mechanical stress applied. High dielectric constant shows a high amount of charge that can be stored in the piezoelectric material, hence, a higher output power of a harvester. Electromechanical coupling factor indicates the effectiveness of mechanical to electrical energy conversion and vice versa. It is defined as the square root of electrical (mechanical) energy stored per unit mechanical (electrical) energy applied. These important parameters should be considered when selecting piezoelectric material. The material of high energy density generally has a high product of strain coefficient and voltage constant. Material with higher dielectric constant and electromechanical coupling factor has a better capacitive characteristic and energy conversion efficiency, respectively. Higher quality factor indicates lower energy losses. Precaution should be taken against Curie temperature as a material would lose its piezoelectric effect. It is advisable to restrict the working temperature to half of the limit.

Piezoelectric Materials for Low-Frequency Applications

The widely used synthetic piezoelectric material such as PZT is an established material and commercially available for researchers. Conventional energy harvester employs a cantilever beam structure. To attain a low natural frequency, beam with low stiffness and high effective tip mass is normally employed. The latter is mainly contributed by partial beam mass and attached external mass. PZT is a high-density material of ca. 7600kgm^{-3} and its elastic modulus are generally above 50GPa. Although the performance of PZT is broadly acknowledged, researchers have been developing new materials with better properties for low-frequency application. PVDF polymer and PZN-PT single crystal have been regarded as having the highest values of piezoelectric voltage constant and energy density, respectively [20]. Their low elastic moduli (ca. 6.9 GPa and ca. 22.93 GPa, respectively) are advantageous for low-frequency energy harvesting [21,22]. However, PVDF is a low-density material and has a low electromechanical coupling factor (ca. 0.16). On the other hand, PZN-PT has a favourable density of 8333kgm^{-3} and an excellent

electromechanical coupling factor of approximately 0.877. But, mass production of both materials is not feasible as they are expensive. Another novel single crystal material is PMN-PT, where it possesses a low modulus of elasticity (19.8GPa). In fact, Yang et al. [23] showed that PMN-PT outperformed PZT in terms of electromechanical properties. Previously, Kim et al. [24] reported that PMN-PT generated more voltage than PZT-5H. At 109.06Hz, the topologically optimised beam of PMN-PT generated 6.74V whereas PZT produced 30.27% less voltage at higher frequency (10.35% higher). PMN-PT also performed better than MFC and PVDF that produced merely 4.36V at 111.07Hz and 3.55V at 95.0Hz, respectively. To address the issue of low Curie point, a modified PMN-PT known as PIN-PMN-PT has been developed. Luo et al. [25] have successfully grown the PIN-PMN-PT crystal that table maintained the outstanding piezoelectric properties of PMN-PT crystal with the possibility to operate at a temperature of 30-40 °C higher. Zhang et al. [26] reported similarly where the electromechanical coupling and strain coefficient were maintained at 90% and 1500pC/N, respectively, at higher operating temperature. The dielectric properties of PIN-PMN-PT also exhibited minimum dependency on thickness whereas the permittivity of PMN-PT halved at a thickness of 40 μm. DeAngelis et al. [27] agreed that PIN-PMN-PT surpassed the performance of PZT where the volume of material could be minimized for the same impedance. To be a good substitute for PZT, there is a need for adequate design guidelines to explore this material further. The parameters of the discussed piezoelectric materials are listed in Table 1.

Table 1. Parameters of common piezoelectric materials.

Material	Charge constant (10^{-12} m/V)			Voltage constant (10^{-3} Vm/N)			Mech. quality factor	Curie point (°C)	Density (kg/m ³)	Ref.
	d ₃₃	d ₃₁	d ₁₅	g ₃₃	g ₃₁	g ₁₅				
PZT-2	152	-60.2	440	38.1	-15.1	50.3	680	370	7600	[28]
PZT-4	289	-123	496	26.1	-11.1	39.4	500	328	7500	[28]
PZT-5A	374	-171	584	24.8	-11.4	38.2	75	365	7750	[28]
PZT-5H	593	-274	741	19.7	-9.1	26.8	65	193	7500	[28]
PZT-8	225	-37	330	25.4	-10.9	28.9	1000	300	7600	[28]
PZT-6A1	189	-80		20.4	-8.5		450	335	7450	[29]
PZT-6A2	151	-59.5		19.2	-7.5		550	335	7450	[29]
PZT-6B	71	-27	130	18.0	-6.85	30.8	1300	350	7550	[29]
PZT-7A	150	-60	362	39.9	-15.9	48.8	600	350	7600	[29]
PMT-PT-0.03Bi	310							200	7900	[30]
PMN-PT	4000						100	130		[30]
PIN24-PMN-PT	2200			39			123	135	8150	[27]
PIN36-PMN-PT	3750						800	175		[26]
BaTiO ₃	145	-58	245	13.1	-5.2	20.5	300	120		[31]
Modified BaTiO ₃	149	-58	242	14.1	-5.5	21	400	115	5550	[32]
BT-CT-Co	150			12			800	109		[33]
KNN (HP)	127			29			240	420		[33]
KNN-Cu	86			42			2280	414		[33]
KNN-KCT	90			40			1300	385		[33]
KNN-LS	265	-114	340	20			40	368	4550	[31]
KNN-LT	230			21			73	323		[33]
KNN-LS-CT(1%)	210	-87	268					330	4550	[31]

KNN-LS-CT(2%)	180	-68	232			296	4550	[31]
BNBK79	135			24	110	280		[33]
BNBK88	170			24	150	262		[33]
PVDF	-33	23		-339		205	1780	[40,34]
MFC	440	-185	560			80		[35]
NKLN-CT(0.5%)	258					464	4250	[36]
SNSBT	18					561		[37]
NBT-KBT-BT	145				110	302		[38]
PIC 700	120	-40	110			200	5600	[39,40]

Table 1 cont. Parameters of common piezoelectric materials.

Material	Relative dielectric constant				Electromechanical coupling factor					Ref.
	K_{33}^T	K_{33}^S	K_{11}^T	K_{11}^S	k_{33}	k_{31}	k_{15}	k_p	k_t	
PZT-2	450	260	990	504	0.626	-0.28	0.701	-0.47	0.508	[28]
PZT-4	1300	635	1475	730	0.7	-0.334	0.71	-0.58	0.513	[28]
PZT-5A	1700	830	1730	916	0.705	-0.334	0.685	-0.60	0.486	[28]
PZT-5H	3400	1470	3130	1700	0.752	-0.388	0.675	-0.65	0.505	[28]
PZT-8	1000	600	1290	900	0.64	-0.30	0.55	-0.51	0.48	[28]
PZT-6A1	1050	730			0.54	-0.248		0.42	0.39	[29]
PZT-6A2	890	680			0.47	-0.207		0.35	0.35	[29]
PZT-6B	460	386	475	407	0.375	-0.145	0.377	0.25	0.302	[29]
PZT-7A	425	235	840	460	0.66	-0.30	0.67	0.51	0.50	[29]
PMT-PT-0.03Bi	6600							0.42		[30]
PMN-PT	5833	750			0.93					[30]
PIN24-PMN-PT	5325				0.92	-0.676				[27]
PIN36-PMN-PT	5625	833			0.92					[26]
BaTiO ₃	1700				0.50					[31]
Modified BaTiO ₃	1200	910	1300	1000	0.48	-0.194	0.48	-0.33	0.384	[32]
BT-CT-Co	1420				0.46					[33]
KNN (HP)	496				0.61					[33]
KNN-Cu	231							0.38		[33]
KNN-KCT	250							0.42		[33]
KNN-LS	1380		1200		0.62	-0.30	0.57	-0.50	0.46	[31]
KNN-LT	1256							0.51		[33]
KNN-LS-CT(1%)	1170		1120		0.61	-0.29	0.56	-0.49	0.43	[31]
KNN-LS-CT(2%)	1022		1100		0.56	-0.25	0.5	-0.42	0.41	[31]
BNBK79	650				0.54					[33]
BNBK88	810				0.60					[33]
PVDF	12				0.16					[40,34]
MFC	1850		1950							[35]
NKLN-CT(0.5%)	1014									[36]
SNSBT	1400							0.59		[37]
NBT-KBT-BT	820				0.519			0.162		[38]
PIC 700	700		570		0.4	0.14	0.3	0.15	0.4	[39,40]

Apart from developing new materials, ways to improve the flexibility of PZT thin films such as those of using thermoplastic as a substrate [41-43] or as an encapsulation [44] have been proposed. Qi et al. [45] demonstrated the effectiveness of integrating piezoelectric materials with rubber for flexibility. Inspired by this innovation, Muhamad and Salleh [46,47] employed natural rubber in the form of latex to coat the commonly used PZT bimorph and revealed that its natural frequency decreased with the number of the coating layer. These findings promoted the role of rubber in increasing the elasticity of PZT-based energy harvester. Japan-based Ricoh Co. [48] developed new rubber-based

energy-generating material. The output power was on par with that of piezoceramics and meanwhile, it exhibited superior flexibility. While research is still ongoing, this new material could improve the wearable and handheld energy harvesters.

