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Ultra-low frequency vibration energy harvesting: Mechanisms, enhancement techniques, and scaling laws

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ABSTRACT

With the increasing demand for clean and sustainable energy, self-powered technologies based on environmental vibrations have attracted a lot of attention recently. Natural vibration sources, exemplified by ocean waves, tall buildings swaying, flow-induced vibrations, human motions, etc, offer abundant energy which usually exhibits ultra-low frequency characteristics. This paper provides a state-of-the-art review on ultra-low frequency vibration energy harvesters and corresponding enhancement methods. Existing designs, underlying principles and associated energy conversion mechanisms are reviewed. Due to the low energy conversion efficiency when the harvesters are directly excited by ultra-low frequency vibrations, enhancement methods are essential. Various issues like principle-based structural optimization, transducer property improvement and combination of hybrid harvesters are discussed. Scaling laws of harvesters, existing challenges and future prospects are presented in view of promoting the development of ultra-low frequency vibration energy harvesters.

1. Introduction

1.1. Background

Vibration energy harvesting triggers increasing and vast attention owing to its potential applications in various self-powered systems, such as structure healthy monitoring systems with low-powered electronics networks, vibration feedback control systems with microcontrollers, emergency powering systems for major disasters or outdoor survivals, etc. As listed in Ref. [1], abundant energy exists in natural sources: vibration, thermal energy and radio frequency waves. In particular, some of vibration energy sources in the natural environment feature low frequencies and large amplitudes, which can be produced by ocean waves [2], tides [3], wind flow [4,5], human motions [6,7], etc.

1.1.1. Ultra-low frequency definition

The range of the so-called low frequency vibration has been loosely defined in the literature depending on applications. For example, Chen and Liu [8] set the range of 20–200 Hz as the low frequency ranges when investigating friction dynamics of vehicle brake systems, while the range of 2–80 Hz was defined as the low frequency range by Thompson [9] when studying the railway noise and vibration. As a rule of thumb, the range from 10 Hz to several hundred Hz can generally be regarded as the low frequency range as far as energy harvesting is concerned.

For the ultra-low frequency definition, Hayakawa et al. [10] limited the maximum frequency to 10 Hz when analyzing geomagnetic variations associated with earthquakes. Other related research, on both vibration isolation and energy harvesting, also widely followed this convention. When conducting vibration isolation, quasi-zero-stiffness (QZS) is usually utilized to achieve the ultra-low frequency excitation. For example, Zhang et al. [11] proposed a nonlinear isolator with the effective working frequencies ranging from 1 Hz to 10 Hz; Wang et al. [12] tested a QZS isolator under the sweeping sinusoidal excitation within the frequency range of 2–15 Hz. The functional frequency range of the QZS structure is typically below 10 Hz, which is also roughly the range targeted by ultra-low frequency energy harvesting. More specifically, Wu et al. [13] proposed a pendulum-like piezoelectric energy harvester (PEH), which provides the peak output power at 2.03 Hz. Shi et al. [14,15] designed rolling ball driven zigzag PEHs working at 3 Hz and 0.9 Hz, respectively. Fan et al. [16] proposed a hybrid harvester combining an electromagnetic energy harvester (EMEH) and two PEHs, with the working frequency range also below 10 Hz. Therefore, it is commonly accepted that the frequency range below 10 Hz is the typical metric to designate the so-called ultra-low frequency range in the field of vibration energy harvesting.

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Nomenclature

List of acronyms

ABH	Acoustic black hole
BEH	Bistable energy harvester
DEEH	Dielectric elastomer energy harvesters
DOF	Degree-of-freedom
DVA	Dynamic vibration absorber
EMEH	Electromagnetic energy harvester
EMF	Electromotive force
EMSD	Electromagnetic shunt damper
MEH	Multistable energy harvester
MEMS	Microelectromechanical systems
PEH	Piezoelectric energy harvester
PAM	Parabolic acoustic mirror
QZS	Quasi zero stiffness
TENG	Triboelectric nanogenerator
TMD	Tuned mass damper

1.1.2. Reviews with different harvesters

Currently, investigations on energy harvesting based on ultra-low frequency vibrations are scarcer when compared with the low frequency ones. To cope with the ultra-low frequency features, structural improvement with dedicated designs is required. Generally speaking, three types of harvesters have been widely used for ultra-low vibration energy harvesting, including PEHs, EMEHs, and triboelectric nanogenerators (TENGs). For the widely used PEHs, Sodano et al. [17] capitalized on the piezoelectric effect of the PEH for both sensing and actuation, then reviewed energy harvesting applications on mechanical vibrations. The achieved efficiency and damping effects in terms of vibration response reduction were also discussed. Liu et al. [18] reviewed the piezoelectric energy harvesting technology with an emphasis on material choice, fabrication, mechanisms and applications. Priya et al. [19] and Yang et al. [20] summarized subsequent developments of PEHs on the improvement of the piezoelectric film preparations and resonating beam structure designs. With the aforementioned methods, the output power density was improved and the bandwidth was widened. Design methods of the PEH interface circuits in terms of impedance matching for maximum output power were summarized and categorized by Rathod [21] and Priya et al. [19]. The applications of PEHs on shoes, peacemakers, tires pressures monitoring systems, buildings, and bridges were reviewed by Yang et al. [20].

Faraday's law-based EMEHs are more suitable for large-scale energy harvesting [22] than PEHs due to their easier fabrication in large size. The basic principles of the EMEHs have been discussed by Beeby and O'Donnell [23], including the effects of the magnetic flux gradient and coil turns on the transduction factor. Wire-wound and micro-fabricated coils were analyzed and compared in terms of their influence on performance improvement. EMEHs with magnetic levitation architectures were categorized and compared by Carneiro et al. [24] for revealing the underlying transduction mechanism. For autonomous sensing applications, Sarker et al. [25] reviewed the existing work on the design of interface circuits, electronic converters, and controllers of EMEHs. Corresponding advantages and drawbacks were also critically analyzed. Three methods for improving the performance of EMEHs and PEHs were reviewed and discussed by Maamer et al. [26], including widening the operating frequency range, conceiving a non-resonant system and multidirectional harvesters.

Another small-scale harvester is the TENG, which contains two dissimilar materials for electrostatic charge creation on their surfaces and generates high voltage and low electric current after the surfaces are separated by external forces, such as mechanical vibrations. In this case, Wang et al. [27-29] summarized the principles, existing devices, and possible applications of TENGs. Then flexible materials and stretching structures for TENGs to be used in flexible electronics were summarized by Wang et al. [30], with corresponding structural designs, material selection and hybrid energy cells being presented. Four applications of TENGs were categorized by Wu et al. [31,32]: micro/nano power sources, self-powered sensors, blue energy, and direct high-voltage power sources. Zhang et al. [33] summarized the work on bioengineering applications by taking TENGs as a sustainable power source, active bio-monitors, and electrical stimulation therapeutics. Kim et al. [34], Zhang and Olin [35] mainly focused on the choice of materials for performance improvement of the TENGs. Dharmasena and Silva [36] commented on possible optimization methods and proposed universal optimization tactics for different TENG designs. Meanwhile, some other harvesters were implemented for ultra-low frequency vibration energy harvesting. For example, Jean-Mistral et al. [37] compared six electroactive polymers in terms of energy harvesting performance.

With the aforementioned energy harvesters, Wei and Jing [38] and Siang et al. [39] reviewed the techniques for universal modeling, theoretical analyses, and realization of harvesters. Zou et al. [40] reviewed and discussed the mechanical modulation for enhancing energy harvesting performance in three aspects: excitation conversion, frequency up-conversion, and force and motion amplification. Recently, bistable and multistable energy harvesters (BEHs & MEHs) have attracted increasing attention due to their unique and appealing characteristics: interwell dynamics, broad bandwidth, and high-performance energy harvesting. Zhou et al. [41] and Fang et al. [42] respectively provided summaries on the design principle and process from BEHs to MEHs. Perspectives of multistability usage on energy harvesting were discussed, including a comparison with other enhancement methods, and a suitable choice of MEHs for real applications. Potential applications of the proposed energy harvesters include powering wireless electronics devices [43-46] for healthy detections, providing an alternative energy source for smart buildings [47], structural health monitoring [48,49], etc. Simultaneous energy harvesting and vibration control were reviewed by Yang et al. [50] and Cai et al. [51], which brought up a promising direction for energy harvesting.

1.2. Motivation

Up to now, plenty of investigations were conducted to explore the efficiency of the ultra-low frequency vibration energy harvesting. However, there is still no detailed review dedicated to this theme. To bridge the missing gap, this paper aims at providing a comprehensive review on the state-of-the-art of ultra-low frequency vibration energy harvesting, including major energy sources, typical harvester design, underlying conversion mechanisms and possible performance enhancement methods. The main difficulty to harvest energy from the ultra-low frequency vibration is the mismatching between the harvesters and external vibrations both in frequency ranges and motion modes. Existing solutions to this problem in the literature are analyzed and categorized based on their characteristics and performance. Other possible enhancement methods based on various physical principles are particularized and analyzed in detail. Scaling laws of harvested energy, current challenges and future research directions for achieving more effective ultra-low frequency vibration energy harvesting are also discussed in this review paper.

Existing review papers mainly focus on one specific type of transducer for energy harvesting, and summarize corresponding principles and the methods to enhance the energy harvesting efficiency. Some of the existing review papers concentrate on the nonlinearity, simultaneous vibration control and energy harvesting. Compared with the existing review papers, the present paper focuses on the ultra-low frequency energy harvesting techniques, particularly the enhancement methods that can accommodate ultra-low frequency vibration energy sources. The state-of-art ultra-low frequency energy harvesting review actualizes recent progress in this research field and offers future research directions to readers.

The rest of the paper is organized as follows: Section 2 introduces the main ultra-low frequency vibration energy sources and discusses corresponding vibration properties. Section 3 presents the commonly used energy harvesting transducers, alongside elaborations on the harvesting mechanisms. Section 4 illustrates the enhancement methods for ultra-low frequency energy harvesting in detail and classifies the methods into four categories that can be easily retrieved by researchers. Section 5 analyzes the scaling laws of both electromechanical coupling and output power reported in the current literature. Section 6 discusses the challenges based on the reviewed research progress to guide future research directions of ultra-low frequency vibration energy harvesting. Section 7 finally summarizes main conclusions of this review paper and depicts the prospects of ultra-low frequency vibration energy harvesting.

2. Ultra-low frequency vibration energy sources

Ultra-low frequency vibration energy sources are universal in natural environment. Four possible ultra-low frequency vibration energy sources are illustrated in this paper: marine energy, infrastructure motions, road roughness or railway track deformations, and human motions. Though not included in the paper, other miscellaneous sources also deserve further exploration to target specific applications. Before commenting on particular harvester designs, this session briefly recalls the main features of these four energy sources.

