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Review

A review on design improvements and techniques for mechanical energy harvesting using piezoelectric and electromagnetic schemes

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ABSTRACT

Energy harvesting has gained a growing attention and has seen great advancements during the last decades. Among energy sources, mechanical energy is one of the most investigated forms due to its abundance, accessibility and ubiquity in the environment, in addition to multiple possible transduction types. Several reviewing articles have been published to organize and categorize these works. Nonetheless, some concepts are missing in most reviews and some improvement strategies have been overlooked such as non-resonant and multi-directional systems, etc. We present in this paper an exhaustive reviewing study of the state-of-the-art of mechanical harvester systems, enclosing main different existing improvement techniques and their design concept, particularly for piezoelectric and electromagnetic (EM) transductions. Accordingly, we propose a new generic categorization approach based on the improvement aspect of the harvester, which includes techniques for widening operating frequency, conceiving a non-resonant system and multidirectional harvester. In the category of widening operating frequency, three approaches are conceivable allowing the improvement of the system frequency response, which are: frequency tuning, multi-frequency and non-linear system. For non-resonant systems, possible approaches consist in Frequency-up conversion and free moving mass. The last improvement allows multiplying the directions to harvest more energy from arbitrary movements. Last section is interested in the applicability of the presented techniques under different conditions and their compatibility with MEMS technology.

1. Introduction

Over the past few decades, the evolution in Integrated Circuits (ICs), which engendered a significant decrease in power consumption, coupled with more efficacious battery cells have led embedded systems to become an integral part of the modern world. Through human daily life such as smart buildings, health care, security equipment and industrial processes, the need for such systems is irreplaceable either for communication or easing activities and comfort. Nonetheless, this luxury in life, boosted by micro-devices, is limited by battery's major drawbacks, namely unclean energy source and short lifespan. Nowadays, while awareness of their harmful effects and the need to reduce our dependency on them as mobile energy source requirement is growing, alternative solutions must be found for supplying various microsystems [1]. Hence, Energy Harvesting (EH) has emerged as an evident evolution of power supply technologies. This process consists of extracting and converting energy from the ambient environment into electrical energy. This technique does not only allow reducing nonecological wastes of batteries but also it extends the lifespan of electronic devices by providing unlimited clean energy [2]. A typical EH system is composed of three parts: energy source, harvesting mechanism and the load [3]. The energy source is the ambient energy from which electrical power will be scavenged. The harvesting mechanism is the structure that will convert the considered ambient energy into electrical energy.

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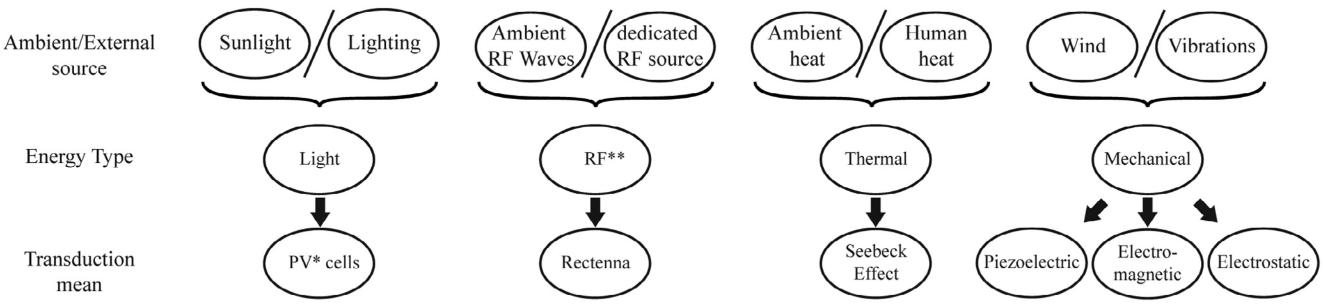


Fig. 1. Taxonomy of energy harvesting sources. (PV for "Photovoltaic" and RF for "Radio Frequency").

The load is the sink that will consume the electrical output energy.

Environment abounds with energies that can be scavenged (e.g., wind, solar, thermal, mechanical, Radio Frequency (RF), acoustic, etc.). Researchers have focused on the development of diverse innovative approaches and harvesting mechanisms to assure enough power generation for most self-powered systems. As a result, the number of papers discussing the improvement in the amount of harvested power from different energy sources keeps increasing significantly. Those sources could be classified into two main categories: *(i)* ambient, which refers to energy sources available in the ambient environment, and *(ii)* external, referring to energy sources that are explicitly deployed [4]. Most common sources of energy harvesting can be regrouped in four types: lighting, RF waves, thermal, and mechanical motion. Fig. 1 shows examples of ambient/external sources for each type along with their popular transduction techniques.

Light energy is harvested through photovoltaic (PV) cells. When stroked by light, the PV cell output behaves as a current source with a voltage limiter [5]. Solar energy is the most common source of light for outdoor harvesting. In recent years, a growing interest has emerged for indoor harvesting under artificial lightings such as compact fluorescent lamp (CFL) and light-emitting diode (LED) [5]. In fact, this technology has generated great interest in applications in the fields of Internet of Things (IoT), home automation, and smart building [6].

Radio Frequency (RF) waves could be harvested through a rectifying antenna (rectenna) which is composed of a receiving antenna, a matching circuit, and an RF to direct current (RF/DC) converter. Recently, this technic has emerged as a promising solution to power wireless devices [7]. Indeed, radio frequency energy harvesting (RF-EH) opened new possibilities for wireless nodes to recharge their batteries from the RF signals instead of traditional energy sources by means of Wireless Powered Network (WPN) technology [8], or by combining wireless powering and information transmission through Simultaneous Wireless Information and Power Transfer (SWIPT) technique [9].

Thermal energy is harvested through thermoelectric generators (TEGs). This conversion is based on the Seebeck effect which is the appearance of an electrical voltage when a temperature difference occurs between the junctions of two thermoelectric materials [10]. TEGs have been used for both low- and high-power generation. High power generation is exploited in some industrial processes, such as the steelworks industry, and automobile engines [11]. Low power TEGs are used mainly in electronic embedded devices, particularly body-mounted devices that generate electrical power from body heat [12].

Mechanical energy is a widespread form of energy that has been widely exploited due to its abundance in the environment. Consequently, the number of proposed Mechanical Energy Harvesting (MEH) systems has been considerably increased during the last decades. This led mechanical energy, and more particularly resonant vibration, to be by far the most investigated in the literature [13]. Given the publications abundance, various reviewing articles appeared with different categorization approaches. Mostly, harvesters are commonly classified according to their transduction type, then applications and/or structures [14,15]. More technical approaches consist in a classification based on a particular aspect, such as the internal mechanism of operation [16], or employed materials [17,18]. More intuitively, Cepnik et al. [19] classified harvesters depending on different aspects, such as excitation direction, excitation form, internal motion, etc. Due to some deficiency in generated power from harvesters, other reviews were concerned about different designs and improvement technics. Therefore, their investigations were based on the best adopted and innovative strategies to design improved systems rather than the structure shape or transduction. Most of these reviews focused on resonant harvesters and frequency range improvement strategies [20–23].

Notwithstanding the number of reviewing papers, some improvement strategies have been overlooked such as non-resonant and multi-directional systems, etc. In order to offset this lack, we propose an exhaustive investigation on applied MEH design improvements and techniques, for which we will present their general concept while explaining their design variations and quoting differences in a new and generic categorization approach. We propose to regroup and classify all improvement approches into three main categories, namely: Widening Operating Frequency (WOF), Non-Resonant Systems (NR), and Multi-Directional-Harvesting (MDH), and each may have specific sub-techniques. Through our bibliographic reading, it is worth to mention that most MEH systems are accomplished mainly through piezoelectric and electromagnetic transductions; therefore this paper will focus on these two means. As it requires deeper studies of theoretical background, the comparison of harvesters is not included in this paper and given examples are for explanatory purposes only. The paper is organized as follow: in section 2, MEH transductions are presented along with the most commonly found solutions for piezoelectric and EM transduction. MEH design and improvement techniques are given in section 3. Section 4 concludes this paper by presenting a brief comparison of the presented technics.

2. MEH transduction types and techniques

Mechanical energy is the most findable form of energy in the environment. In fact, every motion in nature could be considered as a potential source of kinetic energy (e.g., wind, waves, river flows, blood

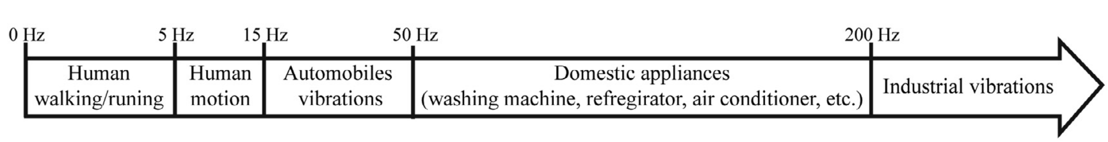


Fig. 2. Frequency levels of common mechanical energy sources.

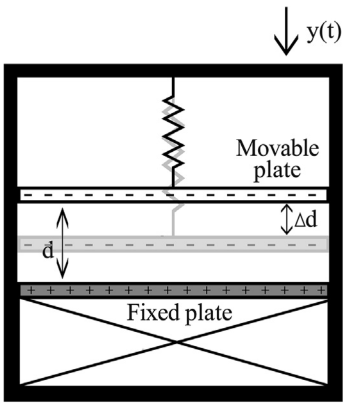


Fig. 3. Electrostatic transduction principle.

flux, human movement, vibration, etc.). Fig. 2 illustrates the approximate working-frequency levels of common mechanical energy sources gathered from some investigation works [24,25]. The harvested power density from different sources is related mainly to their motion frequency and magnitude. It has been proved that the corresponding resonance power P_{res} from any vibration is given by [26]:

$$P_{res} = 4\pi^3 m\, f_{res}^3\, y\, Z_{max} \tag{1}$$

where m and Z_{max} are respectively the inertial mass of the harvester and its maximum displacement, f_{res} is the resonance frequency and y is the amplitude vibration of the housing. Main transduction mechanisms for mechanical energy conversion are piezoelectric, electrostatic and electromagnetic.

2.1. Electrostatic transduction

Electrostatic transducers are based on capacitance variation. As illustrated in Fig. 3, an external vibration *y(t)* causes the gap *d* between two charged plates of a capacitor to vary and hence changing the capacitance value [27]. Consequently, applied mechanical energy is converted into electrical energy that can be stored for future use. We can identify three possible configurations: *(i)* in-plane overlap varying, *(ii)* in-plan gap closing, and *(iii)* out-of-plane gap-closing [28]. All these configurations are capable of generating approximately the same power output [29]. The charge Q of a capacitor is given by $Q = CV$, where C is the capacitance and V is the voltage. According to this relation, capacitance variation causes charge/voltage variation. As a result, there are two possible conversion cycles that depend on which property to held constant while the other changes in response to the capacitance variation, charge constrained conversion and voltage constrained conversion [30]. Electrostatic transducers can be encompassed by microfabrication processes and have been widely employed in MEMS energy harvesting literature. However, contrary to piezoelectric and electromagnetic transduction, electrostatic transduction needs an initial DC voltage to oppositely charge the capacitor plates [28]. Although this is considered as the major drawback of electrostatic harvesters, it may be overcome by inserting an electret (permanently charged dielectric) [31].

2.2. Piezoelectric transduction

The piezoelectric effect was discovered by the Curie brothers and was first reported in 1880 [32,33]. It consists of generating electrical charges when mechanical stress is induced in certain materials, such as quartz, Rochelle salt, etc. and vice versa. For decades, piezoelectric materials have been merely used in military and maritime applications. Three major discoveries have led to their great surge, namely:

(i) The discovery of the mixed oxide compound Barium Titanate ($BaTiO_3$) in 1946 [34];
(ii) The discovery of the Lead Zirconate Titanate (PZT) in 1954 [34];
(iii) The emergence of MEMS and microfabrication technologies in the 1980s [35].

Latterly advances in materials and processing technologies have led to the current avalanche of piezoelectric products such as gyroscopes, accelerometers, etc. Since then, mechanical energy harvesting using piezoelectric materials has the. The piezoelectric phenomenon can be formulated, according to Voigt notation, by [35]:

$$\begin{aligned} D_i &= \varepsilon_0\, \varepsilon_{ij}^{\sigma}\, E_i + d_{iJ}\, \sigma_J \\ \delta_I &= S_{IJ}^{E}\, \sigma_J + d_{Ii}\, E_i \end{aligned} \tag{2}$$

where D, E, δ, and σ are respectively the electric displacement, the electric field, the strain and the stress, while ε, d and S are respectively the material's electric relative permittivity, piezoelectric coefficients, and mechanical compliance (X as superscript indicates that the matrix is considered at X constant); ε_0 is the free space electric permittivity; i and j are indices with values from 1 to 3 while I and J are indices with values from 1 to 6. A piezoelectric harvester benefits from external mechanical excitation to render stress in a piezoelectric layer situated on a deformable structure. Fig. 4, whither *F(t)* is the force caused by the external excitation *y(t)*, illustrates the piezoelectric layer position for maximum stress in two common suspended structures. For those particular cases, the voltage is generated along the vertical axis and the deformation causes an applied stress along the longitudinal axis. It is common to use the terminology 31 mode referring to the axis of tension measure (axis 3) and the axis of applied stress (axis 1). Therefore, the piezoelectric coefficient used is the transverse coefficient d_{31} and the piezoelectric formulation becomes:

$$\begin{aligned} D_3 &= \varepsilon_0\, \varepsilon_{33}^{\sigma}\, E_3 + d_{31}\, \sigma_1 \\ \delta_1 &= S_{11}^{E}\, \sigma_1 + d_{31}\, E_3 \end{aligned} \tag{3}$$

The piezoelectric effect occurs both in monocrystalline materials and in polycrystalline ferroelectric ceramics. With the evolution of thin-film technologies, the number and variety of these materials have been growing. Accordingly, the choice of a particular piezoelectric material for a specific energy-based application is not only limited to their piezoelectric performance but also depends on other parameters like design flexibility, application frequency, available volume, etc. Many reviews have discussed and compared the characteristics and advantages of the most prevalent ones [34–36]. Piezoelectric materials could be classified mainly into four categories: single-crystal materials, lead-based piezoceramics, lead-free piezoceramics, piezopolymers (see Table 1). Single crystal piezoelectric materials such as Quartz, lithium niobate ($LiNbO_3$), etc. are the traditional single crystals; however, they exhibit inferior piezoelectric performances compared to piezoceramics. These components are grown with congruent compositions using many

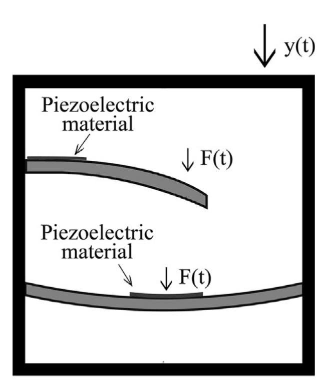


Fig. 4. Piezoelectric transduction principle.

Table 1
Piezoelectric material types: characteristics and exploitation.

