

Review

A Review on Mechanisms for Piezoelectric-Based Energy Harvesters

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Received: 23 May 2018; Accepted: 28 June 2018; Published: 14 July 2018



Abstract: From last few decades, piezoelectric materials have played a vital role as a mechanism of energy harvesting, as they have the tendency to absorb energy from the environment and transform it to electrical energy that can be used to drive electronic devices directly or indirectly. The power of electronic circuits has been cut down to nano or micro watts, which leads towards the development of self-designed piezoelectric transducers that can overcome power generation problems and can be self-powered. Moreover, piezoelectric energy harvesters (PEHs) can reduce the need for batteries, resulting in optimization of the weight of structures. These mechanisms are of great interest for many researchers, as piezoelectric transducers are capable of generating electric voltage in response to thermal, electrical, mechanical and electromagnetic input. In this review paper, Fluid Structure Interaction-based, human-based, and vibration-based energy harvesting mechanisms were studied. Moreover, qualitative and quantitative analysis of existing PEH mechanisms has been carried out.

Keywords: piezoelectric; energy harvesting; vibrations; aeroelastic; smart material; fluid structure interaction; piezoelectricity; review

1. Introduction

The phenomenon of energy harvesting based on piezoelectric transducers can be defined as the transformation of energy absorbed by a transducer from an operating environment to electric voltage that be used on the spot for actuation or stored in batteries for future usage [1–4]. As the world is shifting from electrical equipment to electronic devices due to the energy crisis, it is leading to a reduction in electrical power consumption, resulting in micro and nano powered electronic circuits [5–7]. Numerous researchers have focused on the usage of PEHs as self-powered sources over the storage of electric voltage in batteries because of the voltage drop [8,9]. Due to recent technological advancements, these harvesters are ideal to be used in micro electromechanical systems (MEMS), smart structures, structural health monitoring, and as wireless sensors for suborbital missions [10–14].

As a consequence of the energy crisis, many techniques have been developed to generate electric voltage [15–18]. These techniques have been used to generate power ranging from nano to mega watts [19–21]. These approaches to energy generation are dependent on their utilization. That is, industrial usage, domestic usage, or low-powered electronics actuation [22–25]. This review paper will focus on energy generation for low-powered circuits by piezoelectric (PZT) harvesters. Nano and micro watts of power can be generated from PZT harvesters by applying thermal [26], light [27], mechanical [28–30], fluid [31], and electrical [32] input. Out of these possible options, mechanical input is considered to be the most efficient because it can be easily provided as compared to other inputs [33–35]. The conversion of mechanical energy (from waste vibrations) into electrical energy can be done by electromagnetic [36–39], piezoelectric [33,40], or

electrostatic [41–43] mechanisms of transduction. The piezoelectric transduction mechanism is the most efficient mechanism for microelectronics [44], wireless sensors [45], and nanoelectronics [46] because they are easy to fabricate [47,48] and are able to harvest energy at variable frequencies [49–51]. This phenomenon was discovered by Pierre and Jacques Curie in 1880 [52] as having a direct effect (i.e., conversion of mechanical energy to electrical energy [53]), as expressed in Equation (1) [54] and a converse effect (i.e., the conversion of electrical energy to mechanical energy [55]), as expressed in Equation (2) [56]. Control techniques with/without piezoelectric sensors for different materials have been carried out [57–60]. Many researchers are working on super-capacitors to store electrical energy rather than conventional storage devices (i.e., electrical batteries or electrochemical capacitors [61]). They have the advantages of less maintenance, easy charging, and are more effective as compared to conventional batteries [61,62].

$$D_i = e_{ij}^{\sigma} E_j + d_{im}^d \sigma_m, \quad (1)$$

$$\epsilon_k = d_{jk}^c E_j + S_{km}^E \sigma_m, \quad (2)$$

where D_i is the dielectric displacement vector, ϵ_k is the strain vector, E_j is the applied electric field vector, σ_m is the stress vector, d_{im}^d and d_{jk}^c are piezoelectric coefficients for direct and converse effects of piezoelectricity, respectively, e_{ij}^{σ} is the dielectric permittivity at constant stress, and S_{km}^E is the elastic compliance matrix at constant electric field. Piezoelectric material characteristics are expressed in Table 1.

Table 1. Piezoelectric material properties.

Coefficient	Units	PZT-5H [9]	PZT-5A [10]	PZT-8 [63]	BaTiO ₃ [64]	PIC-255 [65]	PVDF [9]	ZnO [66]	KNN [67]	AlN [68]
Piezoelectric charge constants (d_{31})	10^{-12} m/V	−274	−171	−97	−33	−180	18–24	-	-	-
d_{33}	10^{-12} m/V	593	374	225	82	400	−33	-	689	-
d_{15}	10^{-12} m/V	741	584	330	150	550	-	-	-	-
Density (ρ)	kg/m ³	7500	7750	7600	5600	7800	946	566	-	3260
Curie temperature	°C	193	350	300	123	350	195	-	432	-
Elastic modulus (E)	10^{10} N/m ²	6.2	6.5	6.3	1.16	-	0.418	-	-	-
Permittivity ($\epsilon_{33}^T/\epsilon_0$)	-	3400	1700	1000	800	1750	-	-	-	-
Mechanical quality factor (Q_m)	-	30	80	98	130	80	17.2	-	85	-
Poisson's ratio (ν)	-	0.31	0.31	0.31	0.35	0.34	0.34	0.358	-	0.24

Figure 1 expresses the harvesting electrical circuit of a piezoelectric energy harvester (PEH) for thermo-electro-mechanical shocking; decade resistors are used to shock the PEH at variable external resistances, a DC motor is used to shock the PEH mechanically, an iron filament is used to shock PEH thermally, a mica sheet is used to insulate the PEH, and an oscilloscope is used to measure the output voltage in order to calculate the energy harvested by the PEH [64]. For simple mechanical-based PEH, resistance and capacitance are in parallel to the piezoelectric patch, as shown in Figure 2 [69].

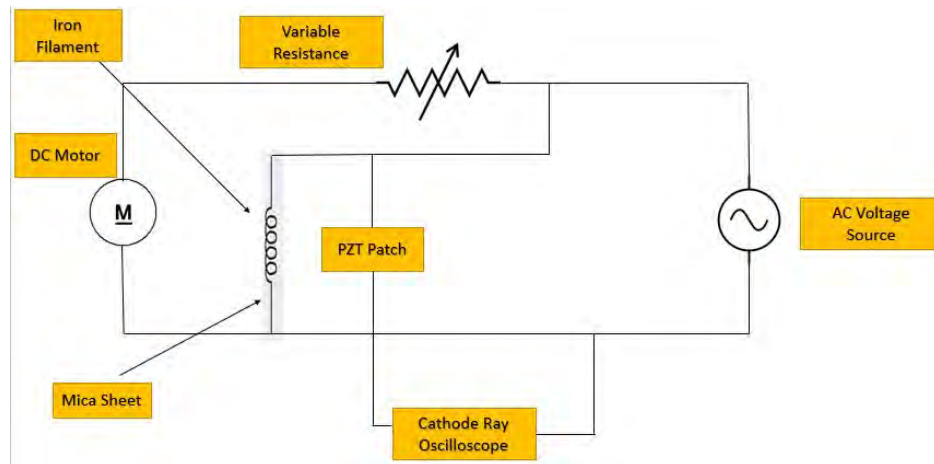


Figure 1. Electrical circuit of a thermo-electro-mechanical-based piezoelectric energy harvester (PEH) (iron filament is used for thermal shocking; function generator is used for electrical shocking; DC motor with CAM shaft is used for mechanical loading; decade box is used to shock PZT externally at variable resistance; PZT has internal resistance R_0 ; mica sheet is used for thermal and electrical insulation; Cathode ray oscilloscope (CRO) is used for data acquisition).

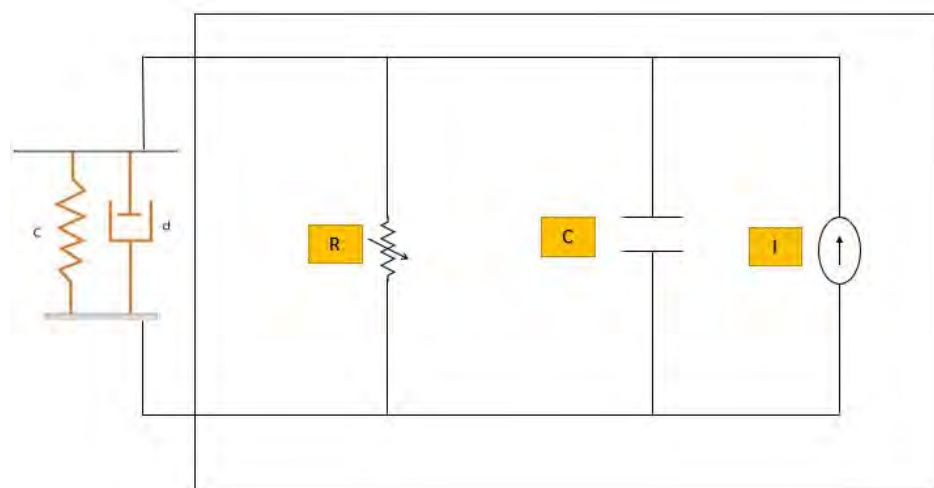


Figure 2. Electrical circuit of mechanical-based PEH. PZT is shocked mechanically (i.e., direct effect of piezoelectricity), which overcomes the internal resistance R_0 , the poling phenomenon occurs, and energy is generated.