2.1. Marine energy

Marine energy is tremendously abundant, sustainable and free of pollution. Ocean waves, offshore wind and even marine creatures can be regarded as typical ultra-low frequency vibration sources, conducive to energy harvesting. Offshore wind energy, one of the main energy sources, can predominantly be harvested by wind turbines in plenty of wind farms around the world. Compared with wind turbines, the design of the foundation that supports the wind turbines is even more difficult due to the hostile offshore environment. Typical foundation design progress [52] includes the identification of mechanical characteristics, studies of the foundation, alongside concurrent theoretical, numerical and experimental efforts. As an example, a floating platform in Fig. 1(a) for both ocean wave and wind energy harvesting [53] has been experimentally investigated to understand its hydrodynamic response. Concurrent base and aeroelastic energy harvesting [54,55] could increase the output power and broaden the working bandwidth with a properly designed hybrid harvester.

However, ocean waves and marine creature motions have not been effectively harvested for human usage. Various energy harvesters are in the stage of design and optimization. The unmanned surface vehicle [56] in Fig. 1(b) still cannot sail for a long distance without a continuous power supply. A pendulum-like EMEH proposed by Mitcheson et al. [57] offers a possible solution. Some long-working monitoring systems in the ocean require power input to maintain their normal operation. Like the boned PEHs in Fig. 1(c), the marine creature motion was investigated for biological habits detection [58]. A properly designed self-powered motion-sensing system in Fig. 1(d) was proposed by Bhatta et al. [59] to monitor the marine environment. The subsea bubble energy is also a ubiquitous potential energy source from the marine. Guan et al. [60] used the liquid propelled by bubble buoyancy to drive the turbine generator, and the harvesting efficiency is highly improved than similar designs.

Due to the immature energy harvesting techniques and the complex working environment, marine energy harvesting, though offering huge potential, it still requires significant research and development effort.

2.2. Infrastructures

Compared with marine energy sources, ultra-low frequency vibrations on land often caused by large-scale infrastructures. Tall buildings and bridges are typical cases with the first resonance frequency lower than 0.2 Hz due to their large equivalent weight. Tall buildings vibrate with large amplitude under extreme conditions, like earthquakes and typhoons. Functional energy harvesters can serve as an emergency power supply for alerting people to escape since the conventional power supply always shuts down during this kind of natural disaster. Conroy and Sideris [61] explored an EMEH for simultaneous energy harvesting and vibration mitigation in tall buildings under wind and seismic excitation. A simplified model with the EMEH applied in a single-degree-of-freedom (SDOF) system was proposed to reduce the computational cost [61], whose accuracy of the simplified model was verified by experimental data.

Another effective vibration mitigation device is the tuned mass damper (TMD), which is also referred to as a dynamic vibration absorber (DVA), to absorb vibrations from a primary system on which it is mounted. Such devices have been installed at two tall buildings over 500 m, namely Shanghai tower [62] and Taipei 101 [63], as shown in Fig. 2(a) and (b), respectively. As an auxiliary structure attached to the primary system, the TMD is capable of converting vibration energy into thermal energy with the contained damper. If regenerative energy harvesters possess the capacity of providing the same level of the damping force as conventional viscous dampers, the harvested energy level will be spectacular for emergency use. Some small-scale

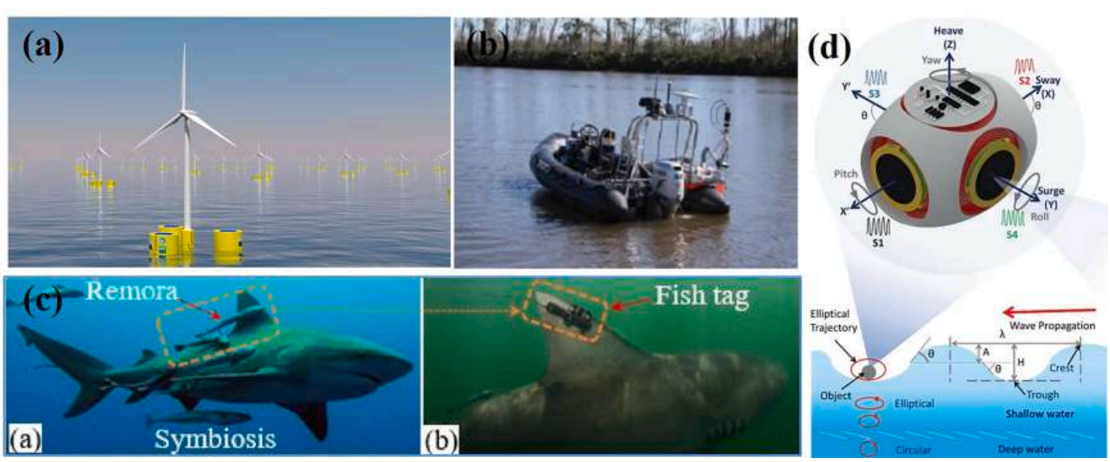

Fig. 1. (a) A floating offshore wind turbine [53]; (b) unmanned surface vehicle for water quality monitoring [56]; (c) animal telemetry tags with a PEH [58]; (d) a self-powered motion sensing system [59].

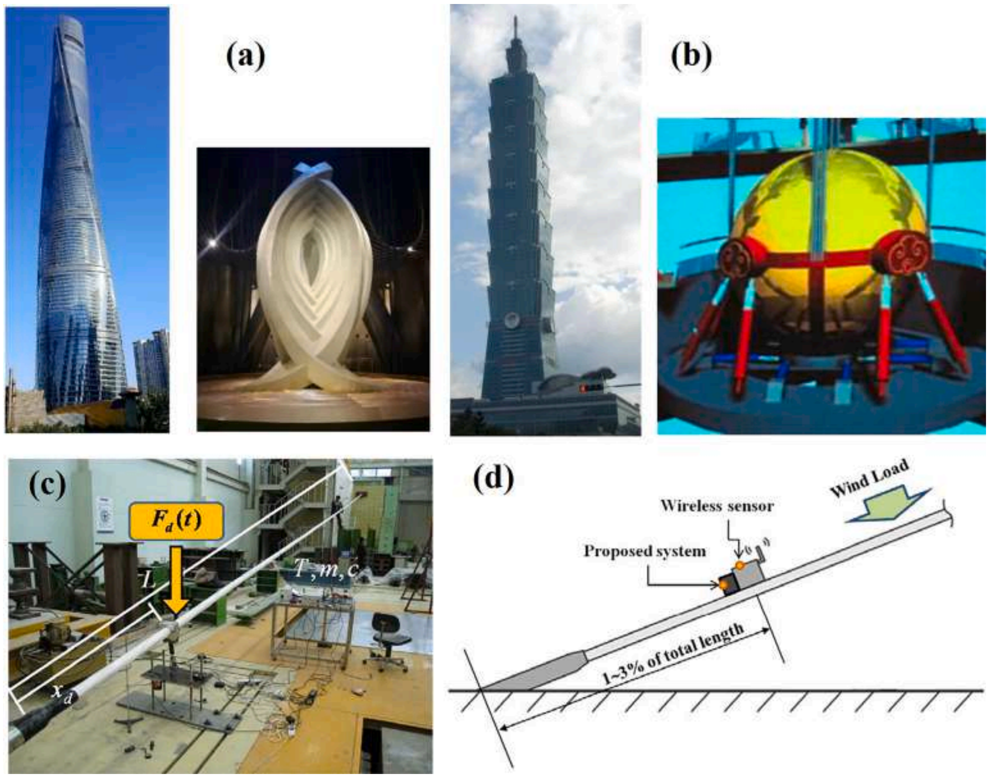

Fig. 2. (a) Shanghai Tower and TMD [62]; (b) Taipei 101 and TMD [63]; (c) stay cable with EMEH [73]; (d) stay cable vibration energy powered wireless sensor [74].

investigations and experiments [64-67] have been conducted in view of their potential applications, but the generated damping and energy harvesting efficiency still require significant improvement to cope with practical needs. The ultra-low frequency vibration energy harvesting from a bridge was investigated by Peigney and Siegeit [68]. A cantilever-like EMEH was used to harvest the vibration energy of a bridge at ultra-low frequencies (typically around 4 Hz), verified by both laboratory and field tests.

Wind-induced vibration with a specific tension force [69-71] and high-pressure pipelines with pressure fluctuation [72] can be regarded as an ultra-low vibration source as well. In an experimental study on stay cable energy harvesting presented by Shen et al. [70], the fundamental frequency of the test cable was set as low as 4.086 Hz. As shown in Fig. 2 (c) and (d), the harvested energy from the stay cables can be used as the power supply to an MR damper [73] and wireless sensors [74]. Moreover, the highway wind generated by passing vehicles on highways [75] may be an invaluable energy source to power streetlights and sensors in regions with insufficient wind energy.

2.3. Vehicles and railway

The vibration of vehicles, especially that of the suspension, also occurs at ultra-low frequencies. Typically, the natural frequency of a passenger car suspension system is tuned at 0.8–2.1 Hz to avoid the most sensitive frequency range of the seated human body (4–10 Hz). With a traditional viscous damper, the suspension vibration energy excited by road harshness is dissipated into thermal energy. Investigations related to energy-regenerative suspension systems in vehicles were reviewed by Zhang et al. [76]. The traditional viscous dampers are substituted by regenerative dampers with the dual function of damping force provision and energy harvesting [77-81]. In Fig. 3(a), an EMEH installed as a replacement of viscous dampers by Li et al. [78] produces an average power of 19 W at the driving speed of 48 km/h. Moreover, engine suspensions [82], rotating tyres [83-85] and seat suspensions [86] are possible energy sources as illustrated in Fig. 3(b)-(e).

Moreover, railway deformation caused by the passing high-speed train can provide energy without affecting the track by bonding energy harvesters on the inner side surface or the bottom pad as shown in Fig. 3(f). With the excitation from the wheels, the generated vibration energy on railway tracks can be harvested by the attached EMEHs [87-89] to power railway monitoring systems. PEHs stacked in ring and tube structures [90,91] were investigated to enhance their performance used for railway track energy harvesting.

2.4. Human motion

Harvesting mechanical energy from human motion attracts increasing attention with the recent advent of wearable electronics. The harvested energy from human motion can essentially power the wearable electronics on account of the low-powered technique development. Arms, legs, knees, insoles and backs are all suitable installing locations for harvesters. Every moveable part of the human body, even the body trunk moving can be an energy source with ultra-low frequency vibrations since most human motions have the low speed or low frequency characteristics.

Suspended-load Backpacks are based on the human trunk motion that causes the barycenter to move up and down during walking or jogging. EMEHs with various motion conversion mechanisms were exploited for energy harvesting, including pinion-gear [92], string-spiral spring [93], inverted pendulum [94], etc. As shown in Fig. 4(a), a string elongates when the EMEH moves down, and the spiral spring retracts in the meantime to store potential energy. When the EMEH moves to the lowest point, the potential energy lifts the EMEH up to overcome gravity. The induced reciprocating motion in the vertical direction provides an ultra-low frequency vibration energy source. Boned piezoelectric layers on shoulder straps in Fig. 4(b) exploit the same principle, i.e. human trunk motions in a vertical direction excite the PEH stretching or contraction to generate electricity [95].