OPTIMISATION OF MATERIAL GEOMETRY

Optimum Shape and Size

Traditionally, the piezoelectric material is bonded on a substrate and built in the form of a rectangular cantilever beam. However, utilising more piezoelectric material does not guarantee the efficiency of a harvester. Mineto et al. [49] identified the highest output power of $6500\mu\text{W}$ was obtained when PZT covered approximately half of the substrate. Meanwhile, many studies [50-55] discussed the possibility to improve output power by modifying the geometry of the conventional rectangular beam to a trapezoidal and triangular shape. Benasciutti et al. [56] found that the output power was dependent on piezoelectric's surface area, particularly the width. With sinusoidal excitation of 2ms^{-2} at 50Hz, both trapezoidal and reversed trapezoidal beams have greater power density by 24% and 113%, respectively when compared to a rectangular beam. Hosseini and Hamed [57] reported that the natural frequency of trapezoidal cantilever decreased with increased length. However, this trend was only valid until the length of 70-80 mm. Beyond this point, the frequency increased unless the width increased. Kherbeet et al. [58] compared the stress-strain distribution of rectangle, trapezoidal and triangle cantilevers (see Figure 1). The triangular beam produced 4.876mW at 85Hz. Whereas trapezoidal and rectangular beams produced 3.25mW and 1.05mW , respectively. Their results were consistent with the data obtained by Siddiqui et al. [59]. They verified that the deflection and internal strain energy per unit area of the triangular beam was much greater than the rectangular beam. This finding was pretty much agreed by Su et al. [60] but they also anticipated the challenge in mounting a triangular beam. Hence, a perforated rectangular piezoelectric beam was proposed. The stress of the cantilever increased as the centreline hole was made farther from the free end. However, when the hole was too close to the fixed end, the extreme concentrated stress around it caused the piezoelectric beam to entirely break. Reddy et al. [61] on the other hand studied a rectangular beam with a trapezoidal cavity with different taper angles (α) as illustrated in Figure 2. There was a favourable trend in which the natural frequency reduces, and the output voltage increases as α increases. But several questions remain unanswered at the present such as optimisations of cavity size and location. Further studies addressing these issues should be undertaken. Figure 3 illustrates an inversed S-shaped beam developed by Mehdipour and Braghin [62]. The proposed beam aimed to interrupt the decreasing trend of bonding area of the piezoelectric layer and in turn maximize the resulting electric potential along with the upper layer. The proposed beam was more flexible than the straight beam and produced a slightly higher voltage at 100Hz. This new shape performed better in terms of the required excitation force; however, its workability in physical testing remained questionable.

Based on the reported findings, the advantages and disadvantages of the piezoelectric beam shapes are presented in Table 2. It is important to note that each of the beam shapes is compared with its respective benchmark.

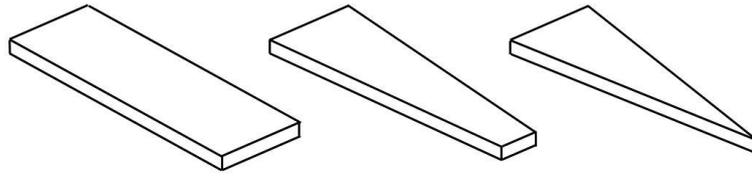


Figure 1. Schematic diagram of beam geometries investigated by Kherbeet et al. [58].

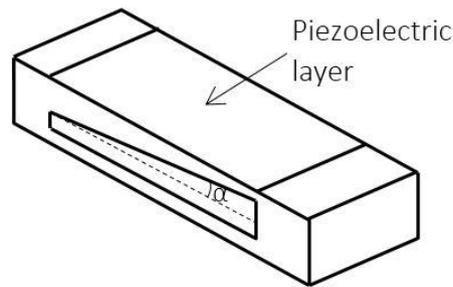


Figure 2. Schematic diagram of a rectangular beam with a trapezoidal cavity proposed by Reddy et al. [61].

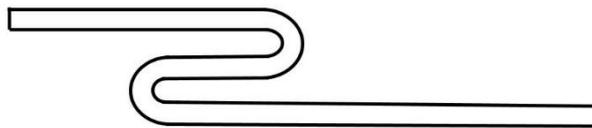


Figure 3. Schematic diagram of inverted S-shaped beam proposed by Mehdipour and Braghin [62].

Optimum Multi-Layer Structure

The number of the piezoelectric layer and electrode connection type influence the performance of an energy harvester. This subject was first explored by Song et al. [63] in 2009. The study revealed that the output voltage suffered a significant drop (in contrast to the output current) as the number of layers connected in parallel increased. However, the largest output power was still produced by single layer harvester. In 2010, Zhu et al. [64] reported a contradicting finding in which a multi-layer bimorph harvester produced more output power at the same total thickness and frequency. In fact, the researchers argued that the previous study was not theoretically supported. Double layer harvester produced 41.51% higher output power than single layer when harmonically excited at 0.41g. However, the output power declined for triple layer harvester. Hence, the fabrication of triple or more layer harvester was not recommended.

Further investigation concluded that multi-layer structure improved the output power regardless how PZT layers were connected [65]. However, higher output power was recorded for series connected harvester and it increased with the number of PZT layers. A maximum of 458.66 μW was recorded for series connected triple layer. After many years, the findings reported by Song et al. [63] was validated by Jemai et al. [66]. While the previous experimental results demonstrated a small reduction of output power ca. 15% as the number of layers was increased, current analysis showed the insignificance of this parameter change against the output power. A possible explanation for this

discrepancy might be the increase in electrode thickness whenever a new layer was introduced in the experiment. Thus, the piezoelectric material volume had to be sacrificed to maintain the total thickness. But the theoretical analysis omitted the influence of electrode thickness, leaving the material volume unaffected. Shin et al. [67] investigated a non-cantilevered multi-storey energy harvester based on PZT multi-layer actuators connected in parallel. The average output power increased with the number of storeys at a constant applied force, achieving a maximum value of 1.25 mW. The increase in output power was expected as more piezoelectric materials were used. However, the declining trend of power density should be addressed in future investigation.

Table 2. Comparison of piezoelectric beam shapes with respective benchmarks.

Beam shapes	Benchmark	Advantages	Disadvantages
Rectangular beam.	<ul style="list-style-type: none"> • Trapezoidal beam • Triangular beam 	<ul style="list-style-type: none"> • Most practical and widely available. • Easily incorporated with overall structure 	<ul style="list-style-type: none"> • Lowest internal strain energy • Lowest output power • Most piezo consumption
Trapezoidal beam	<ul style="list-style-type: none"> • Rectangular beam 	<ul style="list-style-type: none"> • Higher internal strain energy • Higher output power • Less piezo consumption 	<ul style="list-style-type: none"> • Not readily available • Risk for piezo crack or breakage during cutting
Triangular beam	<ul style="list-style-type: none"> • Rectangular beam • Trapezoidal beam 	<ul style="list-style-type: none"> • Highest internal strain energy • Highest output power • Least piezo consumption 	<ul style="list-style-type: none"> • Not readily available • Risk for crack or breakage during cutting
Perforated rectangular beam	<ul style="list-style-type: none"> • Unpunched rectangular beam 	<ul style="list-style-type: none"> • Higher internal strain energy • Higher output power 	<ul style="list-style-type: none"> • Risk of piezo crack or breakage due to extreme concentrated stress
Inverted S-shaped beam	<ul style="list-style-type: none"> • Rectangular beam 	<ul style="list-style-type: none"> • Higher output power • More flexible 	<ul style="list-style-type: none"> • Not readily available • Risk for piezo crack or breakage due to the complicated shape • More piezo consumption due to higher total beam length.