PEH can be a very suitable alternative energy source compared to traditional ones, and has vital applications in the area of automotive, aerospace, and defence sectors due to micro-scale devices [70]. They can operate various sensors and actuators. Moreover, they have very compact structure and are an environmentally friendly source of energy generation. That is why piezoelectric patches are widely used in various optical devices [71], space missions [10], biomedical devices [72], mechanical/civil structures [73], and precise measurement tools [74]. PEHs are preferred because

of their flexibility, low electromagnetic interference, high positioning, and high torque-to-volume ratio [75,76]. A PEH is composed of three major components one, the piezoelectric patch that is responsible for converting environmental input (i.e., fluid structure interaction (FSI), biomechanical, vibration, etc.) into alternating current; two, the storage unit that can be a super capacitor or a battery to store the charge generated by the PEH; three, the modulating circuit that is responsible for the conversion of AC into DC [77]. The storage unit can be ignored in order to utilize energy directly from the PEH [77,78].

The need for PEHs arises because batteries have less operational life than the circuit. In many conditions, replacement or maintenance of the battery is impossible and the cost of the battery is very costly for the operation. The usage of a battery may result in maintenance issues when they are operated in harsh environments (i.e., high-altitude places, cold or hot climates, icy or snowy regions), as these conditions lead to damaged battery life. In such cases, even recycling of the batteries is a problem as well as an environmental hazard (especially lead ion batteries). In these conditions, one of the solutions is to use different external energy sources (i.e., PEHs) so that durability of the battery can be increased [79]. These issues lead to the utilization of PEHs as an additional energy source which can assist electronic devices directly or indirectly via batteries by increasing their operational life time [70]. Many researchers have worked on alternate sources of micro electric voltage generation for wireless sensors by using the electromagnetic phenomenon. Mann and Sims worked on improving the effectiveness of harvesters by inducing nonlinearities experimentally and numerically [80]. Mahmoudi et al. worked on nonlinearities induced by a vibration-based piezo-electromagnetic harvester [81]. The phenomenon of inducing nonlinearities is of great interest for many researchers [82–85].

The efficiency of the harvested energy for direct piezoelectricity can be analyzed by calculating the difference of mechanical energy converted into electrical energy and the loss in energy conversion [14,86–88]. This harvesting mechanism is dependent on the medium of interaction [89–92]; that is, the transformation of kinetic energy to the PZT transducer [93–95]. These media may be mechanical vibrations [51,96,97], fluid–structure interaction [98,99], and thermal interaction [100,101]. In this review paper, PEH mechanisms based on fluid–structure interaction, human based interaction, and vibration are studied. Qualitative and quantitative analysis of existing PEH mechanisms has been carried out. Section 1 is a brief introduction to PEH mechanisms. Section 2 elaborates the fluid–structure interaction mechanisms. Section 3 elaborates human-based PEH, and Section 4 describes vibration-based PEH.

2. Fluid–Structure Interaction-Based PEH

As a consequence of mega products in to micro products, the development of aerospace structures that utilize clean, renewable energy and are self sufficient of energy production are encouraged [102] (i.e., smart structures) [103,104]. Beginning in the last decade, fluid–surface interaction-based PEHs have been of great interest for many researchers [105–107]. In these, the PZT harvester is placed in a fluid flow for energy harvesting, it undergoes limit cycle oscillations (LCOs) that can be converted to output electrical energy to operate electronic devices or for storage [108]. In the fields of aerospace and civil engineering, when the structure is subjected to fluid flow [109,110], it may undergo the phenomenon of bifurcations [111–113], LCO [114–116], internal resonance [117,118], and disorder motion [119,120]. In mega structures, aerodynamic phenomena such as vortex-induced vibrations (VIVs) [121], flutter [106,122], and galloping [123] may result in excessive vibrations that can damage or even destroy the structures [124]. The overall scheme for FSI-based PEHs is expressed in Figure 3 [125]. These effects are described below:

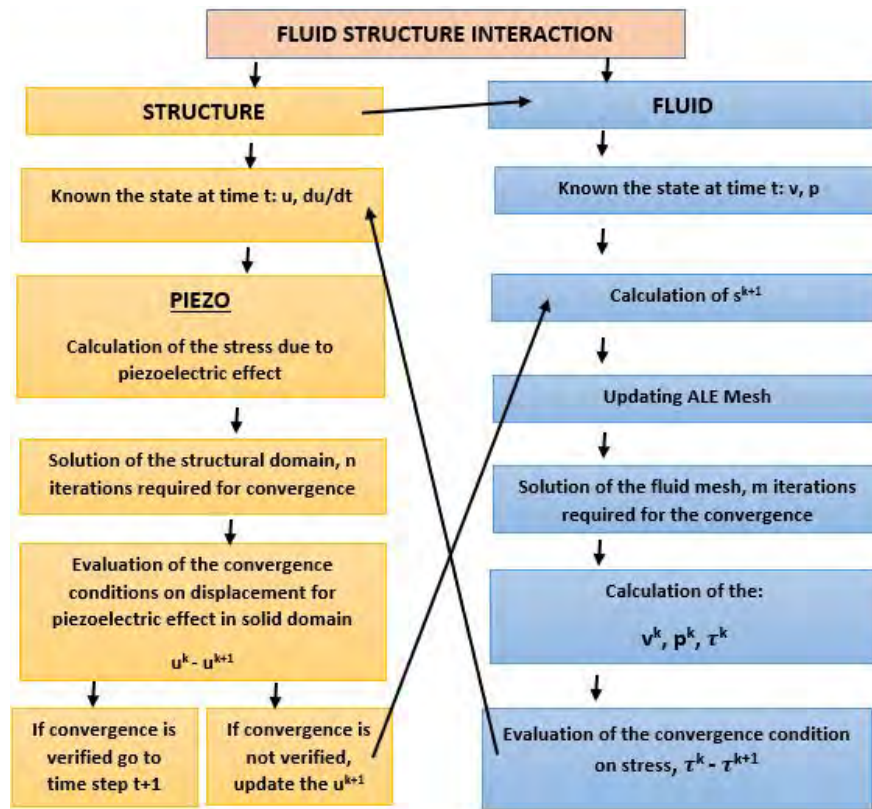


Figure 3. Overall scheme for fluid–structure interaction (FSI)-based PEH [125].

2.1. Vortex-Induced Vibrations-Based PEH

Recently, many researchers have been working on the development of piezoelectric energy harvesters that can absorb energy from the environment (i.e., VIV) and transform it into useful electrical energy [90,126–128]. The most commonly used process is attaching the PZT patch to the fixed end of an elastic cantilever beam and attaching the circular cylinder to the free end of the beam, as shown in Figure 4 [127,128]. The PZT patch is shocked with external resistance as it has a vital effect on the amplitude of oscillations, the coefficient of lift, and the output energy generated by the harvester [124]. Mehmood performed numerical simulations by attaching a PZT patch to the transverse degree of freedom (DOF) by taking into account Reynolds numbers (Re) ranging from 96–118 and resistance from 500 Ω to 5 MΩ [126]. Re are selected on the basis that they can accumulate pre-synchronization, synchronization, and post-synchronization regimes, as shown in Figure 5 [126]. A schematic of this proposed mechanism is expressed in Figure 6 [126], where U_∞ is the free stream velocity, C is the structural damping, K is the structural stiffness, and R is the electric resistance applied. Dai demonstrated based on Galerkin discretization that the first four modes are necessary to evaluate the performance of the harvester correctly [128]. Moreover, both linear and nonlinear analyses have been performed in order to analyze the efficiency of the system, and it was observed that when the flow was at the synchronization region, electromechanical damping associated to it decreased, which resulted in an increase of the harvested energy [127]. Franzini carried out a sensitivity study that can influence the dimensionless quantities characterizing the PZT harvesters and proposed a 50% increase in the efficiency of the harvester for a particular reduced frequency [121]. The enhancement of the voltage generated was carried out by optimizing the parameters based on a genetic algorithm [129]. The efficiency of the energy harvested by VIV can be analyzed for 1 DOF by Equation (3) [121]:

$$\eta_{el,x} = \frac{4\pi^2}{U_r^3} \frac{(\theta^*)^2}{f^*} \frac{\sigma_{2,x}}{\sigma_{1,x}} (m^* + C_\alpha) v_x^2, \quad (3)$$

where $\theta^* = \theta_x / \theta_y$, $f^* = w_{n,x} / w_{n,y}$, $\eta_{el,x}$ is the dimensionless electric power harvested at cross-wise and in-line harvesters, U_r is the reduced velocity, $\sigma_{2,x}$, $\sigma_{1,x}$ are the dimensionless quantities related to the piezoelectric harvesters, θ_x , θ_y are the electro-mechanical coupling constants, $w_{n,x}$, $w_{n,y}$ are the cylinder's natural frequencies, m^* and C_α are the mass parameter and potential added mass coefficient, respectively.