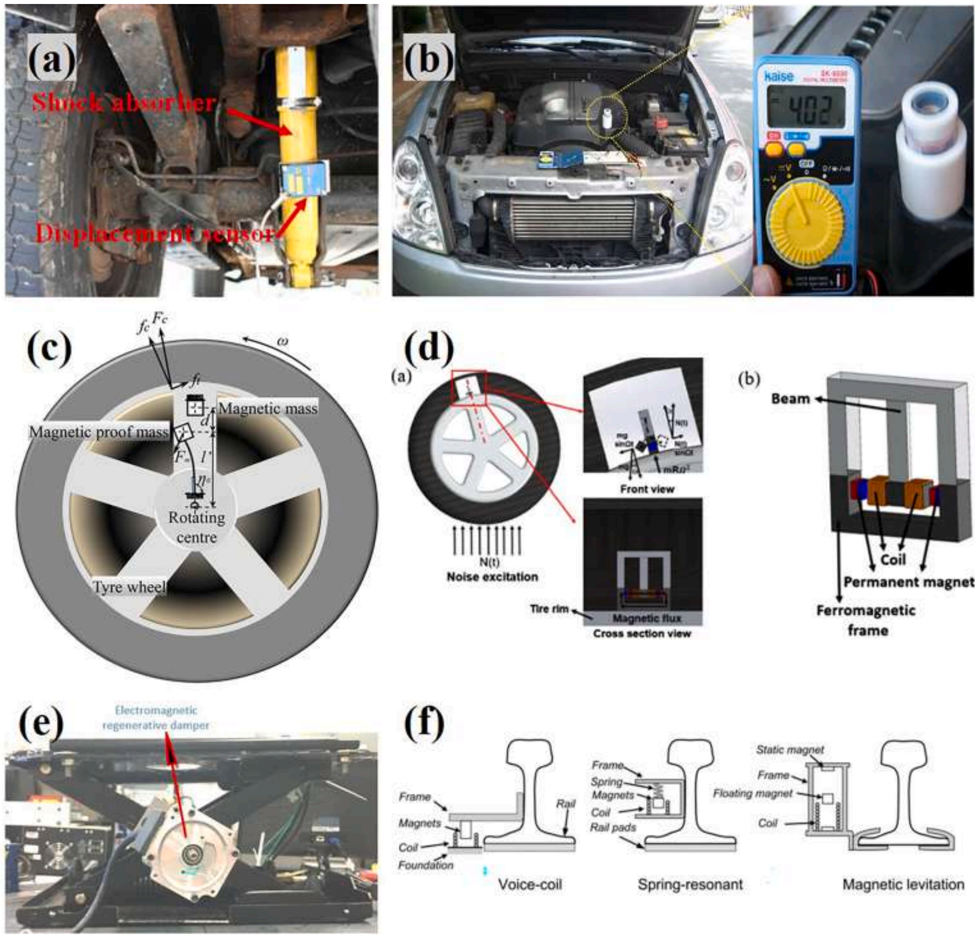

Fig. 3. (a) Vehicle suspension with a regenerative shock absorber [78]; (b) a vehicle engine mounted EMEH [82]; (c) a bistable PEH installed on the external surface of rotating tyre [83]; (d) an EMEH installed on the inner surface of rotating tyre [85]; (e) seat suspensions with an EMEH [86]; (f) an EMEH mounted on railway track [87].

Impact force or bending force on the sole is another energy source for energy harvesting via PEHs [96], TENGs [97] or EMEHs [98]. Since EMEHs rely on a relative motion with larger amplitude compared with PEHs and TENGs, proper conversion mechanisms should be considered when using an EMEH for insole energy harvesting. In Fig. 4(c), a four-bar linkage was used to transform the sole bending motion into the rotation motion. Then a gearbox increases the rotating speed so that the output voltage from the generator can be amplified. The energy from moving knees is another source with installation either on inner embedded implants [99] or external surfaces [100]. The energy-embedded piezoelectric ceramics in knee implants as shown in Fig. 4(d) were designed with dual functions (energy harvesting and sensing). Other works about external knees rotating energy harvesting with structures are shown in Fig. 4(e). The ultra-low frequency handshaking energy was harvested by EMEHs and TENGs [101,102] as shown in Fig. 4(f). Besides the aforementioned specific attachment locations, some enhanced small-scale energy harvesters [103,104] were designed to be bonded at possible positions on the moving bodies to harvest energy.

3. Ultra-low frequency vibration energy conversion mechanisms

The three afore-mentioned energy harvesters are widely used for ultra-low frequency vibration energy harvesting. To investigate the possible ultra-low frequency vibration energy harvester with high efficiency, the basic working principles should be illustrated. Possible enhancement methods can then be developed based on the deep understanding of the energy harvesting mechanisms.

3.1. Electromagnetic induction

Since the concept of the electromagnetic shunt damping was put forward by Moheimani et al. [105], electromagnetic shunt dampers (EMSDs) have been widely used for vibration control owing to their appealing fine tunability. EMSDs are capable of converting mechanical energy into electrical energy, then dissipating it as thermal energy with externally connected electrical resistors. Instead, if the converted electrical energy is not dissipated, the converted energy can be harvested through tactically designed interface circuits, resulting in a so-called electromagnetic energy harvester. An EMEH can be designed by using a permanent magnet linear generator containing magnets and coil based on the Faraday-Lenz law. The induced electromotive force (EMF), ε, of a typical EMEH in Fig. 5(a) can be expressed as [64]:

$$\varepsilon = -\dot{x}\int_{loop} B_r(x,r)dl \tag{1}$$

where B_r denotes the radial magnetic flux density; $\dot{x}$ is the relative velocity between magnets and coils; l is the arc segment of the coil. Since the EMEH vibrates in the vertical direction, only the radial magnetic flux density B_r will come into play, and the vertical component of the magnetic flux density does not contribute to the EMF.

The induced EMF can be regarded as a voltage source V_{oc} which is connected with an internal resistance R_{in} and an inductance L_{in} in series as shown in Fig. 5(b). At ultra-low frequencies, the inductive impedance

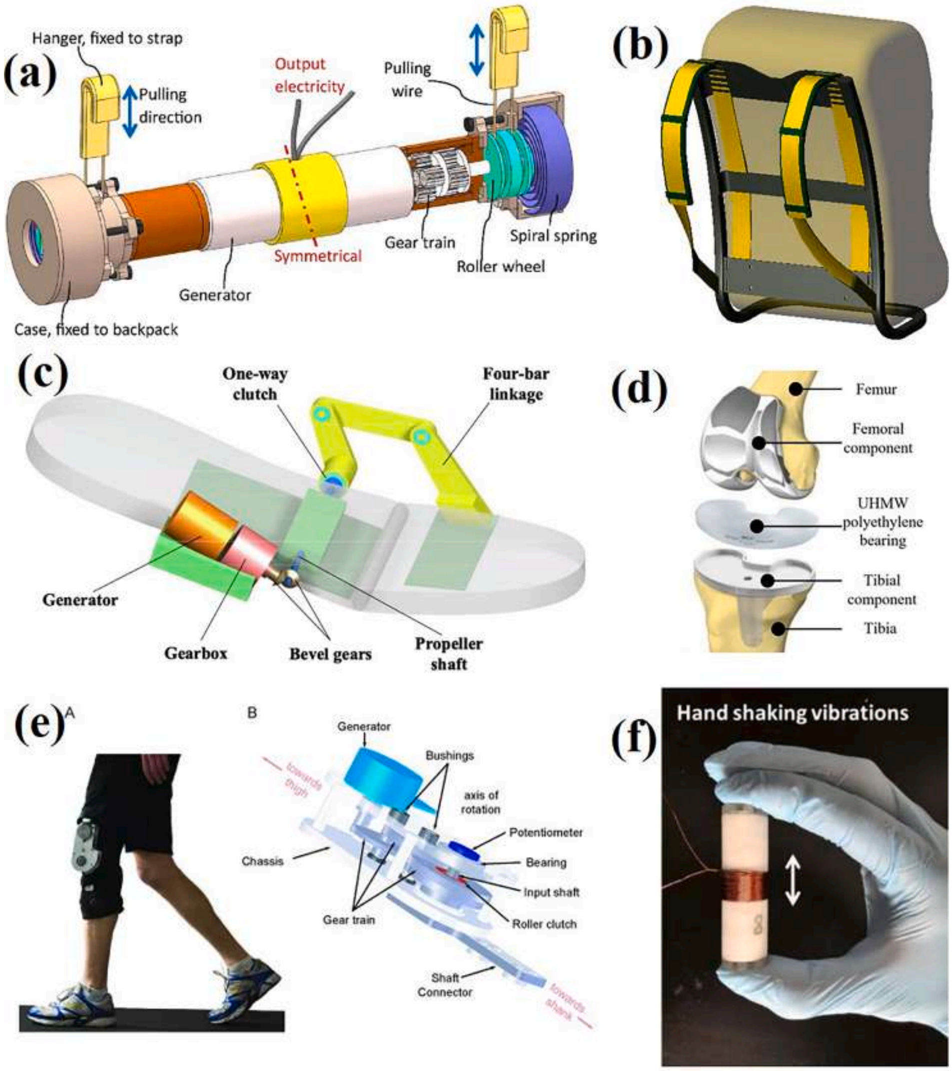

Fig. 4. (a) An EMEH installed on a backpack [93]; (b) a PEH based backpack to harvest energy from the shoulder strap [95]; (c) an insole EMEH [98]; (d) knee-embedded piezoelectric ceramics [99]; (e) a knee rotating excited energy harvester [100]; (f) a handshaking EMEH [101].

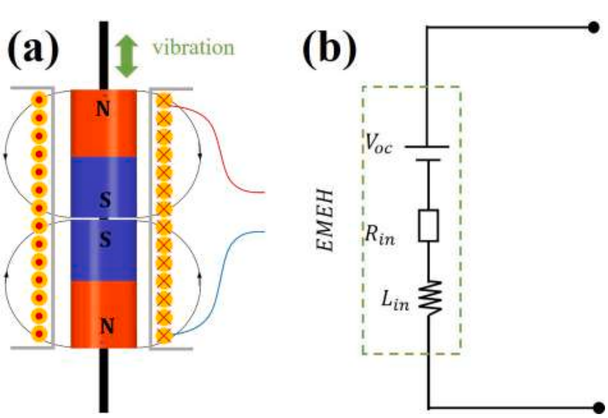

Fig. 5. (a) Working principle of an EMEH; (b) the equivalent circuit.

of the coil is small and can be neglected compared with R_{in}. With the connection between the coil terminals and the interface circuits, the converted electricity by the EMEH can be stored to power specific electrical appliances. However, the electromechanical coupling is normally insufficient for energy harvesting, especially when it works in the ultra-low frequency range. To tackle the problem, enhancement methods are needed. Typical methods reported in the literature are listed and commented in the following sections, including magnet arrangement, optimization of interface circuits and frequency up-conversion designs, etc.