Type	Description and characteristics	Existing solutions and examples
Single crystal materials	- Monocrystals vertically grown on a substrate with Bridgman method or Flux method, etc.; - Outstanding piezoelectric properties, and are mostly used in sensors and actuators applications; - Depending on the growing technique, can have different nanostructure forms [41] (nano-belts, nanowalls, nanowires, etc.).	- Zinc-Oxide (ZnO) [42,43]; - Lead Magnesium Niobate (or PMN) based nanostructures: PMN-PT [44,45].
Lead-based Piezoceramics	- Polycrystalline materials (randomly oriented grains) with perovskite crystal structure; - High piezoelectric effect and low dielectric loss; - Simple fabrication process, compatible with MEMS fabrication; - Highly toxic due to the presence of lead.	Most commun are modified or doped PZT materials such as: Lead Magnesium Niobate–PZT (PMN-PZT) [46], PZT-5A [46], Zinc Oxide enhanced PZT (PZT/ZnO) [47], etc.
Lead-free Piezoceramics	- Non-toxic piezoceramics; - Have lower transduction efficiency; - Competitive lead-free materials are perovskite crystal structured type [18].	- $BaTiO_3$ [48]; - Bismuth Sodium Titanate (BNT-BKT) [49]; - Potassium Sodium Niobate (KNN)-based material: LS45 [50], KNLNTS [51].
Piezopolymers	- Electroactive Polymer (EAP); - Flexible, non-toxic and light-weighted [52]; - Small electromechanical coupling than piezoceramics; - Low manufacturing cost, and rapid processing [40]; - Biocompatible, biodegradable, and low power consumption compared to other piezo-materials.	- Can be used for piezo-MEMS fabrication; - Polyvinylidene Fluoride (PVDF) derived polymers: [39,53,54].

methods such as Czochralski, Chemical vapour transport (CVT), etc. The quality of the single crystals would depend on the purity of the starting materials, growth conditions and the orientation (cut direction) of the crystals. With the advent of crystal synthesis and nanotechnologies, grown single-crystal nanostructures with piezoelectric properties has regained significant attention for harvesting energy from mechanical sources within the human body to supply implantable microsystems for in-vivo medical applications [37]. Meanwhile, lead-based materials were the most commonly used for piezoelectric harvester devices, with the PZT as one of the most studied and used piezoelectric materials. Special doping of the PZT ceramics with, e.g., Ni, Bi, La, Nd, Nb ions make it possible to specifically optimize piezoelectric and dielectric parameters. Thereafter, due to the toxicity of lead, legislative measures have been taken to restrict its use [38]. As a result, research has gone to great lengths to replace PZT by other lead-free materials such as Barium Titanate ($BaTiO_3$), which has lower transduction efficiency. At last, polymer piezoelectric composites for energy harvesting applications are considered as a significant research field which provides the convenience of mechanical flexibility, suitable voltage with sufficient power output, lower manufacturing cost, and rapid processing compared to ceramic-based composites. They have the capability to withstand much higher strain due to their inherent flexibility, making them more suitable for applications demanding a large amount of bending or twisting. Despite their low power density due to their small capacitance, they could generate higher voltage than piezoceramics under some specific conditions, as pointed out in the comparison made by Vatansever et al. [39]. In the last decade, numerous classes of piezoelectric polymers, such as polyvinylidene fluoride (PVDF) and its composites used for energy harvesting applications, are extensively examined and explored. Nowadays, there exist about 200 piezoelectric materials for energy harvesting applications out of which piezoceramics (mainly PZT and $BaTiO_3$) have attracted major attention due to their better piezoelectric properties as compared to other piezoelectric materials [40]. Table 1 provides more details about characteristics and practical examples on these materials described above.

2.3. Electromagnetic transduction

Electromagnetic (EM) induction was discovered by Faraday in 1821. He established the Faraday's law and created the first electric generator (Faraday's wheel) in 1831 [55]. The principle of this phenomenon states that any variation of the magnetic flux φ through a conductor will induce a voltage at its ends, and so, created electrical energy could be transferred and dissipated into a load [19]. The induced electromotive force (*emf*) is expressed by $\varepsilon = - d\varphi/dt$, where t is the time [29]. After Faraday's wheel, electromagnetic transduction has come a long way. Nowadays, since the Seiko AGS Quartz Watch in 1988, EM transducers are integrated into many microsystems aiming the recovery of mechanical vibration energy [19]. EM harvesters are composed mainly of magnetic components and inductors. The principle of any EM harvesting mechanism, illustrated in Fig. 5, is to benefit from an external mechanical excitation to vary the magnetic flux across the coil.

In order to create a time-varying magnetic field across a coil, two main approaches are envisaged: either creating a relative movement between the coil and a magnet, or the use of self-actuated ferromagnetic materials. The first approach is the classical solution to vary the magnetic flux, and this could be achieved by two alternatives: *(i)* moving the coil while fixing the magnet, or *(ii)* moving a magnet nearby a stationary coil. The second approach represents an innovative technic which implicates the use of a ferromagnetic material as an intermediate medium between the coil and the magnet. Ferromagnets are initially unmagnetized materials that exhibit strong magnetic effect when approached to a permanent magnet. As well, two particular solutions using ferromagnets are investigated which are: *(i)* Magnetostriction, and *(ii)* Sloshing ferrofluid. Magnetostriction is the property of some ferromagnets to convert magnetic energy into kinetic energy and vice versa. Over the past few years, an upsurge of interest in Magnetostrictive materials (MsM) has been noted thanks to their

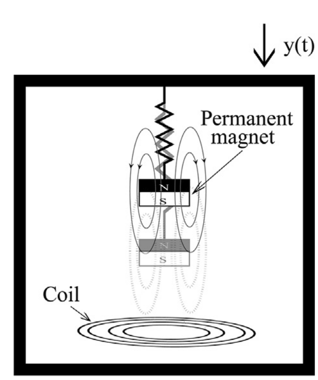


Fig. 5. EM transduction principle.

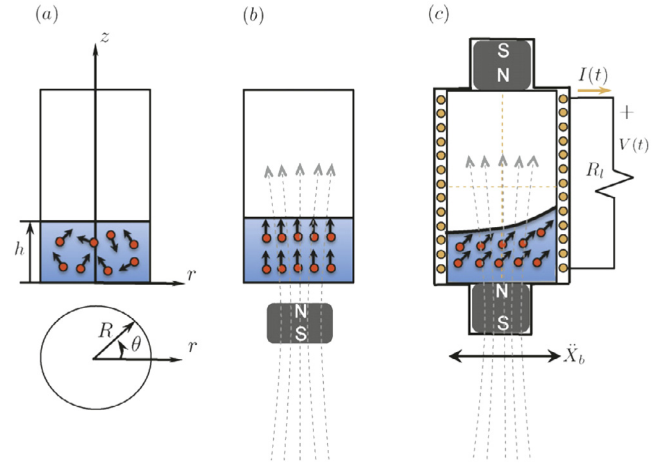


Fig. 6. Schematic illustration of ferrofluid based harvester, (a) Ferrofluid without external magnetic field, (b) Ferrofluid with external magnetic field, and (c) Ferrofluid based harvester under excitation [57].

similarity to piezoelectric materials. The magnetic field is related to the applied stress with the couple of equations given by [56]:

$$\Delta B = \mu^H \, \Delta \mathrm{H} + d_m \, \Delta\sigma$$
$$\Delta\delta = s^H \, \Delta\sigma + d_m \, \Delta H \quad (4)$$

where ΔB, ΔH, $\Delta\sigma$ and $\Delta\delta$ are the increments of the flux density, the magnetic field, the stress, and the strain respectively, while μ, d_m and s are the material's magnetic permeability, piezomagnetic coefficient, and elastic compliance (X as superscript indicates that the matrix is considered at X constant). A ferrofluid is a fluid with the properties of a ferromagnetic material. As shown in Fig. 6a, when not subject to a magnetic field, the magnetic dipoles of the used ferrofluid are randomly oriented [57]. Once a magnetic field is applied, Fig. 6b, all dipoles are lined up generating a magnetic moment. The principle behind Ferrofluid base harvesting is described in Fig. 6c. The sloshing of the ferrofluid when the container is moved creates a time-varying magnetic flux. Table 2 provides more details about characteristics and practical examples on these techniques described above.

2.4. MEH improvement techniques

Tremendous work has been done over the last years to improve MEH systems using different transduction types introduced beforehand, combined with numerous optimization techniques and designs. These approaches have been examined analytically and implemented experimentally to benefit, as much as possible, from external excitations by harvesting more power. From literature, foremost optimized aspects in MEH systems are their response to an excitation form and direction [19]. For a more generic study of such systems, we propose an exhaustive categorization, summarized in Fig. 7, of all exploited design techniques and improvements based on three major features. Two features, related to the excitation form, which are Widening Operating Frequency (WOF) and conceiving a Non-Resonant (NR) system, and last feature is related to multiply the directions of energy harvest, called Multi-Directional-Harvesting (MDH). In the WOF category, the goal is tuning the system response to the excitation frequency. To this end, three approaches are investigated namely resonance frequency tuning, Multi-frequency systems, and nonlinear dynamics. On the other hand, NR systems are more competent for random excitation form. Two approaches for conceiving such a system are investigated consisting in Frequency-Up Conversion (FU-C) and free moving ball. The second aspect to be optimized is the response of the system to different excitation direction unlike most harvesters which are designed to harvest motions from a single direction. In this regard, two approaches can be envisaged which are bi-directional (2D) and tri-directional (3D) harvesting. 2D harvesting techniques are based on the use of perpendicular springs, rotational motion and 2D in-plane movements (2D-IP), while 3D harvesters are less common and can be achieved by 2D-IP plus an out-plan movement (2D-IP + OP) or through a non-resonant system using a free moving mass. Detailed techniques and explanations will be presented next for each approach.

3. Widen operating frequency systems

In general, any structure's vibration is characterized by a single resonance frequency. Therefore, in most cases, vibration energy harvesters (VEHs) operate in a relatively narrow band frequency. In fact, a VEH is a resonant system that can be described by a second-order equation with a single degree of freedom as shown in Fig. 8. The differential equation of motion is given by [67]:

$$m\,z + c_t\,\dot{z} + k\,z = -m\,\ddot{y} \quad (5)$$

where $y(t) = Y\cos(\omega t)$ is the external housing displacement, $z(t) = x(t) - y(t)$ is the relative displacement between the mass and the housing, m is the vibrating seismic mass, k is the spring stiffness, c_t is the

Table 2
EM transduction solutions: characteristics and exploitation.

Technic	Description and characteristics	Existing solution and examples
Moving coil/fixed magnet	- The mobility of the coil is achieved through mechanical spring; - Depending on the structure: the coil motion can be either rotation or displacement; - The magnet is fixed while the coil is attached or printed on a vibrating structure.	- Coil on vibrating cantilever [58]; - Printed coil on MEMS structure [59].
Moving magnet/fixed coil	- The magnet motions can be achieved through mechanical spring, magnetic spring or can be freely moving (no spring).	- Magnet attached to a cantilever [60]; - Halbach generator [61]; - Levitation based generator [24]; - Rolling magnetic ball [62].
Magneto-striction	- Magnetostriction is the property of some ferromagnets to convert magnetic energy into kinetic energy and vice versa; - It relates the generated magnetic field to the applied stress; - Most commonly used materials for energy harvesting are Galfenol and Terfenol-D.	- Axial-type configuration [63,64]; - Bending-type configuration [65].
Sloshing Ferro-fluid	- Fluid with a ferromagnetic properties material; - Can fit into any shape and therefore can be easily injected; - Can respond to an infinite closely-spaced modal frequencies; - Most investigated ferrofluid are water-based ferrofluid (MSG W11), and hydrocarbon-oil-based ferrofluid (EFH1).	- A container filled with ferrofluid and wounded by a coil is put next to a magnet. The sloshing of the ferrofluid when the container is moved causes the variation of the magnetic field [66].

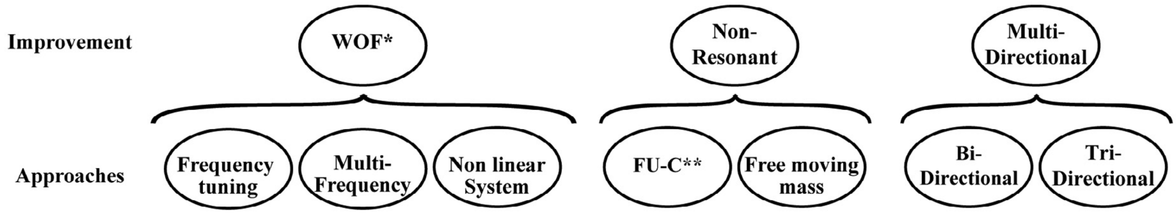


Fig. 7. Classification of MEH improvement techniques. (*WOF: for Widening Operating Frequency, and **FU-C: for Frequency-Up Conversion).

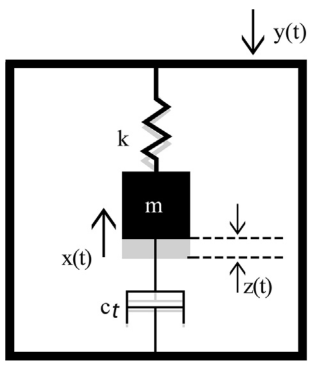


Fig. 8. Operational schematic of a mass-spring-damper system.

damping coefficient and ω is the frequency of the excitation. The standard steady-state solution for this equation is given by [27]:

$$z(t) = \frac{\omega^2}{\sqrt{(\omega_n^2 - \omega^2)^2 + \left(\frac{c_t\,\omega}{m}\right)^2}} Y\sin(\omega t - \varphi) \tag{6}$$

where $\omega_n$is the system resonance frequency and φ is the phase angle which are respectively given by:

$$\omega_n = \sqrt{k/m}\,,\ \varphi = \tan^{-1}\left(\frac{c_t\,\omega}{k - \omega^2 m}\right) \tag{7,8}$$

We can identify on the left side of the Eq. (5) the three forces acting on the mass which are: the inertial force $m\,\ddot{z}$, damping force $c_t\,\dot{z}$ and the elastic force $k\,z$. The conversion of mechanical energy into electrical energy is assumed to have the same effect as mechanical damping. Therefore, the damping coefficient c_t is the sum of mechanical damping c_m and electric damping c_e. Since power is the product of force by velocity, the converted power P_e is given by the product of electric damping force $c_e\dot{z}$ and the velocity $\dot{z}$, expressed by [29]:

$$P_e = \int_0^{\dot{z}} c_e\,\dot{z}\,d\dot{z} = c_e\int_0^{\dot{z}} \dot{z}\,d\dot{z} = \frac{1}{2}c_e\,\dot{z}^2 \tag{9}$$

Roundy et al. [29] showed that the complete analytical expression of P_e is given by:

$$P_e = \frac{m\xi_e\omega_n\omega^2\left(\frac{\omega}{\omega_n}\right)^3 Y^2}{\left[2\xi_t\left(\frac{\omega}{\omega_n}\right)\right]^2 + \left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2} \tag{10}$$

where ξ_e and ξ_t are the unitless damping ratio of the electric and the total damping given by:

$$\xi_i = \frac{c_i}{2\sqrt{km}} = \frac{c_i}{2m\omega_n} \tag{11}$$

where the subscript i is referring to $\{e\ or\ t\}$. If the resonance frequency of the harvester matches the excitation frequency, the converted power is maximized and Eq. (10) can be reduced to:

$$P_{eM} = \frac{m\xi_e\omega_n^3 Y^2}{4\xi_t^2} = \frac{m\xi_e A^2}{4\omega_n\xi_t^2} \tag{12}$$

where $A = \omega_n^2 Y$ is the acceleration magnitude of the external vibration. Therefore, the first solution to maximize harvested power is to tune the harvester vibration to the ambient dominant frequency. This is feasible only when this latter is concentrated around a single driving frequency known beforehand [29]. However, in most cases, the energy of ambient vibrations is distributed over a wide frequencies spectrum [68]. In those cases, methods for broadening the harvester bandwidth are required. One solution consists of using a multi-frequency system. Another approach consists of exploiting non-linear motions characterized by a wider bandwidth [23,69].