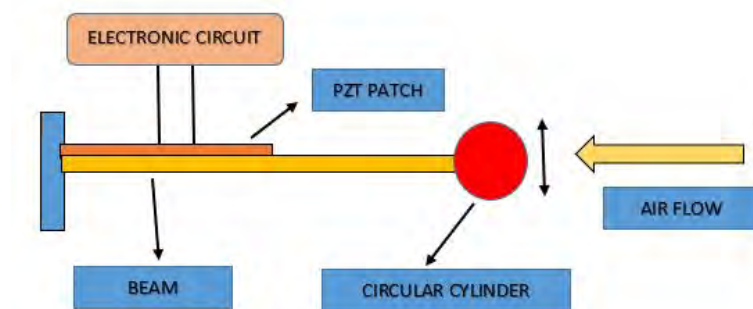


Figure 4. Mechanism of a vortex-induced vibration (VIV)-based PEH.

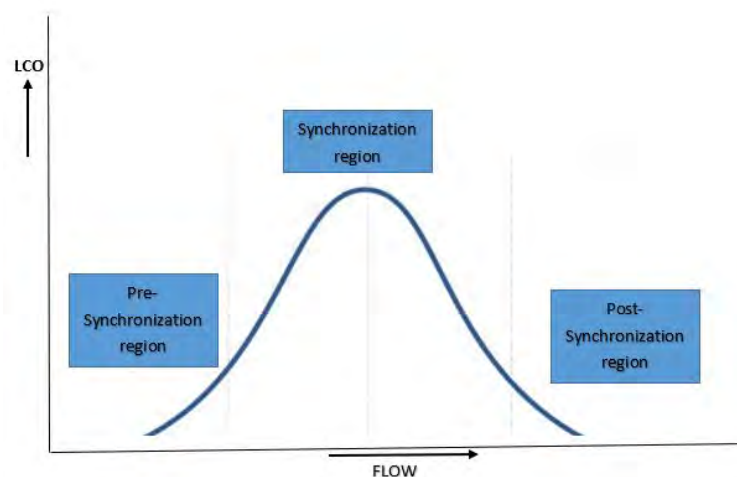


Figure 5. Bifurcation diagram (in dynamical system, this figure is representing data points that have been approached or approximated by a system as a bifurcation parameter in a system revealing bifurcation theory).

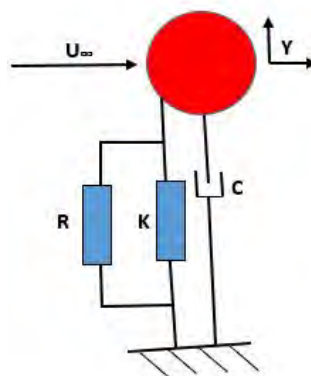


Figure 6. Cylinder-based piezoaeroelastic energy harvester subjected to free stream velocity U_∞ ; R is the electrical load resistance; C and K are structural damping and stiffness.

Franzini carried out a numerical solution of PEH from VIV via the dynamics of a rigid cylinder mounted at the end of an elastic beam attached with a piezoelectric patch. He considered a wake oscillator model as hydrodynamic load, coupling the solid and electric oscillators as considered by linear constitutive equations, and the dynamics of the FSI-based PEH system was investigated for the influence of an additional structural DOF (i.e., in-line oscillations). He demonstrated that the efficiency of PEH could be increased up to 50% at any particular reduced frequency [121].

Experimental studies were carried out for PEH exposed to VIV via pivoted rigid cylinder. The sensitivity study for PEH efficiency was carried out for different parameters. It was concluded that it is not compulsory that PEH increases by increasing Re efficiency; the maximum power harvested was ≈ 60 mW [130]. Another experimental study was carried out in which a secondary cylinder was placed between the generator and the primary cylinder exposed to VIV. In this way, the free-stream velocity range was enhanced and energy harvesting became more effective. The electric tension achieved reached 9 V [131]. Soti numerically investigated the dynamics of a cylinder attached to a magnet. The maximum harvested dimensionless power was 0.13 [132].

An investigation of the energy harvested by a PEH from VIV was carried out in a wind tunnel. The rigid cylinder was mounted to the free end of an elastic beam attached with a piezoelectric patch, nonlinearities were introduced into the system by two magnets. These nonlinearities could increase the efficiency of the harvester by up to 29% [133]. Bunzel and Franzini numerically investigated the harvesting of energy for the first time from 2 DOF VIV by considering a wake oscillator model. The cylinder was mounted on an elastic beam and oscillated in both directions (i.e., cross-wise and in-line directions). The cylinder was coupled to a piezoelectric harvester and it was observed that by changing the value of σ_1 from 0.33 to 3.3 with no change in amplitude of oscillations, the harvested energy was decreased by 0.1 [134].

2.2. Flutter-Based PEH

One of the fundamental tasks of aeroelastic control design is to minimize flutter [135,136]. A flutter-based piezoaeroelastic energy harvester schematic is represented in Figure 7 [124]. The PZT patch is attached on the fixed end of an elastic cantilever beam with an external circuit from which it can be shocked with variable resistance. This elastic beam is subjected to flow. By increasing the flow, there arises a specific speed (i.e., flutter speed) at which, due to aerodynamic effects, structural damping is not enough to damp motions [106,137–140]. Due to nonlinearities, sub-critical or super-critical Hopf bifurcation can take place [141–143], as shown in Figure 8, and a schematic of the piezoaeroelastic system is expressed in Figure 9. For energy harvesting, a large symmetric flutter state is identified as the most suitable [144]. The governing equations are expressed in Equations (4)–(6) [138,145–147]:

$$m_T \ddot{h} + m_W x_\alpha b \ddot{\alpha} + c_h \dot{h} + k_h(h)h - \theta V = -L, \quad (4)$$

$$m_W x_\alpha b \ddot{h} + I_\alpha \ddot{\alpha} + c_\alpha \dot{\alpha} + k_\alpha(\alpha)\alpha = M, \quad (5)$$

$$C_p \dot{V} + \frac{V}{R} + K_{ME} \dot{h} = 0, \quad (6)$$

where h is the plunge deflection, α is the pitch angle, m_T is the total mass of the wing with its support structure, m_W is the wing mass alone, I_α is the mass moment of inertia about the elastic axis, b is the half chord length, x_α is the dimensionless distance between the center of mass and the elastic axis, c_h and c_α are, respectively, the plunge and pitch structural damping coefficients, L and M are the aerodynamic lift and moment about the elastic axis, R is the load resistance, V is the voltage across this load resistance, C_p is the capacitance of the piezoelectric layer, θ and K_{ME} are electromechanical coupling terms, and k_h and k_α are the structural stiffness for the plunge and pitch motions, respectively [138].

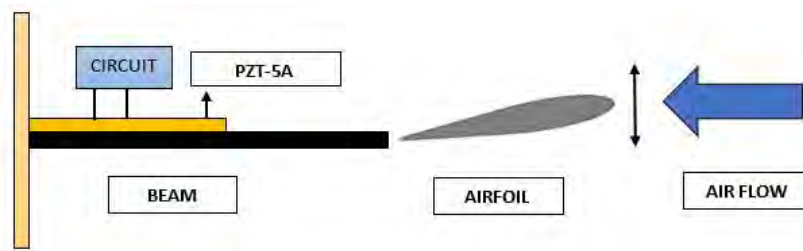


Figure 7. Flutter-based piezoaeroelastic energy harvester schematic.

