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PIEZOELECTRIC CERAMIC FOR ENERGY HARVESTING SYSTEM: A REVIEW

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ABSTRACT

Nowadays, piezoelectric energy harvesting technology has been studied and developed significantly by a lot of researchers. Energy harvesting is a process that an ambient waste energy can be collected and conserved or stored for useful purposes. Piezoelectric transducer is one of the devices that can be used for vibration energy harvesting system. It has a high ability of energy conversion to convert mechanical vibration into electrical energy compared to others. In this paper, a comprehensive review on the piezoelectric energy harvesting system is discussed and presented, including the principles of the piezoelectricity, mechanical configurations of the piezoelectric and techniques employed to the piezoelectric energy harvester. The integral ideas and performance of the reported piezoelectric energy harvester will be reviewed in this paper as well.

Keywords: energy harvesting, piezoelectric transducer, vibration, impact-based

1. INTRODUCTION

Due to increased demand for the mobility of electronic devices, the field of research about the alternative ways of power generator has increased recently. The short lifespan of the battery and the inefficiency of the replacement and recharged battery are the main reasons for the alternative power generator [1]–[3]. Energy harvesting also can be known as power harvesting or scavenging. Energy harvesting is determined by collecting from ambient waste energy and storing them for the uses of electronic devices [3]. The ambient energy sources are many such as thermal, wind, solar, sound, magnetic fields, mechanical vibration and human body movement.

There are three types of techniques to transform mechanical energy from vibration into electrical energy: electrostatic generator, electromagnetic induction and piezoelectricity [1][4][5]. Figure 1 shows the data of the publication of papers on piezoelectric, electromagnetic, and electrostatic energy harvesters indexed in ScienceDirect. Among those three types of energy harvesting techniques, this paper will focus on the review of the piezoelectric energy harvester. The piezoelectric ceramics can be used as sensor in direct effect or actuator in converse effect [3][4]. The piezoelectric energy harvesting system can provide higher energy efficiency, higher power density and flexible in portable electronic systems. It also should be operated at the vibrational structure's resonant frequency to generate a maximum deformation of the piezoelectric materials and prompt a maximum electric energy.

The structure of this paper is structured as follows: Section II illustrates the energy harvesting especially the vibration energy harvesting. Then, the piezoelectricity and piezoelectric energy harvesters are explained in Section III and Section IV, respectively. Next, the different types of configurations of the piezoelectric are classified in Section V. Section VI to Section VIII review the different types of techniques that are used by the piezoelectric energy harvester. And lastly, section IX will summarize the content of this paper.

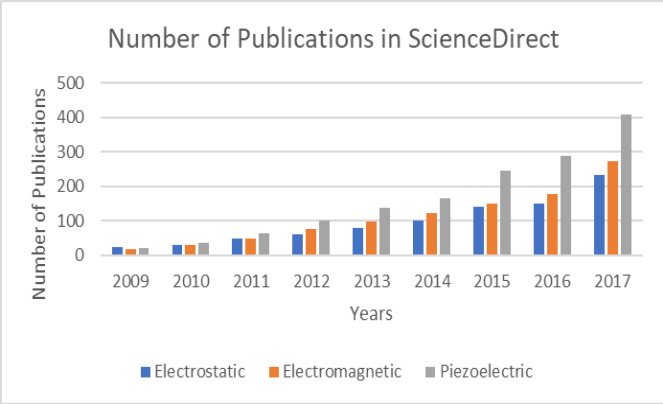

Figure-1. Number of publications on piezoelectric, electromagnetic, and electrostatic energy harvesters in ScienceDirect between years 2009 and 2017.

2. CONCEPT OF ENERGY HARVESTING (EH)

The technology that transforms the ambient waste energy into usable electrical energy for low power electronics especially for portable and wireless devices is known as an "Energy harvesting". There are many ambient energy sources, i.e. vibration, kinetic, solar, electromagnetic field, radio frequency and others that can be considered to be utilized for this purpose. Energy harvesting is also known as "Energy Scavenging", "Power Harvesting", "Parasitic Energy" or "Micro generators" [6].

2.1. Harvesting the vibrational energy

Referring to paper [7], examples of energy harvesting systems and devices are photovoltaics, electrodynamics, biological, piezoelectrics, and thermovoltaics methods. Because of the vibration energy can provide a higher power density. Thus, it has considerable potential for micropower energy harvesting. Some mechanisms which can be used to transform vibrational mechanical energy into electrical energy are electromagnetic, piezoelectric and electrostatic.

Among them, piezoelectric materials can be the first consideration for harvesting power power from ambient vibration sources [8]. This is because they are easily available and can transform mechanical strain into electrical energy efficiently.

One of the methods that can be used to harvest vibrational energy is piezoelectric transducers. The main challenges of piezoelectric energy harvester are broadening the operating frequency bandwidth of the devices and increasing the power density of vibration energy harvesters [9]. There are some techniques that proposed for broadening the resonant frequency bandwidth for the development of nonlinear generators: vibro-impacting designs, mono/bi/multi-stable structures, different frequency-tuning methods and frequency up-converting configurations [10].

3. PIEZOELECTRICITY

Piezoelectricity is the electric charge that captures some solid materials i.e. crystals and certain ceramics [11] to convert mechanical stress and generate an AC voltage. Piezoelectricity is the characteristic of the piezoelectric transducer that will result in an electric power from the mechanical stress. The word "piezo" which came from Greek word means to squeeze or press, while the word "electric" or "electron" means amber, an ancient source of electric charge [12]. The effect of the piezoelectricity was disclosed by the Brothers Pierre, Curie, and Jacques in 1880 [13]. They applied their insight of pyroelectricity and the underlying crystal structures that increase the pyroelectricity to predict crystal behaviour and established the effect using crystals. Gabriel Lippmann derived the converse effect from fundamental thermodynamic principles by using mathematically in 1881 and the existence of the converse effect is established by the Curies [14].

The piezoelectric element's crystal is assembled by elementary cells which consists of electric dipoles. The domains are known as adjoining dipoles form regions of local alignment. A net dipole moment is given by the alignment to the domain. Hence, a net polarization is produced as shown in Figure 2. From Figure 2(a), the polarization's direction amidst the neighbouring domains is random. Thus, the ceramic element does not have overall polarization and electrically neutral. By connecting the element to a strong DC electric field, the domains in a piezoelectric ceramic element are regulated which is shown in Figure 2(b). With the polarizing treatment, domains lined up with the electric field will be increased and the element growths in the field's direction. When the electric field is disconnected, the dipoles are static in a near alignment configuration which is shown in Figure 2(c). The element now has a fixed polarization, the remnant polarization, and is permanently extended.

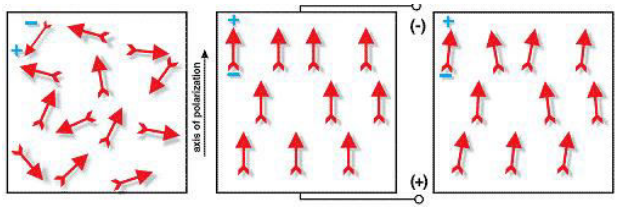

Figure-2. Polarizing a piezoelectric ceramic (a) random alignment of polar domains (b) polarization in DC electric field (c) remnant polarization when electric field disconnected.

4. PIEZOELETRIC ENERGY HARVESTERS (PEHs)

The last decades, the studies of energy harvesting have been increased to discover new techniques for capturing and storing the ambient energy for the purpose of generating energy for low power electronics devices. Piezoelectric transducer can be said has higher power density with a simple structure to integrate into a system and it is cheaper compared to other transduction methods [15].

There are two piezoelectric effects: direct piezoelectric effect and converse piezoelectric effect. Figure 3 indicates the direct piezoelectric effect which is the capability of the material to convert mechanical vibration into electrical charge. This behaviour can be considered as a sensor.

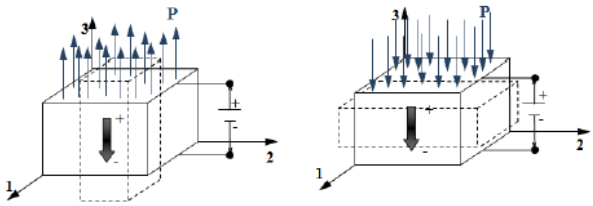

Figure-3. Direct piezoelectric effect [15].

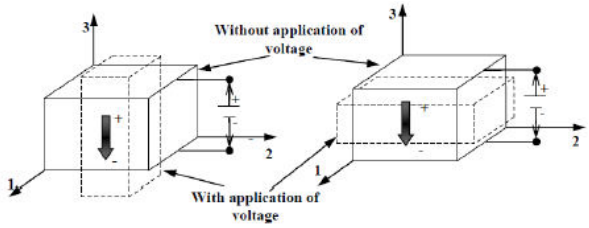

Figure-4. Reverse piezoelectric effect [15].

On the other hand, Figure 4 demonstrates the capability of the material to convert an electrical potential into a mechanical strain energy and it is known as the converse piezoelectric effect. This behaviour can be considered as an actuator.

The energy conversion that is executed by piezoelectric materials is through the generation of electric dipole. The electric dipole in piezoelectric molecular structure dedicates a separation of local charges. Two charges which are positive charge, $+Q$ and negative charge, $-Q$ of the same value and divided by a distance, d compose an electric dipole. The dipole of the piezoelectric transducer will change when deformation is occurred to the material of piezoelectric. Thus, the signification of the electric charge

can be composed and utilized to power some portable and wireless devices [16].

5. CONFIGURATION OF PIEZOELECTRIC ENERGY HARVESTERS (PEHs)

The thin and flat form factors will affect the reaction of a piezoelectric element to the vibration or bending of the host structure. The advantage of the thin and flat form factors is the dimensions and weight of the energy harvesting device will be decreased. Hence, a thin-layer geometric shape of the piezoelectric materials will be utilized in the PEHs designs and structures [5].