MULTI-MODAL ENERGY HARVESTING

An energy harvester with multiple vibrational modes can undergo resonance at a broader frequency range and therefore it is more capable of producing a higher output power. This is termed as multi-modal energy harvesting and usually benefits from a multi-degree of freedom structure or an array of cantilevers. However, several researchers have reported that it can also be realized by segmenting the piezoelectric layer. The studies reveal that the segmented layer has an advantage over the continuous layer in which it allows the higher vibration modes to be simultaneously excited.

Multi-Degree of Freedom Configuration

Coupling the beam can form a multi-degree of freedom (DOF) structure that has multiple resonance peaks. The simplest arrangement is a 2-DOF system. Lam and Salleh [68,69] connected the piezoelectric cantilever to the base via an external slotted aluminium beam

and recorded 56 mW at 30 Hz. Hong et al. [70] harvested a maximum of 7.8 mW at 69 Hz by attaching additional springs at the free end of the piezoelectric cantilever beam. Although, the existence of a second peak had not been reported by both studies. Erturk et al. [71] suggested an L-shaped energy harvester that produced two resonance peaks with the highest amounted to 10mW per base acceleration in g at 22.8 Hz (see Figure 4). The energy harvester had improved bandwidth; however, the exact value was not stated. Notwithstanding this promising theoretical demonstration, there is a concern whether it could perform well in physical condition. Although the researchers mentioned that the experimental validation was under progress, they had not disclosed further details and outcomes. Xu et al. [72] experimented with another right angle coupled beam as shown in Figure 5 that could efficiently smoothen the strain distribution when a torque was introduced. Two resonance peaks were evident with base excitation at 2.5ms^{-2} . The first peak reached 13.54mW at 38.3Hz, which was 64.72% more than the power recorded for traditional cantilever. The superior performance of L-shaped energy harvester had also been acknowledged by X. Nie [73] in their recent work.

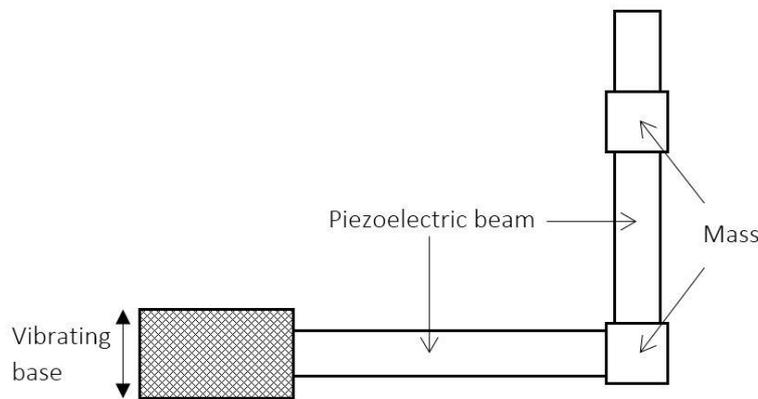


Figure 4. Schematic diagram of L-shaped energy harvester developed by Erturk et al. [71].

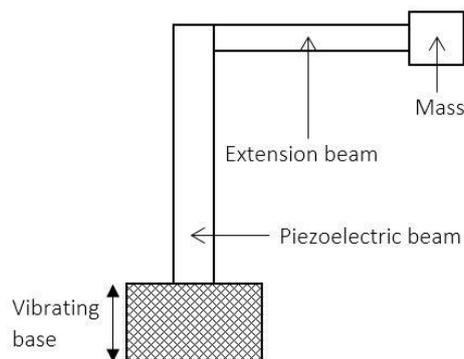


Figure 5. Schematic diagram of right angle coupled energy harvester proposed by Xu et al. [72].

Wang et al. [74] proposed an additional elastic system to amplify the base excitation and induce a closer second peak. The harvester generated two peaks of 67.7 mW and 9.7 mW at 78.3 Hz and 100.3 Hz, respectively, with excitation of 1g. The numerical investigation indicated that the maximum output power and peak distance

could be further improved by specifying a smaller mass ratio. It would be interesting to assess the key design parameters experimentally and identify the practical constraints simultaneously. Staaf et al. [75] coupled two parallel-connected PZT bimorph cantilevers. A peak occurred at 85.2Hz and the other appeared at 135.5Hz which was near the first frequency, suggesting a broadband characteristic. The proposed harvester design outperformed the two parallel uncoupled cantilevers by producing 5.4 times of their output power. The output power and bandwidth could be further enhanced with low damped coupling fixture, but not without compromising the working frequency of the device.

Cantilever Array Configuration

The cantilever array configuration has been widely explored and a few designs have been granted for patent [76-78]. Xue et al. [79] presented an energy harvester with 10 series-connected PZT bimorphs with different thickness. Upon excitation of 1ms^{-2} , the array produced at least $10\ \mu\text{W}$ higher than the maximum output power of single bimorph harvester at 98 Hz. However, the power density of the array reduced by four times. Perhaps the increase in frequency bandwidth from 6 Hz to 28 Hz would compensate for the large piezoelectric material usage. Zhang and Afzalul [80] proposed joining 12 bimorphs with spring connected end masses. As the base was excited at $1\ \text{ms}^{-2}$, it improved the output power by 92.31% to $250\ \mu\text{W}$ at 90 Hz compared to a single harvester and generated the highest amount of $430\ \mu\text{W}$ at 99 Hz. Yet, the proposed harvester still had a relatively low power density. Besides, no comparison with conventional piezoelectric array was carried out to analyse the influence of the springs. Dayou et al. [81,82] split a PVDF bender evenly to form an array. The higher the number of splits, the larger the power harvested for the same amount piezoelectric material. The array produced a maximum of $53\ \mu\text{W}$ at 27.2 Hz, whereas a single bender only produced 36.23% of it. However, the excitation level is too high i.e. 2 mm (nearly 6 g). It raises the question of whether the same outcome can be achieved if the excitation is lowered to a practical value. Kherbeet et al. [58] reported that series connected triangular beams harvested more power than single cantilever whether in a horizontal or vertical arrangement. The former generated a maximum of 6.774 mW at 105 Hz with four cantilevers while the latter surprisingly produced 12.3% higher output power with only three cantilevers. However, single cantilever had 54.33% larger power density. It shows that one would have to achieve a compromise between output power and material usage when proposing for cantilever array configuration.

Segmentation of Piezoelectric Layer

Segmenting the piezoelectric material layer was known to benefit excitation at higher vibration modes. With an excitation force of 0.01 N, Liu et al. [83] discovered that splitting the length of an aluminium nitride layer to 20 segments resulted in 3.86 nJ of energy stored at 970 Hz, presumably the second mode (see Figure 6). Compared with the continuous layer configuration, the energy output was almost doubled with a frequency of 13.39% lower. The stored energy relied on distribution of electrical displacement along the beam. The effect of strain nodes in the continuous layer that caused strong voltage cancellation was explained by De Marqui Jr et al. [84]. The second and higher vibration modes of a piezoelectric beam had certain strain nodes, i.e. positions where the sign of bending strain distribution towards the beam length changed. These modes were excited

as well due to random vibration source. Therefore, the researchers divided the PZT layer and harvested the voltage produced at the opposite sides of a strain node with different electrode pairs to fix this common issue of fixed-free boundary conditions. A simple demonstration on the first two vibration modes i.e. 7.1 Hz and 40.8 Hz showed that the performances of control and segmented energy harvester were comparable for excitation at the first mode, generating 0.3 V. However, the output voltage of segmented harvester increased dramatically at second mode to 2 V, which was more than four times the value of control condition. The approach was also verified by Zizyz et al. [85]. However, the researchers found that segmentation at strain nodes did not always produce the largest output voltage. Thus, the principle to determine the optimum segmentation points were presented.