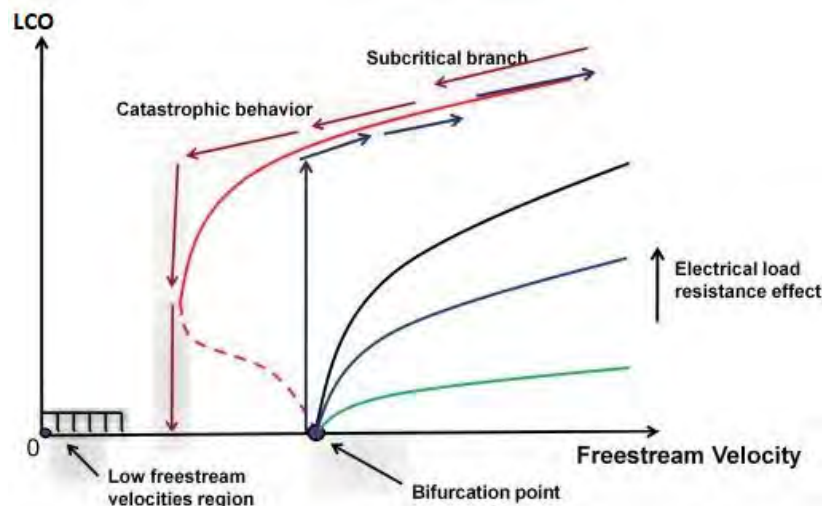


Figure 8. Bifurcation diagram [148]. In a dynamical system, this figure represents data points that have been approached or approximated by a system as a bifurcation parameter in a system revealing bifurcation theory. LCO: limit cycle oscillation.

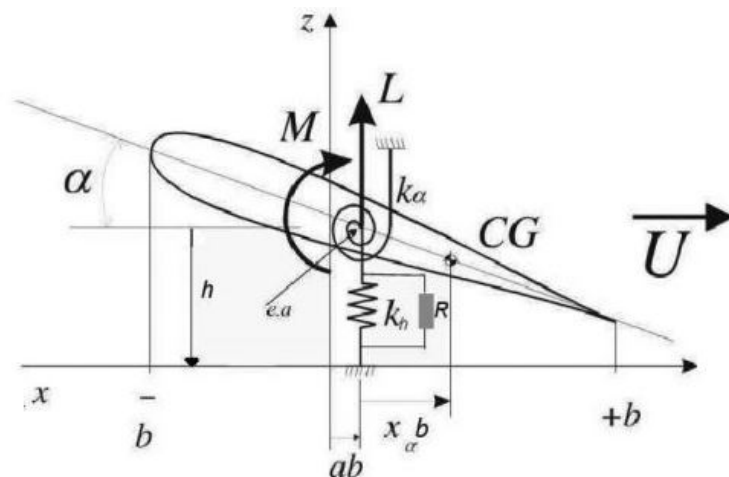


Figure 9. Piezoaeroelastic system schematic [148]. A three-degrees of freedom (DOF) airfoil supported elastically by linear plunge and linear torsional spring.

Eugeni proposed an energy harvester based on the flutter mechanism experienced by a wing. The energy transmitted from the flow to the structure in this self-excited motion of the aeroelastic system is harvested by a PZT patch (i.e., single-layer lead zirconate titanate) applied at the fixed end of the wing. In particular, the wing is equipped with a control surface (flap). This choice was

dictated thinking of the realization of the harvester prototype because it is much easier to design the nonlinearities in the connection between the main wing and flap with respect to those associated to the principal structure. In Figure 10, a sketch of the harvesting mechanism is proposed where the single-layer configuration of the PZT harvester is also stressed [149].

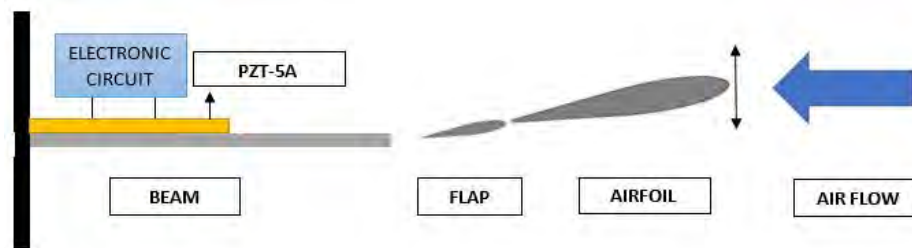


Figure 10. Aeroelastic energy harvester model [149]. A 3-DOF airfoil is constrained with flap motion and is subjected to the airfoil supported elastically by linear plunge and linear torsional spring.

Bahaadini studied the instabilities of flowing fluid in nanotubes of piezoelectric material, and observed that both divergence and flutter were the reason for instability of nanotubes with supported ends for fluid flow. These instabilities can lead to significant energy harvesting. By decreasing the critical flow velocities, an increase in piezoelectric voltage was observed that resulted in a decrease of the system stability [150]. Thiago investigated the flutter instabilities for piezoelectric transducers-based composite panels (tow steered). In order to increase aeroelastic instabilities, he presented optimized size and position using a differential evolution algorithm for composite panels and piezoelectric transducers [135]. The feedback control system for active flutter control were chosen on hit and trial methods which take a great deal of time and are not accurate. Song presented a genetic algorithm which is optimized and smart enough to investigate the thermal flutter control of laminated composite panels in supersonic airflow. The piezoelectric actuators' feedback gains were shown as chromosomes [151]. Sousa investigated the aeroelastic behavior of a typical section, the combined effects of passive pseudo-elastic hysteresis of shape memory springs and piezoelectric material on it. Due to this combined effect, the post-flutter airflow speed range with stable LCOs was increased, which could prove to be an effective piezoaeroelastic harvester [106].

2.3. Galloping-Based PEH

In order to harvest energy from FSI using PZT, two types of galloping mechanisms can be used: transverse galloping [91,152–155] and wake galloping [91,156,157], as shown in Figures 11 and 12, respectively. The PZT patch is attached on the fixed end of an elastic cantilever beam with an external circuit from which it can be shocked with variable resistance. The prismatic structure of any shape (i.e., square, D-shape, or triangle) is attached to the free end of beam, which is subjected to airflow, and oscillations are produced in the direction normal to the flow [158–160]. In wake galloping-based PEH, a bluff body is attached to the free end of the beam and another bluff body is placed in front of it. This phenomenon is dependent on the position of the front bluff body, and vibrations are induced in the spacing distance [161–163]. The galloping mechanism arises when the aerodynamic lift coefficient at steady state has a negative derivative [159]. Upon increasing or decreasing the air flow, the flutter-based harvester and the galloping-based harvester have the same bifurcation diagram. The difference between these two mechanisms is that the flutter phenomenon is basically a 2 or 3 DOF system, while the galloping phenomenon is of 1 DOF system [124,164].

Zhao compared the performance of a standard circuit with a synchronized charge extraction circuit in a galloping-based piezoelectric energy harvester. He demonstrated three advantages of using synchronized charge extraction: The electrical load is independent of output power, which reduces the requirement of impedance matching, resulting in flexible practical applications of galloping-based

piezoelectric energy harvester systems; this circuit saves PZT patches by 75%; and it increases the fatigue life of a system as the displacement amplitude reduces [165]. The quantitative analysis of various FSI-based PEHs is represented in Table 2.

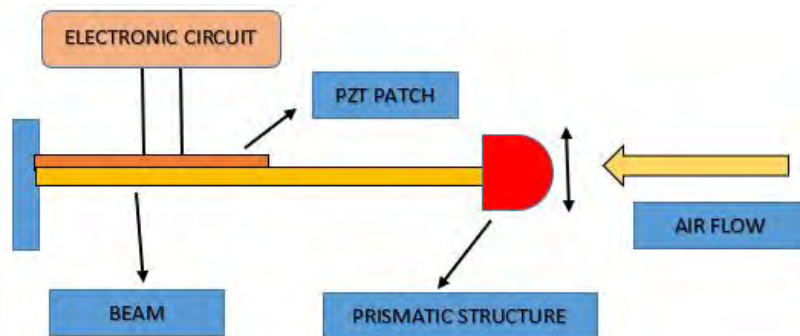


Figure 11. Transverse galloping-based PEH schematic. A D-shaped prismatic structure is subjected to airflow, attached at the end of an elastic cantilever beam.

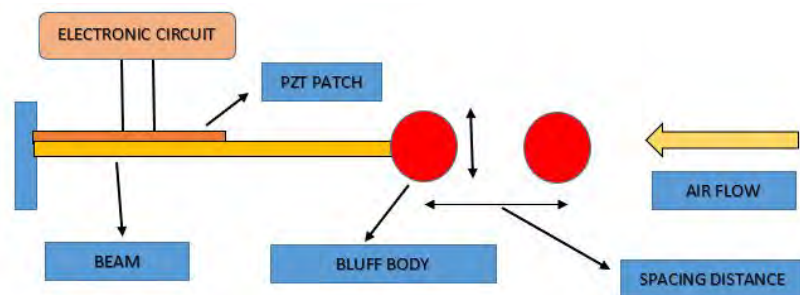


Figure 12. Wake galloping-based PEH schematic. Two bluff bodies are subjected to airflow. One is attached at the end of an elastic cantilever beam and another bluff body is placed in front of it.