5.1. Cantilever beam

One of the frequently used structures in PEHs is cantilever geometry. This is due to a large mechanical strain can be generated within the piezoelectric during vibration. Besides that, the structure of piezoelectric cantilevers is comparatively simple [5]. Moreover, the resonance frequency of a piezoelectric cantilever is much lower compared to the other vibration modes of the piezoelectric element. Hence, there are many research and studies about the unimorph or bimorph cantilever design of the piezoelectric energy harvesting devices.

Piezoelectric cantilever configuration is fabricated with a thin layer of piezoelectric ceramics and a non-piezoelectric layer. At one end of the cantilever is static to develop the flexural mode of the structure which is shown in Figure 5(a). A "unimorph" cantilever design is fabricated by having only one piezoelectric layer which also known as an active layer in this structure. The unimorph cantilever's structure is illustrated in Figure 5(a). From Figure 5(b), it dedicated that two thin layers of piezoelectric ceramic attached on a cantilever. It is known as a "bimorph" structure as two active layers are utilized. The bimorph structure can increase two times the output energy or power of the PEHs without significant increase in the dimensions of the devices compare to the unimorph structure [5]. As a result, bimorph piezoelectric cantilevers are more frequently used in studies of piezoelectric energy harvesting system.

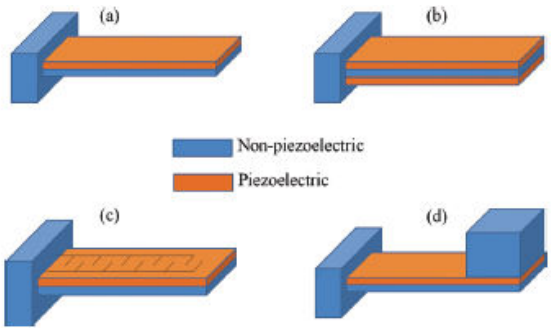

Figure-5. Different Structures of piezoelectric cantilevers: (a) unimorph piezoelectric cantilever; (b) bimorph piezoelectric cantilever; (c) a piezoelectric cantilever with interdigitated electrodes; (d) a piezoelectric cantilever with tip mass at one end [5].

5.2. Disc

Beside the cantilevers beam type, circular shape of piezoelectric energy harvesters: cymbal transducers and piezoelectric diaphragms have also been studied.

5.2.1. Cymbal transducer

Cymbal transducer which composes of a piezoelectric ceramic disc and a metal end cap on both side were dedicated in Figure 6. Because of steel can provide higher yield strength compared to brass and aluminum, so it is typically employed as the metal end cap. Hence, the higher force loading ability of the transducer can be conducted [17]. Due to a higher impact can be endured by the cymbal structure, the cymbal transducers can generate a higher output power compared to the cantilever energy harvesters. Yet, the cymbal structure transducers also have weakness and limitation i.e. they are not suitable to be used for energy harvesting from low vibration magnitude of natural ambient vibration sources.

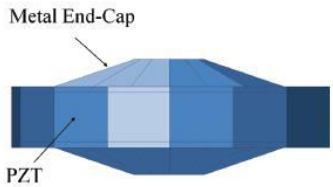

Figure-6. Schematic diagram of a piezoelectric cymbal transducer [5].

5.2.2. Circular diaphragms

The operation of a circular diaphragm of the piezoelectric transducer is same as piezoelectric cantilevers. A circular diaphragm of the piezoelectric transducer is developed with a thin circular piezoelectric ceramic disc. The piezoelectric disc is attached to a metal shim and the whole structure is fixed on the edge. The pre-stress within the piezoelectric element can enhance the low-frequency performance and the output power of the energy harvester [17]–[19]. Thus, a proof mass is enclosed at the center of the diaphragm. Another technique was introduced for THUNDER which is also known as Thin Layer Unimorph Driver transducer. The technique was used to introduce pre-stress within the piezoelectric ceramic happens when the piezoelectric-metal compounds in the fabrication stage [20]. At first, the two dissimilar metal layers are attached to the piezoelectric ceramic layer. Next, the compound is heated and cooled to room temperature. The pre-stress in the piezoelectric will be presented when the whole construction is bend because of the difference in the thermal expansion coefficients of the two dissimilar metals.

6. PIEZOELECTRIC VIBRATION ENERGY HARVESTER (PVEH)

A cantilever structure of piezoelectric which composed a substrate and a layer of piezoelectric material is shown in Figure 7. It is developed for a PVEHs. The layer of the piezoelectric material is allocated between two metal electrode layers [21]. This type of mechanical configuration is simpler and has a higher power density. A tip mass or

proof mass will be enclosed at the other end of the cantilever to increase the output power of the energy harvester [22].

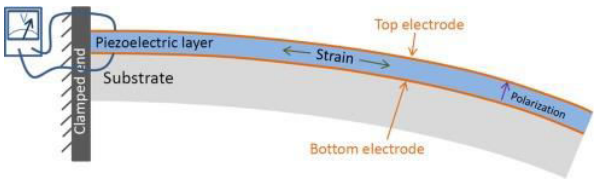

Figure-7. Simple cantilevered piezoelectric harvester [21].

The equation of the mechanical stress for the load-bearing material with the linear assumption is as Equation (6.1) below [23]:

$$T = C^H S \quad (1)$$

Where,
T = Mechanical stress,
C^H = The elasticity matrix of the host layer, and
S = Strain.

Equation (6.2) and Equation (6.3) below show the electromechanical coupling effect of the piezoelectric material [23]:

$$T = C^P S - eES \quad (2)$$
$$D = e^T S + \varepsilon^S ES \quad (3)$$

Where,
C^P = The elasticity matrix of the piezoelectric layer,
D = The electric displacement,
e = The piezoelectricity matrix
E = The applied electric field, and
ε^S = The permittivity matrix.

In order to increase the output power of the PVEH, the concept of by using inertia mass [24]–[36], magnetic stopper [37]–[41], geometry of the piezoelectric [42]–[46],the combination of magnetic stopper with geometry of the piezoelectric [47], the combination of inertia mass and geometry of the piezoelectric [8], [48] and piezoelectric disk [49], [50] have been approached. There are many researchers investigate about the PVEHs by using inertia mass method. [24]–[36] used the same mechanical configuration which is at the end of the piezoelectric beam attached with an inertia mass. The function of the proof mass is to increase the bending motion of the piezoelectric beam. [32] generated a highest output power compared to others. This is because the proof mass of the energy harvester is different from others in terms of length and shape. While [33] designed a different energy harvester compared to others. They used different type of proof mass which is liquid filled mass.

[34] developed a piezoelectric generator on a bimorph cantilever beam. The cantilever beam's top and bottom are made-up from the piezoelectric material. The end of the cantilever beam is enclosed with an inertia mass. This design was combined with the tuning actuators to tune the natural frequency of the generator and match with the driving frequency. The scavenger operating frequency bandwidth can be increased from 6Hz to 24Hz with a multiple proof masses. [36] demonstrated a piezoelectric generator which is employed the change of the cantilever beam strain. The cantilever beam is attached together with the weight of the tip mass. The designed is to ensure it can contact the piezoelectric devices which are positioned on both sides. There are two approaches were used for the rectified output voltage: DC voltages from the rectifiers were interfaced in series then supplied to the capacitor and the DC voltages from each group were supplied to different capacitors. They proved that when the DC voltages from each group was supplied to different capacitors with the initial vibration amplitude of 18mm at the resonant frequency of 18.5Hz, the total output electric energy for the piezoelectric generator can provide 43nJ for one vibration. Yet, in the charging loop, there was a lot of energy loss.

[35] implemented a PEH that has a mechanical end stop on one side. An optimum load resistance of 209.6kΩ was connected to a metal plate enclosed to the piezoelectric. It was operated at a resonant frequency of 120Hz. The results show that show that the increment of the acceleration level will increase the output power as well. A piezoelectric energy harvester by using liquid filled mass was proposed in [33]. The structure is shown in Figure 8. The objective of this research is to widen the operating frequency bandwidth without decrease the peak output voltage. Among the variables that have been evaluated are cavity mass, acceleration of the vibrational shaker, amount of the fluid mass and types of the fluids. They found out that 50% of the water filled mass with 4g of acceleration was the best input variables. This is due to the operating resonant frequency bandwidth was increased from 1.6Hz to 4.45Hz without reducing the peak-to-peak voltage. [35] and [33] show that the proof mass not only can gain the output power. It also can widen the operating resonant frequency bandwidth.

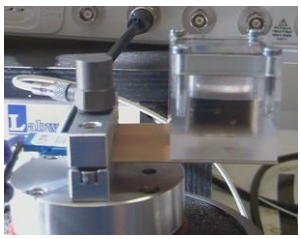

Figure-8. The piezoelectric energy harvesters using liquid filled mass [33].

[24] developed a self-power vibration measurement system. The dimension of the piezoelectric cantilever is 66.7mm×2.5mm×31.8mm. A proof mass is enclosed on the end of the cantilever. A RMS voltage of 5.2V is produced at the resonant frequency of 78Hz with 1g of acceleration. Then, [25] analyzed the effect of the stiffness and effective mass of the piezoelectric cantilever to the resonant frequency. They proved that the resonant frequency will be decreased as the weight of the inertia mass is increased. The output voltage will be increased 52% when the 1.5g of inertia mass is attached compared to the without inertia mass cantilever. When the length of the cantilever is reduced, the resonant frequency will be

increased while the output voltage will be decreased. The resonant frequency is increased to 750Hz when 1.5cm of cantilever length is decreased. Based on the data in [25], the effect of the different connection of the piezoelectric arrays to the performance of the PVEH was analyzed [26]–[28]. They found out that the operating frequency bandwidth of the piezoelectric cantilever arrays can be widen by interfacing the different resonant frequency of cantilevers together. The series configuration generated a higher output voltage. While the parallel configuration generated a higher output power. The output gaps between the peaks can be increased with the changed of polarities connections of the piezoelectric.