3.2. Piezoelectricity

The direct piezoelectric effect produces electric charge accumulation in a piezoelectric material when subjected to an externally applied mechanical stress. This effect was first demonstrated by brothers Pierre Curie and Jacques Curie while testing crystals. Subsequent studies show that most piezoelectric effects are related to the non-centrosymmetric crystal structures. If the piezoelectric material in Fig. 6(a) is stressed along the *i*-axis by an applied force *F*, the induced voltage *V* can be expressed as [106]:

$$V = \frac{g_{ki}F}{l} \tag{2}$$

where g_{ki} is the piezoelectric constant that denotes the electric field developed along the *k*-axis with the applied force along the *i*-axis, and *l* is the length of the piezoelectric material along *j*-axis.

The harvested energy can be maximized when the external

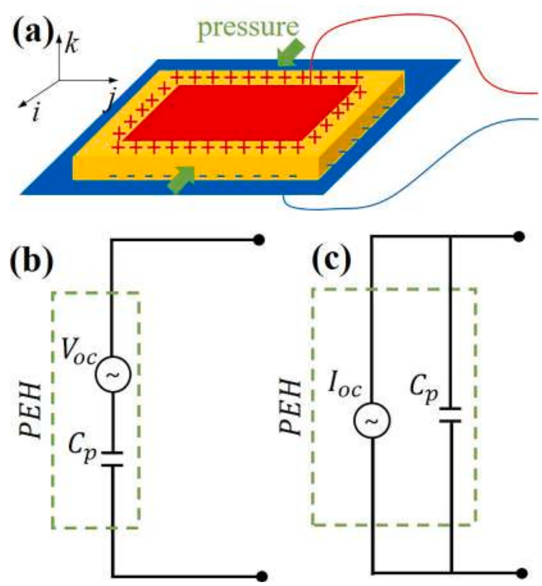

Fig. 6. (a) Working principle a PEH; the equivalent circuit when the PEH is regarded as: (b) a voltage source or (c) a current source.

impedance is equal to the internal impedance. For the PEHs with two types of equivalent circuits when it is regarded as a voltage source or a current source as respectively shown in Fig. 6(b) and (c), the equivalent internal impedance of PEHs is much higher than that of EMEHs due to their dielectric material properties. Cantilevered PEHs with a unimorph or a bimorph are the commonly used structures for energy harvesting. Corresponding closed-form solutions were deduced and verified by Erturk and Inman [107,108]. To harvest ultra-low frequency vibration energy, large proof mass blocks can be added at the tip of PEHs to reduce the natural frequency. Otherwise, proper frequency up-conversion techniques can be applied to enhance energy harvesting performance.

3.3. Triboelectricity

Based on the triboelectric effect and the electrostatic effect, TENGs were exploited by Fan et al. [109] to power electronic devices. As shown in Fig. 7(a), a typical TENG contains two thin films with opposite tribo-polarity. When a relative sliding occurs between the two films, frictions due to the nano-scale roughness induce charges on both sides. The generated pulse voltage of TENGs is much higher than that of EMEHs and PEHs, but the ultra-high internal resistance leads to low electric current and limits their applications. Theoretical modeling of TENGs [29] mainly concentrated on the generated charge density with particular dimensions. Analytical expression of the output voltage is still not available due to the complex charge transfer process and nano-scale friction effects. The equivalent current source circuits [110] with resistive loading and capacitive loading are shown in Fig. 7(b) and (c) with a mega-ohms resistance and a nano-farad capacitance. The modeling effectiveness was verified numerically and experimentally. The proposed circuit model benefits the impedance matching for higher output power.

3.4. Other mechanisms

TENG is not the only way for electrostatic energy harvesting; electret-free and electret-based electrostatic energy harvesters were reviewed by Khan and Qadir [111]. In particular, vibration energy harvesters using dielectric materials were widely investigated by researchers. Typical materials include dielectric polymers [112] and dielectric elastomers [113], etc. Magneto-electric composites with vibration excited variable magnetic fields were used for low-frequency vibration energy harvesting [114]. In Fig. 8(a) and (b), magneto-rheological (MR) dampers with a DVA [115] or an EMEH [116] were proposed for power generation. Moreover, combining an EMEH and an MR damper in parallel [117–119] as shown in Fig. 8(c) is a commonly used design method for energy harvesting.

4. Enhancement methods

The low efficiency of the aforementioned energy harvesters working at ultra-low frequencies results in insufficient harvested energy to power electronics and appliances, which in turn hinders their wide applications. To compensate for this deficiency, numerous enhancement methods were proposed. Existing literature can be roughly divided into four categories. The first method, which is the most commonly used one, is through structural design and optimization, including inherent resonant design for large-amplitude vibration, frequency up-conversions to overlap working frequency ranges of energy harvesting transducers, motion conversions to adapt motion modes of harvesters, bio-inspired structural designs for high efficiency or broad bandwidth. The second category explores transducer properties, such as enhancing electromechanical coupling, interface circuits tuning, and better materials replacements. The third category deploys and combines different harvesters for achieving enhanced energy harvesting efficiency. The last one explores nonlinear properties of designs that are beneficial to the energy harvesting efficiency under ultra-low frequency excitations, particularly the provision of QZS harvesters.

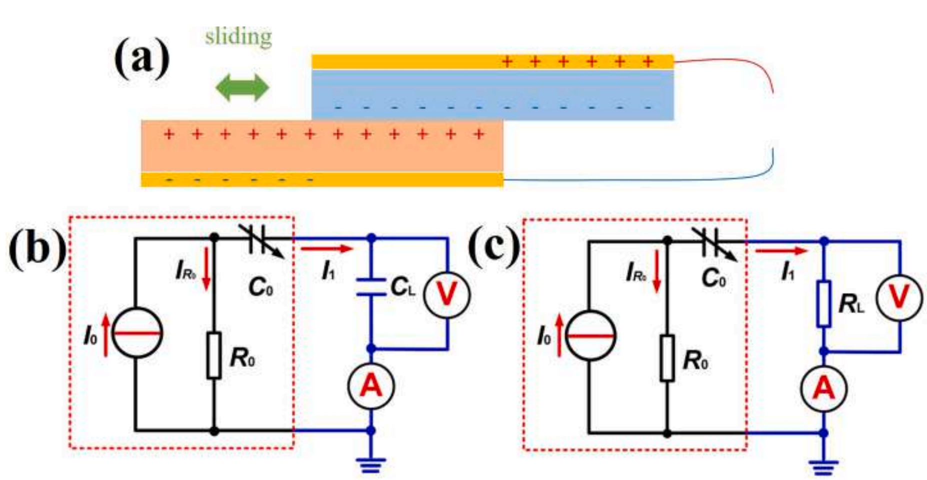

Fig. 7. (a) Working principle of a TENG, the equivalent circuit of TENG when connected with (b) resistive loading and (c) capacitive loading [110].

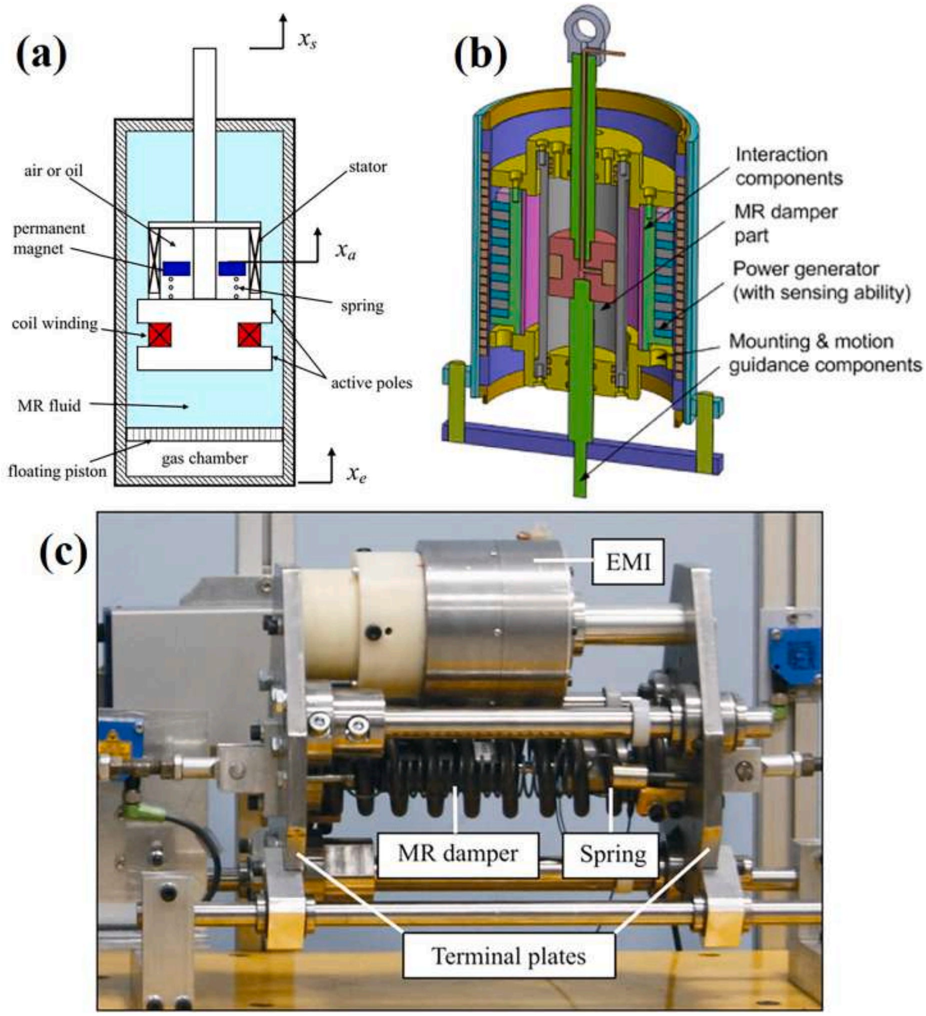

Fig. 8. MR damper-based vibration control systems with energy harvesting from electromagnetic induction device: (a) internal added DVA [115]; (b) internal added EMEH [116]; (c) external EMEH in parallel [118].

4.1. Response amplification

Possible adverse effects on working machines call for careful consideration of the occurrence of structural resonances, which should be avoided from a vibration control perspective in the initial structural design. However, resonance phenomena also contribute to high energy harvesting efficiency, which can be exploited based on compromised considerations. Besides a series of internal resonant designs for enhancement of energy harvesting performance, energy harvesters with tunable natural frequencies were proposed to accommodate the variation of the excitation frequency. Moreover, some adaptive natural frequency tuning methods were presented for real-time adjustment of excitations.