3.1. Natural frequency tuning

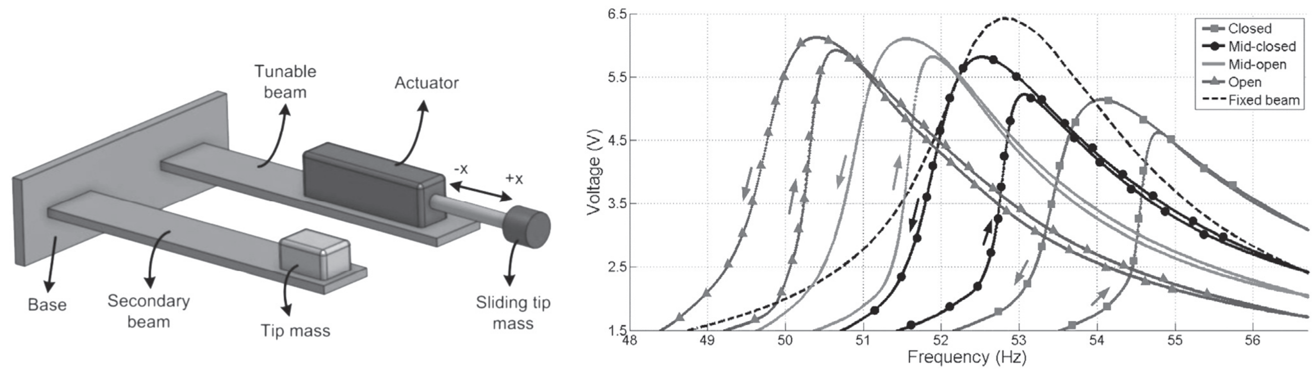
Frequency tuning techniques serves to adjust harvester's resonance frequency after fabrication. But for this end, a complex design is needed and, in most cases, an external intervention that could be human or automated through actuators. Frequency adjustment can be achieved through many techniques including geometrical tuning, axial preload, extensional mode resonator or variable stiffness.

3.1.1. Geometrical adjustment

In geometrically tuned systems, the resonance frequency could be set by adjusting some geometrical parameters of the resonator such as its inertial mass [70,71], or geometry/shape [72,73]. These techniques allow adjusting the resonance frequency without affecting the system damping. However, this tuning approach is very challenging to be applied for MEMS-based harvesting systems. The system proposed by Karadag et al. [71] is an automated tunable system with alterable inertial mass. The device shown in Fig. 9a consists of two piezoelectric cantilevers, a secondary and a tunable one. In this work, a phase-difference based tuning algorithm is implemented by using the second piezoelectric beam as an accelerometer. A 14 mm-length micro-linear actuator is fixed to the tunable beam, with a tip mass connected to its shaft. When the mass tip is at its starting position (closed), the tunable beam resonates at its highest frequency value. As the tip mass slides out, the beam resonant frequency increases until the tip mass reaches its last position (open). This behavior can be seen in the system frequency response given in Fig. 8b. The piezoelectric vibration energy harvester was able to tune its resonance frequency from 49 Hz to 54 Hz to stay in resonance with ambient vibration through a tiny piezomotor controlling the mass tip.

3.1.2. Preload application

The resonance frequency can as well be reduced by applying a preload. In fact, applying an axial compression preload destabilizes the cantilever and thus reduces its rigidity. It has been proven that the application of a preload can adjust resonance frequency to minus 24% [74] and could, therefore, be suitable for wide range adjustment. A piezoelectric energy converter has been proposed by Eichhorn *et al.* [75] which consists of a piezoelectric beam with two additional arms that connect the cantilever tip to the base. Two wings attached to the arms from the clamped side allow applying a compression load as shown in Fig. 10a. The measured resonance frequency of the system when no load is applied was 380 Hz. No effect is observed for loads bellow 7 N. As from preloads above 7 N, the resonance frequency drops



(a) (b)

Fig. 9. Frequency tunable piezoelectric harvester with geometrical auto-change proposed by Karadag et al. [71]: (a) Schematic design of the proposed harvester, (b) Frequency response for different tip mass adjustment.

down to 290 Hz for a preload of 22.75 N as seen in Fig. 10b.

3.1.3. Extensional mode resonator

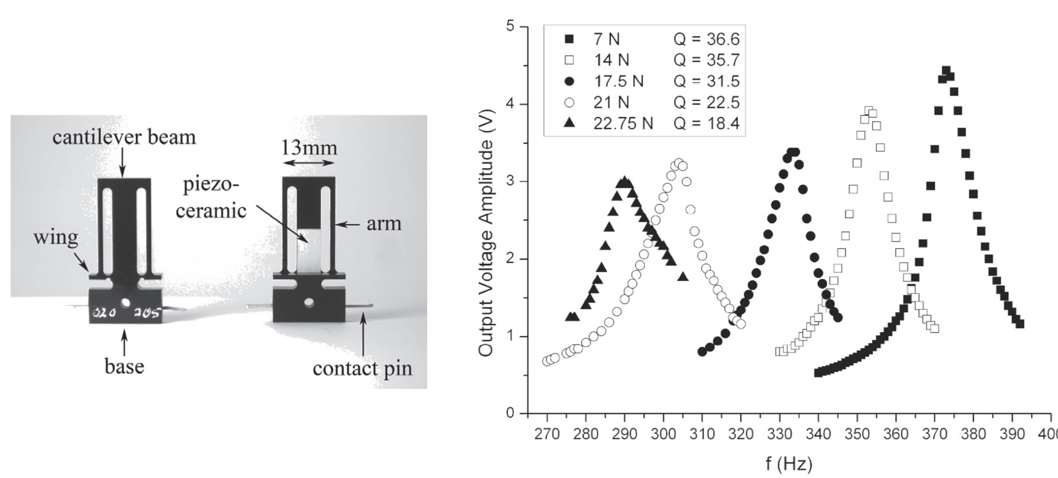
In common piezoelectric harvesters, the cantilevered beam is supposed to be an element undergoing a bending. Morris et al. [76] proposed a new device based on cantilever's extension rather than bending. Fig. 11a shows the principle of the proposed eXtensional Mode Resonator (XMR). The design is formed by a disk-shaped seismic mass with two piezoelectric sheets which are linked at their center by a $2u_p$-length rigid link (Fig. 11a). These two PVDF-based (Polyvinylidene-fluoride) sheets are clamped to the seismic mass at their extremities on the top and bottom sides with clamping rings (Fig. 11b). When an external excitation occurs, the tension due to the seismic mass vibrations causes extensional/contractive deformation to the membranes. PVDF-based elements are suspended at the center with flanged brass spools linked by a screw that passes through the hole of the seismic mass. Therefore, tighten the screw allows to adjust the distance between the center of the films, initially equal u_p, and consequently tuning the resonance frequency f_n. Theoretically, the coupled mechanism showed a linear relationship between f_n and the pre-deflection of the extensional elements u_p, given by [76]:

$$f_n = u_p \frac{1}{2\pi}\sqrt{6\frac{Ewh}{ml^3}} \tag{13}$$

where E is the Young's modulus, w is the width, h is the thickness, m is the seismic mass and l is the half-length from one end to the other. Based on this equation, they proposed a frequency tunable device, shown in Fig. 11c. Thus, the mechanism is made frequency tunable by an adjustable link that symmetrically pre-tensions both piezoelectric sheets. For experimental tests, starting from a random initial position 2, the distance u_p is reduced by 0.1 mm for position 1 and increased by 0.2 mm for position 3. The frequency response of the system, given in Fig. 11c, shows variable resonance frequencies around 110, 130 and 160 Hz for positions 1, 2 and 3, respectively. These results indicate also the ability to reproduce the specific frequency of interest by changing between the three positions in random orders.

3.1.4. Stiffness variation

Zhu et al. reported a variable spring stiffness system whose resonant frequency is tuned by applying a negative spring parallel to the existing mechanical one [69]. Negative spring can be applied through piezoelectric [77], electrostatic [78] or magnetic [79] effects. However, piezoelectric and electrostatic methods are in principle power consuming. Therefore, they are not very suitable for power harvesting and only magnetic tuning techniques are considered for energy harvesting [22,23]. It is important to note that for high magnetic forces, the system behavior may become nonlinear. This will be further discussed with nonlinear systems in section 3.1.3. Challa et al. presented a piezoelectric harvester with magnetic tuning system [79]. The proposed device comprises a vibrating structure with two magnets at its free end,



(a) (b)

Fig. 10. Frequency tunable piezoelectric energy converter with preload proposed by Eichhorn et al. [75]: (a) Upper side with notches on the wings (left) and Bottom side without notches on the wings (right), (b) Frequency response for different preloads adjustment.

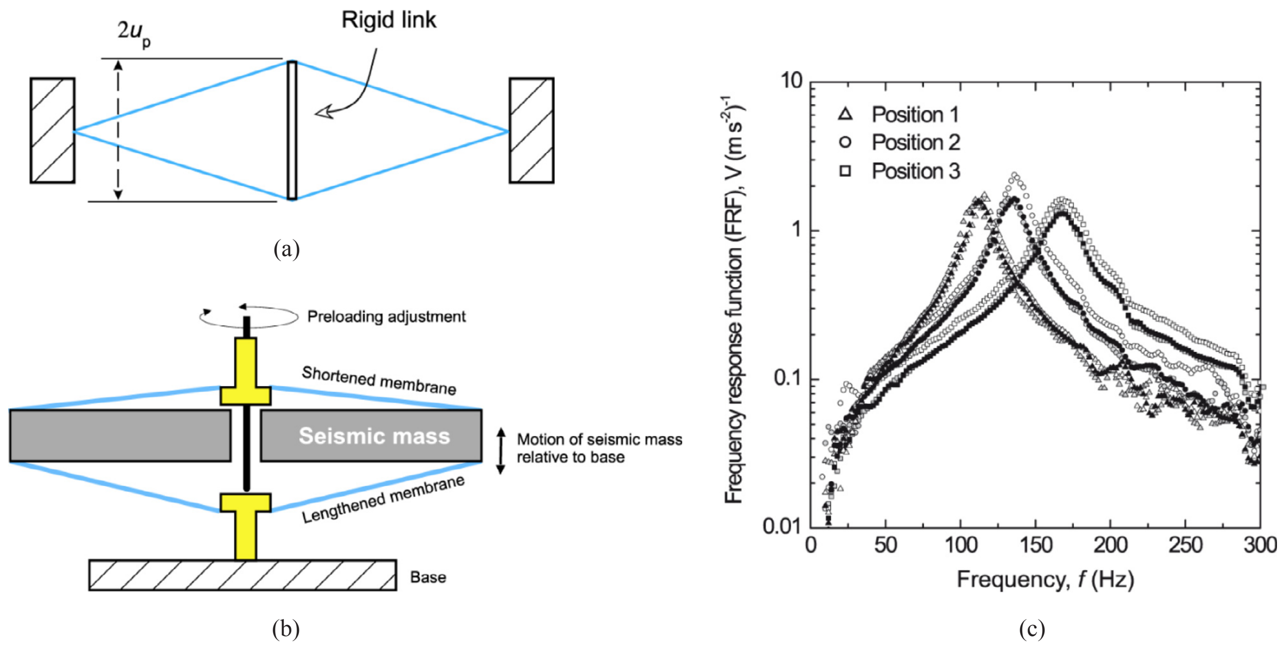


Fig. 11. Frequency tunable piezoelectric XMR harvester proposed by Morris et al. [76]: (a) Basic concept (without seismic mass), (b) Cross-sectional schematic when driven by base excitation, (c) Frequency response for different positions.

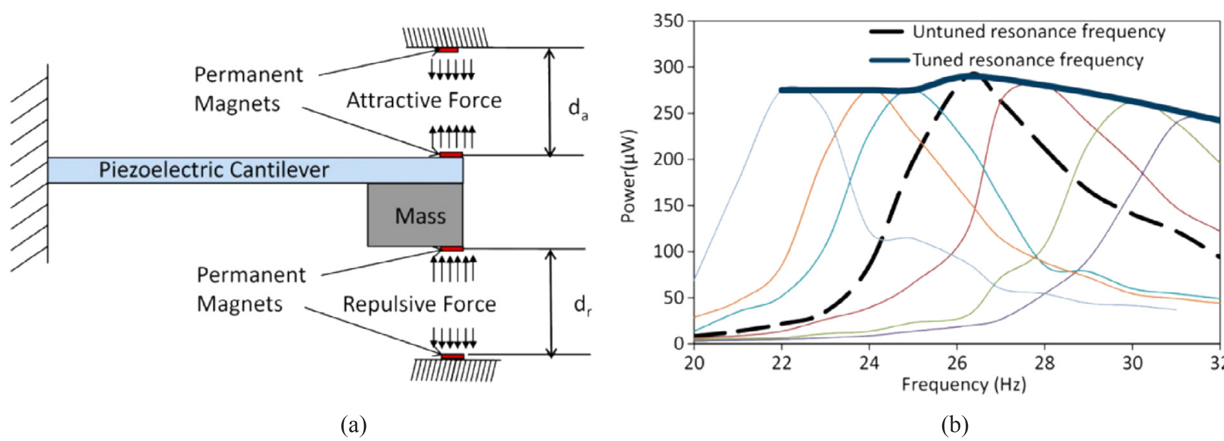


Fig. 12. Frequency tunable harvester with geometrical tuning proposed by Challa et al. [79]: (a) Schematic design of the proposed harvester, (b) Frequency response for different adjustment.

and two magnets fixed at the enclosure arranged as shown in Fig. 12a. The cantilever is fixed on a vertically movable clamp that allows changing the distance between the magnets on its tip and the fixed magnets. By changing that distance, the magnetic forces can be adjusted thus, tuning the resonance frequency. When no magnetic forces are applied, the resonance frequency of the untuned system is 26.2 Hz. This latter is then reduced when the cantilever is displaced toward the attractive magnetic force and increased when displaced toward the repulsive force. The displacement is limited by the condition that the magnets come into contact. The frequency response of the system, given in Fig. 12b, shows a cantilever frequency tuning down to 22 Hz and up to 32 Hz.