[30] developed a PVDF-based piezoelectric energy harvester that composes of a PVDF bimorph cantilever beam with the steel load mass. The steel load mass is attached to the end of the beam which is shown in Figure 9. The resonant frequency and the maximum stress of the designed model were 34.4Hz and 28.5MPa, respectively. The PVDF-based PEH can harvest the output power of 112.8μW and power density of 8.61mW/cm^3. [31] suggested a piezoelectric energy harvester that composes of a unimorph piezoelectric cantilever beam with a tip mass. With the absence of the proof mass, the Matlab and Comsol simulations results show that the maximum average output power were 0.36mW and 0.37mW respectively. With the presence of the proof mass which were equal to 30g, 50g and 70g, the maximum output power were 4.5mW, 5.5mW and 6.8mW respectively. The higher the proof mass, the higher the maximum output power that was generated. The output power will be decreased with the presence of the damping ratio. [31] generated a higher output power compared to [30]. This is because of the length of PVDF bimorph cantilever beam is shorter. The shorter the cantilever will result in lower output power [25].

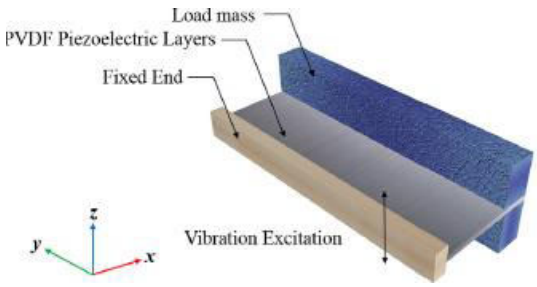

Figure-9. The structure of the PVDF-based PEH device [30].

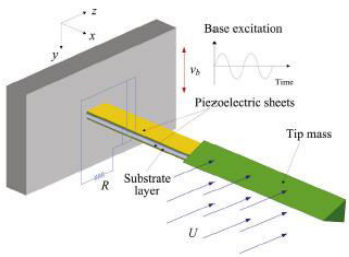

Figure-10. Schematics of a hybrid piezoelectric energy harvester [32].

A hybrid PEH that combined the galloping effect is shown in Figure 10. It was proposed by [32]. The PEH consists of a cantilever beam and a tip mass. The cantilever beam composes of a substrate layer and two piezoelectric layers. The substrate layer was sandwiched between the piezoelectric layers. The optimal load resistor can be found in two ways: through the base-excitation alone system and galloping-alone system. The harvested energy was 1 W for 0.5g acceleration and 1.34 W for 1g acceleration during the excitation frequency was near to the modified natural frequency of the system. [29] presented a PEH by using an unimorph piezoelectric cantilever beam. One end of the cantilever beam was fixed at the vibration source while the other end was enclosed with a block mass. The electromechanical coupling system for the PEH was demonstrated by using an equivalent lumped-parameter single degree of freedom (SDOF) dynamic system. When the excitation frequency inclines up and down, the phase shifts closer to 180°. The phase difference is 90° for both linear PEHs and nonlinear PEHs as the frequency was around the resonance frequency. The 90° of phase difference produced excellent opportunities in evaluating the energy conversion process' efficiency.

Another method to improve the performance of the PEHs from magnetic stopper is used. [37]–[41] used a similar magnetic force concept to tune with respect to the environmental vibration. The magnetic force can provide a smoother operation to the piezoelectric beam compared to the mechanical stopper. The magnetic force can provide a non-contact stopper. [41] introduced a piezoelectric cantilever array with magnetic tips in order to tune the resonance frequency regarding to the original resonance frequency of the beams. They proved that the proposed design was able to increase the power density as long as the beams were adjusted by using a single efficient actuator. The benefit of this PEH was it can widen the range of the frequency compared to other, yet it will generate a lower power density. This is due to the power was released to the broader bandwidth of the frequency. [40] experimentally studied and verified a model of bimorph piezoelectric beam. Dimension of the beam is 60mm×5mm×0.5mm and it was connected to a 120kΩ of resistance load and a 24.6nF of capacitor. In order to move the beam without any physical impact, the magnetic coupling was introduced. The output voltage and the tip displacement were measured. It shows that the voltage of the repulsive magnet arrangement is greater and offered a clean declining oscillation compared with the attractive arrangement. Yet, the output voltage for the initial gap of magnet arrangement of a 4mm gap is smaller than the 2mm gap. The benefits of this magnetic coupling technique are it is contactless impact and it can avoid damage to the piezoelectric material.

[37] suggested a PEH by using piezoelectric and electromagnetic mechanism. There are four structures i.e. single piezoelectric cantilever, the cantilever that has four magnets, in series and in parallel configurations. The single PZT cantilever can generate 27.56mW of output power. The single piezoelectric cantilever generated three times higher of output power compared to interface the electromagnetic energy harvester in series. While the parallel connection can

generated three times output power higher than the single piezoelectric cantilever. [39] suggested a PEH that has a magnetic stopper on one side of the main beam. There are three beams for the PEH with non-contact connection by using the magnetic force or repelling force. The magnetic stopper pair was allocated on the two single beams which are top and below of the main beam. The output power for the stopper beam and the single beam were 0.1μW and 0.098μW respectively within the operation time of 38.8s. [Investigation] generated higher output power than [39]. This is due to the mechanical configuration of the PEHs is different. The piezoelectric beam consists of copper coil that turn around the magnets to induce magnetic force instead of using repelling force.

[38] introduced a dual coupled cantilever based PVEH system which consists of a cantilever beam and piezoelectric cantilever plate. The PVEH with a dimension of 63.5mm×0.51mm×31.8mm was attached to the steel host structure with a dimension of 450mm×5mm×20mm. The Experimental Modal Analysis (EMA) and Operating Deflection Shape (ODS) analysis were be applied for investigating the two non-destructive vibration techniques. The maximum output peak voltage is 6.0Vac during the cantilever beam is vibrated at a frequency of 52Hz and it was 33.3% of enhancement in harvested voltage.

Different types of piezoelectric geometric are developed and discussed in [42]–[46]. Different types of piezoelectric geometry can affect their mechanical strain. The strain distribution from the piezoelectric would be optimal uniform with an optimal geometry of the piezoelectric. [44] proposed an array of piezoelectric multi-cantilever. Two configurations of multi-cantilever: six cantilevers with different lengths and fix cantilevers with different widths. The number of the cantilever decreased, the peak value of the output power increased. The cantilever's width affected the vibration order mode of the cantilever. While the cantilever's length affected the output voltage value. [45] studied about the performance of the PZT piezoelectric transducer. The impedance matching method and free fall experiment were applied to analyze the PZT transducer. They found out the impedance matching value can improve the efficiency of the PZT transducer. The triangle shape of the PZT transducer can generated higher output power and efficiency compared to rectangular PZT transducer. [44] and [45] analyzed that the parameters, i.e. dimension of the cantilever, impedance value, shape of the piezoelectric and load mass can affect the performance of the piezoelectric transducer.

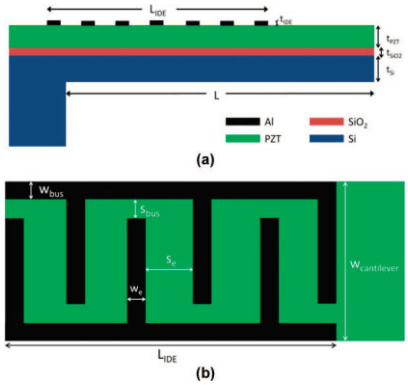

Figure-11. Schematic drawing from (a) Side view (b) top view of a cantilever PEH [46].

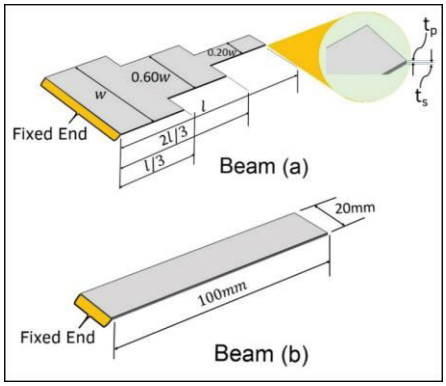

Figure-12. Beam (a) and Beam (b) designed for the Unimorph Piezoelectric Energy Harvester [43].

[46] presented a new two-stage method based on the finite element method. It is utilized to find the optimal thickness of the piezoelectric material. The Interdigitated-Electrode (IDE) geometry for a cantilever beam is fabricated and is shown in Figure 11. The IDE geometry is fabricated on the top of a Si structural layer with a 4μm thickness and a SiO_2 isolation layer with 1μm thickness. The lengths of the cantilever and IDE are set at 320μm and 240μm respectively. The opposing effect is decreased, and output charge is increased when the poling is not orthogonal under the electrodes. With a 15μN of force applied on a 0.6μm of PZT thickness and 12 finger pairs of IDE, a maximum output energy of 0.37pJ was generated. A 3D finite element analysis of changing the width of the piezoelectric cantilever beam of energy harvester was demonstrated in [43]. The block pulse function (BFFs) was applied to develop the 3D finite element analysis. Figure 12 shows the schematic of the piezoelectric cantilever beam. They found out that beam (a) generated a peak voltage of 2.5 times greater than the beam (b). Beam (a) has a better distribution strain to harvest energy from vibration or kinetic energy. Both [46] and [43] used the finite element approach to analyze the effect of the width and thickness of the piezoelectric transducer to the performance of the energy harvester.

[42] designed a PEH which consists of a tapered cantilever surface bonded with piezoelectric patches. The designed PEH is shown in Figure 13. They proved that the larger the taper ratio of thickness or the cantilever width to

the PZT4 patch width, the lower the value of RMS of the generated power. The material and geometric parameters of b0 = 0.04m, h0 = 0.003m, l = 0.6m, $b_1/b_0 = h_1/h_0 = 0.2$, w_p = 0.012m, tp = 0.3mm, Y = 1m and ω' = 10rad/s are shown in Fig 13. The PEH can generate the RMS output power of 0.1376W which is power up to 70 times higher than the uniform counterpart.