A new piezoelectric structure which was called the energy harvesting skin was proposed by Lee et al. [86-89]. The skin structure could be directly attached to the vibrating surface without clamping. Therefore, it was expected to be more practical than the cantilever structure. The output power increased as more segmentations were performed to the skin. However, the sensitivity of the skin to boundary conditions such as the tightness of the joint could be regarded as one of the concerns and therefore it should be emphasized in the future work. Moreover, multiple segmentations can increase the layout complexity with crammed electrical wiring. Hence, a more sophisticated wiring method such as conductive tape or silver pen is required to deal with this issue.

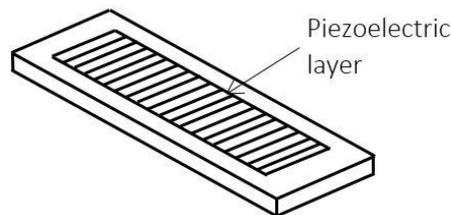


Figure 6. Schematic diagram of 20-segmented piezoelectric layer proposed by Liu et al. [83].

NONLINEAR ENERGY HARVESTING

In recent years, a large and growing body of literature has explored the potential of nonlinear energy harvesters. Piezoelectric energy harvester can be nonlinear in terms of its stiffness or material coupling [90]. Normally, the former is relatively easier to attain and control as compared to the latter which is dependent on the manufacturing process. Thus, the remaining part of this section proceeds with energy harvesting systems that exploit different types of oscillator to introduce nonlinear stiffness. However, it is important to note that the nonlinear behaviour generally emerges when the energy harvester is subjected to vibration with significant amplitude.

Impact-Enhanced Configuration

An impact-enhanced configuration employs the nonlinear dynamics of piecewise linear oscillator and commonly associates with the use of a stopper that protects the piezoelectric material from over bending. Ferrari et al. [91] introduced a central stopper in between the top and bottom piezoelectric bimorphs to exert intermittent impact, causing a nonlinear frequency up-conversion mechanism (see Figure 7). Two individual beams produced only

two voltage peaks of 15 V and 13 V at 40 Hz and 65 Hz, respectively, when harmonically excited at 1 g. With the stopper, multiple peaks occurred at various frequencies between 20-100 Hz. The maximum peak of 13 V appeared at 20 Hz. This reduction was due to the energy loss when in contact with the stopper. However, the quadratic sum of output voltage was larger over a wider bandwidth. The output power was calculated to be 16.91 mW. Dauksevičius et al. [92] used two central stoppers instead of different length. When excited at 1 g, the output power was increased up to 90% for all clearance values when compared to the individual stoppers. 30-37 μW was produced over a bandwidth of 8-9 Hz at the largest clearance of 2.5mm.

Vijayan et al. [93] replaced the use of central stopper with a spring element attached to the free end of the bottom piezoelectric beam. The output power was dependent on the clearance and thickness ratio (the power dropped when the thickness ratio approached 1. The highest output power of 6mW was obtained at a ratio of 0.168 and excitation of 0.2mm. However, there has been a concern that it would promote the wear and tear of the beam and generate significant noise. Therefore, Shih et al. [94] proposed the use of magnetic stopper that caused the same effect without actual contact. The output power could be enhanced up to 10.41 times the value for harvester without the stopper structure. Unfortunately, the researchers reported that crack formed at the PZT patch after a few repetitions of experiment.

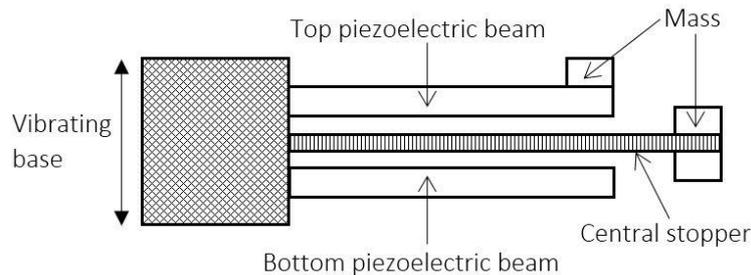


Figure 7. Schematic diagram of impact-enhanced energy harvester proposed by Ferarri et al. [91]

Liu et al. [95] combined the multi-modal and nonlinear configurations by adding a stopper to a 2-DOF piecewise linear MFC energy harvester. The schematic diagram is presented in Figure 8. The bandwidth was 5.2 times greater than that of the 2-DOF linear harvester without a resonator. The peak powers reached 429 μW and 411 μW at 21.4 Hz and 51.8 Hz, respectively, when subjected to a harmonic excitation of 3 ms^{-2} . This work can serve as a base for future studies involving other types of material and multi-DOF design. Maeguchi et al. [96] combined mechanical stoppers with a magnetic tuning method (see Figure 9). The stoppers increased the bandwidth as the distance to central piezoelectric beam reduced. The magnets had more influence on the frequency shift as they were getting closer to each other. Combining these two effects, the proposed energy harvester had broader bandwidth at low-frequency region. It is important to reduce damping due to contact by specifying the appropriate shape and material of the stoppers as well as the end mass. However, this configuration accelerates the fatigue failure rate, and this is a major challenge for impact-enhanced energy harvester employing PZT beams. Despite their superior piezoelectric properties, piezoceramics are generally very

hard and brittle. Further study that focuses on increasing the durability of piezoelectric material is therefore recommended.

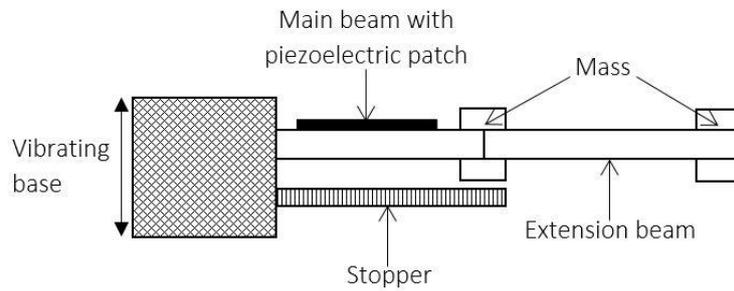


Figure 8. Schematic diagram of 2DOF piecewise linear energy harvester explored by Liu et al. [95]

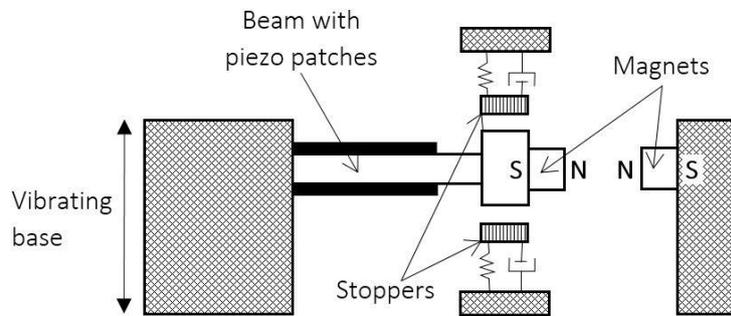


Figure 9. Schematic diagram of energy harvester with mechanical stoppers and magnets proposed by Maeguchi et al. [96].

Multi-Stable Configuration

Several attempts have been made to achieve multiple stable states by using the Duffing nonlinear oscillator. The nonlinearity of multi-stable energy harvester is demonstrated by the cubic spring restoring force that influences its hysteretic behaviour (spring hardening or softening). Jiang and Chen [97], and Daqaq [98] revealed that the monostable energy harvester did not perform well under random vibration excitation, suggesting that the configuration might only work with harmonic excitation. Ramlan et al. [99,100] found that the bistable configuration amplified the given input excitation. At a much lower excitation frequency than the natural frequency, the harvested energy was higher than that of its linear counterpart. This finding was experimentally proven by Cotton et al. [101] and Li et al. [102]. Pellegrini et al. [103] classified bistable energy harvesters based on their practicability for a smaller size. A prominent advantage of the bistable system is that the transition from one stable state to another at a high magnitude of excitation allows the device to have a large vibration amplitude. The gaining distance between two potential wells can amplify the amplitude of snap-through motion. However, the height of the potential barrier will increase accordingly; therefore, higher excitation is required. The great dependency of excitation level becomes a serious drawback which inhibits not only the performance of the bistable system but also other nonlinear energy harvesters [104].