4.1.1. Structural resonance

Aiming at exploiting resonance phenomena for vibration amplification, low stiffness and heavy mass of the vibration system are required to match the ultra-low frequency excitation. Soft supports and heavy masses are commonly used in various forms as illustrated by Fig. 9 (a)-(e), such as the PEH with a soft cantilever beam [120], EMEHs with heavy mass blocks attached to the beam [121], PEHs with S-shaped soft spring [122,123], variant beams with heavy proof mass for a PEH [124] or a hybrid harvester [125], a flow-induced vibration energy harvester with soft string hanging [126,127], etc. As shown in Fig. 9(b) and (d), some structural designs entail several resonance peaks and a wide working frequency bandwidth.

In addition to the direct design of resonant structures, the aforementioned DVAs in Fig. 2(a) and (b) cloud be used for ultra-low frequency vibration energy harvesting based on the internal resonance of the auxiliary device. The natural frequency of the DVA, before being coupled to the primary system, is tuned near the natural frequency of the primary system for absorbing vibration energy as much as possible. The energy transferred from the primary system can be captured by properly designed harvesters. Optimization of a DVA with theoretical analysis to minimize kinetic energy and maximize energy dissipation has been conducted by Zilletti et al. [128]. The possibility of achieving simultaneous energy harvesting and vibration suppression was theoretically analyzed by Brennan et al. [129]. Some prototypes [130,131] were fabricated to verify the energy harvesting performance of the DVAs. The experimental setup in Fig. 10(a) depicts a typical DVA in a translational direction for simultaneous vibration suppression and energy harvesting. The structural resonance of properly designed energy harvesters in above literature benefits the harvesting efficiency, while the occurrence of resonance phenomenon is always pretty strict that the harvesting continuity cannot be guaranteed. Some tuning methods or adaptive harvesting structures are required to fit the time-varying environmental vibrations.

4.1.2. Resonance frequency tuning

Due to the narrow bandwidth, pre-designed resonant energy

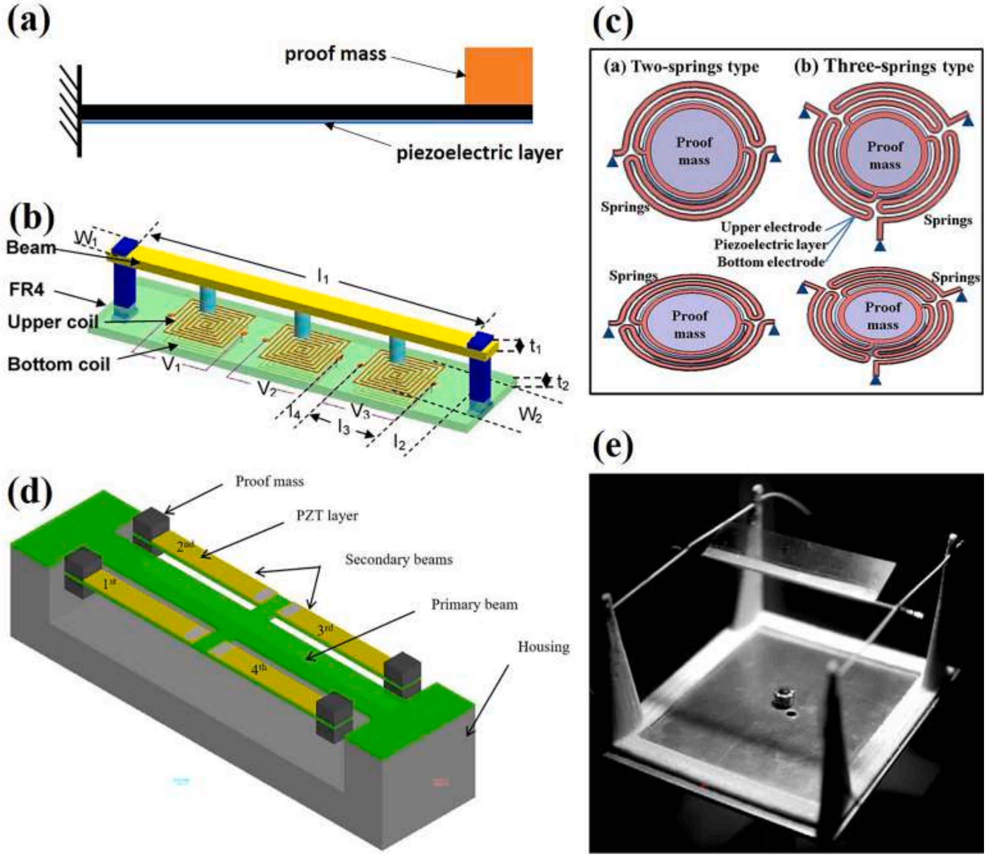

Fig. 9. (a) A cantilever-like PEH with proof mass; (b) an EMEH with three resonant modes to be harvested [121]; (c) schematic view of the low-frequency vibration sensor design: two- and three-spring sensor structures, respectively [122]; (d) a PEH with multi resonant modes [124]; (e) a flow-induced vibration energy harvester with an elastically bounded wing [126].

harvesters are only effective within specific excitation frequency ranges. To cope with variable excitations, harvesters with tunable natural frequencies were proposed by many researchers. For the widely used cantilever beams and pendulums in ultra-low frequency vibration harvesting, effective length can be easily changed as a means for natural frequency tuning. For example, Yuan et al. [131] tuned the natural frequency of a DVA by changing the effective length of the cantilever beam, as shown in Fig. 10(a). A double-mass pendulum EMEH was proposed by Cai and Zhu [132] for natural frequencies tuning by relocating the pendulum mass as shown in Fig. 10(b). Changing the preloading of a cantilever beam [133] in Fig. 10(c) and the stress of flexible springs [134] were shown to be feasible ways for natural frequency tuning of harvesters.

Manual calibrations are required to tune the natural frequency with the aforementioned tuning methods, no matter whether one wants to change the effective length of the cantilever beam or the preloading on springs. Persistent efforts have been made to investigate the possibility of achieving adaptive natural frequency tuning without manual intervention to cope with the excitation frequency changes. The natural frequency tuning of so-called self-tuning or self-adaptive energy harvesters is based on the dynamic characteristics of properly designed structures. For rotating energy harvesters, the driving frequency-based centrifugal force was used for tuning the natural frequency of harvesters [136-138]. Owing to the relationship between the centrifugal force and the bending vibration response of the flexible beams in Fig. 11 (a) and (b), the resonance frequency of the harvester depends on the driving frequency. Then, better fitting can be achieved by changing related parameters, such as the size of the beam and tip-mounted proof mass block. Another natural frequency self-tuning mechanism with a weighted swing disk installed on a rotating wheel is shown in Fig. 11(c). The natural frequency of the weighted swing disk with a constant wheel rotating speed is expressed as:

$$\omega_n = \dot{\Theta}\sqrt{\frac{R_2}{L^*}} \tag{3}$$

where Θ denotes the wheel rotation angle; R_2 is the distance between the wheel center and the pivot of the weighted swing disk; L^* is a dimensionless character related to the mass moment of inertia of the weighted swing disk. The natural frequency can be set equal to the rotating speed with well-designed wheel parameters that meet $R_2 = L^*$.

Another promising adaptive technique, shown in Fig. 11(d), was designed for reciprocating vibration energy harvesters. A slider can move in the translational direction due to the impact and the friction between the slider and the beam. With the variant base excitation in the vertical direction, the slider can adapt the translational location to generate variable natural frequencies so that resonance can be maintained. Aboulfotoh et al. [138] demonstrated the self-resonating behavior from an experimental study, then conducted theoretical analyses [139] to explain the observed phenomenon. Shin et al. [140] developed an efficient energy harvester based on this mechanism.

The above tuning strategies with tunable length, mass, preloading or stress are effective for the steady-state vibration energy harvesting, but may not be suitable to the variable vibration sources. Based on the variable centrifugal force, or the balance of backlash and friction, the adaptive energy harvesters in literature can effectively tune their resonance frequency automatically. However, the real applications are still narrow due to the specific requirement of energy sources and vibration directions. Further tuning structures with better adaptability should be developed in the future research.

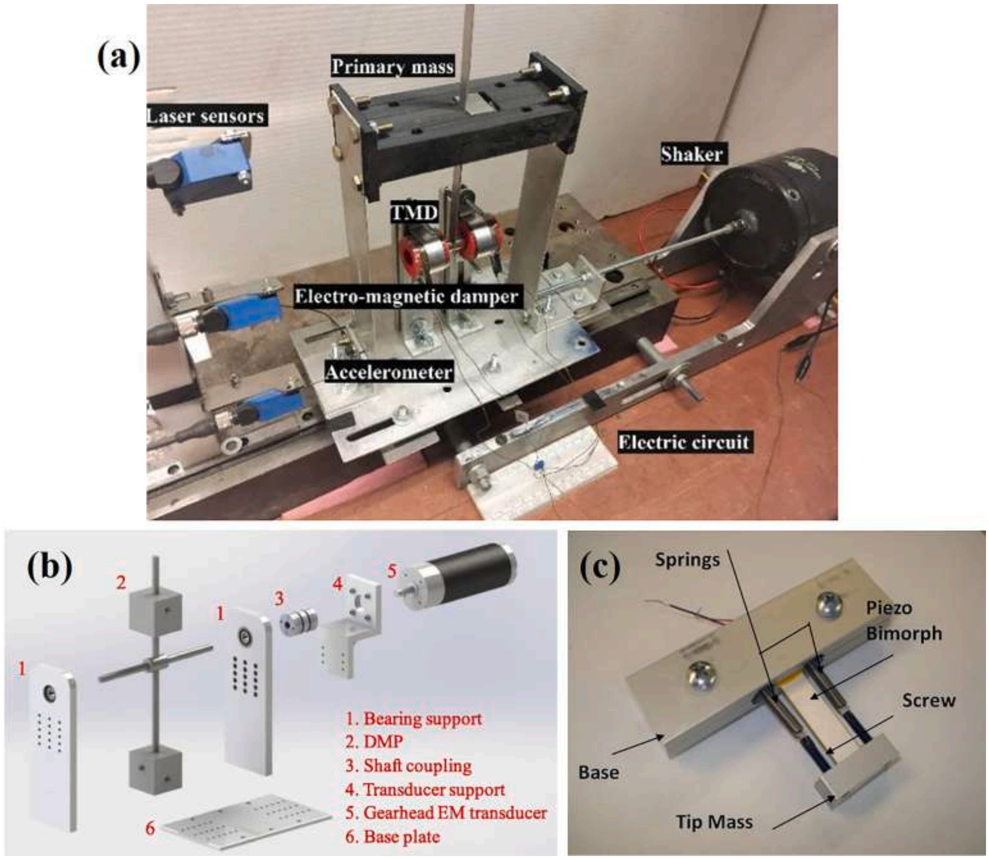

Fig. 10. (a) A frequency tunable EMEH with adjustable length of the beam [131]; (b) a frequency tunable EMEH with double mass pendulum [132]; (c) a frequency tunable PEH by adjusting the preload with the length of springs [133].