An analytical model was developed for a triangular shaped bluff for galloping-based PEH. The effects of inductance, load resistance, and wind speed on the Hopf bifurcation of the system were analyzed. Galloping arises when the electrical damping corresponding to Hopf bifurcation (EDHB) is greater than the electrical damping of the system. The EDHB has a positive linear relationship to the wind speed. So, in order to achieve galloping, wind speed should increase [123]. Tan and Yan developed a theoretical model of galloping-based PEH to analyze the intrinsic effect of inductance and the electrical load resistance on the performance of a cantilever PEH. The average output obtained by this model is given by Equation (7) [166]:

$$P_{opt.}^{avg.} = \frac{(A - 2\zeta\omega)^2}{-6B}, \quad (7)$$

where $P_{opt.}^{avg.}$ is the average output of galloping-based PEH, ζ is the damping ratio, ω is the the first natural frequency of the cantilever beam, A is the aerodynamic damping, and B is the cubic nonlinear coefficient due to galloping.

To characterize the performance of PEH excited by galloping, experimentation was carried out in a wind tunnel for the comparison of harvested voltage and LCOs. For this purpose, bluff bodies of identical geometry and weight were analyzed. It was observed that the optimal bluff body had a wavelength of 2.5, wave-steepness of 0.1, and amplitude of 0.25. The PEH could harvest energy up to 18% lower wind velocity, but the maximum voltage reduced to 7% [167]. This experimental setup is shown in Figure 13.

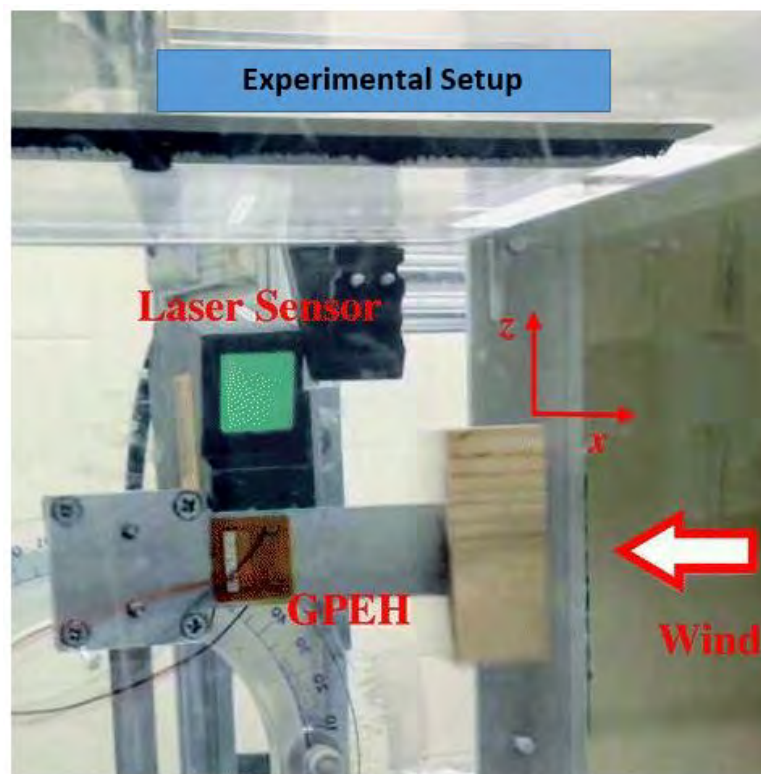


Figure 13. Galloping-based PEH (GPEH) in a test section of a subsonic wind tunnel [167].

Yan and Lei proposed a model for PEH that was excited by galloping but with a different AC and DC interface. They investigated the maximum output power by adjusting the optimal electrical load resistance in order to attain optimal/maximum electrical damping [168]. Petrini and Gkoumas analytically and experimentally investigated a PEH excited by galloping inside HVAC ducts. The device was excited by the airflow due to heating, ventilation, and air conditioning. The estimated power obtained from experimentation in a wind tunnel ranged from 3×10^{-5} to 3×10^{-7} W [155]. The design steps are expressed in Figure 14.

Table 2. Comparison of various FSI-based PEHs.

Mechanism	Design	PZT Type	Layer(s)	Power (mW)	Reference
VIV	Circular	PZT	1	23	[169]
VIV	Circular	PVDF	1	0.004	[170]
VIV	Circular	PZT-5A	2	0.1	[171]
Flutter	NACA0014	PZT	1	0.003	[122]
Flutter	Typical section	PZT-5A4E	1	0.0005	[149]
Flutter	Symmetric	PSI-5A4E	1	0.2	[172]
Flutter	NACA 0012	QP 10N	2	2.2	[173]
Galloping	Triangle	PZT	2	3.8	[123]
Galloping	Equilateral	PSI-5H4E	4	50	[174]
Galloping	Square	P-876.A12	2	8.4	[175]
Galloping	Square	MFC-M8514-P2	1	0.22	[176]

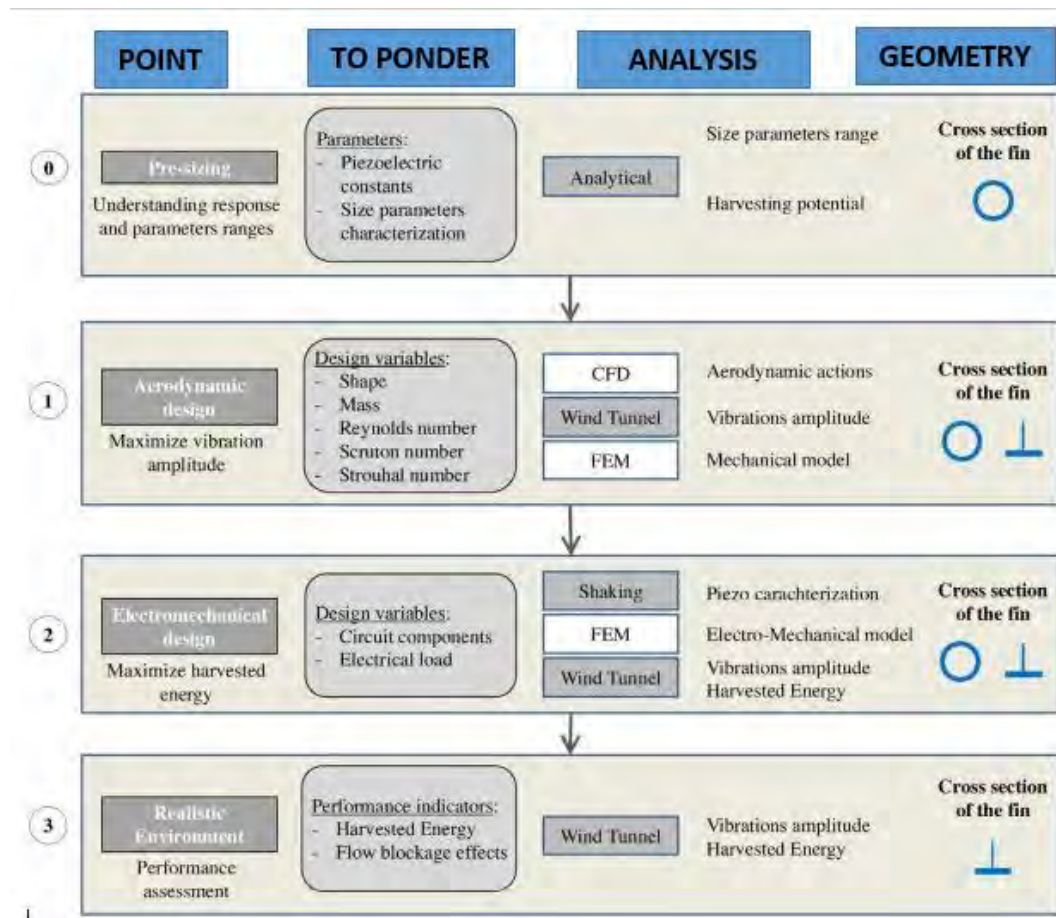


Figure 14. Design steps for PEH [155].