Figure 10 represents the working principle of two-dimensional bistable energy harvester studied by Andó et al. [105]. It harvested $3.2 \mu\text{W}$ which was 10 times larger

than that of the linear system. Their magnetically coupled antiphase cantilevers produced $3.5 \mu\text{W}$ which was twice of the output of nonlinear single beam and 10 times more than that of a linear system [106]. However, both designs were extremely excited at 12.7 g and 8.2 g. Several magnetically coupled energy harvesters have also been developed by [107-109]. Unfortunately, the issue occurred when the harvesters were fed with small excitations was not properly addressed. However, Wu and Lee [110] proposed a magnetically coupled energy harvester with folded cantilever design (2-DOF) to improve space and output power. The cantilevers drove each other due to the magnetic force, resulting in greater deflection upon ambient excitation. At a constant excitation of 0.1 g, the total output power reached $18.45 \mu\text{W}$ at 30Hz. But there was a lack of evidence for its robustness and durability. Further study should focus on the structural material.

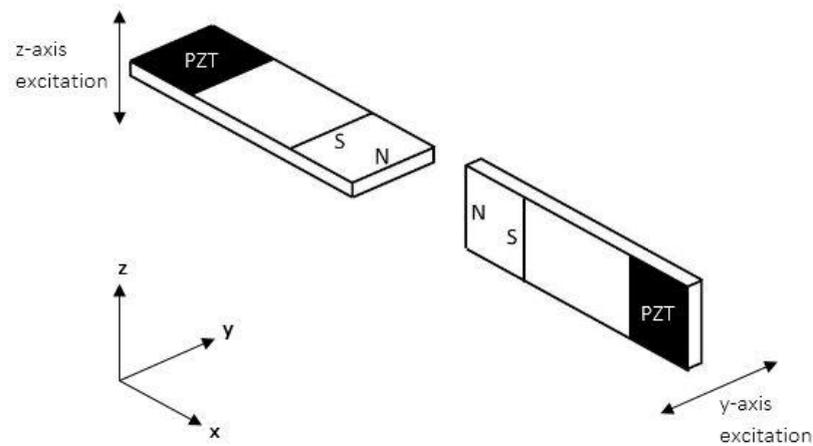


Figure 10. Working principle of two-dimensional bistable energy harvester studied by Andó et al. [105].

Over the past few years, there has been an increasing interest in a more complex multi-stable energy harvesting system to have shallower potential wells. Zhou et al. [111, 112] proposed a tristable energy harvester. With stochastic excitation at 4 ms^{-2} , it produced 22 V at 5 Hz while bistable energy harvester hardly generated 5 V, most probably because it was only oscillating intra-well due to deeper potential wells. Panyam and Daqaq [113] described that even when the excitation was inadequate to exhibit inter-well oscillations, the bandwidth was significantly improved due to the presence of two resonant frequencies: one associated with the middle potential well and the other with the outer potential wells. A few researchers [114,115] engaged with quadstable piezoelectric energy harvester which was more capable to snap from one stable position to another. In addition, Wang et al. [116] proposed an impact-driven quinstable piezoelectric energy harvester to further decrease the frequency threshold for jumping between potential wells without increasing the vibration amplitude. The schematic diagram of the bottom view is illustrated in Figure 11. It generated a maximum of 5.16 mW at 7 Hz with a harmonic excitation of 4 ms^{-2} . Nevertheless, it is always challenging to design multi-stable devices as they require a precise parameter choice. Reducing the depth of potential wells for them to perform at low excitation amplitude causes a significant drop in the corresponding electrical output response. Furthermore, multi-stable energy harvester is more complex than other systems. Past breakthroughs of multi-modal approach and nonlinear dynamics encourage Wang and Tang [117] to propose a magnetically coupled 2-DOF bistable

piezoelectric energy harvester. It generated 5.5 mW at 37 Hz when harmonically excited at 4 ms^{-2} . However, the resistive load influenced the nonlinear response peak in which its optimum value not only shifted the peak to the highest frequency range but also reduced the bandwidth.

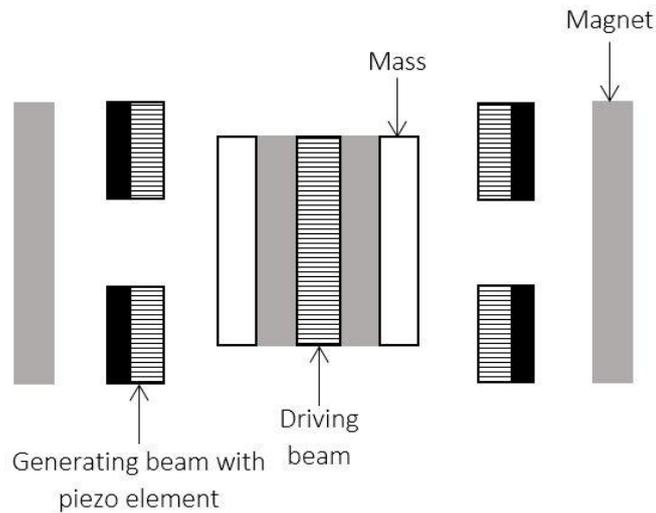


Figure 11. Schematic diagram of impact-driven quinstable energy harvester developed by Wang et al. [116] (bottom view).

Hybrid Configuration

Other than a single transduction mechanism, researchers have also been dealing with hybrid piezoelectric (voltage generator) and electromagnetic (current generator) harvester. Green et al. [118] stated that electromagnetic harvester was more capable of harvesting energy from a very low-frequency ambient. When the electromagnetism is introduced to the piezoelectric generator, the increase in damping decreases the vibration amplitude of the piezoelectric counterpart as well as the output power. Hence, electromagnetic harvester must contribute more energy to compensate for this loss. The maximum output power of a hybrid device is achieved when the total electrical damping matches the mechanical damping. The total electrical damping is controlled by the load resistance. In specific, the piezoelectric and electromagnetic resistance values should match the beam impedance and coil resistance, respectively, for maximum output power. Challa et al. [119] proposed a linear hybrid energy harvester. With harmonic excitation at 21.6Hz, the hybrid device produced $332\mu\text{W}$ which was at least 30% higher compared to that generated by the standalone piezoelectric and electromagnetic harvester. Lallart and Inman [120] introduced Figure of Merit (FOM) given by $k^2 Q_M$. When the FOM exceeded a critical value, the bandwidth would be enhanced. Even when the FOM was low, the hybrid arrangement exhibited the larger output power and bandwidth features as those reported in the previous study. The harmonically excited hybrid system produced 1.25mW at 17Hz with an amplitude of 0.1 g. It was 10% and 30% higher than those of pure piezoelectric harvester and electromagnetic element alone, respectively. Wang et al. [121] added a spring connected magnet to the free end of the piezoelectric cantilever to amplify the excitation of electromagnetic transduction mode (see Figure 12). It generated 2.16 mW and 0.9 mW at 68 Hz and 92 Hz, respectively, when harmonically excited at 1.41 ms^{-2} . Resali and Salleh [122] incorporated PTFE extension into the piezoelectric

beam to reduce its natural frequency to 50 Hz. The schematic diagram is represented in Figure 13. The proposed hybrid energy harvester produced 3 mW upon excitation at 0.25 g_{rms}.

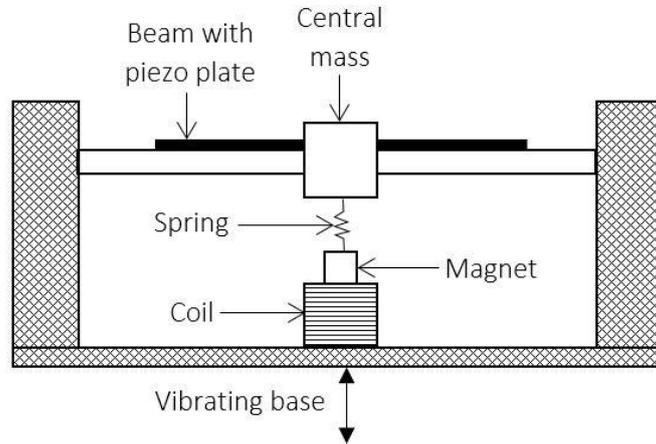


Figure 12. Schematic diagram of 2DOF hybrid energy harvester proposed by Wang et al. [121].