3.2. Multi-frequency systems

One solution for increasing the operating frequency range is to have a multi-frequency system, which consists of an array of sub-systems; each is characterized by its own resonance frequency. Once an external vibration whose dominant frequency is within the frequencies band occurs, at least one of the structures vibrates at its resonance frequency. The major drawback of this approach is the larger area required for the sub-systems array particularly for small-scale devices. For a multi-frequency sub-system, two techniques are possible namely cantilever array and multimodal system.

3.2.1. Cantilevers array

The typical technique for a multi-frequency sub-system is the use of a cantilevers array of different dimensions. This technique allows having a better control over the final frequency range of the harvester by adjusting the number and the dimensions of cantilevers as needed. Consequently, the output power is the overall of output powers provided from each cantilever. However, it's important to optimize the dimension increments in order to achieve a continuous and uniform spectrum. The proposed EM harvester by Sari *et al.* [80] shown in Fig. 13a, is composed of a set of 40-coil cantilevers vibrating around one common magnet added in the die center. The cantilevers had the same configuration but different lengths. For optimizing the configuration, three different length increments were studied as shown in Fig. 13b, c and d. An incrimination of 10 µm, would widen the bandwidth but the power output would be discontinuous. A smaller

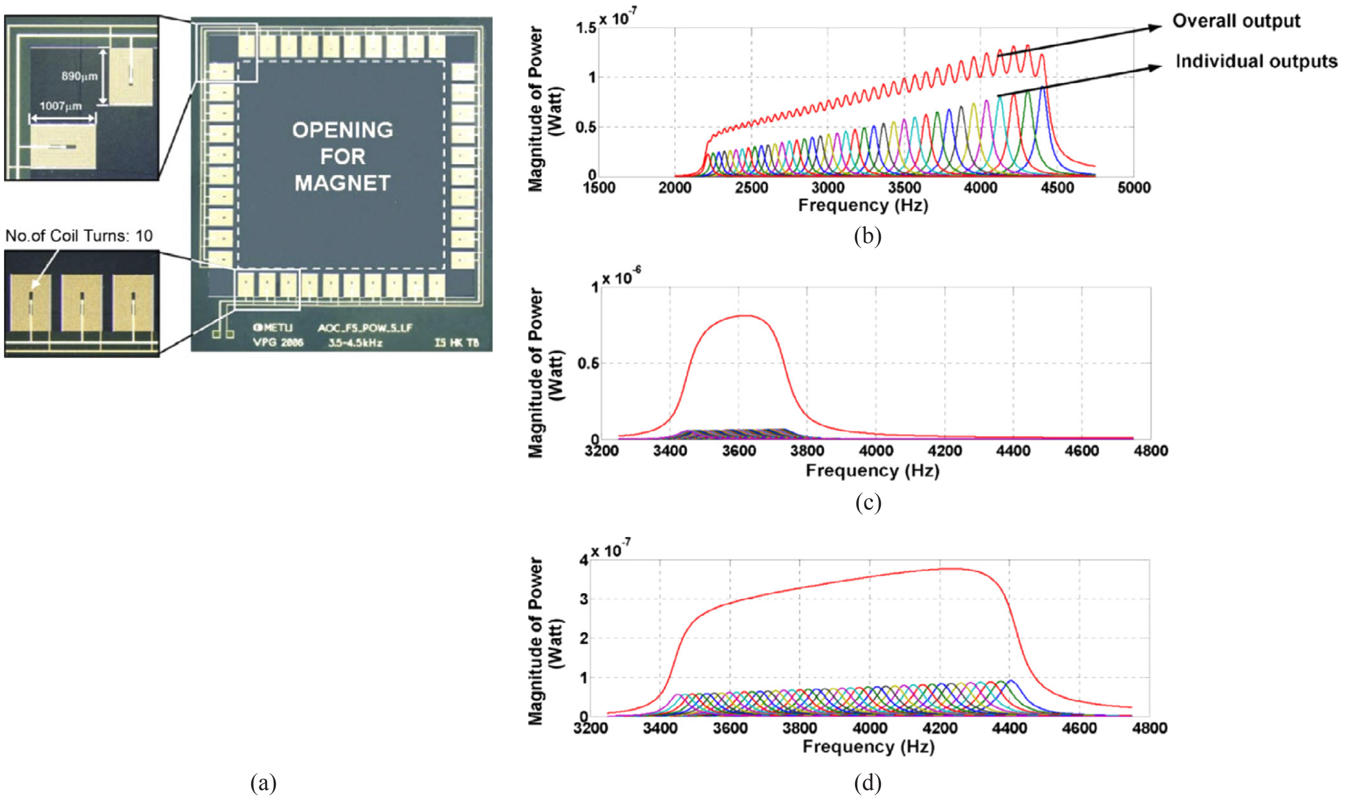


Fig. 13. Generators array harvester proposed by Sari et al. [80]: (a) Schematic design of the harvester, (b, c, d) Frequency responses for cantilever length increments of 10, 1 and 3 µm, respectively.

incrimination of 1 µm would stabilize the output power, but the bandwidth would be smaller. An optimized case would be an incrimination of 3 µm where both the bandwidth and the output power are increased. As can be seen for the optimized case, the design covered a 1 kHz frequency band with a maximum steady output power of 0.4 µW for a bandwidth of 300 Hz.

3.2.2. Multimodal systems

Another technique for generators array consists of multimodal systems. In this case, the vibrating structure is composed of more than one seismic mass. Therefore, the structure has different modes of vibration with different resonance frequencies. Such a system was proposed by Toyabur *et al.* [81], illustrating a hybrid harvester composed of a primary beam in a clamped–clamped configuration, as shown in Fig. 14a. Four lateral symmetric piezoelectric beams with magnets attached at their tips constitute secondary systems. A coil is placed bellow each magnet for EM transduction. The system exhibits four vibration modes of resonant frequencies of 10.802, 14.268, 15.425 and 20.15 Hz. The frequency response of the system for an input acceleration of 0.2 g is given in Fig. 14b. Four resonant peaks can be observed at the resonance frequencies of the vibration modes. Maximum power of 229.31 µW is generated at the frequency corresponding to the third vibration mode.

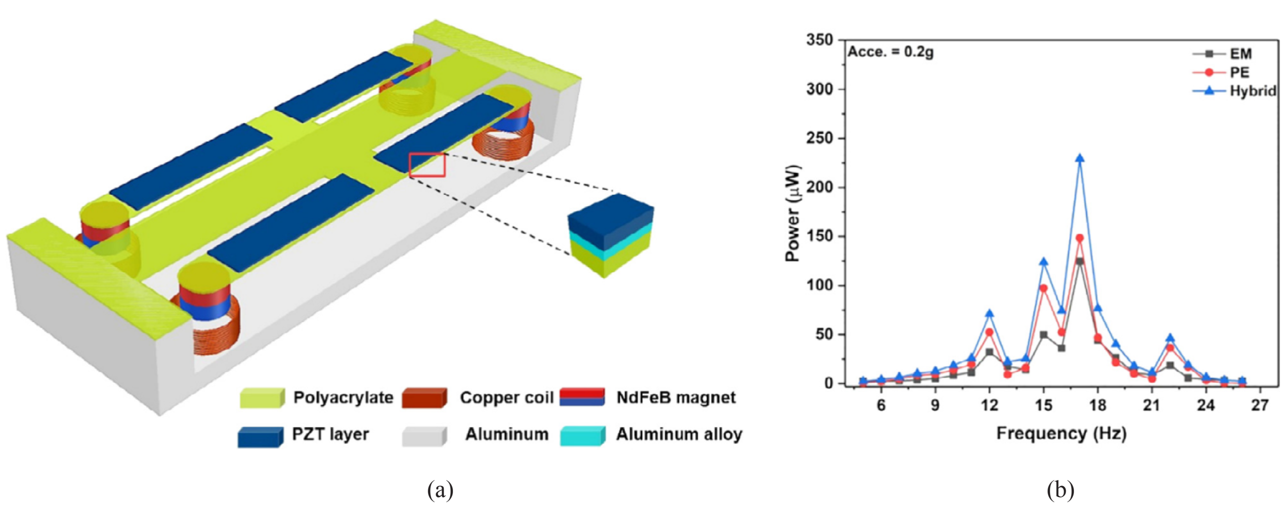


Fig. 14. Multimodal harvester proposed by Toyabur et al. [81]: (a) Schematic design of the harvester, (b) Harvested power as a function of the frequency.

3.3. Nonlinear systems

Usually, nonlinearities are inherently present in dynamic systems due to geometric or material properties. Generally, these nonlinearities are of limited impact on VEH and are hardly controlled. Recently, the intentional introduction of nonlinearity in VEH by external means has received much attention. The approach basis consists of introducing a nonlinear restoring force which magnitude and nature can be controlled [82]. For a nonlinear system, the motion equation, given in equation (9), is replaced by a Duffing's equation as given by Ramlan [83]:

$$m\,\ddot{z} + c_t\,\dot{z} + f(z) = -m\,\ddot{y} \tag{14}$$

where *f(z)* is the restoring force, which is the combination of linear stiffness k and nonlinear stiffness $k_n z^2$, given by:

$$f(z) = (-k + k_n z^2)z \tag{15}$$

Considering this equation, for $k_n \neq 0$, the total stiffness of the system would vary with varying z. Therefore, the total spring stiffness would get harder for $k_n > 0$ and softer for $k_n < 0$. Consequently, the restoring force of the system would be non-linear for high excitations as illustrated in Fig. 15a. For a Duffing type oscillation, the potential energy (PE) function *U(z),* illustrated in Fig. 15b, can be considered in a quadratic form [22] as follows:

$$U(z) = -\frac{1}{2}kz^2 + \frac{1}{4}k_n z^4 \tag{16}$$

From Fig. 15b, the PE of a linear system is obtained for $k \leq 0$ and $k_n = 0$ (Blue line). We can identify three different nonlinear configurations that are most used in vibration energy harvesting [22]. When $k < 0$ the system response is monostable. A nonlinear stiffness $k_n > 0$ determines a hardening response (Green line) and a nonlinear stiffness $k_n < 0$ determines a softening response (red line). For $k > 0$ and $k_n > 0$ the system becomes bi-stable (Solid black line).

The frequency response of non-linear systems is illustrated in Fig. 15c. In a hardening configuration system, the frequency response would bend to the right, widening the frequency bandwidth and conserving the output power for higher frequencies. However, this would only happen when the resonant frequency is approached from lower frequencies [69]. Such a system has been investigated by Ramlan et al. [83]. They showed that ideally, a hardening configuration would generate the same maximum amount of power as a linear system but at a different frequency depending on the degree of non-linearity. On contrary, in a softening configuration system, the frequency response would bend to the left, widening the frequency bandwidth and conserving the output power for lower frequencies but, only when the resonant frequency is approached from a higher frequency [69]. In a bi-stable system, the PE of the system is characterized by a single double-well restoring force potential that allows three different oscillation modes [84] as illustrated in Fig. 15b (dashed black line). The mode of oscillation depends on the excitation amplitude. For a low excitation, the system behaves as a monostable system with a softening configuration (mode a). It consists of an intra-well oscillation where the inertial mass oscillates around one of the stable equilibrium. As the excitation amplitude is increased and from a certain level, the system starts to exhibit aperiodic or chaotic oscillations between wells (mode b). Further increased excitation amplitude may lead to a stable or periodic inter wells oscillation (mode c). It is also possible to have multi-stable system with more than two equilibrium points [85,86].

To create non-linearity, most of the existing literature exploits magnetic interactions. This is possible either by using moving magnet in levitation [87,89] or by combining magnetic interactions with vibrating beams [90–93]. Another approach consists of using nonlinear springs [94,95]. Nonlinearity can also be applied by using an amplitude limiter [96].

3.3.1. Levitation based systems

Levitation-Based Harvesters (LBHs) exploit magnetic repulsion to keep a permanent magnet oscillating between two fixed magnets at the ends of a tube as illustrated in Fig. 16a. LBHs are EM transducers with no mechanical forces. Therefore, no fatigue or dysfunction can occur over time since there are no mechanical forces, and movements are smoother. LBHs are more suited for low-frequency harvesting and particularly from human motion which is characterized by arbitrary

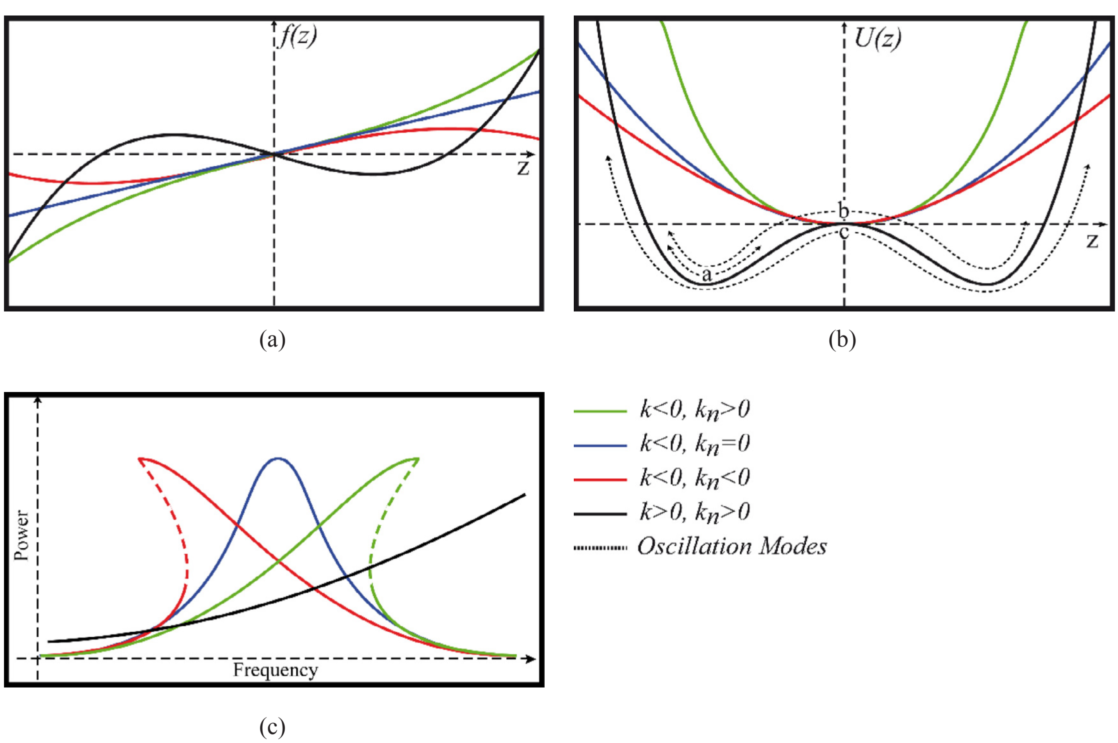


Fig. 15. Nonlinear dynamics (a) Total restoring force f(z), (b) Potential energy function U(z), (c) Harvested power versus frequency.