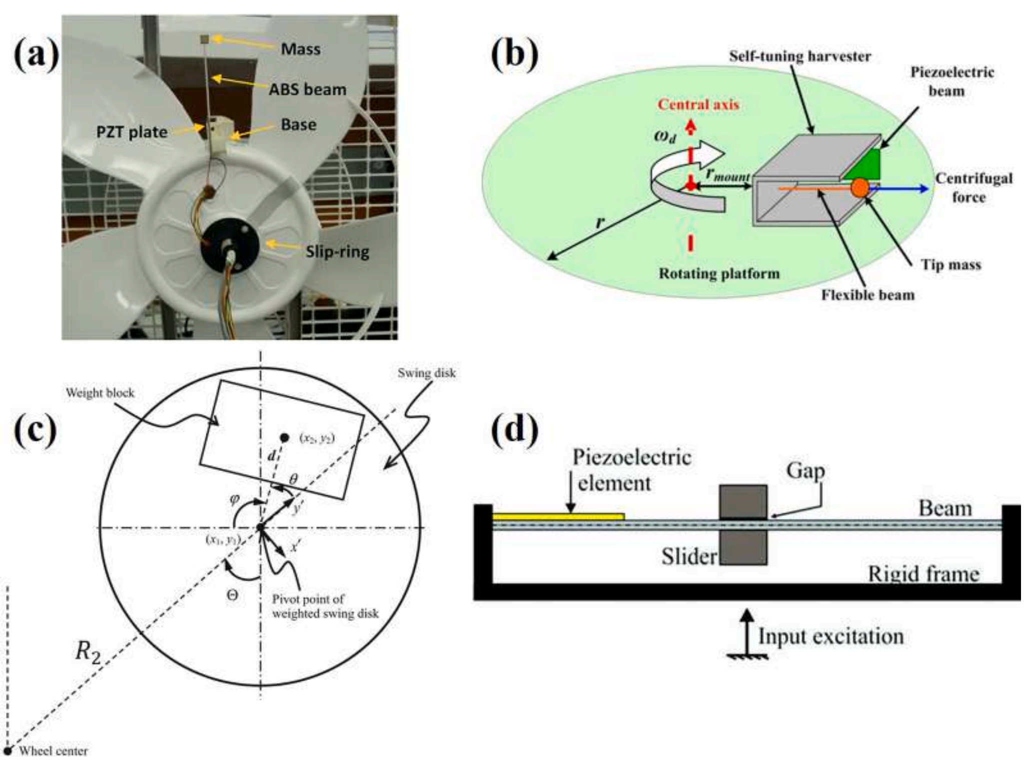

Fig. 11. (a) A passive self-tuning energy harvester due to the centrifugal force [135]; (b) compact passively self-tuning energy harvesting for rotating applications [136]; (c) frequency self-tuning with the weighted swing disk [137]; (d) a self-adaptive resonating PEH [138].

4.1.3. ABH effect

With its unique features governing the flexural wave propagation, the so-called acoustic black hole (ABH) effect has attracted a lot of attention for energy harvesting from thin-walled vibrating structures recently. The typical ABH effect features a propagation speed decreasing process of the flexural waves inside a thin-walled structure with a power-law decreasing thickness profile as shown in Fig. 12(a). In the ideal analytical modeling, the group velocity of the flexural waves is shown to be gradually slowed down towards the thin tip of the structure, thus producing enhanced energy focalization there. The trapped high-density energy can then either be fully absorbed by a small amount of damping materials placed at the tip of the wedge in Fig. 12(a), or harvested through the proper design of an energy harvester such as intentionally attached energy conversion transducers like piezoelectric patches.

However, the added electrical devices may affect and compromise the ABH effect via added mass and stiffness effects [141,142]. Therefore, a properly designed electromechanical coupling is needed, and a topic which was discussed by Zhang et al. [143,144] to maximize the energy concentration and the electromechanical coupling strength at the same time. Besides the tailored standard ABH profile on conventional beams as shown in Fig. 12(a), compound ABH beams [145] and ABH plates [146] were also used for energy harvesting as shown in Fig. 12(b) and (c). Currently, the ABH effect is effective in a rather high frequency range above the so-called cut-on frequency, which may reach several hundreds or thousands Hz. With a proper conversion mechanism, the ultra-low frequency vibration energy harvesting efficiency is capable of being improved through the ABH effect. This possibility has been demonstrated through exploiting intentionally added nonlinear effects to create cross-frequency energy transfer [137]. Of course, further work is needed along this direction before the potential offered by the ABH-based technology is fully exploited.

Based on the amplified response with the aforementioned methods, the vibration energy is maximized but may not be captured effectively, because many harvesters do not perform well under ultra-low frequency excitation. Frequency up-conversion and motion conversion mechanisms may solve this issue.

4.2. Frequency up-conversion mechanism

Ultra-low frequency vibration with large amplitude contains high density energy. However, vibration with low-frequency features may be not suitable to be harvested and converted into electrical energy, particularly when using the bending PEHs and rotating EMEHs which usually deliver good performance at a higher frequency than the vibration sources [147,148]. Proper frequency up-conversion methods are capable of compensating for the mismatching. For micro-electromechanical systems (MEMS) based energy harvesters, Ashraf et al. [149] indicated three challenges for ultra-low frequency energy harvesting: micro spring fabrication, limited amplitude, and low average power. To overcome these difficulties, frequency up-conversion methods were discussed and analyzed for improving energy harvesting performance. Recently, Ahamd et al. [150] summarized frequency up-conversion harvesters with impact and plucking mechanisms, and Li et al. [151] categorized four ways for frequency up-conversion of harvesters: impact, mechanical plucking, magnetic plucking and snap-through mechanisms. The four methods are briefly discussed below using representative cases.

4.2.1. Impact

Impact based frequency up-conversion method usually contains a mass moving freely due to the ultra-low frequency excitation. The shape of mass blocks is limitless, which can be a ball in Fig. 13(a) and (b), a water drop in Fig. 13(c), or a square block. The resonant energy harvester with high natural frequency starts oscillating until the next impact from the mass block. Mass impacted PEHs [152] and EMEHs [153,154] were both proved effective for rotational and reciprocating energy harvesting. Peng et al. [155] investigated the influence of frequency-up conversion effect based on impacts between a proof mass block and the piezostack on piezoelectric generators for high-performance energy harvesting. Due to the frequency up-converted by 69 times, and natural high capacitance of the stack, the matched resistance is significantly reduced from over 5 kΩ to 73.10 Ω. With the impact frequency-up conversion, corresponding instantaneous power and average power are improved by over 1000 times and 177 times, respectively. Xu et al. [156] proposed a raindrop impacted PEH with high energy harvesting efficiency.

4.2.2. Mechanical plucking

Like plucking the string of a guitar, mechanical plucking can be more regular than impact driving. For a buoy-based wave energy harvester [157] and a rotational energy harvester with a constant speed [158] in Fig. 14(a) and (b), the regular reciprocating motion or rotation provides periodic plucking to activate the beams with a high natural frequency. More impact-plucking combined harvesters [159,160] are shown in Fig. 14(c)-(e). This kind of structure always contains an excitation receiver with a lower resonance frequency and a harvester with a higher resonance frequency. Once the amplitude of the receiver is large enough to impact or pluck the harvester, it is triggered and starts to operate. The harvester in Fig. 14(e) adds a rope to drive the harvester with a high resonance frequency, which generates more complex dynamics while making the working frequency range much wider than that with only

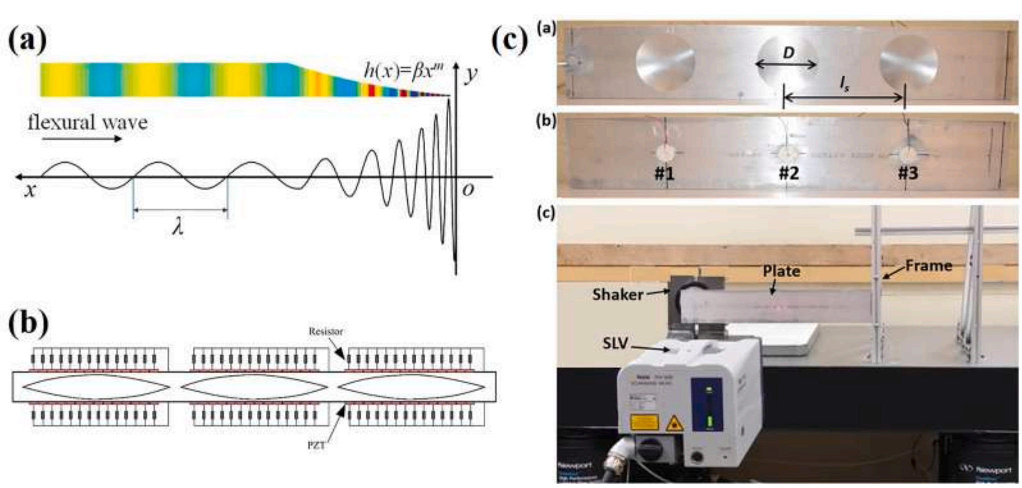

Fig. 12. (a) ABH effect [143]; (b) energy harvesting with compound ABH beam [145]; (c) ABH plate for energy harvesting [146].

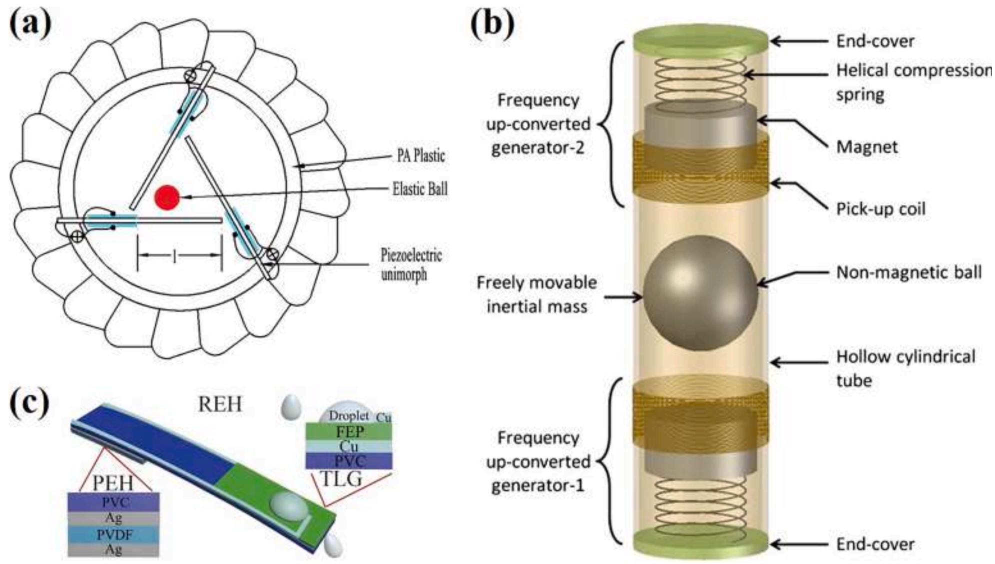

Fig. 13. (a) A ball impacted rotational PEH [152]; (b) schematic structure of a ball impact driven EMEH [153]; (c) raindrops impacted PEH [156].