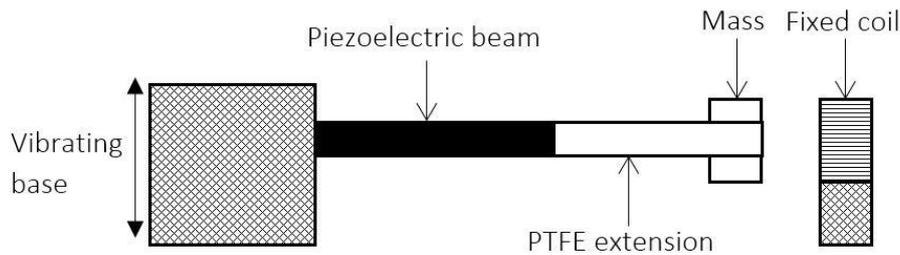


Figure 13. Schematic diagram of hybrid energy harvester with PTFE extension proposed by Resali and Salleh [122].

To further enhance the performance in a low-frequency environment, researchers have explored the nonlinear hybrid harvester. Shan et al. [123] fixed a magnetic suspension system at the free end PZT cantilever. The top and bottom magnets were oriented to repel the middle magnet, providing enough nonlinear restoring force for suspension. The harmonically excited harvester generated 7.2 mW and 16.4 mW at 8.5 Hz and 16 Hz, respectively, with input acceleration of 5ms^{-2} . An appreciable amount of power could be harvested in the range of 6-20 Hz. The effect of magnetic interaction was not clearly understood until 2016 where Xu et al. [124] proposed another 2DOF magnetically coupled hybrid device with a tuneable feature. This was realised by interacting the magnetic end mass of piezoelectric cantilever and the magnetic ring oscillator surrounded by an induction coil. With harmonic excitation of 2ms^{-2} , 1.4 mW was caused by the magnetic oscillator at 22.6 Hz. It was 16.7% better than that of the single electromagnetic harvester. In fact, it already outperformed the combined linear piezoelectric and electromagnetic harvesters by 2.36 times at the same excitation condition. Meanwhile, 2.82 mW was contributed by the piezoelectric generator at 25.6 Hz which was 833% higher than its individual performance! Xu et al. [125] then continued to explore the proposed energy harvester's structure and reported that 2.96 mW

and 4.76 mW were generated at 23.6 Hz and 32.8 Hz, respectively, with the same amount of excitation amplitude. Li et al. [126] proposed another magnetically coupled hybrid device. With harmonic excitation of 0.2 g, it generated 440 μW at 113.5 Hz which was 10% higher than without magnetic interaction. This amount possibly fulfils the minimum power requirement of a sensor node in wireless sensor networks [127]. But, the frequency responses of the hybrid harvester did not significantly demonstrate an improved half-power bandwidth as claimed. There was only a mere increase of 1.2 Hz from the linear half-power bandwidth. The emphasis on using higher acceleration to get larger output power and bandwidth is not practical for low-frequency applications since most of them have low vibration amplitude. This report could be more interesting if there are other relevant suggestions for industrial implementation. Kwon et al. [128] offered a new hybrid design employing the impact-based configuration with an additional cantilever which produced 3.16 mW and 2.6 mW at 31 Hz and 62 Hz, respectively. The working principle is shown in Figure 14. The integration with the frequency up-conversion method could contribute to an effective energy harvesting even at extremely low frequency (less than 10 Hz). This claim was indeed supported by the work presented by Edwards et al. [129]. Their nonlinear hybrid harvester produced a 49.8 μW at 5 Hz with broad-spectrum random excitation of 1g. However, it was unknown whether the wideband characteristic was achieved.

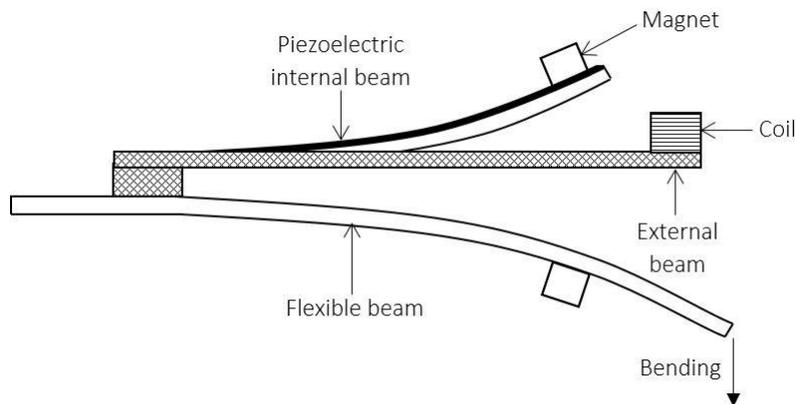


Figure 14. Schematic diagram of impact-enhanced hybrid energy harvester presented by Kwon et al. [128].

MULTI-DIRECTIONAL ENERGY HARVESTING

In most studies, it is commonly assumed that the ambient vibration only excites an energy harvester from a single direction. However, low-frequency energy sources such as building vibration and human motion are normally complex and multi-dimensional. Therefore, it is necessary for an energy harvester to demonstrate better environment adaptability. Chen et al. [130] remedied this issue by proposing a dandelion-like multi-directional energy harvester with 13 bimorphs. A significant level of output power was recorded in most excitation directions. 280 μW was harvested at 22 Hz with excitation of 0.28 mm at an angle of 1.5 rad in the XY plane. However, the total output power reduced tremendously in some excitation directions. This issue should be properly addressed in future works. Furthermore, the overall outcome needs to justify the generous material usage for this proposed design. Yang and Zu [131,132] placed a PZT plate in between two bow-shaped aluminium plates. This arrangement constituted a flexural centre that

deformed when vibration was applied, causing the PZT plate to generate electricity in compressive mode. The output voltage was maintained at a significant level for all tested directions of excitation. An entirely different result was observed for a conventional cantilever type harvester whereby more than 90% of the vibration energy was lost at 90° angle of excitation. The harvester produced 1.74 mW with a sinusoidal excitation of 0.2 g at 17 Hz. But, the issue of space occupied by this harvester was not adequately addressed. It can be more than 150 mm long even without the clamp structure. This raises the question whether the structure can be made smaller while maintaining its performance. Park et al. [133] attached an asymmetric aluminium mass at the free end of the vertical piezoelectric beam. 7.5 mW and 1.4 mW were produced at 34 Hz and 40.5 Hz when it was excited from z -axis and x -axis, respectively. But the excitation was too high i.e. 10 ms^{-2} and the power reduced tremendously when the amplitude was lowered especially in the z -axis direction. A source of weakness which could have affected the lifetime and environment adaptability is the lack of mechanical robustness due to brittle piezoelectric material. Thus, more research is required to determine the efficacy of this harvester. It should be compared to the conventional configuration not only in terms of harvesting capability but also the durability and the fatigue development subjected to dynamic bending stress.

Wang et al. [134] adopted the principle of mechanical energy buffering to achieve the frequency up-conversion and proposed a cantilever-spring energy harvester with magnetic interaction at the free end to benefit from bi-directional vibrations. The energy harvester is illustrated in Figure 15 where 14 V was produced at 33 Hz due to z -axis excitation, whereas 9.6 V was measured at the same frequency when it was excited horizontally with unknown excitation amplitude. A minimum of 5 V can be harvested approximately between 28.5-33.5 Hz and 29.5-36.5 Hz when excited in vertical and horizontal directions, respectively. However, there is no benchmark set in the investigation. It would have been more convincing if the researchers compared the performance with that of a control energy harvester.

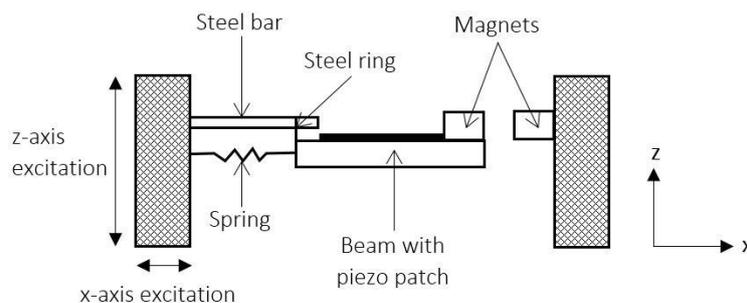


Figure 15. Bidirectional energy harvester with spring and magnetic coupling presented by Wang et al. [134].