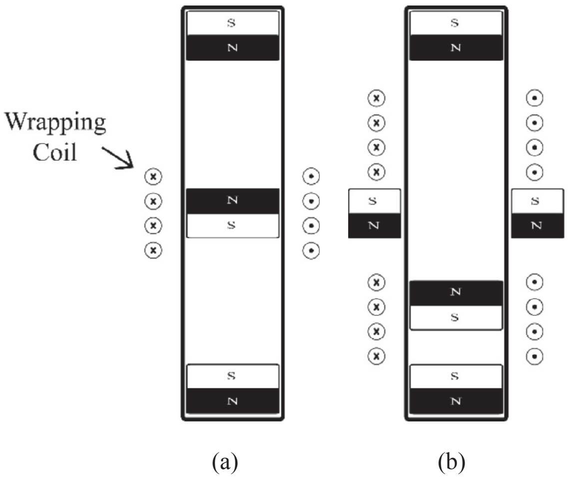


Fig. 16. Schematic diagram of levitation based design: (a) Usual monostable system, (b) Bistable system proposed by Mann et al. [88].

and high amplitude movement [97,89]. Such systems are not dedicated to microsystems integration.

Commonly found LBHs are monostable hardening systems. In a particular design, Mann *et al.* [88] proposed a bistable LBH, which schematic diagram is shown in Fig. 16b. They added four magnets around the tube's midpoint to repel the magnet levitating away from the midpoint making the system bi-stable. The frequency responses of the harvester are given in Fig. 17 (a, b, c and d). As can be seen in Fig. 17a, for lower excitations, the system behaves as a linear system and the output peak is reached at the resonance frequency of the system. While for higher excitations, the system shows a bi-stable behavior and the frequency response begins to broaden.

3.4. Vibrating beam with magnetic interaction

Combining vibrating beams and magnetic interactions is possible by attaching a permanent magnet to the free end of a cantilever while other magnets are fixed in the reference frame. In the case of magnetic attraction, it is also possible to use a ferromagnetic material. These configurations have been used for piezoelectric [90,98–101] and EM [92,102] transductions. However, for MEMS such configurations can be

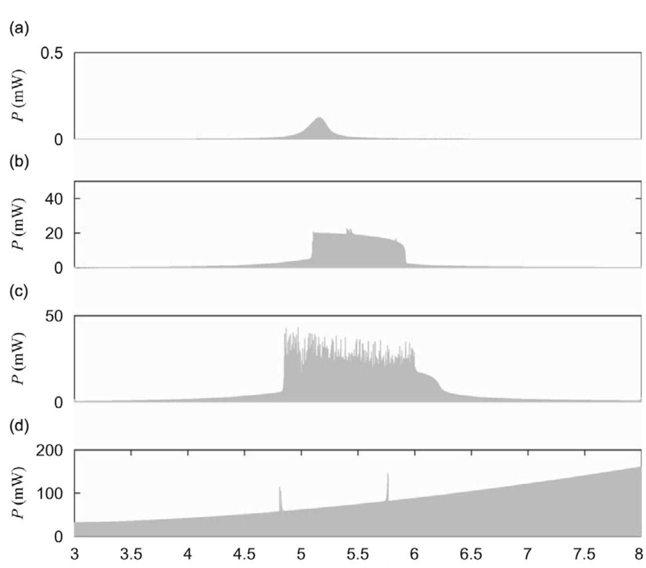


Fig. 17. Frequency response of the Bi-stable levitation-based harvester for accelerations of: (a) 0.1 m/s^2, (b) 3 m/s^2, (c) 6 m/s^2 and (d) 10 m/s^2 [88].

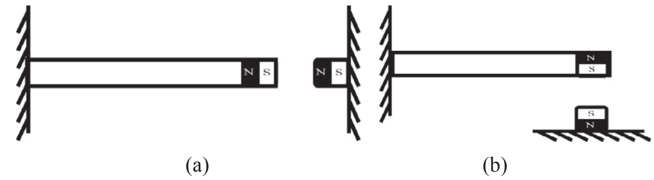


Fig. 18. Commonly found Monostable nonlinear systems: (a) Cantilever with magnetic attraction, (b) Cantilever with magnetic repulsion.

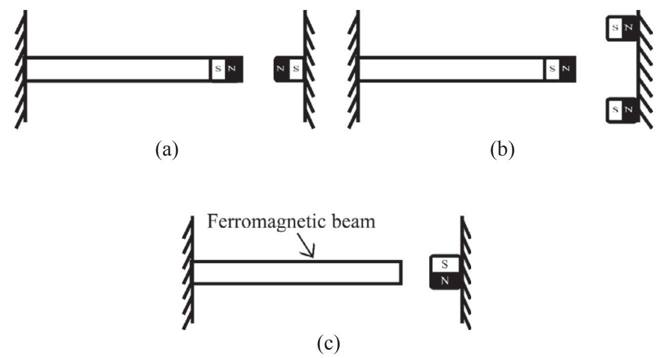


Fig. 19. Commonly found bi-stable systems: (a) Cantilever with single magnetic repulsion, (b) Cantilever with two magnetic attractions, (c) Ferromagnetic cantilever with a single magnet.

hard to implement because of the volume needed for the number of magnets. The basic concept of most commonly found configurations, but not limited to, are presented in Fig. 18 for a monostable nonlinear system and in Fig. 19 for a bi-stable system. The configuration from Fig. 18a exploits magnetic attraction to the equilibrium point of the vibrating structure [102]. The configuration from Fig. 18b exploits magnetic repulsion to the equilibrium point of the vibrating structure [103]. Some works reported the same concept using two fixed magnets above and below the free end of the cantilever [90,99].

For bi-stable systems, the same concept is adopted but with different interactions. In fact, spring forces must repel the seismic mass from the central position either through repulsion [98,101,104] as illustrated in Fig. 19a, attraction to two different equilibrium points [91] as illustrated in Fig. 19b or by exploiting the poles of a single vertically magnetized magnet and a ferromagnetic cantilever [105] as illustrated in Fig. 19c.

The resulted nonlinear force is highly dependent on the distance separating the free end of the cantilever and the opposite magnet. A bi-stable system tends to have a softening response for larger distances [68,105]. The system behavior depends also on the relative positioning and the distance between the cantilever and the external magnets. In fact, it may change from hardening to softening system as reported by Stanton et al. [99]. Their device consists of a piezoelectric beam with magnetic end mass. Two fixed magnets were placed on both sides of the cantilever as shown in Fig. 20a. Their study shows that a hardening response, given in Fig. 20b, arises when the magnets were set behind the end mass. Otherwise, a softening response arises, as given in Fig. 20c.

3.5. Mechanical nonlinearity

Mechanical nonlinearities are based on uncommon architectures to create nonlinear systems. Therefore, they are suited for MEMS devices despite their complexity, so only mechanical forces will be exploited. For a monostable nonlinear system, a M-shaped structure, illustrated in Fig. 21a, have been reported. The nonlinear behavior of such a system depends on its geometrical parameters such as angles and dimensions. Therefore, the M-shaped structure has shown a softening response

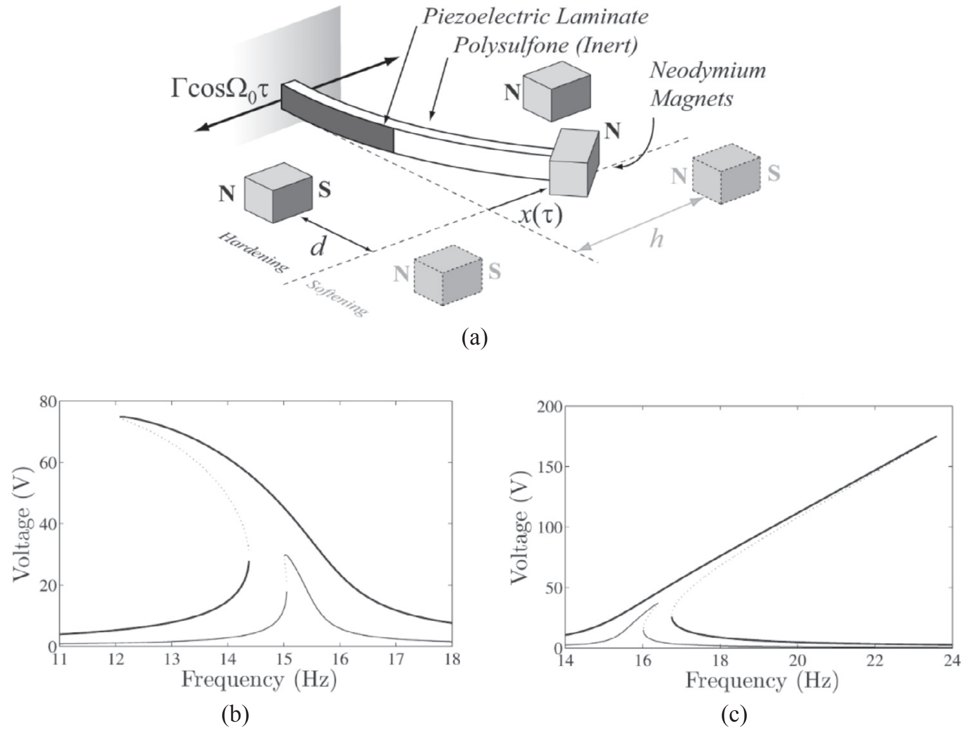


Fig. 20. Nonlinear harvester proposed by Stanton et al. [99]: (a) Schematic of the nonlinear harvester, (b) Hardening response for d = 5, (c) Softening response for d = 2.

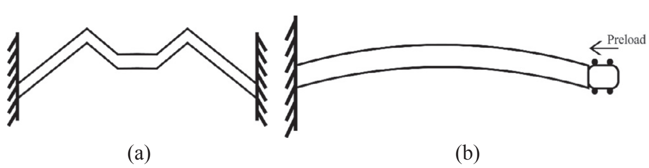


Fig. 21. Mechanical nonlinear architectures: (a) Monostable nonlinear M – shaped architecture, (b) Bi-stable buckled beam structure.

[106] and a hardening response [95]. A buckled beam structure, shown in Fig. 21b can also be used for non-linear systems. When no preload is applied, the system behaves as a monostable system [107,108]. For bistability, the system exploits a preload to impose two mechanical stable points [94,109]. Another less common but efficient solution for mechanical bistability is the use of bistable composite plate [110,111].

The reported bi-stable harvester presented by Masana et al. [109] is a piezoelectric harvester with a clamped–clamped beam and an adjustable axial load. As illustrated in Fig. 22a, when the axial load is below the critical buckling load, the system response is monostable, as shown in Fig. 22b and the resonance frequency of the system can be tuned. When critical buckling load is reached, the frequency response of the system becomes bi-stable as shown in Fig. 22c.

3.6. Amplitude limiter configuration

Another nonlinear method for broadening the operating frequency range is to use an amplitude limiter known as a Piecewise Linear Oscillator (PLO). The basic concept behind is to use mechanical stopper at both ends of the vibrating structure as shown in Fig. 23a. Before reaching its maximum displacement, the vibrating structure strikes the stoppers which cause energy dissipation during impact [23]. Consequently, the linear motion of the EH is dominated by the sudden changes of the spring stiffness and damping during impact between the EH and the stopper resulting in a widened frequency bandwidth [112]. Soliman *et al.* [113] investigated this configuration through analytical and experimental studies. Their results showed a 240% wider bandwidth than that of the same architecture without stoppers as illustrated in Fig. 23b [113]. Despite its efficiency, such systems have fatigue as a major drawback due to mechanical friction during impact.

4. Non-resonant systems

As pointed out, WOF techniques are dedicated to resonant systems. The majority of those systems operate at frequencies above 50 Hz. However, for frequencies below 50 Hz, energy harvesting with resonant systems becomes more challenging. Furthermore, for frequencies below 10 Hz, employing a spring-mass system becomes unrealistic [114]. To address this challenge, researchers have worked on non-resonant systems that do not depend on any specific frequency to operate and can generate relatively higher power at all operating frequencies. Two approaches are considered; Frequency-up conversion FU-C and free moving mass.

4.1. Frequency-Up conversion

FU-C systems have been suggested over the past years as a solution for harvesting from low frequencies. They combine a Low-Frequency System (LF-S) and a High-Frequency System (HF-S). When a low-frequency excitation occurs, energy is absorbed by the LF-S and then transferred to the HF-S to be converted into electric energy. However, a relatively high amplitude of excitation is needed in order to have an interaction between the LF-S and the HF-S. Numbers of designs and techniques have been proposed for FU-C [114–117]. We propose a categorization for these techniques based on the structure of the LF-S. Therefore, we can identify resonator-based FU-C and Free moving mass-based FU-C.

4.1.1. Resonators-based FU-C

In a resonator-based FU-C system, the LF-S and HF-S are resonant systems. In most of the case, they are vibrating beams with relatively high and low inertial mass, respectively. Energy can be transferred from LF-S to HF-S through direct impact [58,116,117] as illustrated in

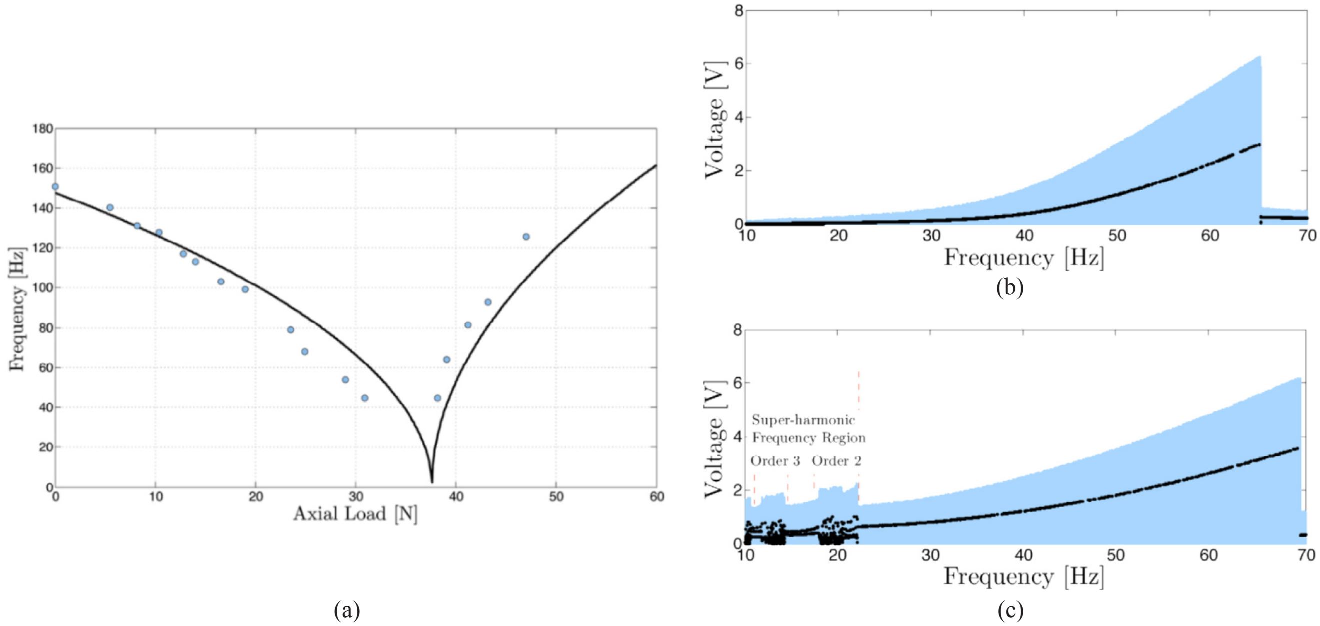


Fig. 22. Buckled beam harvester with axial load proposed by Masana et al. [109]: (a) Frequency versus axial load- curve, (b) Frequency response of the system when being monostable, (c) Frequency response of the system when being bi-stable.