2.4. Other Mechanisms for FSI-Based PEH

The generation of energy under water by using a piezoaeroelastic energy harvester based on a heavy flag was developed by Giacomello and Porfiri. They obtained outputs on the order of 10^{-10} W, which is not useful for most electronic devices [177]. Optimization of this design by playing with the Re of the fluid has been done by Aramendia et al., obtaining energy generation up to 0.9 mW for $Re = 12,000$ [178]. Flapping-leaf or flag-shaped piezoaeroelastic energy harvesters are of great interest for many researchers. Dunnmon et al. presented an experimental model of a flexible cantilever beam with piezoelectric lamination over it that is subjected to airflow. The harvested power was almost 2.5 mW for a 21 m/s critical speed [179]. A further improvement was achieved by Li et al. by making an L-shape aeroelastic harvester using PVDF to oscillate at fluttering frequencies [180,181]. A further improvement was done by Kwon et al. by making a T-shape aeroelastic harvester using a bimorph piezoelectric cantilever beam [182]. It was capable of generating 4 mW of energy at a speed of 4 m/s.

Other mechanisms for FSI-based piezoelectric energy harvesters are explained in Table 3.

Table 3. Other mechanisms for FSI-based PEHs. Re: Reynolds number.

Description	References
Optimized underwater piezoelectric energy harvester that can generate 0.9 mW of power for $Re = 12,000$.	[178]
Underwater aeroelastic energy harvester from a heavy flag that can generate power on the order of 10^{-10} W at $0.6\text{--}1.1\text{ ms}^{-1}$ fluid flow.	[177]
Piezoelectric wind energy harvester circuit proposed to destroy the harmonics and increase the battery charge performance.	[70]
A cantilever beam with PZT laminate subjected to axial flow in a manner similar to a flapping leaf or flag. The system accessed 17% of the energy to which it was exposed. Output power RMS value was obtained to be maximum of 2.5 mW at $\approx 27\text{ ms}^{-1}$ of flow.	[179]
Aeroelastic vibrations-based PVDF flapping flag which can oscillate at wide fluttering frequency.	[180]
Predicted vortex shedding from bluff body is the dominant exciter of oscillations.	[183,184]
The bluff body effect is ignored in the leading edge and more importance is given to self-induced vibrations at the trailing edge. This generator results in 615 μW power harvesting at $< 8\text{ ms}^{-1}$ of flow	[181]
T-shaped piezoelectric harvester for aeroelastic flutter. It can generate at 4 mW at 4 ms^{-1} of flow	[182]
Piezoelectric energy harvester based on turbulence-induced vibrations. It can generate 1 mW for a wind speed of 11 ms^{-1} for PZT and 1 μW for a wind speed of 7 ms^{-1} .	[185,186]
Three piezoelectric patches are attached to harvest energy from the wing of an aircraft. It can generate 10.1–24 μW of power at a wind speed of 11–25 kmh^{-1} .	[187]
Tree-shaped harvester to generate a power of 2.24 mW from the wind speed of an electric fan.	[188]
A piezoelectric windmill to generate power of 7.5 mW from a wind speed of 10 mph.	[189]

3. Human-Based PEH

In the past several decades, generating energy from the motion of humans [190–192], animals [193–195] and plants [196,197] has been of great interest for many researchers. Due to the development of this technology, the charging of mobile micro or nanoelectronics is of great ease [198,199]. There are three mechanisms of harvesting energy from biomechanics: PZT [200–202], electromagnetic [203], and triboelectric [204]. In this section, only biomechanical-based PEHs are discussed. Energy that can be harvested from PZT patches from the movement of different human organs are expressed in Figure 15, and are elaborated in Table 4.

Table 4. Biomechanic-based PEH.

Mechanism	PZT Type	Power (mW)	References
Center of Gravity	PVDF	9.1	[205]
Center of Gravity	PZT	0.15	[206]
Foot Strike	PZT	8.4, 90.3, 0.35	[207–209]
Foot Strike	PVDF	0.013, 1, 0.5	[210–212]
Knee	PZT	3.5, 5.8	[213,214]
Heel	PVDF	120	[215]
Jaw Movement	PVDF	0.0174	[216]

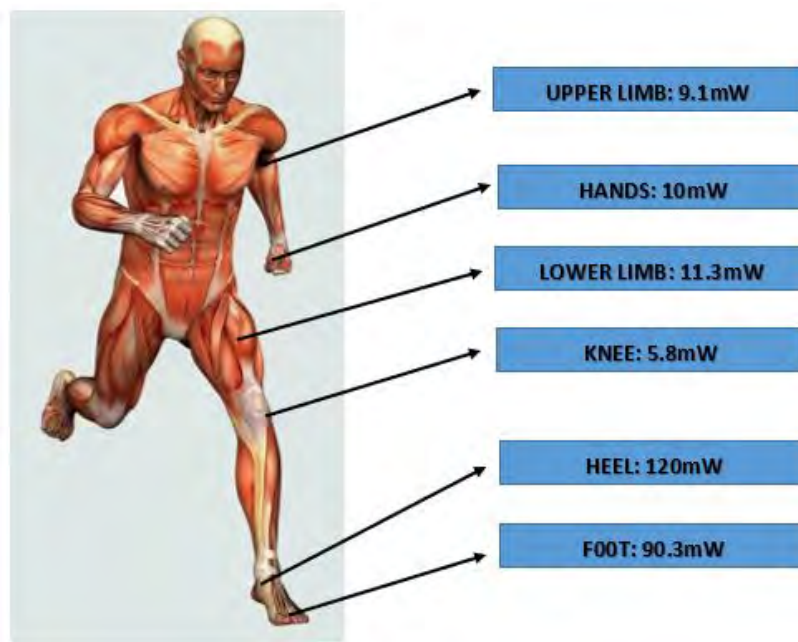


Figure 15. Piezoelectric energy harvesting from the human body.

The joints of the human body are in a continuous state of motion in a fixed axis, providing an excellent opportunity to harvest energy utilizing this motion as an input mechanical source [217,218]. The human body is capable of generating 2–20 W of power from foot strike, 66.8 W from ankle movement, 36.4 W from knee movement, 38 W from hip movement, 2.1 W from elbow movement, 2.2 W from shoulder movement, and 20 W from the center of gravity [217,219–221]. The energy that can be harvested from a human-based PZT harvester is given by Equation (8) [221]:

$$E = \Delta P_M * \eta_{Muscle} * \eta_{Device}, \quad (8)$$

where E is the electrical energy generated, ΔP_M is the change in metabolic power, η_{Muscle} is the efficiency of muscles related to energy conversion for a given motion, and η_{Device} is the efficiency of the device.

Renaud analyzed the parameters that can influence PEH for human limb. Experimentation was done on a prototype of 25 cm³ and 60 g in weight. Forty-seven μ W of energy was generated with 180° phase change, 600 μ W cm^{−3} were generated for the 10 Hz of frequency, and were further optimized to 120 μ W [222]. Siddiqui demonstrated the usage of 3D micro printed omni-directional substrates that are very flexible and robust even for the stretching of the knee. An output power of 1.76 μ W cm^{−2} was obtained from knee movements during a walk [4]. Kim analyzed the effect of force (4N) and frequency (2 Hz) on output power for human-based piezoelectric energy harvesters at different angles (i.e., 0°, 45°, and 90°). The output maximum power obtained was 0.064, 0.026, and 0.02 μ W, respectively [192]. Bai performed experimentation and numerical solution to harvest energy from a piezoelectric wrist band; output RMS power obtained from movement of human wrist was 50 μ W [223]. Fan proposed a nonlinear PEH mounted on a shoe to generate voltage from human walking consisting of a PZT elastic cantilever beam that is magnetically linked to a ferromagnetic ball and cross beam; 0.035–0.35 mW of output power could be obtained while walking from 2 km/h to 8 km/h [209]. The design of a glove having piezoelectric patches was proposed that can harvest energy because of flexion motion in fingers of the hand; 50 V could be generated from this mechanism, and could be utilized to drive a heat coil in a glove in order to provide thermal heating [224]. Halim and Park presented a model for PEH based on human limb motion as shown in Figure 16. The model consisted of two mass-loaded unimorph piezoelectric beams clamped on two flexible sidewalls that can be driven from low frequency.

Each unimorph piezoelectric beam was able to generate power of $96 \mu\text{W}$ at optimum load conditions and a frequency of 4.96 Hz [225].