In recent work, Ceponis et al. [135] proposed fixing the piezoelectric beam at a minimum angle, α of 1.13 rad to allow for a more rotational moment (see Figure 16). A 0.1 ms^{-2} excitation in z -direction generated $16.85 \mu\text{W}$ at most at 26.65 Hz. Meanwhile, $15.94 \mu\text{W}$ was produced at 11.25 Hz when excited with the same amplitude in the y -direction. The proposed energy harvester also had a stable electrical characteristic even with an impact-based excitation in both directions. One question that needs to be asked is, however, whether it really eliminates the requirement of exact excitation directions as concluded by the researchers. Apparently, they had overlooked the fact that the reported

results were only obtained from certain directions of excitation. The findings from this work therefore, need to be interpreted with caution.

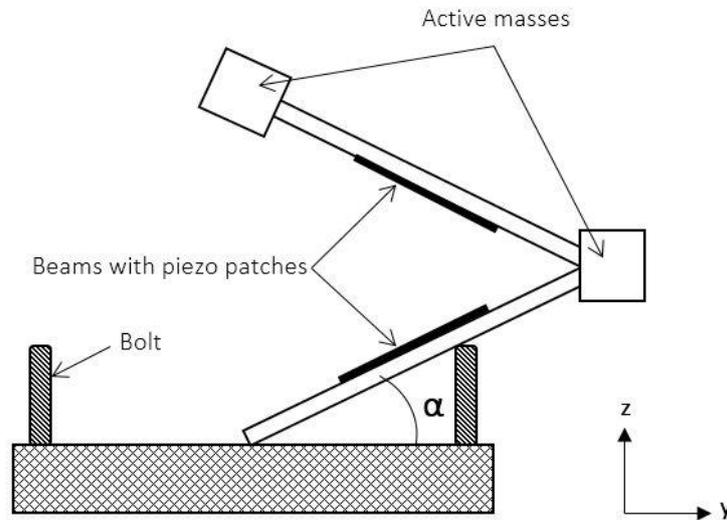


Figure 16. Bidirectional energy harvester with an inclined angle and active masses proposed by Ceponis et al. [135].

EFFECTIVE STRATEGIES AND KEY FACTORS

A comprehensive summary of selected work including the calculated power density is provided in Table 3 and used to determine the effective strategies for developing high-performance piezoelectric energy harvester at low frequency. Assuming a linear relationship, the power density is normalised at an acceleration of 1 g. The power density was plotted against excitation frequency as presented in Figure 17.

Most works fall in the second quadrant of the figure. It indicates that the recent developments are inclined towards generating more power from low frequency and low amplitude ambient vibration with less piezoelectric material. It is apparent that the design proposed by Lam and Salleh [68,69] results in the highest power density per g among others. The normalised amount is computed to be $1085 \mu\text{W}/\text{mm}^3/\text{g}$. The researchers utilised a low-cost material with respect to PZT to improve the harvester's performance at low frequency. Perhaps this idea is stemming from the amplification of input energy by the extension beam. Future work can be undertaken with different slotted beam materials and geometries. However, the extension of the beam increases the overall size as well. Thus, its application in limited space is questionable. The rank is followed by the bidirectional energy harvester with an inclined angle and active masses proposed by Ceponis et al. [135]. The normalised power density is $465.06217 \mu\text{W}/\text{mm}^3/\text{g}$. It is now almost certain that the rotational moment due to the use of active masses and the inclination contributes to higher strain energy of piezoelectric material. Despite this promising result, the question remains about the aftermath of continuous knocking between the piezoelectric beam and the fixed bolts. It is known that piezoceramics are brittle. Therefore, this is an important issue for future research. The 2-DOF right angle coupled energy harvester designed by Xu et al. [72] occupies the third rank. The significant normalised power density of $217 \mu\text{W}/\text{mm}^3/\text{g}$ is likely due to the increase in bending induced by the extension at the end of the piezoelectric beam. As mentioned

before, piezoceramics are prone to crack or total breakage. Hence, the lifetime of piezoelectric harvester might be reduced due to fatigue failure resulting from overbending.

Table 3. A comprehensive summary of selected work.

Strategy	Piezo material	Material	Input			Output power (μW)	Power density (μW/mm ³)	Ref.
			Volume (mm ³)	Excitation	Freq. (Hz)			
Optimum shape and size	PZT	S. Steel	6500		13.4	6500	1	[49]
	PSI-5A4E	S. Steel		0.2g	50		9.64	[56]
	PSI-5H4E		347		85	4876	14.0534	[58]
	PSI-5H4E		893.2		105	7607	8.5166	[58]
	PZT-5H	Aluminium	950	0.4N	58.5	11079	11.6621	[61]
Optimum multi-layer structure	PZT-5H	S. Steel	75.9	0.41g	64.5	97.9	1.2899	[64]
	PZT-5H	S. Steel	227.7	0.41g	64.5	458.7	2.0143	[65]
	PZT	Aluminium	1500		20	1250	0.8333	[67]
Multi-DOF config.	PZT	Brass	206.4	0.25g	30	56000	271.3178	[68]
	PZT-CN	S. Steel	326.4		69	7800	23.8971	[70]
	PZT-5A	S. Steel	394	1g	22.8	10000	25.3807	[71]
	PZT	Titanium	240	0.26g	38.3	13540	56.4167	[72]
	PZT	Brass	480	1g	78.3	67700	141.0417	[74]
Cantilever array config.	PZT	Aluminium	2327.5	0.1g	94.5	57.5	0.0247	[79]
	PZT-5H	Composite	5760	0.1g	99	430	0.0747	[80]
	PVDF	Poly-propylene	46.8	2mm	27.2	53	1.1325	[82]
Impact-enhanced config.	PZT	S. Steel		1g	20	16910		[91]
	PZT-5H	PET PEN	16.64	1g	38.1	37	2.2240	[92]
	PZT		98	0.2mm	29.09	6000	61.2250	[93]
	PZT	S. Steel			13.5	0.1		[94]
	MFC M2814-P2	Aluminium	117.6	0.31g	21.4	429	3.6480	[95]
Multi-stable config.	PZT	Aluminium		12.73g		4.5		[105]
	PZT	Aluminium		8.2g		3.5		[106]
	PVDF	PMMA		0.1g	30	18.45		[110]
	MFC M2807-P2	Beryllium Bronze	235.2	0.41g	7	5160	21.9388	[116]
	MFC M2814-P2		235.2	0.41g	37	5500	23.3844	[117]
Hybrid config.	PZT	Carbon Fibre	230.4		21.6	332	1.4140	[119]
	PZT-5H		320	0.51g	16	16400	51.2500	[120]
	PZT	Brass	206.4	0.25g	50	3000	14.5349	[122]
	PZT-5H	Phosphor Bronze	320	0.2g	32.8	4760	14.8750	[125]
	PZT-5H	Phosphor Bronze	400	0.2g	25.6	2820	7.0500	[124]
	PZT	S. Steel	256	0.2g	113.5	440	1.7188	[126]
Multi-directional energy harvesting	PZT-5H	Beryllium Bronze	1123.2	0.28mm	22	280	0.2493	[130]
	PZT-5A	Aluminium	420	0.2g	17	1739	4.1416	[131]
	PZT		259.2	1.02g	34	7500	28.9352	[133]
	PZT	Aluminium	3.6	0.01g	26.65	16.85	4.6806	[135]