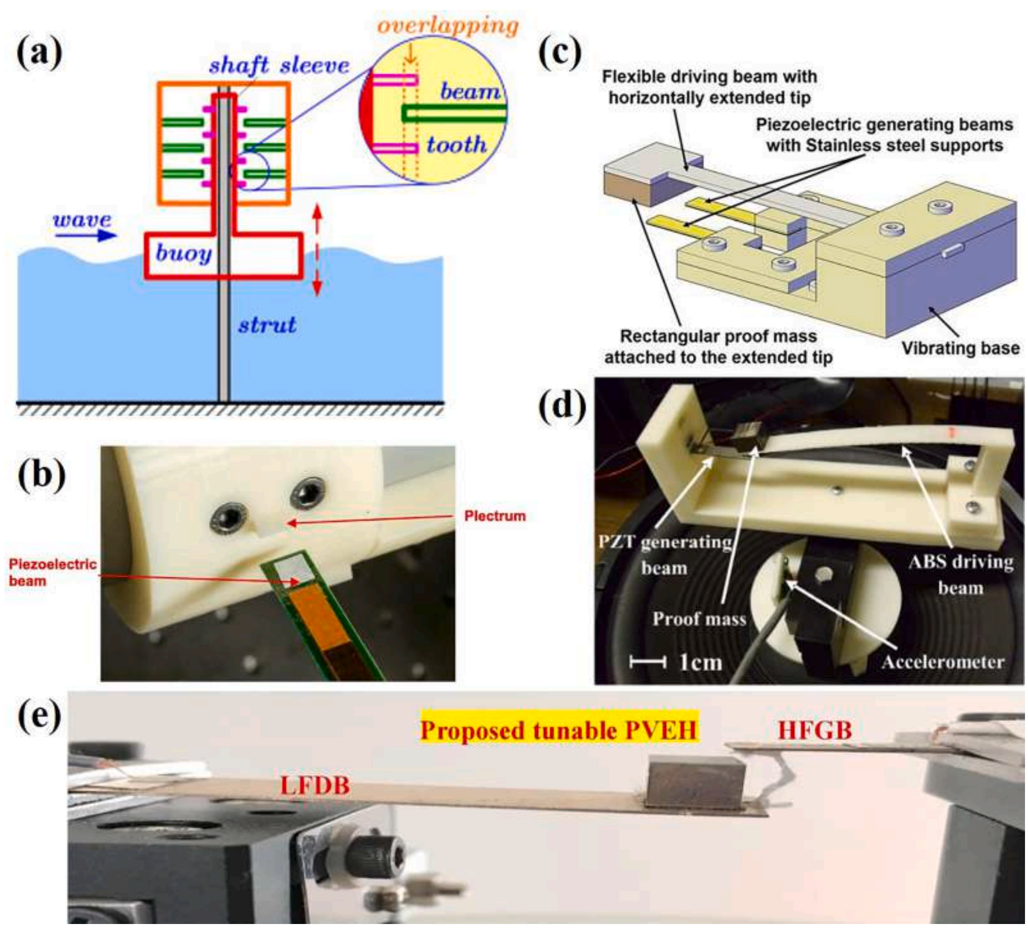

Fig. 14. (a) Schematic of the frequency up-converted wave energy harvesting device [157]; (b) schematic of the occurrence of interference in rotational mechanical plucking energy harvester [158]; (c) a mechanical plucking PEH [159]; (d) a PEH with an ABS driving beam and a PZT generating beam [147]; (e) an impact- and rope- driven PEH system [160].

impact-plucking.

4.2.3. Magnetic plucking

To avoid mechanical plucking-induced abrasion and damage, magnetic plucking was proposed to generate a smooth driving force for high-frequency energy harvesters. Tang et al. [161] proposed a repulsive magnet-driven EMEH for frequency up-conversion as shown in Fig. 15 (a). Miao et al. [162] designed a rotational EMEH with magnetic

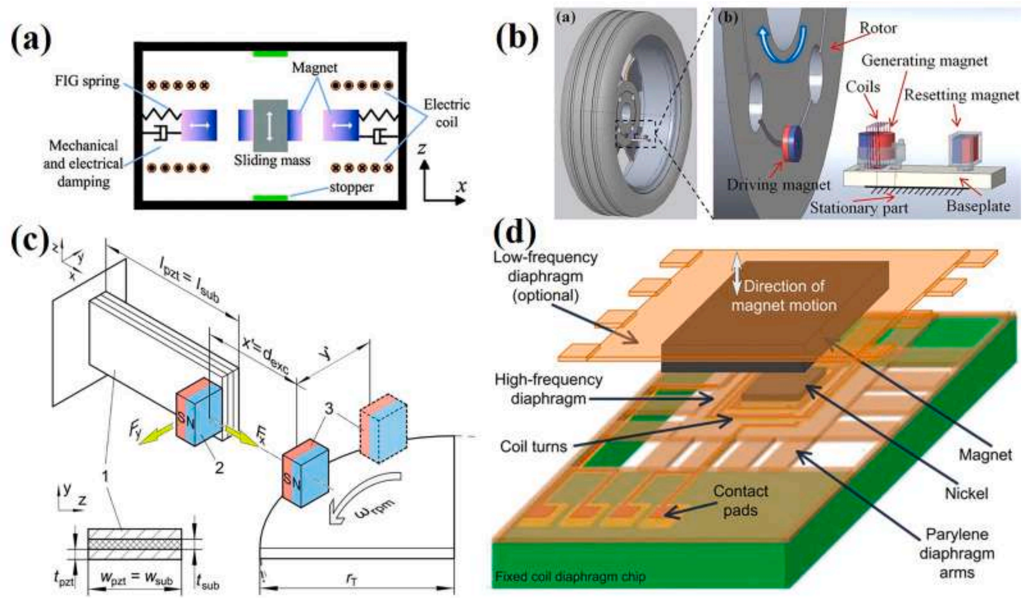

Fig. 15. (a) A vertical moving magnet driven EMEH in translational direction [161]; (b) a magnetic plucked EMEH installed on a vehicle tire [162]; (c) a magnetically excited PEH (in-plane arrangement) [163]; (d) a proposed EMEH: coil diaphragm chip fixed to a base and the magnet moves with external vibrations [166].

plucking from a rotating wheel and resetting with a back fixed magnet in Fig. 15(b). Cantilever-based PEHs [163] with rotating magnetic plucking were widely used for rotating energy harvesting. For some MEMS-based energy harvesting systems, the magnetic plucking is a preferred method for frequency up-conversion [164–166].

4.2.4. Snap-through phenomenon

The snap-through phenomenon is a nonlinear behavior which makes a system rapidly transit from one position to another. As shown in Fig. 16, supporting materials or structures are very soft for the status jump. Han and Yun [167] proposed a snap-through structure in Fig. 16 (a), in which a buckled bridge beam is clamped on flexible sidewalls with a proof mass, and cantilever beams are attached to the bridge. With the low-frequency excitation, the bridge with cantilever beams snap-through up and down to harvest energy. The bio-inspired bistable PEH [168] in Fig. 16(b) follows a similar working principle. The sub-beams curve with external excitations due to the constraints of the base and the proof mass block.

4.2.5. Enhancement analysis

Some experimental results with the aforementioned four types of frequency up-conversion methods are tabulated and compared in

Table 1
Frequency up-conversion energy harvesters.

Method	Refs.	Harvester type	f_{ex}(Hz)	Up-converted f (Hz)	Resistance (Ω)
Impact	[153]	EMEH	5.2	50.7	20k
	[154]	EMEH	4.9	159	43
Mechanical plucking	[157]	–	1	29.1	–
	[158]	PEH	1	19.5	15 k
	[159]	PEH	6	10–14	180 k
	[147]	PEH	6.7	49.1	228 k
	[160]	PEH	3	69.5	–
Magnetic plucking	[161]	EMEH	0.5	54.8	1.1 k
	[162]	EMEH	1–3.5	1.5–4	24.6
	[166]	EMEH	10	63	10 k
Snap-through	[167]	PEH	12	77	5 M
	[168]	PEH	12	250/310	8.2 k

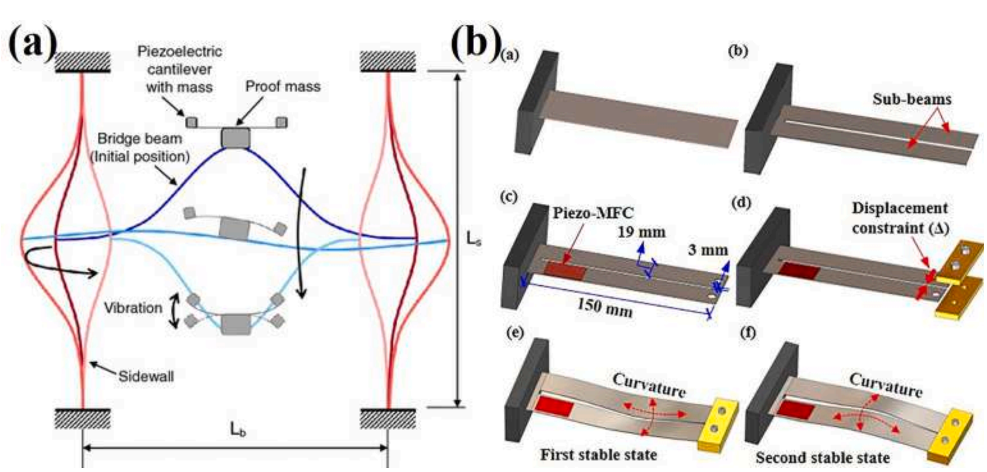

Fig. 16. (a) Concept of proposed energy harvester using mechanical frequency up-conversion with flexible sidewalls [167]; (b) bio-inspired bistable PEH, Venus flytrap's rapid shape transition [168].

Table 1. The working frequency of the harvesters can be significantly improved to satisfy the efficient frequency range of transducers rather than the exciting frequency f_{ex}. Each frequency up-conversion mechanism corresponds its respective application: impact mechanism is applicable for the irregular crash-like vibration; mechanical and magnetic plucking is suitable for the rotary energy harvesting; snap-through phenomenon with nonlinearity is applicable on the inter-well crossing to enhance the harvesting efficiency. Overall, proper selection and structural design for specific applications are required. More developments to harvest ultra-low frequency vibration energy should be conducted to satisfy the hostile environment.

4.3. Motion conversion mechanism

The frequency up-conversion mechanisms mentioned above allow for boosting vibration into a high frequency interval that can be more easily and efficiently harvested. However, motion transfer also needs to be considered to configure effective energy harvesters, particularly for the non-resonant harvesters. Like a wind turbine, motion conversion from translational wind flow to rotational blades benefits energy harvesting with commonly used rotating generators. With the main purpose of transferring translational vibration to rotation, frequency up-conversion may be implemented to gain additional benefit. Motion conversion methods reported in the open literature are divided into six categories and discussed as follows.