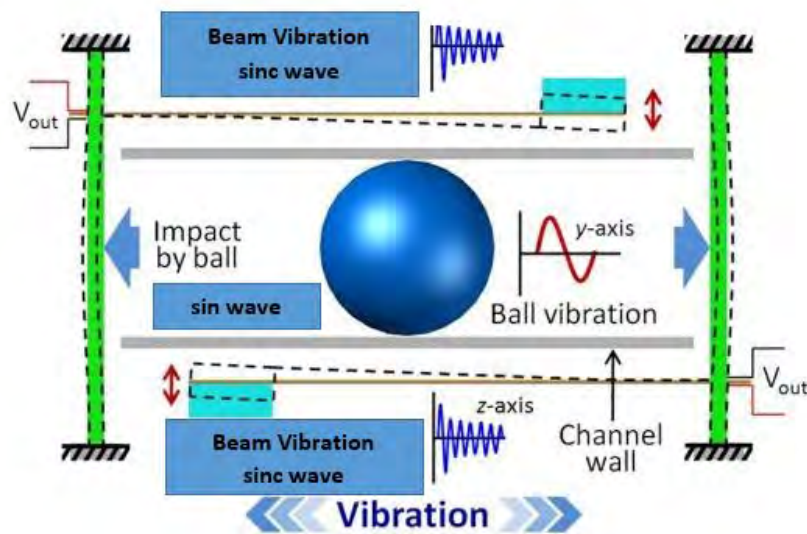


Figure 16. Schematic model of human limb-based PEH [225].

Researchers have shown great interest in biomechanics-based PEH, especially for pacemakers (Figure 17). From the relaxation and expansion motion of the heart, the PZT nanogenerator can generate electrical energy and it can be stored inside a specifically designed battery in the pacemaker [226]; 3 mV of voltage could be generated from this mechanism for an adult. Ansari and Karami performed experimentation on PEH for pacemakers; a 1 cm^3 PEH could generate $16 \mu\text{W}$ of power from a normal human heart beat with a fan-folded structure consisting of a bimorph piezoelectric beam [227].

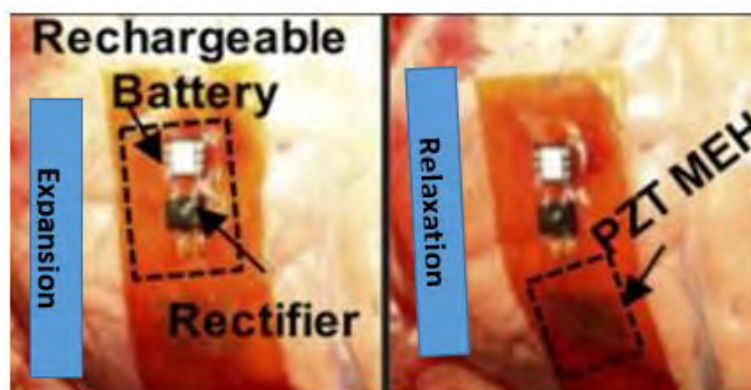


Figure 17. PEH for pacemaker. Expansion and relaxation of the pacemaker for the generation of voltage [226].

4. Mechanical Vibrations-Based PEH

Energy harvesting is driven by mechanical vibrations that result in the deformation of the host structures. These vibrations are transformed to piezoelectric patches for energy conversion [228]. In this section, continuous sources of mechanical vibrations at a few frequencies are studied considering their energy harvesting mechanism. For mechanical vibration-based energy harvesting, two phenomena are involved: structural resonance [229,230] and local resonance [231]. In this section, the structural resonance-based harvesters are studied and a brief introduction to local resonance is incorporated.

4.1. Structural Resonance

In this mechanism, the whole host structure undergoes a resonance behavior for harvesting energy via PZT [232]. This phenomenon can make use of a cantilever beam harvester mechanism or a plate-type harvester mechanism [228].

4.1.1. Cantilever Beam Harvester Mechanism

This mechanism is considered as the most efficient phenomenon, as energy is harvested from the resonance of the entire host cantilever beam [228]. The overall schematic of this mechanism is expressed in Figure 18, where either of layer 1 or layer 2 is a piezoelectric layer and the other is non-piezoelectric layer. These two layers are attached to each other by bonding, and the piezoelectric layer is shocked electrically at the desired resistance via external circuitry [10]. The number of PZT harvesters may vary according to the application (i.e., unimorph PZT configuration [233] and bimorph PZT configuration [234]). A quantitative analysis (summary) of various cantilever beam mechanism-based piezoelectric energy harvesting schemes is expressed in Table 5.

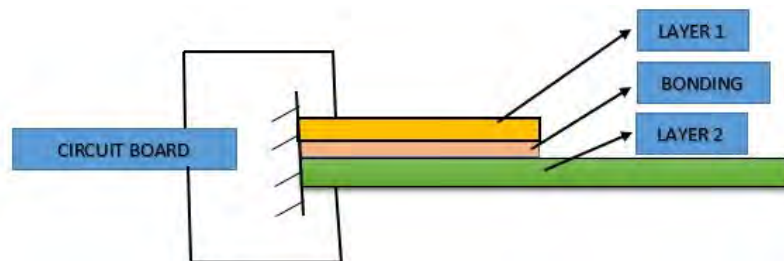


Figure 18. Cantilever beam mechanism-based piezoelectric energy harvesting schematic.

Table 5. Comparison of various cantilever-based PEHs.

Mechanism	Frequency (Hz)	Electrical Load (k Ω)	Power (mW)	References
Cantilever-type magnetic non-contact PEH	32.56	0–200	1.23	[235]
PZT cantilever beam energy harvester for wireless sensors in a satellite at variable temperature	10–10,000	0–100	0.87	[10]
BaTiO ₃ cantilever beam energy harvester for aerospace applications	10–10,000	0–100	0.064	[64]
PZT-5A4E beam energy harvester for cyclic loading	10–100	0–100	0.32	[28]
PZT beam with tungsten mass at fixed end	26.2	26	0.002	[236]
M-shaped PZT harvester	4–8	300	1	[237]
Microfabricated PZT radioisotope generator	38	90	0.0013	[238]
PZT unimorph cantilever	90	-	0.0057	[239]
Two PZT layers with opposite polarization	100	9.9	0.0163	[240]
Bimorph PZT harvester with mass on free end	120	$\approx$ 300	0.375	[241,242]
Sandwiched PZT cantilever beam	125	-	0.03	[243]
PZT bimorph with mass at center	200–250	173	0.3–0.4	[244]
Asymmetric air-spaced PZT energy harvester	200–250	173	0.3–0.4	[245]
Improved power array-based PZT energy harvester	$\approx$ 230	-	0.00398	[245]
PZT laminated energy harvester	$\approx$ 3000	68	0.66	[246]
PZT energy harvester that can resonate at vibration of specific frequency	13,970	5200	0.001	[247]

4.1.2. Plate-Type Harvester Mechanism

Few researchers have emphasized the importance of plate-type PZT harvesters [228]. A schematic of an embedded-based PZT harvester is shown in Figure 19 [248], and a simple plate type-based PEH is shown in Figure 20 [249]. Recent developments in the field of plate-type PEHs are expressed in Table 6.

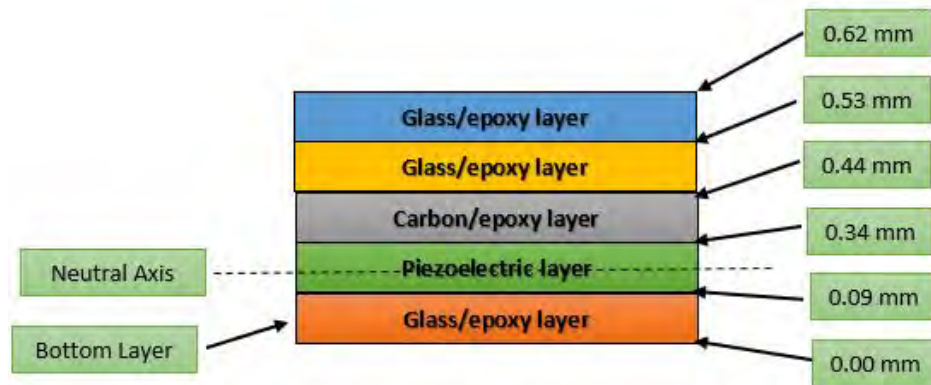


Figure 19. Plate-type mechanism-based embedded PEH schematic.

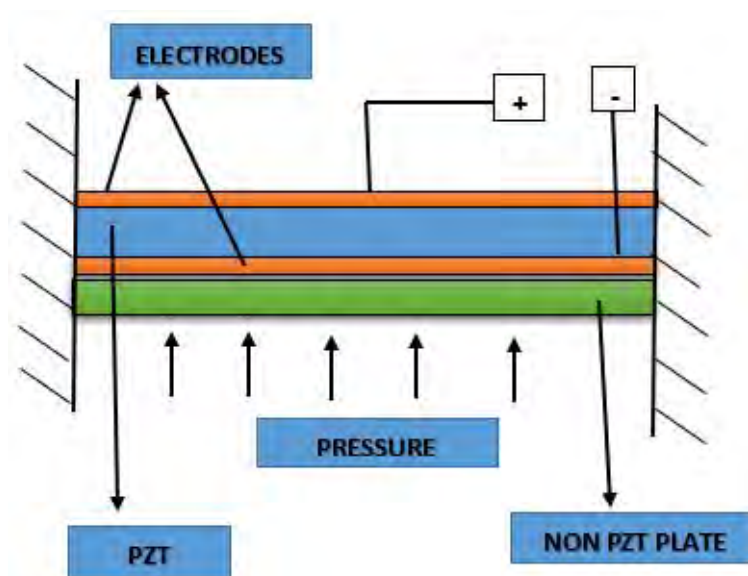


Figure 20. Plate-type mechanism-based PEH schematic.