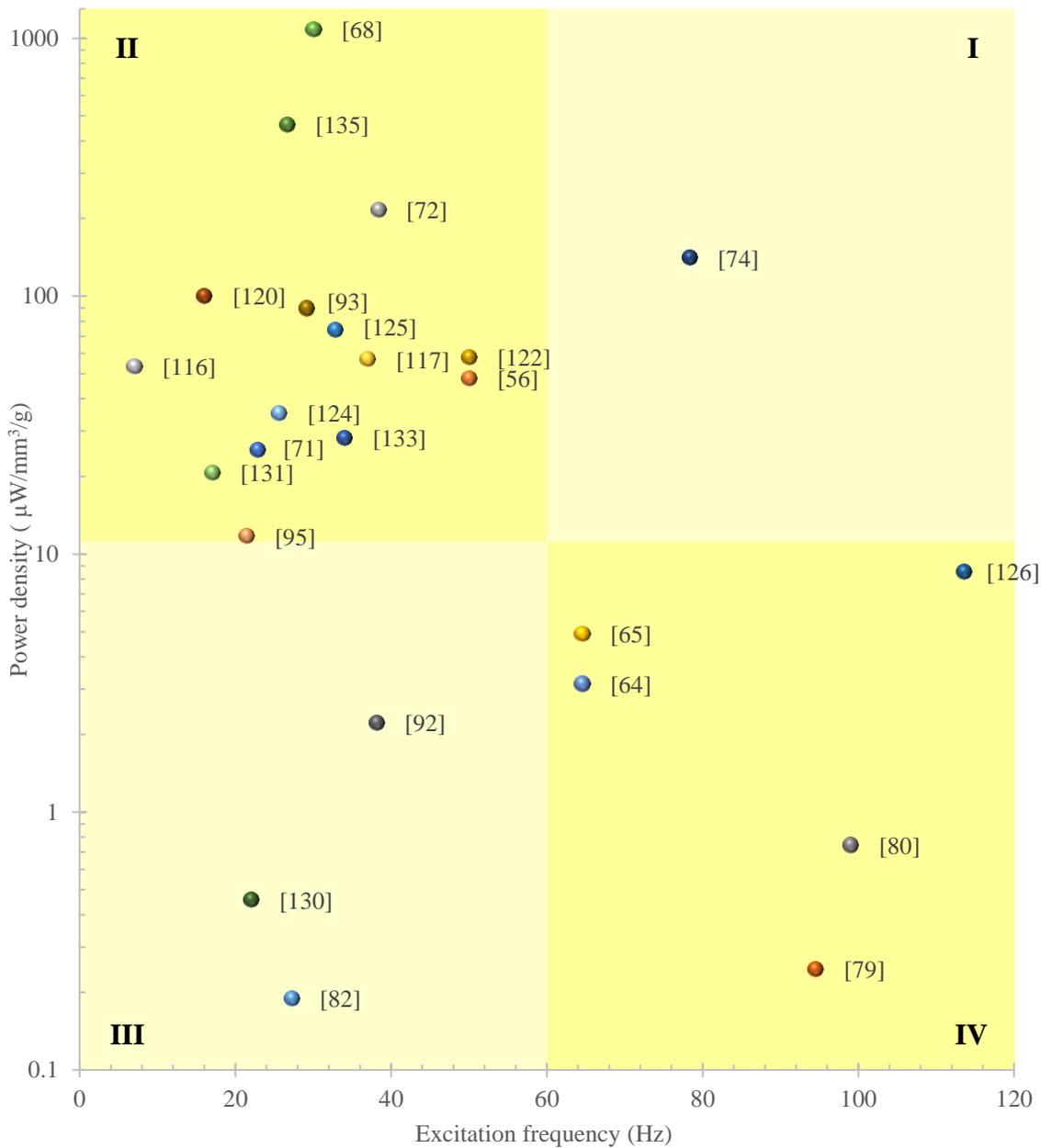


Figure 17. Comparison of power density per weight of selected work at the corresponding excitation frequency.

The fourth rank is earned by the 2-DOF harvester developed by Wang et al. [74] with a normalised power density of $141 \mu\text{W}/\text{mm}^3/\text{g}$. Their design employs the same concept as that of the first-ranked energy harvester which is the amplification of input vibration by adding a spring at the base. But it is important to note that it falls on the first quadrant. Thus, future work is required to comprehensively compare these two input amplification methods. Besides producing a large power density, these multi-modal energy harvesters are exhibiting broader bandwidths. The hybrid energy harvester proposed by Shan et al. [120] is at the fifth place with a normalised power density of $101 \mu\text{W}/\text{mm}^3/\text{g}$. The nonlinear impact-enhanced harvester developed by Vijayan et al.

[93] secures the sixth place with a normalised power density of $90 \mu\text{W}/\text{mm}^3/\text{g}$. Seemingly, there is a trade-off between output power and bandwidth for an energy harvester.

The harvesters by Dayou et al. [82] exhibit relatively low normalised power density of only $0.15 \mu\text{W}/\text{mm}^3/\text{g}$ despite a very high base displacement of 2 mm. This may be due to the significantly low electromechanical coupling factor of PVDF material compared to that of PZT. The reasoning behind this material selection has not been explained by the researchers. Therefore, it is important to consider the characteristic of piezoelectric material in designing a practical energy harvester. It is also worth pointing out the normalised power density of $0.46 \mu\text{W}/\text{mm}^3/\text{g}$ which belongs to dandelion-like harvester proposed by Chen et al. [130]. It was likely not the best way to harvest energy from a common source with one dominant excitation direction. However, the proposed energy harvester may be more useful if the excitation comes from multiple directions.

Several key factors are identified in the analysis. The first key factor is the excellent characteristics of piezoelectric material. Superior strain coefficient and voltage constant are basic indicators for higher energy density. However, this characteristic alone does not assure the performance of energy harvester. Higher dielectric constant would promote the capacitive characteristic and larger electromechanical coupling factor implies higher energy conversion efficiency. The sharpness of resonance frequency is achieved through high mechanical quality factor. Although the use of PZT is popular, there is a wide range of products offered by manufacturers to cater to different conditions and requirements of energy harvesting technology. The second key factor is associated with optimised geometry for high strain energy density. Usually, the cantilever configuration is adopted for an energy harvester with a rectangular beam. But numerous studies have reported that a triangular beam outperforms a rectangular beam in terms of internal strain energy density, leading to higher output power ($\sim 4\times$ increase). However, it does not necessarily give more favourable result if the size is not optimised. Yet, energy harvester with triangular PZT beam is not extensively studied, which is likely due to the technical challenge while cutting the brittle rectangular beam to the triangular one. The third key factor is excellent flexibility. PZT is very stiff and prone to fracture during operation. Coating the PZT beam with rubber material can reduce its stiffness and natural frequency by 8.33%. The next equally important key factor is the high excitation amplitude. Nevertheless, the acceptable vibration level for industrial applications is generally very low. For example, according to ISO 10816-3, the vibration level of a healthy electrical motor operating at 50 Hz should not exceed 0.5 g. Hence, amplifying the excitation can escalate the process, for example by implementing a multi-DOF configuration. The frequency spectrum of ambient vibrations is very broad. Consequently, a piezoelectric energy harvester might become invaluable and unreliable when there is a sudden variation of the excitation frequency. In turn, this leads to the last key factor which is broad bandwidth. Worldwide researchers have explored various configurations to enhance the bandwidth. Unfortunately, the challenging part is keeping the complexity tolerable. Apart from focusing on quality and performance, the technology should also be affordable.

CONCLUSION

Various studies have been conducted in the last two decades to improve the performance of a piezoelectric energy harvester at low frequency. However, its application is limited due to low output power. This paper reviewed the strategies implemented to improve the output power such as the selection of piezoelectric materials for low-frequency

applications as well as optimisation of geometry in terms of shape, size and structure. Based on the comprehensive summary of the normalised power density at 1g acceleration, it was found that most works fell in the second quadrant of low frequency and high power density. The maximum value was around 1 mW/mm³/g. It indicates that the recent developments are inclined towards generating more power from low frequency and low amplitude ambient vibration with less piezoelectric material. The analysis from the previous works suggests that adding a single DOF system in the form of an extension beam or a spring to the piezoelectric beam can dramatically enhance the normalised power density. Additionally, the resulting multi-modal energy harvester exhibits broader bandwidth when its multiple resonance peaks get closer. The findings indicate that the anticipated performance of a piezoelectric energy harvester can be achieved despite the trade-off between output power and operating bandwidth. However, high excitation amplitude and generous material usage do not warrant high output power. Based on these findings, five key factors have been identified to ensure high performance at low frequency i.e. excellent characteristics, optimised geometry for high strain energy density, excellent flexibility, high excitation amplitude and broad bandwidth.

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