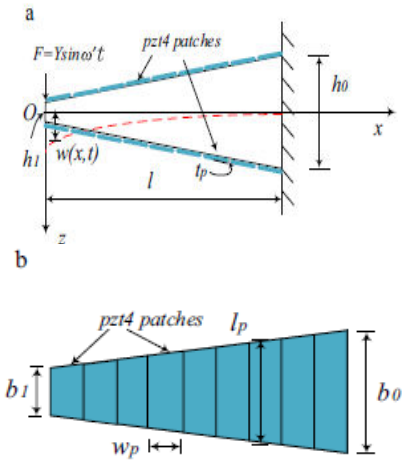

Figure-13. The piezoelectric energy harvester in (a) Normal section view, (b) Top view [42].

A new approach which is the combination of magnetic force and geometric concept is used in [47]. A low frequency piezoelectric-electromagnetic-triboelectric hybrid broadband vibrational energy harvester (LB-HVEH) is designed and shown in Figure 14. There are three main parts for the LB-HVEH: electromagnetic energy harvester (EMEH), piezoelectric energy harvester (PEH) and triboelectric energy harvester (TEH) PEH is worked on piezoelectric effect, EMEH is used the Faraday's Law and TEH is utilized the tribo-electrification and electrostatic induction. With a 0.5g acceleration at a frequency of 20Hz, the PEH that connected to a load resistance value of 800.1kΩ yielded a maximum output power of 41.0μW and operating bandwidth of 3.5Hz. The EMEH produced a 66.5μW of maximum output power and 10Hz of operating bandwidth at 343.1Ω of load resistance value while the TEH generated a 4.6μW of maximum output power and 18.1Hz of operating frequency bandwidth at load resistance value of 1.4MΩ. The PEH and TEH have high internal impedance while the EMEH has the low internal impedance. Meanwhile, the PEH and TEH can produce higher voltage compared to the EMEH.

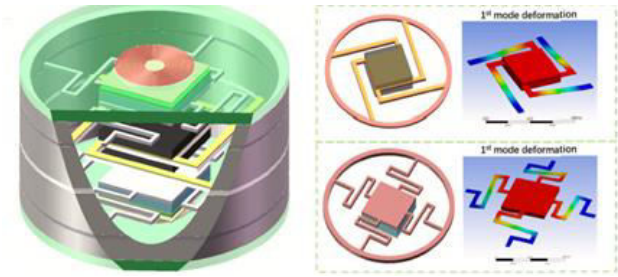

Figure-14. Schematic of the low-frequency hybrid broadband vibration energy harvester [47].

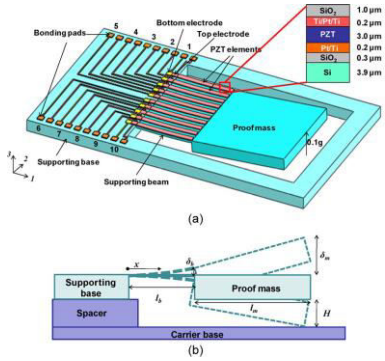

Figure-15. (a) Schematic diagram of the piezoelectric cantilever attached with an inertia mass. (b) Cross-section illustration of the piezoelectric cantilever generator with a spacer [48].

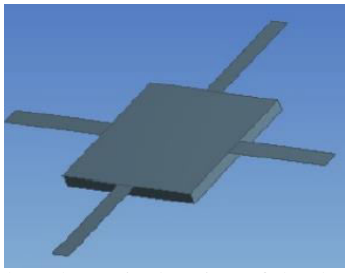

Figure-16. The schematic drawing of the designed for the vibrator [8].

Another new approach which is combining the inertia mass and geometry concept was analyzed and developed in [8], [48]. A MEMS PEH consists of a cantilever and ten parallel-arrayed PZT energy harvesting element [48]. The cantilever composes of a silicon proof mass with size of 5mm×5mm×0.4mm and silicon beam with size of 3mm×5mm×5μm. The structure is described in Figure 15. They found out that the PEH which consists of PZT element in parallel connection can generate higher output power compared to the series connection with a low load resistance. The energy harvester yielded the power in the range of 19.4nW to 51.3nW at the operating frequency range of 30Hz to 47Hz with the acceleration of 1g condition. A PVEH which consists of a micro-machined thick silicon inertia mass mounted with quad-beams was developed in [8]. The type of the quad-beam is monolithic single crystal silicon. The structure is shown in Figure 16. The thickness of the quad Si beams was fixed, while the sizes of the structures are 5000, 7000 and 10,000μm in length and the optimal ratio of the length of the beams (Lc) to the edge length (Lp) of the inertia mass was identified. The results show that nine devices in an array are suggested to widen the bandwidth of the PVEH. Each device can widen 50Hz bandwidth frequency to obtain the bandwidth resonant frequency from 100Hz to 500Hz. With an acceleration of 1g, the output voltage was 0.4V.

Another approach of PVEH from piezoelectric disk is discussed and analyzed in [49][50]. [49] introduced a multi-order parametric resonant MEMS piezoelectric disk membrane. A circular disk membrane design topology was applied. When the sinusoidal drive is at 2.0g of acceleration,

as the orders are increased, the resonant peaks will be narrower and smaller. With an acceleration of 2.0g and 55Hz of frequency, the -3dB bandwidth of first parametric resonant peak showed at 365Hz while the 8th orders demonstrated at 604Hz. A piezoelectric disk flexure resonators (DFRs) connected with a 50Ω terminated network analyzer was demonstrated in [50]. The disk resonator indicated that the coupling factor was 4 times larger compared with the device of length extension. While the length extension resonator (LER) has a quality factor of 3.75 times larger and bandwidth of the resonant frequency was 5.5 times narrower.

A Double Piezo – Snap Through Buckling (DP-STB) energy harvester was developed in [51]. The energy harvester consists of a bistable clamped Poly Ethylene Terephthalate (PET) beam and two piezoelectric transducers. The type of the transducer is 7BB-35-3L0, manufactured by Murata. The piezoelectric transducers were interfaced in a parallel configuration and an inertial mass was located in the middle of the beam. The results show that when decreasing the proof mass, the acceleration can affect the beam buckling with the distance between the stable states. Furthermore, as the operating frequency increased, the output power will be increased as well. The unit of the output power is μW. There are many approaches such as bending, vibration and impact-mode have been analyzed by using a micropower piezoelectric generator [52]. The output voltage that was generated by using impact, bending and vibration methods were 4V, 0.2V and 0.2V, respectively. The impact generated voltage value was 20 times higher than the bending and vibration generated voltages. For the impact generated voltage, a single piezoelectric element with the speed of 200 strokes/s produced an output voltage of 4V and current of 4mA. The generated output power of the impact mode is equal to 16mW. In order to produce 0.4W of output power, 25 elements were being estimated to be needed for the energy harvester.

A new method to improve the performance of PVEH is used a parallel-plate spring-mass system through multiple nonlinear technique [53]. The system makes up of a thin spring-plate, a proof mass and a rigid stopper-plate. The spring-plate was an L-type beam which attached to a 3mm×24mm×0.4mm piezoelectric ceramic plate. When the gap between the spring-plate and the stopper-plate (SSG) changed from positive value to negative value, the bandwidth is increased yet the RMS output voltage is reduced. For the input variables such as large-SSG, small-SSG and over-SSG, the -3dB bandwidth is 15.2Hz, 41.6Hz and 67Hz, respectively. Another method of the combination of the triboelectric generator and bi-stable piezoelectric cantilever energy harvester based on the low-frequency stochastic resonance is used to designed an energy harvester [54]. The average output voltage for the open circuit was 105V when the size of the friction area is 93.51mm^2.

7. IMPACT-BASED PIEZOELECTRIC ENERGY HARVESTER (IPEH)

There are two modes for the basic process of the power generator for linear motion of vibration of the energy harvesting with piezoelectric transducers. Bending mode is the first mode for the basic operation while impact mode is the second mode. For the impact mode power generation, the deformations occurred during an impact force is applied. The impact force deforms the piezoelectric transducer then produces strain forces and the flow of charges. The impact mode of piezoelectric energy harvesters have their capability to function in a relatively broader operating frequency bandwidth [55]. There are some methods that are used to analyze the performance of the IPEH, i.e. piezoelectric beam [56]–[61], free moving object [62]–[65], piezoelectric disk [66], [67], free fall [55], [68]–[74], the combination of piezoelectric disk with the free moving object [75] and rotating gear [76].

The method that used piezoelectric beam for the IPEH was early introduced by [59]. A PEH mechanism with three types of modules is designed. The first module is an electromagnetic induction module in U-shaped beam. The U-shaped beam was made up from U-shaped aluminum beam and Neodymium Boron Iron (NdFeB) permanent magnets. The second module is an impact mode piezoelectric energy harvesting module which has stainless steel beam and two plates of piezoelectric with tip mass. While the third module is an impact-induced vibration piezoelectric energy harvesting module. The third module consists of cantilever bronze beam and tip assembled with impact body, coil housing and hand-wound enameled copper coil. It showed that the third module can harvest more electric output energy compared to the other modules. It produced 6547.2μJ of energy while the first and second module produced 57.2μJ and 429.3μJ of energy respectively. [58] analyzed the effect of the mechanical impact on the PEH which comprises a driving beam allocated between two piezoelectric parallel bimorph beams. There are two conditions that has been evaluated: the non-interacting condition and the interacting condition. The results indicate that the generated output voltage and the bandwidth of the operating frequency in the interacting condition are higher and broader compared to the non-interacting condition.