Fig. 24a or magnetic interaction [115,118,119] as illustrated in Fig. 24b. Therefore, the maximum displacement of the LF-S seismic mass and the distance between the two systems must be taken into consideration for the interaction to happen.

The advantage of such a system is that energy can be maximized, given that each LF-S and HF-S is a resonant system, when the excitation resonance frequency matches the resonance frequency of one of the systems. This behavior can be observed in the frequency response of such systems. The FU-C harvester presented by Liu et al. [116] consists of two piezoelectric cantilevers as illustrated in Fig. 25a. The first is a low-resonant-frequency of 36 Hz cantilever (LRF), and the second is a high-resonant-frequency of 618 Hz cantilever (HRF). Both piezoelectric materials are then connected in series for energy harvesting measurement. As illustrated in Fig. 25b, for an acceleration of 0.1 g, the frequency response of the system is similar than a resonant linear system at the resonance frequency of the LF-S. For higher amplitudes of acceleration, the interaction between the two systems is more likely to happen, therefore, the system responds to lower frequencies and have a broadened bandwidth.

4.1.2. Free moving ball-based FU-C

In a free moving ball-based FU-C system, the LF-S is replaced by a free moving ball. When an excitation occurs, the kinetic energy is transferred to the free-moving ball. The ball then hits a vibrating system that converts the impact into electric energy. This approach has been proposed by Halim *et al.* [114]. Their device, illustrated in Fig. 26a, consists of a tube with two spring-magnet systems at its extremities and a nonmagnetic ball moving inside. The two spring-magnet systems with the two coils wrapped around the tube form two EM transducers denoted as Frequency-Up Generator (FUG). When the ball moves in response to an external excitation, it hits the magnets of the FUGs resulting in their vibration. The relative motion of the magnet within the

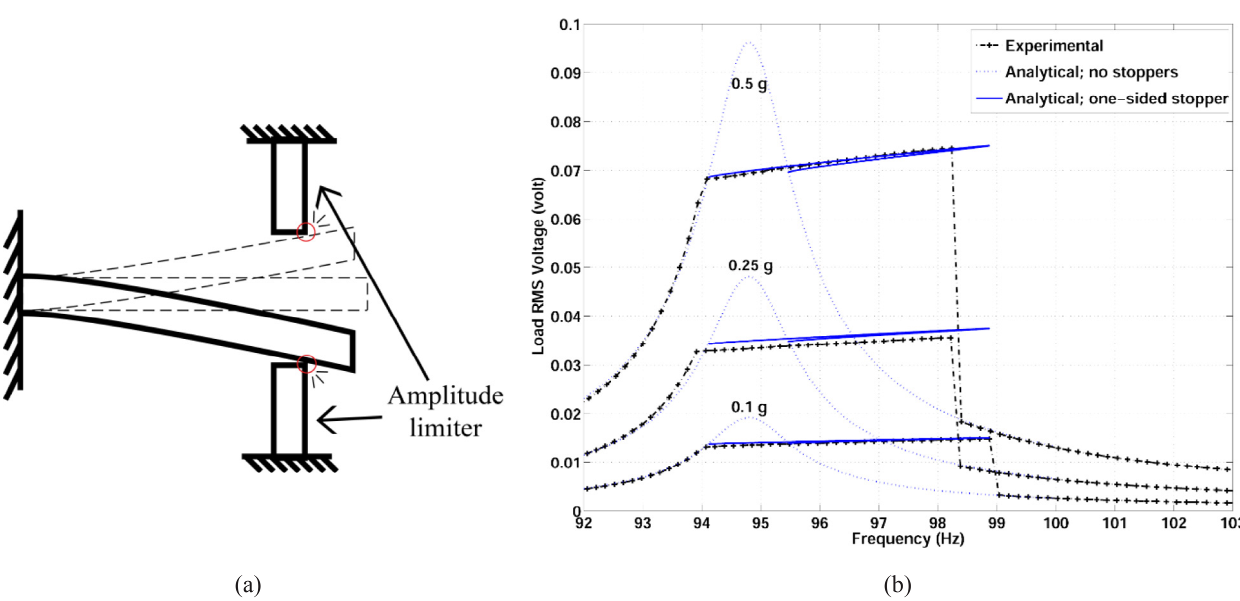


Fig. 23. PLO harvester proposed by Soliman et al. [113]: (a) Amplitude limiter general configuration, (b) Frequency response.

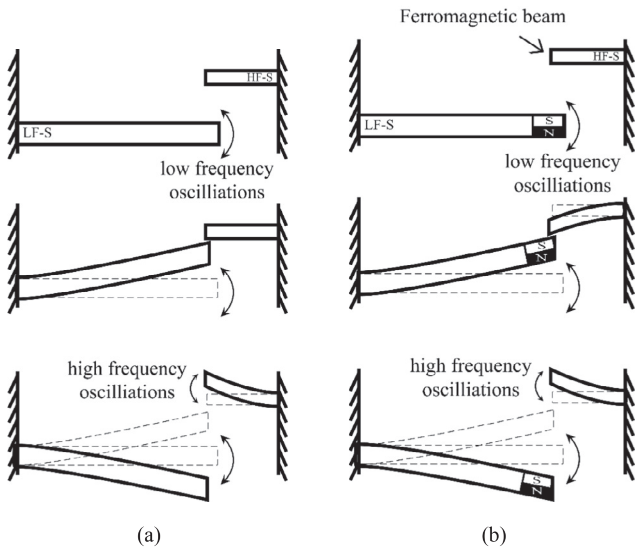


Fig. 24. Schematic design of : (a) FU-C with direct impact, (b) FU-C with magnetic interaction.

coils generates electric energy. The frequency response of the system, given in Fig. 26b, shows the non-reasoning behavior of the system. The generated voltage of the FUGs is almost constant with an average value of 1.88 V.

4.2. Free moving mass

Even though FU-C systems are non-resonant systems dedicated to low-frequency harvesting, they require at least one resonating structure for transduction. Free moving mass harvesters are entirely non-resonant which principle is mainly based on the arbitrary motion of a mass. Such systems are less found in literature, but they are particularly interesting for harvesting from very low frequencies bellow 10 Hz such as human-induced motions characterized by large-amplitude, unpredictable and time-varying motions. In addition, these techniques also imply a 3D harvesting since the arbitrary movements of the mass are in general multidirectional, but without any resonance frequency.

4.2.1. Free moving object

These harvesters consist generally of a free moving object that can be attached by a rope [120], a rod [121] or rolling inside a cage as reported by Bowers et al. [62]. This latter system consists of a rolling magnetic ball inside a spherical cage surrounded by a coil. In response to an external motion, the ball will roll inside the cage causing a magnetic flux variation through the coil. Two different prototypes were tested, the first consists of a single coil wrapped around the center of the spherical cage, and the second, shown in Fig. 27a, utilizes two counter- wounded coils connected in series. Many parameters have been taken into consideration when designing the system such as the number of coil turns, the cavity diameter and the ball to cavity diameter ratio. All experiences were made when walking or running while holding the device in hand or in the pocket. Fig. 27b illustrates the recorded Power Spectral Density (PSD) of the second prototype when running. It shows that even though accelerations peaks where in the 1–15 Hz, output voltage dominant frequencies were in the range of 5–25 Hz. During testes, a peak voltage of 700 mV has been noted while running with the second prototype in the pocket.

4.2.2. Free moving liquid

As mentioned in section 2.3, ferrofluid can respond to infinite closely spaced modal frequencies which can enhance the harvester's performance under random and non-stationary excitations. Therefore, the use of ferrofluidic mass for very low frequencies has also been investigated [57,66]. The harvester proposed by Kim *et al.* [66], shown in Fig. 28a, is a closed-loop magnetic circuit consisting of two permanent magnets, a ferromagnetic core wrapped by a coil and a 300 ml- container filled with ferrofluid. The sloshing of the ferrofluid in the container when an excitation occurs changes the magnetic flux across the ferromagnetic core, which creates an induced current in the coil. Experimental tests were made under different conditions related to the ferrofluid volume and the magnetic flux density, for excitation frequencies below 5 Hz. Fig. 28b shows that the highest generated voltage is noted for a ferrofluid volume of 1/2 of the overall container volume. Another test shows that the generated voltage is reduced for higher magnetic induction since it reduces the sloshing of the ferrofluid which in turn reduce the magnetic flux variation. The characterization results show that a peak voltage of ~ 14 mV has been generated for a vibration frequency of 5 Hz.

5. Multi-directional harvesting

In general, a harvester is designed to harvest from motions in a unique direction. However, given the three-dimensional nature of motions, harvesting from different directions is another improvement that can be considered when designing a harvester. It's important to notice that excitation form improvement techniques can be combined with multi-directional harvesting systems. Many researchers have been

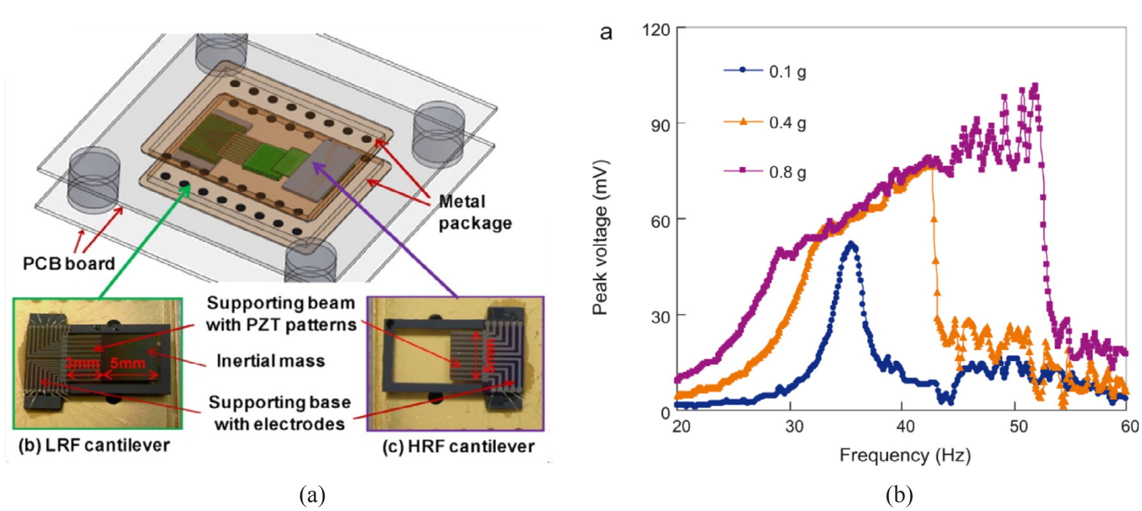
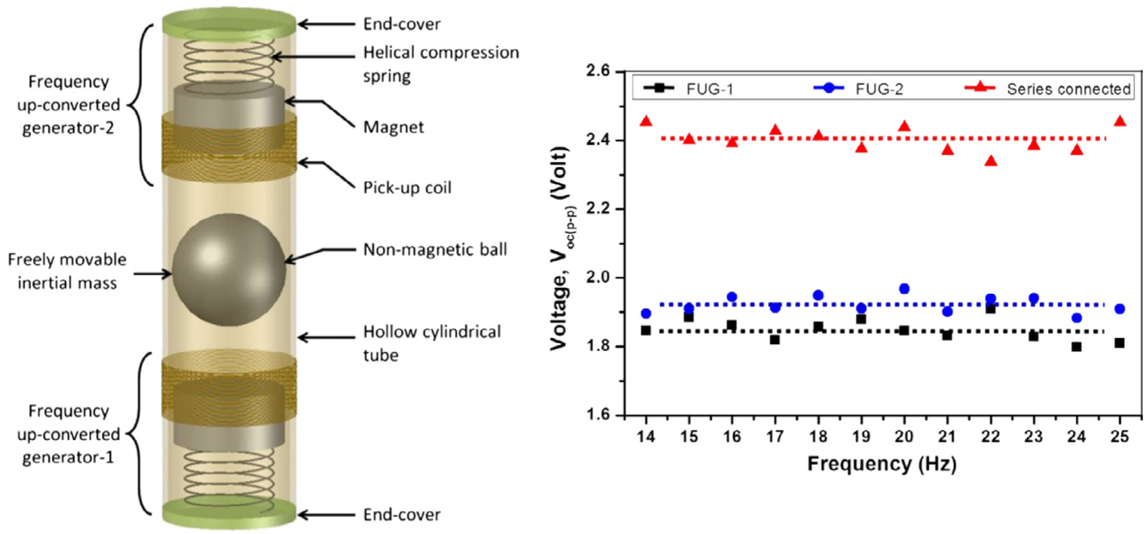
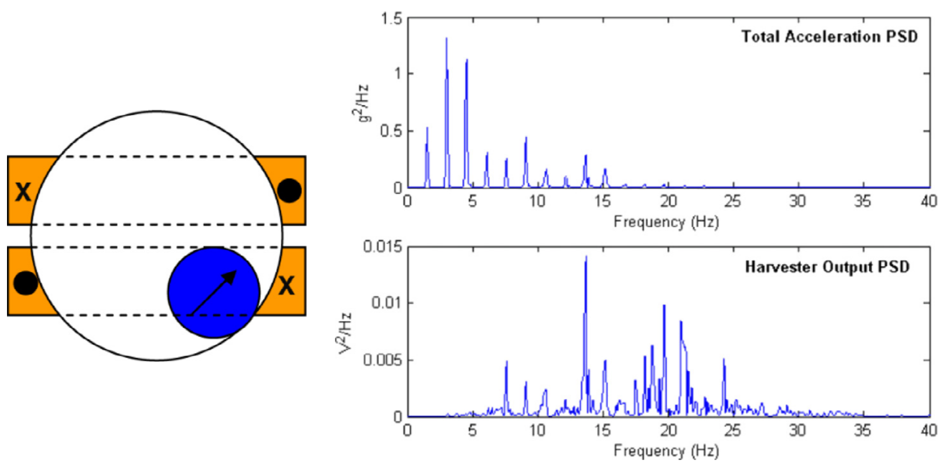


Fig. 25. FU-C proposed by Liu et al. [116]: (a) Schematic drawing of the device, (b) Frequency response.