Table 6. Comparison of various cantilever-based PEHs.

Mechanism	Frequency (Hz)	Electrical Load (k Ω)	Power (mW)	Reference
Bi-stable composite PZT plate for broadband energy harvesting	38	-	36.2	[250]
PZT energy harvester for pavements	10, 15	20, 10	0.88, 11.67	[251]
Simply supported plate type PZT layered harvester	≈ 3000 –20,000	0.1–20	≈ 0.0008 –0.125	[248]
Multi-layered harvester with PZT, carbon/epoxy and glass/epoxy layers	212–310	23	0.22–0.28	[248]
Micropower harvester for gloves	≈ 60	≈ 1000	0.011	[252]
PZT nanofibers for nanogenerator in soft polymers	≈ 35	6000	0.00003	[253]

4.2. Local Resonance

In the last few decades, many materials have been synthesized artificially in order to harvest electrical energy, which are known as metamaterials. These materials are capable of harvesting energy using the phenomenon of local resonance. In metamaterials, a piezoelectric material is placed close to a local resonating point to get maximum energy harvesting [228]. These materials have vast applications in complicated integrated circuits in various electronic devices.

PCs use various types of band filters to filter out waves known as the band gap. These frequencies can be utilized to resonate a localized smart material inside a structure, which is an ideal condition to harvest energy [254]. Carrera et al. performed an experimental campaign under various conditions (Figure 21), and concluded that PC-based harvesters are more efficient as compared to others. Just like PCs, SCs are also used as energy harvesters because of their ability to block or filter out specific frequencies. Unlike PCs, however, SCs use soft material as host to house the resonator [255]. Zhang et al. designed a square-shape SC that is capable of generating power on the order of nW. The square mass is surrounded by four square convolute beams, as shown in Figure 22.

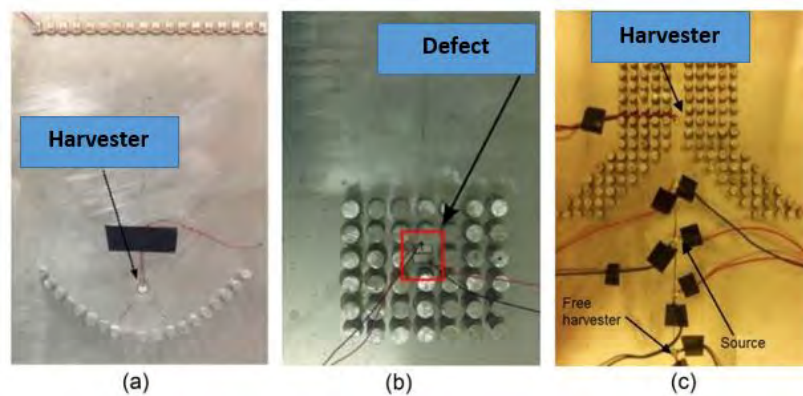


Figure 21. PEH configurations: (a) parabolic acoustic mirror; (b) point defect; and (c) acoustic funnel [256].

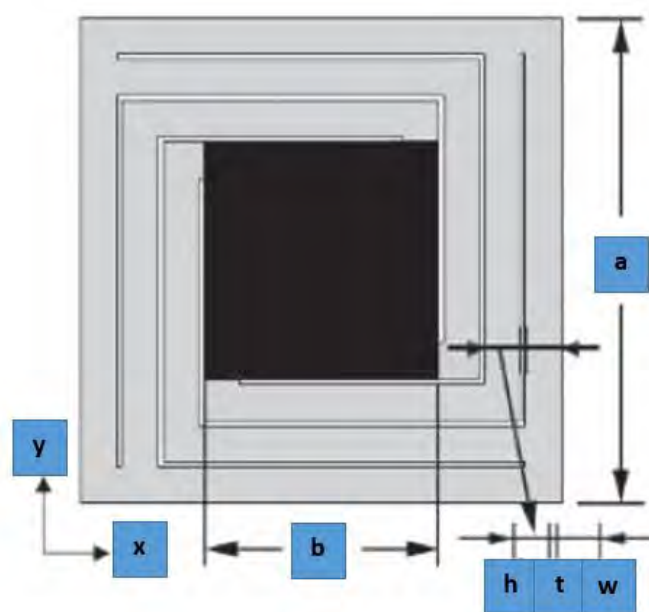


Figure 22. Unit cell in the proposed locally resonant structure [255].

5. Concluding Remarks

In this review paper, mechanisms of piezoelectric energy harvesting based on fluid–structure interaction, human movement, and vibration are studied. Quantitative as well as qualitative analysis of the existing state-of-the-art literature was carried out. Piezoelectric materials are highlighted as an alternate source of energy for defence industries.

The lifespan of batteries is unpredictable, and in many cases their replacement or maintenance is impossible. Furthermore, battery terminals can be destroyed quickly, as it is charged by the micro or nano Watt extracted by PEH. Thirdly, if batteries (i.e., lead ion battery) are not dumped properly, they can be environmental hazards. So, there is a vast scope of PEH to replace batteries or to improve the lifespan of batteries by reducing the charging time, and the design of battery terminals can be improved so that they may not be affected by low voltage input. In harsh conditions such as hot weather, the battery life reduces, whereas the efficiency of PEH is improved in hot weather.

Significant research has been done on aeroelastic energy harvesters, but aerodynamic models can be improved by taking into account the difference and comparison of steady, quasi-steady, and unsteady aerodynamics. No significant experimentation has been done on underwater-based PEH, which can be utilized to drive wireless sensors in submarines or ships. As the energy generated from FSI is on the order of micro or nano watts, it is recommended to construct a model with multiple flexible piezoelectric patches in order to improve efficiency.

As the world is shifting towards nano-electronics, human-based PEH can play a vital role in charging mobile electronic devices (i.e., cellular phones, laptop batteries, etc.). Because human joints/organs are in almost-continuous motion, this PEH modality may prove to be very efficient. Harvesters for human joints (e.g., elbow, wrist) are recommended. It can also be proposed to have a laptop keyboard or the keypad of a cellular phone with piezoelectric patches, allowing batteries to be charged while the users type.

In order to harvest high energy from PEH, it is recommended to use piezoelectric materials with a higher coupling coefficient. There is a vacuum for material engineers to develop doped piezoelectric patches with higher coupling coefficients. Specialized amplifiers can also be utilized in order to amplify the output voltage generated by piezoelectric materials. The efficiency of vibration-based PEH can be improved by optimizing the geometry of the system and locating the piezoelectric patch close to the resonating point so that maximum mechanical energy can be absorbed by the PEH and converted to useful electrical energy.

Author Contributions: All the authors contributed equally for literature survey, discussions, and review of the paper.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

α	pitch angle
ΔP_M	change in metabolic power
ϵ_k	strain vector
η_{Device}	efficiency of device
η_{Muscle}	efficiency of muscles related to energy conversion for a given motion
σ_m	stress vector
θ	angular displacement
b	half chord length
c_α	pitch structural damping coefficient
c_h	plunge structural damping coefficient
C_p	capacitance of the piezoelectric layer

d_{im}^d	piezoelectric coefficients for direct piezoelectricity
d_{jk}^e	piezoelectric coefficients for converse piezoelectricity
D_i	dielectric displacement vector
DOF	degree of freedom
ϵ_{ij}^σ	dielectric permittivity at constant stress
E	electrical energy generated
E_j	applied electric field vector
FSI	fluid–structure interaction
h	plunge deflection
I_α	mass moment of inertia about the elastic axis
k_α	structural stiffness for the pitch motion
k_h	structural stiffness for the plunge motion
K_{ME}	electromechanical coupling
L	aerodynamic lift
LCO	limit cycle oscillations
M	moment about the elastic axis
m_T	total mass of the wing with its support structure
m_W	wing mass alone
MEMS	micro electromechanical systems
PEH	piezoelectric energy harvester
PZT	piezoelectric
R	load resistance
Re	Reynolds numbers
S_{km}^E	elastic compliance matrix at constant electric field
U	flow velocity
U_∞	free stream velocity
V	voltage across this load resistance
VIV	vortex induced vibrations
x_α	dimensionless distance between the center of mass and the elastic axis

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