[60] also used the piezoelectric beam to study the performance of the IPEH. A driving beam impact with horizontally extended rectangular tip for low frequency applications is suggested. This configuration caused the two piezoelectric generating beams oscillated simultaneously and yielded an output power. The structure is shown in Figure 17. Single degree of freedom (SDOF) spring-mass-damper model is utilized to demonstrate the IPEH model. The higher the resistance load value is, the higher the output voltage produced. By using a 200kΩ of load resistance, the maximum output power of 129.15μW was harvested at an acceleration of 6ms^{-2} compared to 46.51μW that was generated at an acceleration of 4ms^{-2}. Therefore, the faster the acceleration of the vibration, the larger the output voltage and the output power that generated. A micro energy harvesters with an impact-induced oscillation was discussed in [61]. A cylindrical cavity to lead a metal ball to vertically hit on the cantilever beam. Finite-element method

(FEM) was utilized in the analysis. The bandwidth of the frequency response for the harvester was from 20Hz to 150Hz. When the metal ball hit on the cantilever beam that connected to a load resistance value of 10kΩ at a frequency of 150Hz with an acceleration of 39m/s^2, 34.6nW of maximum output power was generated. The output power of the IPEH in [60] is higher than the output power in [61]. This is because there are two piezoelectric beam have been used in [60].The output of both piezoelectric beams is connected in series. Thus, the generated output power is larger than a single piezoelectric beam device.

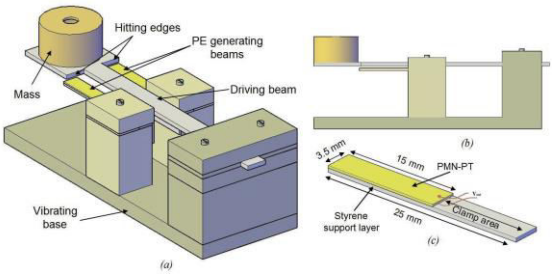

Figure-17. The structure of the piezoelectric vibration energy harvester [60].

A similar kind of approach of IPEH that used piezoelectric beam was designed by [56]. An impact energy harvester which comprises a cantilever beam and a ball was proposed. The cantilever beam composes of piezoelectric patches. SDOF model is used to design the energy harvester. With these parameters, i.e. ball displacement, BC_{gap}, resistance value, and mass and thickness of the piezoelectric beam, the performance of the impact energy harvester (IEH) was compared with a non-impact energy harvester (NIEH). The higher the value of the BC_{gap}, the smaller the impact force. The IEH can generate higher instantaneous power and output average power than the NIEH with the same value of BCgap. The output power of IEH is almost two times higher than the NIEH at a frequency of 2.2Hz. As the mass and thickness of the piezoelectric beam increase, the average output power will be increased as well. They proved that the IEH can harvest more energy compared to the NIEH. An impact-engaged two-degrees-of-freedom (2DOF) PEH with stopper was implemented in [57]. The multi-modal technique and impact-engaged nonlinearity technique are applied. As the stopper distance decreased, the effective of the operating frequency bandwidth will be increased yet the amplitude of the voltage at first resonant will be decreased. The stopper distance of 12mm is the optimal distance for the PEH. While increasing the stopper stiffness, the amplitude of the voltage will be decreased but the effective of the operating frequency bandwidth will be increased at first then decreased. The optimal stiffness of the stopper of the PEH is 4. Both [56] and [57] analyzed the parameters that will affect the performance of IPEH by using piezoelectric cantilever beam.

Another method which is by using free moving object is used for IPEH. [62]–[65] used the same mechanical configuration for the energy harvester which the object is collided on the piezoelectric beam in perpendicular direction. [64] generated the highest output power compared to others. This is because two channels are designed for objects to collide perpendicular to the piezoelectric beam. [63] developed a PEH which a pulse type force of impaction was applied on the piezoelectric bimorph cantilever beams. The piezoelectric beams were connected in series or parallel configuration and interfaced to the powered device with a signal conditioner. The IPEH can harvest 600μW of output power at 10Hz of frequency and 10cm of linear motion's amplitude. In terms of power density, it produced 120μW/cm^3 of output power density. However, there is a limitation for the proposed IPEH which is only one dimensional of collision was being analyzed on a flexible beam. The collision direction of the object is perpendicular to the beam's surface. A similar approach has been developed in [62]. The PEH consists of two unimorph piezoelectric cantilever beam and a channel for a sliding mass. They found out that the parameters, i.e. electric load, sliding distance, piezoelectric beam length, gap between the piezoelectric beams with the housing and sliding mass are main factors that will affect the performance of the piezoelectric energy harvester.

An indirect IPEH system which consists of a freely movable metal spheres and a piezoelectric cantilever beam was developed in [64]. The type of piezoelectric transducer is of MFC (Macro Fiber Composite). The structure is shown in Figure 18. Three different types of aluminum housings which are shown in Figure 19 and three different types of experiment were conducted. The Housing 2 has a perpendicular cavity end with the wall's thickness of 0.5mm. It produced 23.8V of output voltage compared to the Housing 1 and Housing 3 at a frequency of 20Hz and 3g of acceleration. The manual vibration test is better compared to the vibration excited test and pendulum test. The manual vibration test produced a maximum output voltage of 54Vmax, average output power of 621μW and average output power density of 135.3μW/cm^3. [65] developed an impact-based piezoelectric VEH which integrates of two bimorphs cantilevers, a rolling steel ball and a guiding channel that has two open ends. The rolling steel ball acted as an inertia mass. The structure is shown in Figure 20. The output efficiency can be enhanced by increasing the channel length or having the rolling inertia mass in the harvester. A maximum output power of 511μW of one bimorph cantilever was produced with an acceleration of 1g at a frequency of 18.4Hz.

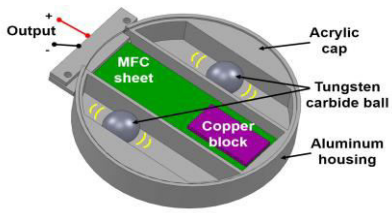

Figure-18. Schematic drawing of the piezoelectric energy harvester [64].

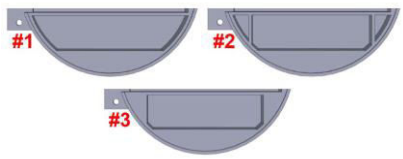

Figure-19. Different types of Housing for the piezoelectric energy harvester [64].

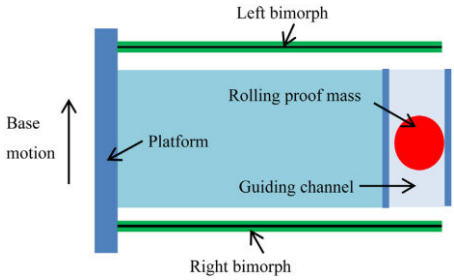

Figure-20. Schematic drawing of energy harvester with a rolling proof mass [65].

Another novel approach which is by using piezoelectric disk is applied for the IPEH in [67]. A cymbal bridge transducer that composed of a square soft PZT ceramic and hardened steel end caps on the energy harvester from the impact load is implemented. The dimension of the square soft PZT ceramic is 32mm×32mm×2mm. As the resistive load increased, the output power is increased. This is because of the impedance of the transducer is increased. For a 600lb load, each loading and unloading cycle produced 0.83mJ of output energy. 2.1mW of a maximum output power was harvested at a frequency of 5Hz and 500lb loading interfaced with a resistive load value of 400kΩ. [66] analyzed a piezoelectric vibration energy harvester in impact mode. It used 5grams of lead ball. The lead ball acted as an impact mass. There are three different types of experiment that were implemented to evaluate and analyze the performance of the IPEH: shaker at a frequency of 17.735kHz, shaker at a resonant frequency of 177.143kHz, and hand vibration at 3Hz. The output power of shaker at resonant frequency of 177.143kHz, shaker at a frequency of 17.735kHz and hand vibration at 3Hz are 9.072W (10.08Vout and 0.9A), 0.392W (3.92Vout and 0.1A) and 40Vout in very low current in mA, respectively. The output power of shaker at resonant frequency of 177.143kHz was the largest compared to the shaker at a frequency of 17.735kHz and hand vibration at 3Hz. The output power in [66] is higher than the output power in [67]. This is because of the energy harvester in [66] interfaced with power conditioning and the acceleration of the shaker is 20g.

A free fall method is applied to IPEH in [55], [68]–[74]. [68][70] used a bending beam that is caused by an impact force while [69][71][73][74] used a piezoelectric disk when an impact force is applied. [71][74] proposed a foot step platform which consists of a piezoelectric disk that was sandwiched between wooden plates. The diameter of the piezoelectric disk is 44mm and it has 10mm of thickness. The power generator yielded the output power of 14.5μW when connected to a 500kΩ of resistor load. They found out that the output energy is 1.7 times higher when the velocity is increased with fixed force compared to the force is increased with fixed velocity.

A rectangular piezoelectric transducer in bending motion with the size of 32mm×70mm×0.55mm is shown in Figure 21 [68]. An impact force was suggested to be applied to the beam. A free fall test was conducted. When 80N force was employed on the transducer, a maximum instantaneous output voltage of 50V was produced. When 50N impact force was applied and the transducer was connected with a resistive load value of 0.175kΩ, a maximum DC output power of 8.8mW was generated. [70] improved the performance of the power generator by proposing a piezoelectric prestressed bending mechanism. The dimension of piezoelectric transducer is 29mm×70mm×0.55mm while the dimension housing is 29mm×121mm×21.4mm which shown in Figure 22. When 80N force was applied to the transducer, the output voltage is increased to 70V. A resistive load of 0.7kΩ is connected to the transducer. 53mW of output power is increased when a force of 50N was employed to the transducer. [70] generated higher output power than [68] due to the mechanism housing is used pre-stressed concept.

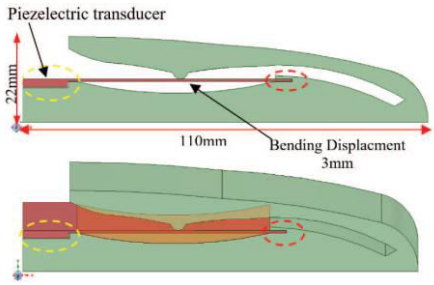

Figure-21. The proposed piezoelectric bending mechanism [68].