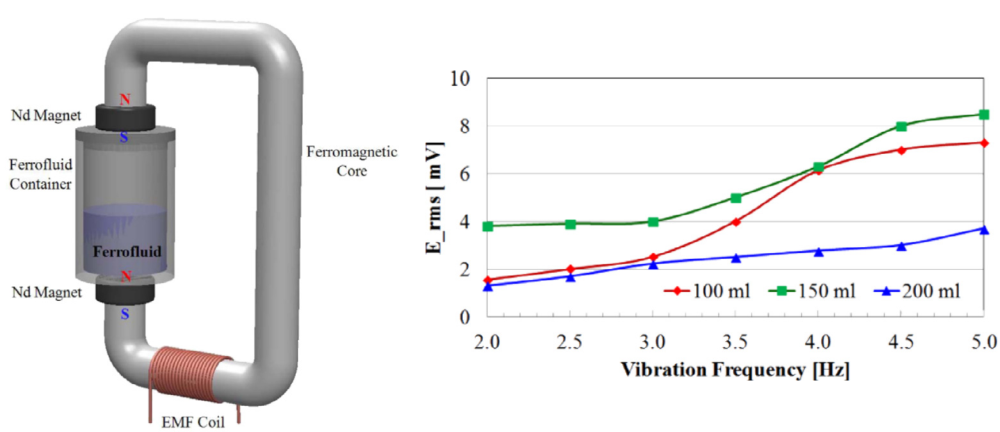
(a) (b)

Fig. 26. FU-C proposed by Halim et al. [114]: (a) Schematic structure, (b) Frequency response.



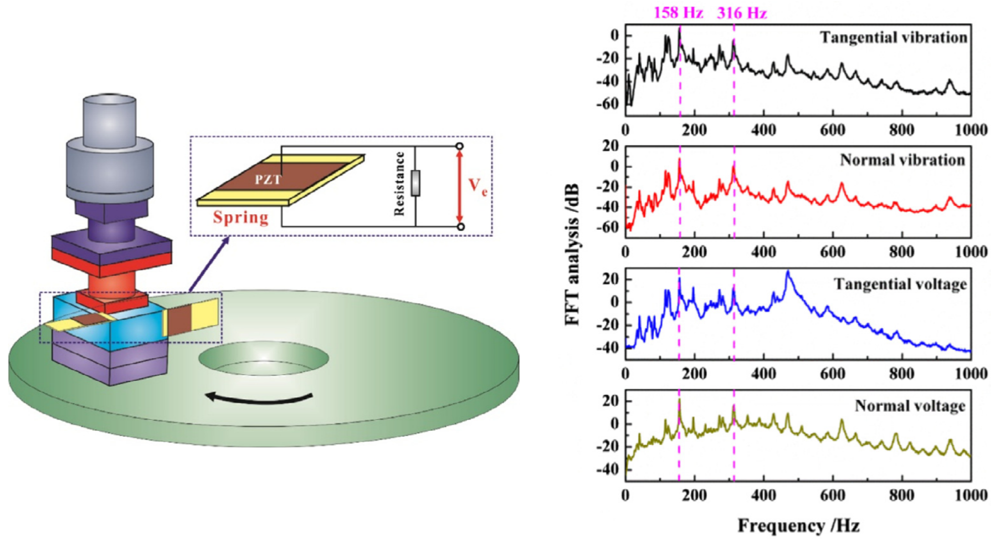
(a) (b)

Fig. 27. Harvester with a rolling ball proposed by Bowers et al. [62]: (a) Schematic structure, (b) Power Spectral Density (PSD) under running condition.



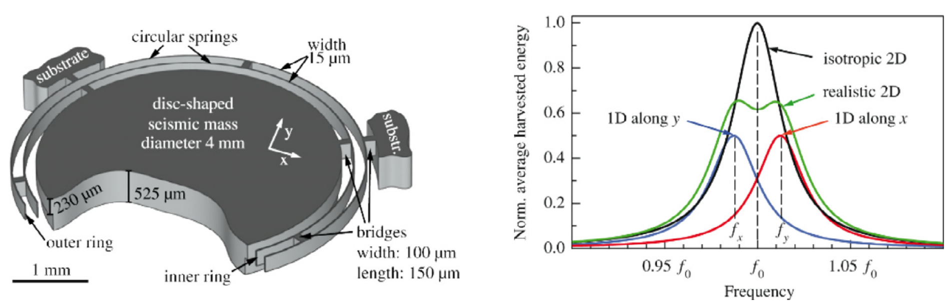
(a) (b)

Fig. 28. Ferrofluid based EM harvester proposed by Kim et al. [66]: (a) Schematic structure, (b) Frequency response for different ferrofluid volumes.



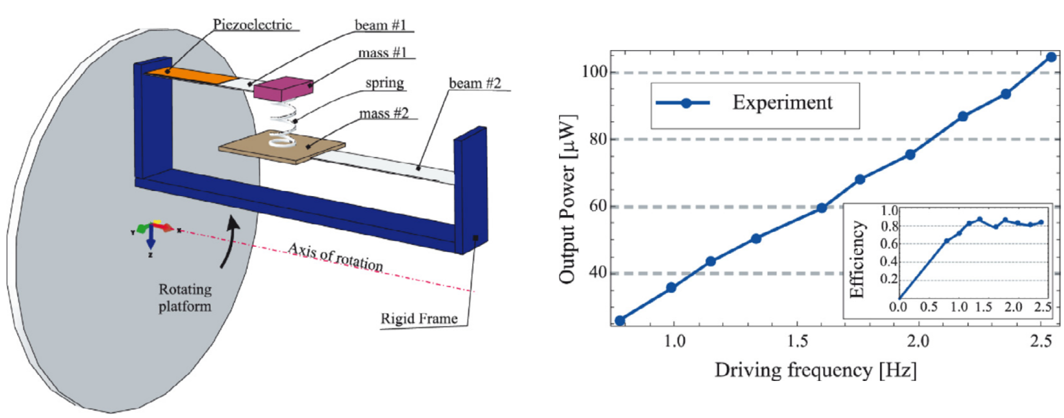
(a) (b)

Fig. 29. 2D harvester proposed by Wang et al. [124]: (a) Schematic structure, (b) FFT analysis.



(a) (b)

Fig. 30. 2D-IP resonator proposed by Bartsch et al. [125]: (a) Schematic diagram of the proposed structure, (b) Theoretical effectiveness for energy harvesting.



(a) (b)

Fig. 31. Rotating harvester proposed by Febbo et al. [126]: (a) Schematic structure, (b) Frequency response.

working on multi-directional designs. Therefore, we will present different harvester prototypes found in literature based on their design techniques that could be classified as bi-dimensional 2D and tri-dimensional 3D technique.

5.1. 2D harvesting

5.1.1. Perpendicular springs

The simplest technique for designing a bi-directional harvester is the use of two perpendicular springs that can be cantilevers [122] or magnetic springs [123]. Such a system is simple to design and implement since it can be considered as two individual 1D harvesting systems with different orientations. Wang *et al.* [124] proposed to harvest from Friction Induced Vibrations (FIV). Their device, shown in Fig. 29a, consists of two piezoelectric cantilevers mounted on the pad of a braking system to harvest from both normal and tangential vibrations. Fig. 29b shows the Fast Fourier Transform (FFT) of the resulting vibration and voltage signals generated due to braking along the

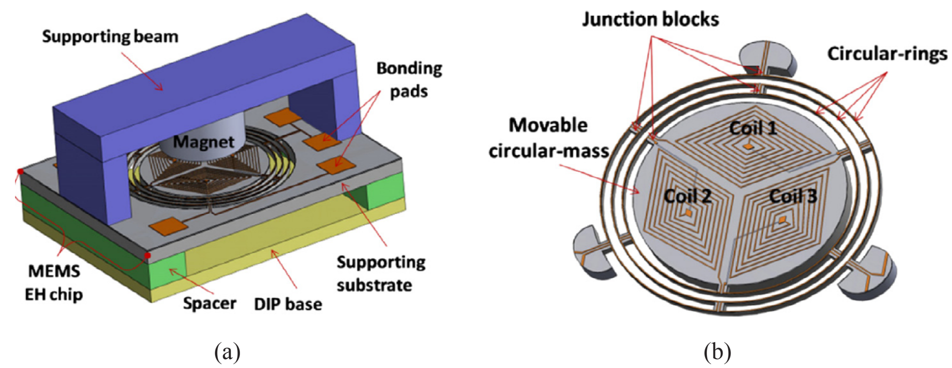


Fig. 32. 3D harvester proposed by Liu et al. [59]: (a) Schematic design of the device, (b) Schematic design of the MEMS structure.

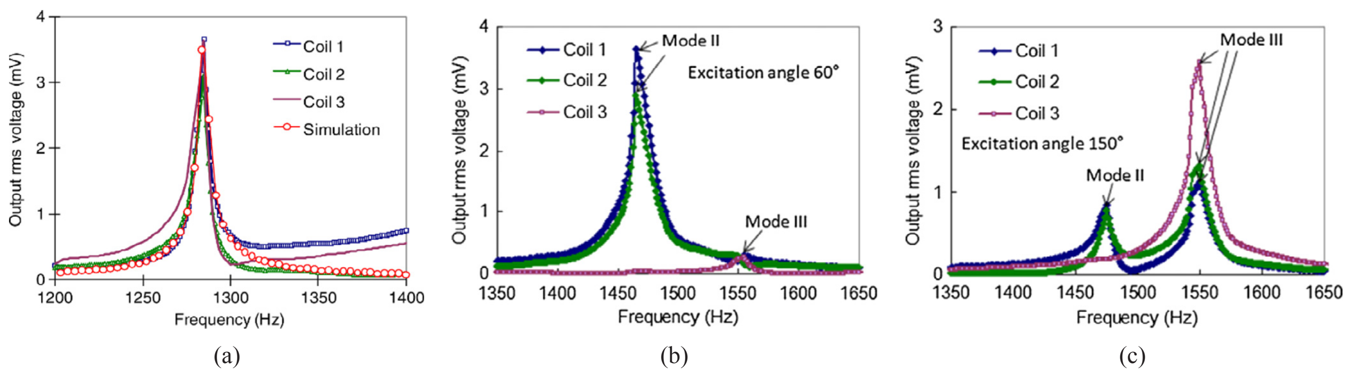


Fig. 33. Frequency response [59] for (a) out of plan excitation, (b) in plan excitation with angle 60° outward x-axis, (c) in-plan excitation with angle 150° outward x-axis.

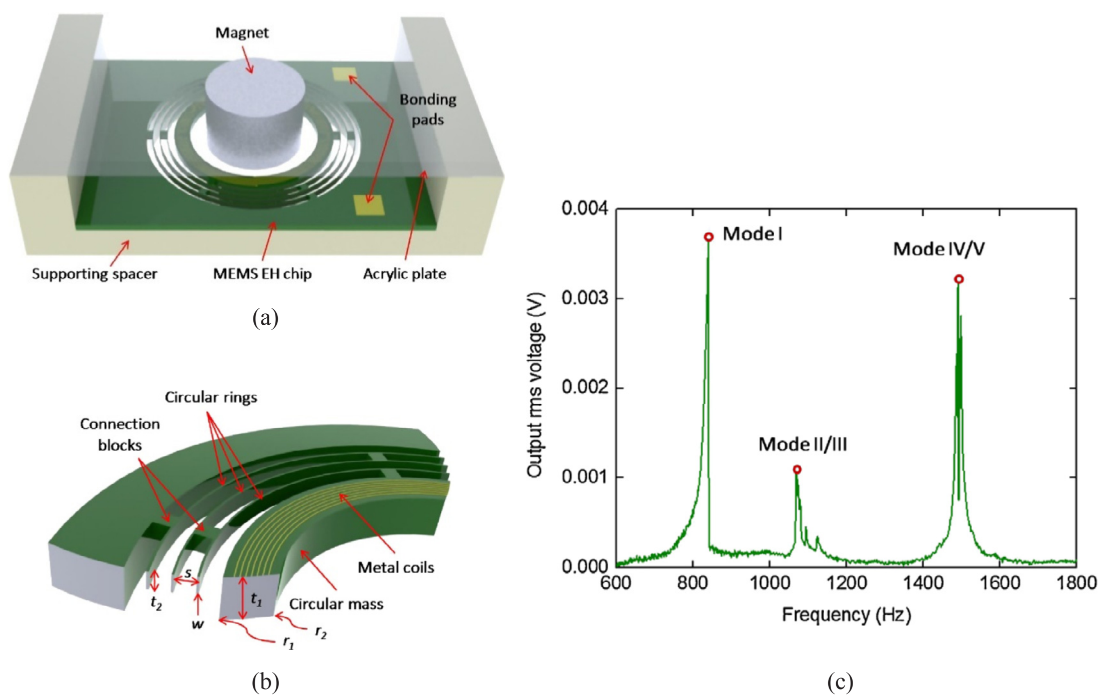


Fig. 34. 6 DoF harvester proposed by Liu et al. [127]: (a) Schematic design of the device, (b) Schematic design of the MEMS structure, (c) Frequency response.

tangential and normal axis. We can identify two peaks at frequencies 158 and 316 Hz meaning that the system was able to harvest energy from both directions. Different tests have been made under different conditions related to the velocity of the turning disc and the damping factor of the brakes. A maximum generated peak voltage of 6 V from the tangential direction and 5.5 V from the normal direction was noted.

5.1.2. 2D in-plane

2D in-plane (2D-IP) movements require more complex design but are more suitable for MEMS integration. In fact, such systems are based on a seismic mass attached by very flexible mechanical springs that allow having 2 degrees of freedom in-plane. Such design, proposed by Bartsch *et al.* [125] and shown in Fig. 30a, consists of a disk-shaped

Table 3
Harvesters optimization techniques summary: advantages / drawbacks and applicability in MEMS technology. *(- : Rare, +: Possible, ++: Common, in literature) **(^{2}: bi-stable systems).