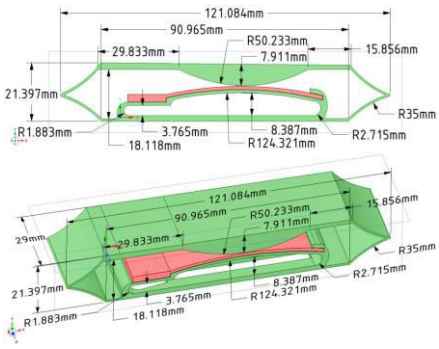

Figure-22. The proposed piezoelectric pre-stressed bending mechanism [70].

[69][73] used free fall concept to develop a power generator. The parameters that will affect the output power for the IPEH were analyzed by using free fall experiment. As the impact velocity is same, the output power of the 8g of steel ball is larger than the 4g steel ball. This is because of the momentum of 8g steel ball is twice compared with

the 4g steel ball. The output power is proportional to the impact velocity. When the value of the momentum is same, the velocity of 4g steel ball is two times faster than the 8g steel ball. Therefore, the output power of 4g steel ball is two times larger than 8g steel ball. For the power generator experiment, the lighter the proof mass, the smaller the bandwidth of the operating frequency and the higher the output power. The output power of 120µW was generated with a 26g of the proof mass. [55][72] enhanced an impact mode of piezoelectric power generator by attaching a shim plate between a piezoelectric ceramic disc and the hitting structure. The structure is shown in Figure 23. There are two types of configurations for the impact mode piezoelectric power generator: pre-load configuration and non-touching configuration. The bandwidth of the operating frequency for the pre-load configuration was broaden compared to the non-touching configuration. By attaching shim plate configuration, the output efficiency will be increased until 4.3 times higher than the direct hit to the piezoelectric ceramic. The smaller the diameter of the shim plate, the larger the output power of the power generator. The power generator was able to harvest 1.5mJ of energy within 120s of vibration time.

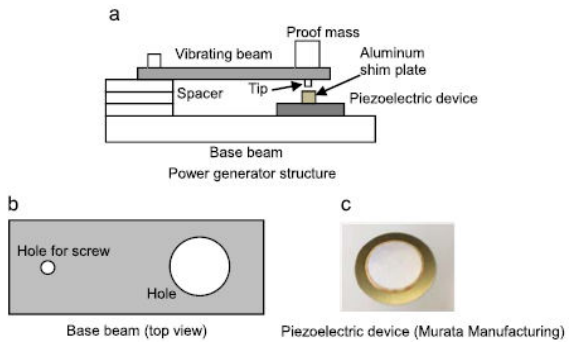

Figure-23. The power generator, base beam and piezoelectric device [55].

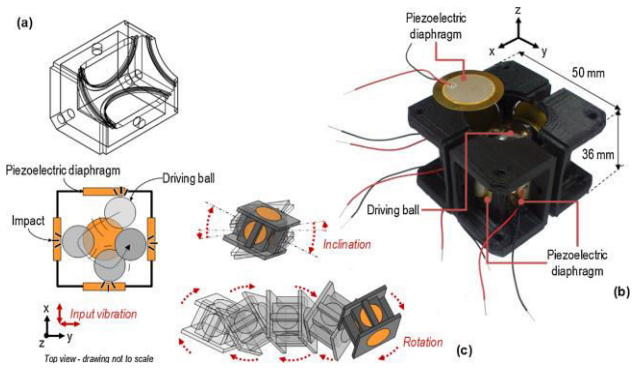

Figure-24. Structure of the proposed triaxial BIPC [75].

The approach of combination of piezoelectric disk and free moving object is used in [75]. An energy harvester of a triaxial ball-impact piezoelectric converter for human motion was designed. The 90cm^3 of cube energy harvester which composes of an AISI 316 stainless steel ball is shown in Figure 24. The diameter of the stainless steel ball is 30mm. It was enclosed by three pairs of piezoelectric diaphragms. The type of the piezoelectric transducer is 7BB-27-4A0, manufactured by Murata. A peak instantaneous power of 16mW was generated when a person was running at 7km/h. The energy harvester was estimated to yield energy of 1.4mJ within 260s of time when walking at 2km/h.

A new method of impact-based piezoelectric energy harvesting from rotating gear is designed in [76]. An IPEH which consists of a PZT sheet that was attached to a silicon AFM type of cantilever beam is developed. The thickness of the PZT sheet is 135µm. The structure is shown in Figure 25. An inertial mass system is utilized for the gear driven energy harvester. There are three main factors for the geometry of the PEH: the support layer's thickness, the piezoelectric beam's thickness and the beam's area. The deeper the depth of the tip and the longer the displacement of the harvesting device is, the larger the output power of the energy harvester. When the depth of the tip was 100µm and a 2.7kΩ of the resistive load is connected, as the rotation speed is at 25rpm, the energy harvester yields an average output power of 1.26µW.

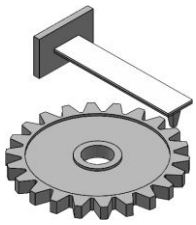

Figure-25. Schematic drawing of the energy harvester system [76].

8. FREQUENCY UP-CONVERTING FOR PIEZOELECTRIC ENERGY HARVESTER (FUCPEH)

There are different types of techniques to develop nonlinear generators for broadening resonant frequency bandwidth, i.e. vibro-impacting designs, different frequency-tuning methods, mono/bi/multi-stable structures and frequency up-converting configurations [10][77]. Frequency up-conversion technology is the technology that forcing the low-frequency ambient vibration to be transformed to the high-frequency vibration for micro energy harvesting. Therefore, the frequency up-converting piezoelectric energy harvester (FUCPEH) has been executed through mechanical impact or mechanical plucking [78]. The kinetic energy that is absorbed from the environmental vibrations is transmitted by a low-frequency oscillator to a high-frequency oscillator. Then, the high-frequency oscillator energy is transmitted to the electrical energy [79]. The optimum output power can be obtained only when the ambient vibration frequency same with the resonant frequency of the EH device. However, when ambient vibration frequency is at a distance from the resonant frequency of EHs, the harvested output power will be decreased [80]. This section discusses some concepts that have been used i.e. combination of d_{33} and d_{31} [77], [79]–[82], handy motion driven [83] and rotating gear [84].

The d_{31} mode device is the stress which is perpendicular to the electric field of the piezoelectric elements. In most of the cases the d_{31} mode is occurred when the piezoelectric transducer is working under bending mode. On the other hand, the d_{33} mode occurred when the device is the being stress and it is parallel to the electric field of the piezoelectric elements [85]. The d_{33} mode is happened during an impact force is applied to the piezoelectric transducer. It referred to impact-based mode. The output power and performance of the PEH can be tuned by combining the d_{31} mode and d_{33} mode devices in series or parallel configurations.

The combination of d_{33} and d_{31} approach is shown in [80]. A MEMS-based PEH system by combining nonlinear spring effect with an impact-based FUC mechanism was developed. The PEH employed a top PZT-T cantilever, a bottom PZT-B cantilever and an inertia mass. The PZT-T cantilever composes of a silicon beam combined with PZT thin film patterns. The dimension of the silicon beam is 3mm×5mm×5μm. The PZT-B cantilever has same structure as PZT-T. The dimension of the inertia mass is 5mm×5mm×0.4mm. At the resonant frequency of 36Hz, the operation frequency bandwidth is widened to 22Hz. The maximum output voltage and power of the PZT-B and PZT-T were 101mV, 0.011μW, 111mV and 0.019μW respectively. [77] proposed an impact-coupled vibration energy harvester (IC-VEH). The IC-VEH combines a couple of low-frequency resonators with different natural frequencies. The objective of this research is to enhanced power output and operational bandwidth performance. There are two bimorphs cantilevered with low-frequency resonators and end masses which is illustrated in Figure 26. These two cantilevers are allocated between two unimorph piezoelectric generators with proof masses and connected to the electrical load R_L. The output power of 37μW was generated and operating frequency bandwidth is broadened to 9Hz at 1g of acceleration.

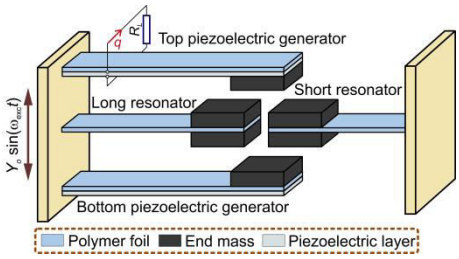

Figure-26. Schematic diagram of the designed dual-resonator IC-VEH [77].

A similar type of method was developed and experimented in [79][81]. A mechanical impact driven and frequency up-converting wideband PVEH was introduced. The objective of this research is to broaden the operating frequency bandwidth for producing a significant amount of power at different low-frequency vibrations. A PVEH which consists of a flexible driving beam and two stiff generating beams was developed. The stiff generating beams were made up from a piezoelectric layer attached on a non-piezoelectric layer. The non-piezoelectric layer acted as a support layer. A single degree of freedom (SDOF) spring mass damper model is applied. The operating frequency range is 6Hz to 15Hz in [81]. The energy harvester can widen 8Hz of the operating frequency bandwidth. The PVEH generated 377μW of output power with an acceleration of $6ms^{-2}$ at resonant frequency of 14Hz. The PVEH was enhanced by changing the dimension of the beam [79]. In a range of the resonant frequency from 7Hz to 14.5Hz produced a minimum peak power of 233μW. With a $6ms^{-2}$ of acceleration at 14.5Hz of the resonant frequency, a maximum peak power of 378μW was generated. However, more consideration of the device parameters such as overlapped tip areas, stiffness of the generating beams and others can be performed in order to enhance the optimization of the device performance.

[82] implemented a mechanical stopper-based frequency-up converting PEH. Two phases were applied: coupled vibrations phase and free vibrations phase. A tip displacement of the stopper beam was increased from 13μm to 32μm. The lateral overlap length between the two beams was reduced from 50% to 3% of the length of the stopper beam. Due to the result of the output open circuit voltage increased from 0.8V to 1.9V. Thus, the relevance between the effective stiffness of the two beams in coupled vibrations phase with the position of the impact point along the stopper was demonstrated. [79] generated the highest output power compared to others. The generating beam of the energy harvester makes up of a piezoelectric and a non-piezoelectric layers in [77][79] can yield a higher output power compared to the cantilever beam that only has piezoelectric layer [80]. The bonding between the PMN-PT single crystal piezoelectric layer and the stainless steel layer [79] is perfect for the energy harvester compared to the cantilever beam that consisted of PET/PEN substrate with the PZT-5H piezoelectric [77].

The handy motion driven concept is approached in [83]. A metal ball of the harvester impacted on the two flexible side-walls when shaken instead of direct impacts on the piezoelectric beams was presented. The side-walls acted as bases for piezoelectric unimorph cantilever generating beams. The structure is illustrated in Figure 27. The mechanical frequency-up converting strategy was used. A maximum 175μW of average output power was produced at 4.96Hz of frequency. However, the power density of the device is $7.6\mu W/cm^3$ can be considered low. Besides that, another approach which is rotating gear method is used in [84]. An atomic force microscope (AFM) type of piezoelectric cantilever was pulled off by the rotating gear teeth. The rotating gear teeth was driven by an oscillating mass. Finite element method and analytical modeling were applied. The relationship between the tip depth, rotational speed and load resistance with output power was analyzed. The performance of energy harvester with non-contact magnetic plucking also was evaluated. By including the load mass, the effectiveness of the system will be increased. The results show that the maximum efficiency of the impact piezoelectric harvester was 1.4%.

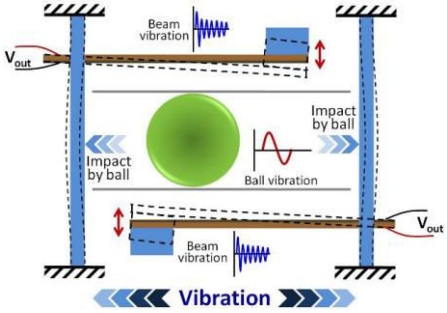

Figure-27. Schematic drawing of handy motion driven, FUCPEH [83].

9. CONCLUSION

The state of research on piezoelectric energy harvesters was studied in this paper. The principles of piezoelectric energy harvesting, different types of configuration of the PEH and techniques used to improve the performance of the PEH were discussed. The vibration and impact-based techniques are mostly applied on the piezoelectric energy harvester compared with the bending technique. This is because of the generated power of the vibration and impact-based techniques are larger than the bending mode technique. Table 1 demonstrates the review summary of the piezoelectric vibrational energy harvester (PVEH) in the context of the material of piezoelectric, dimension of the piezoelectric, proof mass, resonant frequency, resistive load, acceleration, output voltage and output power. From the data in Table 1, it can be concluded that the maximum output power and the minimum output power that were harvested by the piezoelectric vibrational energy harvesters were 1.34W and 51.3.6nW, respectively.

While for the impact-based type of piezoelectric energy harvester, the instantaneous pulse impact force that is applied will yield the larger output power without varying the operating resonant frequency. Table 2 establishes the review summary of the impact-based piezoelectric energy harvester (IPEH). From Table 2, it can be determined that the highest output power and the lowest output power that were produced by the impact-based piezoelectric energy harvesters were 9.072W and 34.6nW, respectively. The highest output power of 9.072W that was generated by the IPEH was in an acceleration of 20g condition. From the data in Table 1 and Table 2 shows that the bimorph cantilever beam is mostly utilized in PEH. This is due to the configuration of the bimorph cantilever beam that can harvest double output power or energy without increasing the volume of the device.

The data of the piezoelectric energy harvester by using frequency-up conversion (FUC) was summarized in Table 3. It is evident from the Table 3 that, with the frequency-up conversion approach, the output power can be yielded within 0.011μW to 378μW. Based on data in Table 1, 2 and 3, the PZT is the mainly used for the piezoelectric materials. This is because the PZT has good piezoelectric properties and cheaper compared to others. Moreover, it is evident that the cantilever geometry is frequently utilized for design the piezoelectric energy harvester. This is because of it has a high response to small vibrations and produce a large mechanical stain.

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Table-1. Summary of literature review of PVEH.

Refere-nce, year	Material	Dimensions ($W \times L \times H$)	Configuration of Piezoelectric	Proof Mass ($W \times L \times H$)	Resonant Frequency (Hz)	Load Resista-nce (Ω)	Accelera-tion (g = 9.81 m•s^{-2})	Voltage	Max output Power (W)	Outcomes
Eli S. Leland et al. [34], 2005	PZT	1 cm^3	Bimorph cantilever beam	9 grams	120		2.5 m/s^2		375 µ	• Power Vs mass to improve the strain from a given mass. • Power Vs piezoelectric coupling coefficient for system coupling and improve thin-film piezoelectric material properties. • The power density is 375 µW/cm^3.
Lars-Cyril Julin Blystad et al. [35], 2010	PZT, PSI-5A-S4-ENH	PZT: $12.7mm \times 14.3mm \times 0.51mm$	Cantilever beam	6.75 grams	120	209.6k	0.24g			• Output power increases very slowly as the acceleration levels increases after end impacts occur. • The mechanical end stop on one side will result in higher maximum velocity in the direction towards the end stop.
Huicong Liu et al. [48], 2011	PZT element	Silicon supporting beam: $5mm \times 3mm \times 5\mu m$		$5mm \times 5mm \times 0.4mm$	36	1M	1g	94mV at 0.1g, 119mV at 0.2g	51.3n	With a low value of load resistance, the PZT element that is connected in parallel connection can produce higher output power compared to the series connection.
B. Ando et al. [51], 2013	7BB-35-3L0	Diameter of 3.5cm	Piezoelectric connected in parallel configuration	3g to 15g	10	14k	16.81m/s^2		$\geq 300\mu$	• The acceleration can affect the beam buckling with the distance between the stable states by decreasing the proof mass. • The higher the operating frequency, the higher the output value.
P.Pillatsch et al. [40], 2013		$60mm \times 5mm \times 0.5mm$	Bimorph piezoelectric beam		2	120k	Speed rotation of 2rpm			• The parameters of the initial gap and magnetic force will affect the output voltage. • Output voltage of the repulsive magnet arrangement is greater than the attractive management. • Advantage of the magnetic coupling technique: Contactless impact and avoid damage to piezoelectric material. • The harvested energy is 0.37pJ.
Norainí Mat Ali al et. [37], 2013	PSI-5A43	$64mm \times 31mm \times 0.5mm$	Cantilever Beam		76.2		1g		27.56 m	• The single piezoelectric cantilever yielded 3 times higher output power than the piezoelectric and electromagnetic connected in series. • The piezoelectric and electromagnetic connected in parallel produced 3 times higher output power than single piezoelectric.
Y. S. Shih et al. [39], 2015	PZT	Main Beam: $77mm \times 15mm \times 0.3mm$ Stopper beams: $46mm \times 15mm \times 0.3mm$	Cantilever Beam	Main Beam: 3.7mg Stopper Beams: 23.6mg (upper), 23mg (lower)	26.8				0.1µ (stop-per struc-ture), 0.098µ (single beam)	• With the stopper beam, the amplitude is increased, and the ringing signal is higher compared to without stopper. • The harvested energy is 1.43nJ.
Kyoo Nam Choi et al. [52], 2015			Rectangular shape		70	1k	200 strokes/ sec	Impact: 4V, 4mA Vibration: 0.2V Bending: 0.2V	16m	The output voltage of impact mode is 20 times higher than the output voltage of vibration and bending mode.
Shaurya Kaushal et al. [8], 2015			A square proof mass with a four cantilever beams structure		100		1g	0.4V		• Optimum ratio of Lc to Lp is 0.75. • Each device can widen 50Hz of resonant frequency.
Tarun Kumar et al. [43], 2015	PZT-5A	$60mm \times 100mm \times 0.22mm$	Piezoelectric unimorph cantilever composed of varying width		48.8	10^6	0.2g			• BFFs technique is used to design cantilever beam that varying width can give higher distributed strains. • The cantilever beam that varying width can generate 2.5 times higher output voltage than piezoelectric cantilever.
Xiang Wang et al. [53], 2016		$3mm \times 24mm \times 0.4mm$	Piezoelectric Ceramic plate				1g	Large-SSG: 0.75V, small-SSG:		• By varying the SSG, the resonant frequency and bandwidth of VEH can be tuned.