	Technique	Basic Concept	Advantages	Drawbacks	For Piezoelectric*	For EM*	In MEMS*
Frequency Tuning	Geometrical tuning	Adjusts some geometrical parameters of the system to tune its resonance frequency	- Simple design - Damping is not affected - Fine-tuning before installation	Geometrical change may not be applicable for in situ tuning	++ [70,71]	++ [72]	-
	Applying a preload	Applies an axial preload to the beam to reduce its stiffness.	- Simple design - Larger effective operating region - Suited for in situ tuning	- Affects damping - Delicate for fine-tuning	++ [74,75,128]	+	-
	Variable stiffness tuning	Adds a magnetic stiffness to the system	- Simple design - Suited for in situ tuning - Easy to implement	- Added magnet reduces resonance power - Unpredictable nonlinear behavior may occur	++ [79,129]	++ [129–131]	-
	Extensional mode	Uses extension deformation and adjust the distance between the vibrating beams.	- Larger effective operating region	- Complex design - Delicate for fine-tuning	++ [76,132]	-	-
Multi-frequency	Cantilevers array	Uses an array of individual generators each with its own resonance frequency.	- Simple design - Frequency spectrum can be uniform	- Increased total volume	++ [100,133]	++ [80,100]	++ [80,133]
	Multimodal system	Uses more than one seismic mass to have different vibration modes with different resonance frequency.	Multi-frequency	- Complex design - Increased total volume - Non-uniform frequency spectrum	++ [81,134]	++ [81,135,136]	++ [137]
Nonlinear system**	Levitation based system	Uses magnetic repulsion to keep a magnet in levitated oscillations	- Simple design - Low-frequency harvesting - No mechanical friction	Closed enclosure for the harvesting system is required	-	++ [24,138,139] [88]^2	-
	Vibrating beamwith magnetic interactions	Exploits nonlinear magnetic forces to change the dynamics of a vibrating structure.	Frequency response can be adjusted	- Complex design - Increased total volume	++ [93,100,103] [85,140–142]^2	++ [93,100,143]	-
	Mechanical nonlinearity	Uses preloaded clamped–clamped structure for nonlinearity.	- Possible for frequency tuning with preload configuration - No external systems are needed	Complex design	++ [95,144] [109–111]^2	++ [95,144]	++ [106]
	Mechanical stopper	Add mechanical stopper to instantly change the damping and the stiffness of the system at the impact.	Simple design	- Lost energy due to mechanical impact - Risks of mechanical impact fatigue	++ [96]	++ [113]	+
FU-C	Resonators-based	A low frequency resonant system absorbs the excitation energy and transfers it to a high frequency resonant system.	- Simple design - Wide bandwidth	- Increased total volume - Risks of mechanical impact fatigue	++ [115–117,145]	++ [58,119]	++ [116,119]
	Free moving ball-based	Exploits a moving ball to transfer energy to a vibrating structure.	- Simple design - Harvesting from arbitrary motion.	- Increased total volume - Non-uniform frequency spectrum	-	++ [114]	-
Free moving mass	Free moving object	Uses a suspended mass or a free rolling ball inside a cage.	- Simple design - Relatively high generated power	Unpredictable movements of the ball	++ [120,121]	++ [62]	-
	Free moving liquid	Uses ferrofluid motions to vary the magnetic field across a coil.	- Simple design - Detects infinitely low displacement	Low generated power	-	++ [57,66]	-

(*continued on next page*)

Table 3 (*continued*)

	Technique	Basic Concept	Advantages	Drawbacks	For Piezoelectric*	For EM*	In MEMS*
2D harvesting	Perpendicular springs	Uses two perpendicular springs to detect excitation from two different directions	- Simple design - 2D harvesting - Resonance frequency for each direction is controlled individually	Two non-planed structures	+ + [122,124,140]	+ + [123]	+
	Rotational movement	Uses a rotating structure that can harvest from in-plane excitations and rotational movement.	- 2D harvesting - Harvesting from rotational motions	- Complex design - Not suited for 2D non-rotational motion	+ + [115]	+ + [61,130,146]	+
	2D-IP movement	Circular design that allows 2D in-plane movements of the seismic mass	- 2D harvesting - Unique planned structure	- Complex design - Resonance frequencies are coupled	+ + [147]	+ + [148]	+ + [125]
3D harvesting	2D-IP + OP movement	Circular design that allows 2D in plane and out plane movements of the seismic mass	- 3D harvesting - Unique planned structure	- Complex design - Resonance frequencies are coupled	+	+ + [59,127]	+ + [59,127]

seismic mass suspended by two concentric rings. These latter were connected to each other by nine bridges to form a thin circular-shaped springs. The bridges distribution between the rings and the seismic mass allows 2D in-plane movements. In the work, they discussed the effectiveness of their structure for extracting energy from an external driving oscillator. They proved that for isotropic spring material (i.e. x- and y-axis resonance frequencies are equal) the normalized average harvested energy is the double than harvested from 1D system. In realistic case, due to the material anisotropic properties, resonance frequencies along both axes are not equivalent, so the average harvested energy is reduced but is still more effective than 1D harvesting.

5.1.3. Rotational movement

A pendulum and rotational movements can also be considered as 2D harvesting system, and have been investigated particularly for rotating machines and car tires. The harvester proposed by Febbo *et al.* [126] consists of two beams facing each other, with two masses on their tip related by a spring, in addition to a piezoelectric layer deposed on one of the beams. The system is then mounted on a rotating platform as shown in Fig. 31a. The latter takes advantage of the gravitational force to oscillate. Therefore, when rotating, the mass in the bottom position pulls the second, and then the roles will be alternated during a cycle. The harvester was mainly dedicated to low-frequency rotations. A maximum harvested power of 104.74 µW was observed for a rotating frequency of 2.54 Hz (Fig. 31b).

5.2. 3D harvesting

3D harvesting systems are the least found in the literature. In fact, the possibility for a unique device to harvest from all the directions with relatively important generated power is still a technological area that few researchers have investigated. Nonetheless, for the few found harvesters, we can classify them into non-resonant free moving mass systems and 2D-IP + OP movements structures. The free moving mass systems have been investigated in section 4.2. Therefore, we will present in this section the prototypes found for 2D-IP + OP movements systems.

2D-IP + OP systems are an improvement of 2D-IP ones that involves adding a third degree of freedom along the z-axis. Therefore, they can also be integrated using MEMS technology, but are complex to design. Liu *et al.* [59] presented the first 3D harvester that could harvest energy from tri-directional motion. Their device, shown in Fig. 32a, consists of a permanent magnet attached to a supporting beam placed above a MEMS vibrating structure shown in Fig. 33b. The MEMS structure is an improved 2D-IP system. It consists of a moveable circular seismic mass, with three coils printed on the surface, suspended by three concentric rings. The mass and the rings are interconnected by a series of bridges. The seismic mass was able to oscillate in three modes. Mode I correspond to an out of plan oscillation along the z-axis with a resonant frequency of 1216 Hz. Mode II and III correspond to in-plane oscillations with resonant frequencies of 1479 and 1522 Hz along y-axis and x-axis respectively. The frequency responses for each coil are given in Fig. 33 (a, b and c) for an out-of-plane excitation and two in-plane excitations with direction angles of 60° and 150° outward from the x-axis.

Some authors, Liu *et al.* [127] proposed also an improved structure of their device shown in Fig. 34a. The system exhibits 6 degrees of freedom (DoF) allowing 3D translation and rotational movements. Similarly, it consists of a permanent magnet suspended from a supporting beam above a vibrating MEMS structure. For this system, the seismic mass of the MEMS structure, shown in Fig. 34b, consists of a disk with an inner radius that allows the magnet to fit inside. The metal coil patterned on the seismic mass consists of 7 winding cycles of wires. The circular mass exhibits 5 vibration modes. Mode I corresponds to an out-of-plane oscillation along the z-axis with a resonant frequency of 988 Hz. Mode II and III are torsion vibrations along the x- and y-axes,

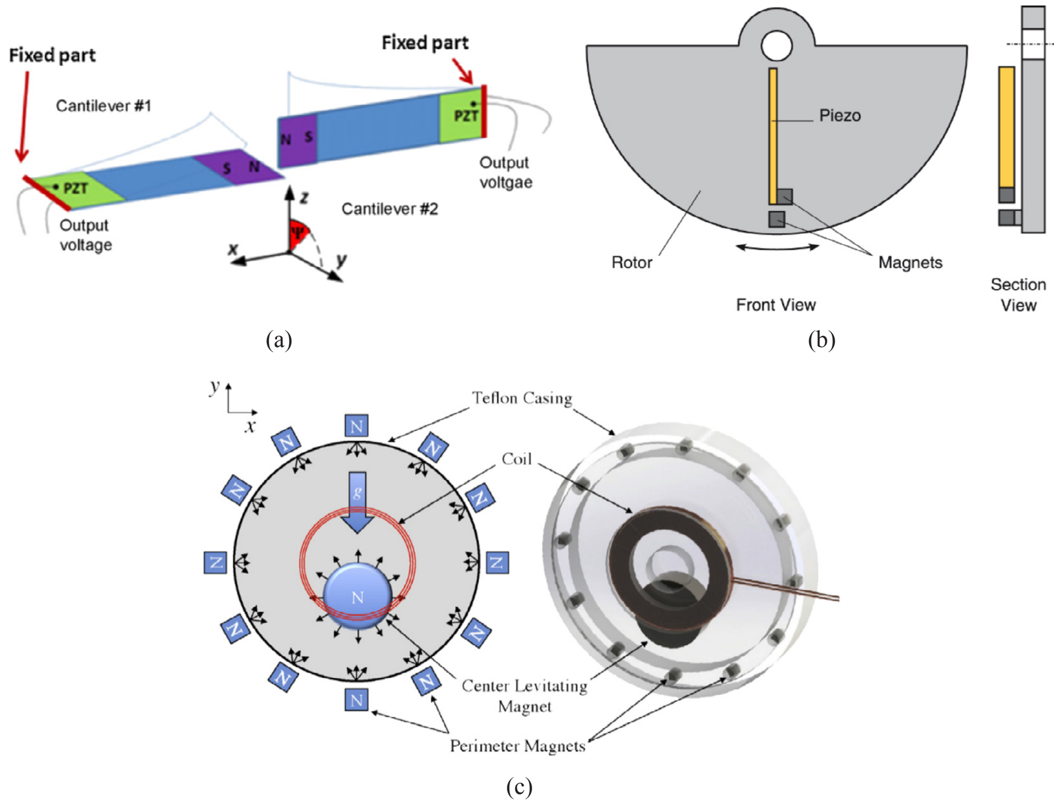


Fig. 35. Combined improvement techniques (a) Bistable 2D harvester proposed by Ando et al. [140], (b) Rotating FU-C system proposed by Pillatsch et al. [115], (c) 2D-IP levitating-based harvester proposed by Gutierrez et al. [148].

with resonant frequencies of 1333 and 1355 Hz, respectively. And Mode IV and V correspond to in-plane oscillations along the *x*- and *y*-axis, with resonant frequencies of 1494 and 1513 Hz, respectively. The device was tested for an acceleration of 1 g. The frequency response of the system, given in Fig. 34c, shows three voltage peaks of 3.7, 1.1 and 3.2 mV at resonant frequencies of 840 Hz that correspond to the vibration mode 1, 1070 Hz that correspond to modes 2 and 3 and 1490 Hz that correspond to modes 4 and 5.

6. Applicability of investigated techniques

All improvements mooted by all presented techniques have one common aim, which is increasing generated power. Along the paper, these improvement designs and techniques have been categorized according to the improved aspect. Indeed, the excitation form plays an important role in determining the frequency spectrum of the harvesting system, while the excitation direction defines the orientation from which the system can harvest energy. To improve system frequency response, the designer can act either to widen the operating frequency band (WOF); or to conceive a non-resonant system (NR) allowing to harvest from low-frequency vibrations. Applying WOF techniques is more appropriate in cases when the excitation has a dominant frequency known beforehand. The improved system can operate with a tunable resonant frequency, multiple resonant frequencies or an enlarged bandwidth. On the other hand, achieving a non-resonant system technique is more suitable for harvesting from unpredictable low-frequency motions. Two approaches are feasible namely frequency-up conversion and free moving mass system. As for the second aspect, it can be improved when achieving a multi-directional harvester (MDH). Since the majority of harvesting systems are excited only from one direction, therefore, 2D and 3D harvesting techniques can be advantageous in cases when the excitation is not unidirectional. It is worth to note that 2D harvesting is more retrievable in literature than 3D harvesting. From the literature, we identified three useful techniques consisting of designing perpendicular springs, 2D-IP and rotating systems. 3D harvesting system is the least found in the literature and can be considered as the most complex improvement in term of excitation direction.

Beside the desired improvement brought by each technique, a key aspect that must be taken into consideration is the applicability of these techniques for different systems. In our classification, two constraints will be considered namely transduction type and dimensions. Table 3 summarizes the pros and cons of all investigated techniques, their applicability for Piezoelectric and EM transductions and the possibility of integration in MEMS devices. Even though most of the techniques are suited for piezoelectric and EM transduction, some techniques are more dedicated to specific transduction. In frequency tuning techniques, the Extensional mode puts the cantilever under extensional strain for piezoelectric harvesting. Therefore, such a system cannot be applied for EM harvesting. Generators array techniques can be applied both for piezoelectric and EM harvesting. For nonlinear system techniques, the levitation-based system exploits magnet movement with no mechanical deformation; therefore, it cannot be used for piezoelectric harvesting. Non-resonant systems exploit in most of the case a moving magnet except for the resonators-based FU-C that can also be used for piezoelectric transduction. Multi-directional harvesting techniques have been used both for piezoelectric and EM harvesting except for 2D-IP + OP movements that were EM harvesters.MEMS integration has a dimension constraint. In fact, all investigated techniques are suited for mesoscale systems. However, not all of them can be integrated with MEMS technology. Therefore, for applications where the dimension of the system is imposed on a microscale, a prior investigation of the applicability of the technique to be used is needed. For MEMS, frequency tuning techniques cannot be applied since they require an adjustment after fabrication which is unrealistic for MEMS. Generators array techniques and nonlinear systems have both been reported for

MEMS system except for levitation based system that is based on a moving magnet inside a tube which is also unrealistic for MEMS. For non-resonant systems, only the FU-C can be integrated into MEMS. In fact, it is obvious that free movements are not possible in microscale. All of the multi-directional harvesting techniques are integrable in MEMS but requires a complex design and microfabrication process.

In addition, it is worth to mention the possibility to combine MDH with WOF techniques leading to a multi-directional with a widened frequency range. Ando *et al.* [140] proposed a system, shown in Fig. 35a, that combines perpendicular springs with magnetic repulsion for bi-stable 2D harvesting system. Therefore, not only the system was able to harvest from two different directions, but also, each cantilever has a broadened bandwidth and power harvested was 10 times more compared with the linear system. A similar 3D system with three springs was reported by Su *et al.* [149]. The system proposed by Pillatsch et al. [115], shown in Fig. 35b is a rotating FU-C system. It consists of an eccentric inertial mass that carries a permanent magnet and that is free to rotate around its axis. A vertical piezoelectric beam with a magnet at its free tip is fixed on the outer case. When the eccentric mass rotates, the beam is deflected due to magnets attractions. And when it is released it oscillates at its resonance frequency. In most experiences, power outputs were in the range of tens of microwatts. Particularly, for frequencies around 2 Hz, the device achieved a peak power output of 43 μW. Gutierrez *et al.* [148] proposed a levitation based 2D-IP movement system illustrated in Fig. 35c. An axially magnetized disk lies on a circular 2D planed cage with freedom of radial movement. Stationary magnets distributed along the sidewall of the cage provide a repulsive magnetic spring force to keep the magnet to an equilibrium position in the center of the circular structure. For energy harvesting, a coil is displaced above the magnet on one side of the system. Since there is no mechanical deformation that causes anisotropic behavior, resonant frequencies along the *x*- and *y*-axis are equivalent and have been tuned to 8.2 Hz. Their results show a power peak of 41 and 101 μW has been generated for an input excitation of 8.2 Hz with 0.1 g and 0.2 g acceleration, respectively.

7. Conclusion

Technology evolution has mostly been driven by present world issues. Nowadays, battery dependency is raising more concerns, and the necessity for a solution to reduce their number or improve their lifespan has grown. Therefore, works for improving energy harvesting have increased considerably. Among energy sources, mechanical energy is the most investigated form of energy. Innovative designs have been made to increase harvested power and improve system efficiency. Although most common technics have been investigated, some concepts are missing in most reviews. In this paper, we firstly presented main transduction techniques with emphasis on piezoelectric and EM transductions. Thereafter, we presented a new categorization of available design technics based on improvement aspects of the harvester. Along with widening operating frequency techniques, this categorization allowed to point out two overlooked improvement techniques that consist in conceiving non-resonant systems and multidirectional harvesting. To conclude this work, we studied the applicability of presented techniques for different cases. Two constraints were considered that are possible transduction and integration in MEMS devices. In addition, the possibility of combining two or more techniques in a unique system was explored with different cited examples.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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