								0.59V over-SSG: 0.12V		
Meng SU et al. [54], 2016		Friction area size of 93.51mm^2	Perpendicular bi-stable cantilever with piezoelectric films					105V		The triboelectric-piezoelectric hybridized way is used.
Yu Jia et al. [49], 2016			Circular disk membrane design		980	~ 70k	2g		1st order: 7μ 2nd order: 6.4μ 3rd order: 4.2μ	•The higher the initiation threshold amplitude of the damped higher order, the faster the nature of frequency bandwidth become narrow. •The higher the orders, the narrower and smaller peaks power. •The power density of membrane resonator is 0.0005 g^2/Hz and cantilever resonator: 0.05 g^2/Hz.
Xianming He et al. [47], 2017	PVDF	$25mm \times 5mm \times 100\mu m$	Others configuration		20	800.1k	0.5g	12.6V	41.0μ	•PEH and TEH have large internal impedance while the EMEH has low internal impedance. •PEH and TEH can produce higher voltage than EMEH.
Jundong Song et al. [30], 2017	PVDF	13.1mm^3	Bimorph cantilever beam	$20mm \times 2mm \times 3mm$	34.4	100M	0.5		112.8μ	•The experimental result is lower than analytical result due to the influence of external resistance and additional capacitance are ignored in analytical model. •The power density is 8.61 mW/cm^3.
Peyman Firoozy et al. [31], 2017			Unimorph piezoelectric cantilever beam	70g	30.19 and 30.59	0.35M	1g		6.8m	•The larger the proof mass, the larger the output power and shifts the nonlinear frequency response curves to left of the frequency axis. •The piezoelectric layer of length Lp of 40mm can harvest the maximum output power. •The presence of damping ratio will decrease the output power.
X.D. Xie et al. [42], 2017	PZT4	Width of the PZT patches: 1-6cm	Rectangular crossed section						0.1376	•The higher the taper ratios in width and thickness of the cantilever, the greater the width of PZT4 patch, and the larger the width at the end of the cantilever will result in the lower the value of RMS output power. •The thickness at the fixed end of cantilever increases, the RMS of the generated power nonlinearly decreases.
Ting Tan et al. [32], 2017		$36.2mm \times 90mm \times 0.267mm$	Cantilever beam	65g		10^4	1g		1.34	•While the maximal value output power will be produce at the excitation frequency same with the modified natural frequency. •The hybrid system performs wider bandwidth of the base-excitation-alone system by including the galloping-alone system.
Khoo Shin Yee et al. [38], 2017	PZT	$31.8mm \times 63.5mm \times 0.51mm$	Piezoelectric cantilever plate		80			6Vac		The optimal location for the piezoelectric place to be placed could harvest 33.3% of improvement in output voltage.
Zhengbao Yang et al. [29], 2017	PZT-5A	$15.1mm \times 37.6mm \times 0.5mm$	Rectangular unimorph cantilever	15.6g	28.4	400k	0.3g			The efficiency is related with the electromachanical coupling effect, damping effect, excitation frequency and electrical load.

Table-2. Summary of literature review of IPEH.

Reference, year	**Material**	**Dimensions ($W \times L \times H$)**	**Configuration of Piezoelectric**	**Proof Mass ($W \times L \times H$)**	**Resonant Frequency** (Hz)	**Load Resistance (Ω)**	**Acceleration** (g = 9.81 m•s^{-2})	**Voltage**	**Max output Power** (W)	**Outcomes**
M. Renaud et al. [63], 2009		$35mm \times 20mm \times 20mm$	Piezoelectric bimorph		10	60k			600μ	• Limit the analysis to one dimensional collision on flexible beam. • The measured efficiency value is lower 50% than the predicted because of the losses occurring during motion. • Power density is 120μW/cm^3.

P. Janphuang et al. [76], 2011	PZT-5A	4.2mm^3				2.7M	25 rpm		1.26µ	• Three main geometry of PEH factors: support layer's thickness, piezoelectric beam's thickness and beam's area. • The higher the tip's depth, the higher the displacement, the higher the output power.
Song-mao Chen et al. [59], 2011	PZT				13			8V		• With fixed amplitude of base vibration, the higher the frequency the higher the generated electric energy. Until certain frequency, then decrease sharply the value of electric energy. • The PEH with impact-based vibration module is the best among the three modules, which can harvest 343.211µJ. • Total harvested electrical energy is 7.03mJ in 30 sec.
M. Ferrari et al. [58], 2012	WAC 3X/18	$45mm \times 19mm \times 0.58mm$	Piezoelectric parallel bimorph beam		100	20k				• Non-interacting condition: resonance peaks of top and bottom are 40Hz and 65Hz, respectively. • Interacting condition: resonance peaks of top and bottom are about 20Hz. • The quadratic sum of RMS output voltage in interacting condition is higher than the wider bandwidth in non-interacting condition.
Miah A. Halim et al. [60], 2013		$3.5mm \times 15mm \times 0.3mm$	Unimorph piezoelectric generating beam	4.36g	12.5	200k	6m/s^2	9.6V	129.15 µ	• The larger the load resistance value, the larger the output voltage. • The higher the value of acceleration, the higher the output load voltage, thus the higher the output power.
Amat A. Basari et al. [69][73], 2015				26g and 40g		5k			120µ	The larger the value of proof mass, the smaller the value of output power, the wider he resonant frequency bandwidth.
S. Ju et al. [64], 2015	Macro Fiber Composit e (MFC)	4.59cm^3						54V	621µ	• Three different types of aluminium housings were designed and Housing 2 was the best among these three housings. • Output from manual vibration test was obtained better compared to the other two tests. • The power density of the manual vibration test is 135.3µW/cm^3.
D. Alghisi et al. [75], 2015	7BB-27-4A0	Diameter of 30mm	Piezoelectric diaphragm	47 to 63		1k	7km/h		16m	Walking at 2km/h within 260s, 1.4mJ of energy was produced.
Le Van Minh et al. [61], 2015	KNN/Si (lead-free)		Triangular shape		150	10k	39m/s^2		34.6n	The contact time of the metal ball on the cantilever was the main parameter for the efficient induction of free oscillation.
G. Yesner et al. [67], 2016	PZT-5X	$32mm \times 32mm \times 2mm$	Cymbal design		5	400k			2.1m	• When the resistive load value is higher, the impedance of the transducer is higher than the output power is higher as well. • The transducer can produce 0.83mJ of energy for a 600lb load.
Ali Mohammed abdal-Kadhim et al. [71] [74], 2016		Diameter of 44mm Thickness of 10mm	Piezoelectric disc			500k	600mm/ min		14.5µ	When velocity is increased with fixed force, the output energy is 1.7 times higher than the force is increased with fixed velocity.
Ali Mohammed abdal-Kadhim et al. [68], 2016		$32mm \times 70mm \times 0.55mm$	Rectangle shape			0.175k	1g	50V	8.8m	• The different value of masses and different height of fall free will produce different value of forces. • The higher the forces value, the larger the output voltage and power.
A.A. Basari, et al. [55][72], 2016				26g	48	10k	Less than 1g			• The pre-load configuration can widen the resonant frequency bandwidth. • Output voltage of the structure with shim plate is 4.3 times higher than without shim plate structure. • The smallest diameter of the shim plate can generate higher value of output power. • The harvested output energy is 1.57mJ.
K. Viswanath	PZT 5H	$21mm \times$		5g	177.143k		20g	10.08V	9.072	The Cyson 20g shaker at resonant

et al. [66], 2016		$0.2mm$								frequency of 177.143kHz is better compared with others.
Xuefeng He et al. [65], 2016	PZT 5H	$6.4mm \times 27mm \times 139\mu m$	Bimorph cantilever	Radius of the steel ball: 4mm	18.4	140k	1g		511µ	• The scavenging energy can be increased as the channel length is increased. • By having a rolling proof mass, the capability of low-level vibration energy scavenging will be increased.
Ali Mohammed abdal-Kadhim et al. [70], 2017		$29mm \times 70mm \times 0.55mm$	Rectangle shape			0.7k	1g	70V	53m	• Improve the mechanical impact force into bending mode on the PEH. • Higher output power was generated compared to non-prestressed piezoelectric configuration.

Table-3. Summary of literature review of PEH by using FUC.

Refere-nce, year	Material	Dimensions ($W \times L \times H$)	Configuration of Piezoelectric	Proof Mass ($W \times L \times H$)	Resonant Frequency (Hz)	Load Resista-nce (Ω)	Accelera-tion (g = 9.81 m•s^{-2})	Voltage	Max output Power (W)	Outcomes
Huicong Liu et al. [80], 2011	PZT	$5mm \times 3mm \times 5\mu m$	Cantilever beam	$5mm \times 5mm \times 0.4mm$	PZT-B: 36, PZT-T: 618		0.8g	PZT-B: 101mV, PZT-T: 111mV	PZT-B: 0.011µ PZT-T: 0.019µ	• The operating resonant frequency bandwidth of PZT-B can be widened to 22Hz at resonant frequency of 36Hz. • The low frequency oscillation of PZT-B is up-converted into self-oscillation of PZT-T at high frequency. • Advantage: Widen the matching frequency range of external vibration and recognizes a high resonant frequency at the same time.
Rolanas Dauksevicius et al. [77], 2014	PZT-5H	$4mm \times 16mm \times 0.13mm$	Unimorph piezoelectric	$4mm \times 4mm \times 1mm$		40k	1g		37 µ	• For the highest clearance value of the dual-resonator IC-VEH of ~2.5mm, the frequency range can widen about 9Hz and the bandwidth can achieve to be widened about 220%. • The IC-VEH can improve the output up to 37µW, which is 140% of higher power.
Miah A. Halim et al. [81], 2014	PMN-PT	$55mm \times 4.8mm \times 1mm$	Unimorph cantilever beam	4.36g	14	180k	6m/s^2	28.16V	378 µ	• The performance of the stainless steel device for the generating beams is better than the styrene support device. • The operating frequency bandwidth of 8Hz is widen. • 2.9 times increased output power is generated.
Miah A. Halim et al. [79], 2014	PMN-PT Single Crystal	$43.5mm \times 25mm \times 0.4mm$	Unimorph cantilever beam	4.36g	14.5	180k	6m/s^2	28.5V	378µ	• A low frequency flexible driving beam hit two piezoelectric generating beams and caused the changes of the driving beam stiffness. • Maximum peak power density: 38.8µW/cm^3 at 6m/s^2 of acceleration. • Advantage: Broaden the operating resonant frequency range for producing significant value of power at low frequency vibrations.
Miah A. Halim et al. [83], 2015	PZT	$5mm \times 35mm \times 0.19mm$	Piezoelectric unimorph beam	0.59g	4.96	15k		Right after impact: 5.05V, Genera-tor free vibra-tion: 1.76V	175µ	• When the device is in low frequency vibration, the flexible sidewalls will be hit by ball and impulsive force on the piezoelectric beams will be produced and vibrated freely according to their resonant frequency which is high-frequency vibration to produce voltage or power. • The power density: 7.6µW/cm^3 (consider as low power density).
Mostafa Shadoufa et al. [82], 2016	PVDF	Primary beam: $L \times H$: $35mm \times 0.11mm$ Stopper beam: $L \times H$: $10mm \times 0.11mm$			15.6		0.1g	1.9V		The smaller the overlap average of the stopper beam length, the higher the output power.

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