4.3.1. String suspended rotors

A string suspended rotor is capable of converting the string elastic energy in the vertical direction into the rotor inertia in the horizontal plane as shown in Fig. 17(a) and (b). The elastic energy is stored when the string is stretched and released to drive the rotor when the string retracts and twists. Fan et al. [169,170] proposed an EMEH with the string suspended rotor, which was proved to be effective for low-frequency vibration energy harvesting. With one more inelastic string added as the excitation input port, the rotor is shifted to the vertical plane [171]. The string suspended rotor is easy to be manufactured to create high energy transfer efficiency, but the theoretical modeling still demands deep investigations.

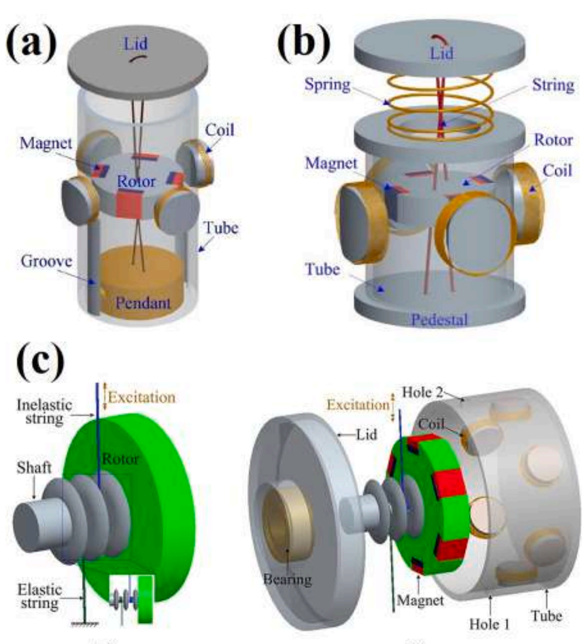

Fig. 17. (a) An EMEH with string suspended rotor [169]; (b) an EMEH based on the 2-DOF string-driven rotor [170]; (c) an EMEH with the string-driven rotor [171].

4.3.2. Ball-screw mechanism

The ball-screw mechanism was widely exploited for the lathe tool support movement due to its high precision and fast response. The large transmission ratio contributes to its availability for motion conversions in ultra-low frequency vibration energy harvesting. Luo et al. [172] developed an inertial-based rotational vibration EMEH for ultra-low human motion-induced vibration energy harvesting as shown in Fig. 18(a). Xie et al. [173-175] proposed ball-screw mechanism based EMEHs for vehicle suspension vibration energy harvesting. As shown in Fig. 18(b), a gear train can be added for improving the transmission ratio. However, the required manufacturing precision may be more costly, and long-time working induced abrasion can cause the mechanism to stick. This calls for a compromised design for onsite applications.

4.3.3. Rack-pinion method

As a conventional motion conversion mechanism, rack-pinion has been widely used in heavy construction machinery owing to its high stiffness, such as automotive steering systems, offshore platform lifting systems, etc. The rack-pinion conversion can be regarded as an extension of pinions with zero or infinite transmission ratio. This type of motion conversion contributes to frequency up-conversion, which depends on the linear speed of the rack and that of the pinion radius. Typical application scenarios include human steps [176], backpacks [177], finger pressing [178], etc. As shown in Fig. 19(a), a one-way clutch can be added for continuous rotation of the generator. Rack-pinion has been proved to be very stable for long-time working, but the abrasion may induce unwanted noises.

4.3.4. Magnet array

Similar to magnetic plucking, motion conversion with magnets array utilizes the repulsive and attractive forces to drive the subsystem motion. Wang et al. [179] proposed an EMEH using a magnet-array-based vibration-to-rotation conversion mechanism. The magnets were equally arranged along a triangle-wave line on the cylindrical surfaces as shown in Fig. 20(a). The attracting force from the linear vibration magnet drives the cylinder to rotate and harvest energy.

4.3.5. Pendulum

The pendulum is an attractive motion conversion mechanism for ultra-low frequency vibration energy harvesting owing to its simple structure and low natural frequency. Numerous pendulum-like PEHs [13,114] and EMEHs [181-184] have been developed for ultra-low frequency energy harvesting. A binder clip pendulum PEH in Fig. 21(a) can result in large deformation on the piezoelectric layers for ultra-low frequency vibration energy harvesting. A pendulum-flywheel EMEH in Fig. 21(b) can switch between the pendulum mode and the eccentric mode. The repulsive magnetic force between the tip magnet and the fixed magnet conduces to the frequency range broadening and amplitude enlargement. A double mass pendulum EMEH in Fig. 21(c) is applied on unmanned surface vehicles for self-powering. Another eccentric pendulum EMEH with self-designed magnets and coils in Fig. 21(d) exhibits high efficiency for ultra-low frequency vibration energy harvesting.

4.3.6. Rolling magnets

To better cope with the ultra-low frequency vibration, the moving parts without any elastic component or even connection have been provided by some researchers [184-187]. As shown in Fig. 22(a)-(c), three EMEHs [184-186] with rolling magnets for rotary-translational motion conversion were proposed for ultra-low frequency vibration energy harvesting. The main difference among the three EMEHs is in the magnet's polarization direction and coil arrangement. The magnet polarization is in the radial direction for the EMEHs in Fig. 22(a) and (c), while in the axial direction as the EMEH is shown in Fig. 22(b). The coil is arranged on the top of the rolling magnet in Fig. 22(a), while in circumference to surround the rolling magnet in Fig. 22(b) and (c). The

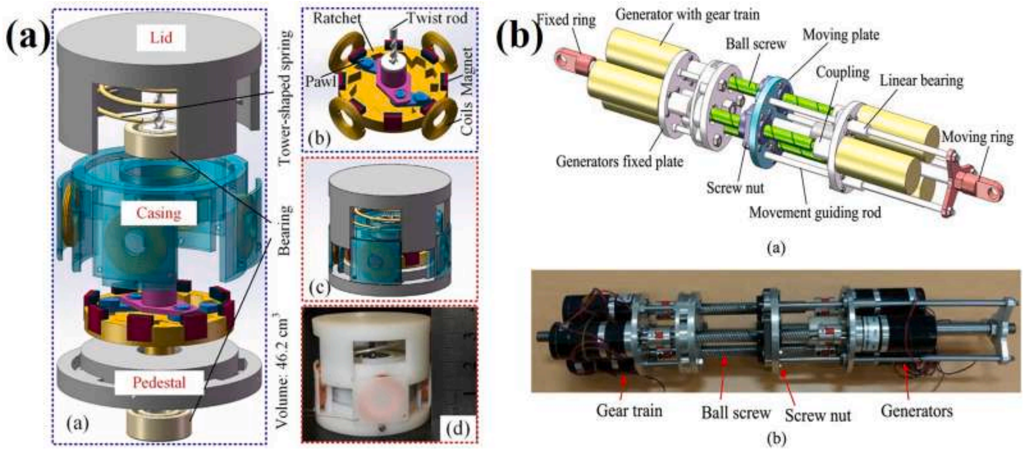

Fig. 18. (a) 3D schematic of an inertial-based rotational vibration energy harvester with three sub-systems: a twist-rod, a pawl-ratchet clutch, and a magnet-coil transduction systems [172]; (b) 3D model and the prototype of an EMEH with ball-screw conversion [175].

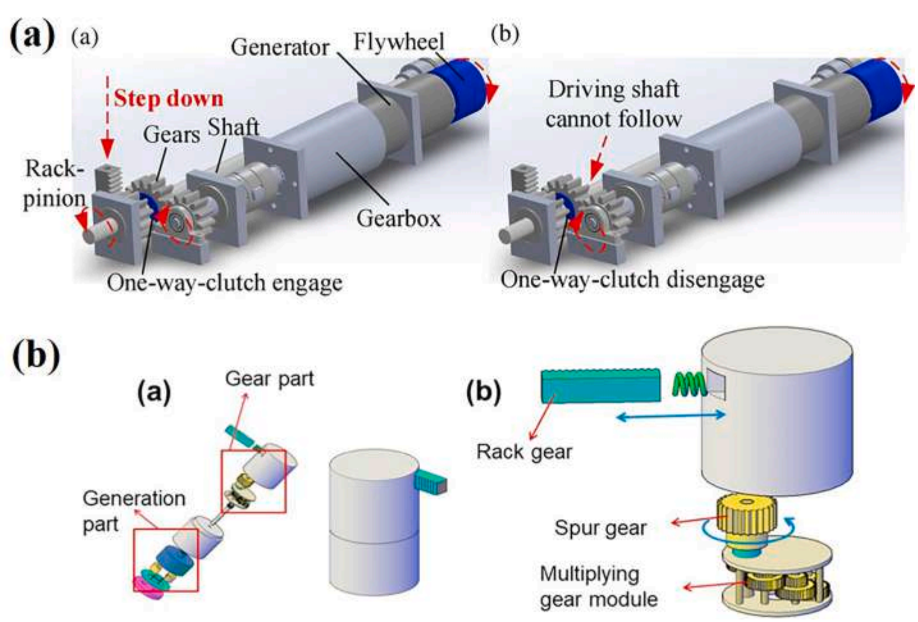

Fig. 19. (a) A rack-pinion EMEH applied on railway track [176]; (b) a finger-triggered EMEH with rack-pinion mechanism [178].

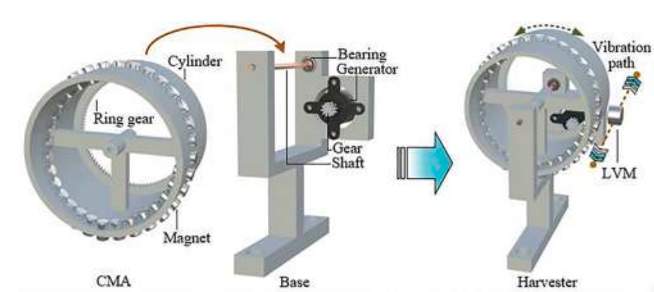

Fig. 20. An EMEH converting vibration into rotation with magnet array [179].

EMEH proposed by Choi et al. [187] in Fig. 22(d) has a similar structure to that of Fig. 22(a), except the magnet is covered with an asymmetric mass coating to behave like a toly-poly for auto-resetting.

The above mentioned six motion conversion mechanisms were proved to be effective for transferring the linear vibration into the rotation or swing, which is very suitable for higher working performance of harvesters. The rack-pinion method is suitable for the heavy machine vibration energy harvesting. The pendulum usually requires a proof mass block that will results in heavy additional weight of the primary system, but properly tuning of the DVA system will lead to the balance of vibration control and energy harvesting. Rolling magnets require no springs for supporting but the efficiency should be improved. Other three types of motion conversion mechanisms are more propitious for slight structures with higher frequency up-conversion ratio. Further research of motion conversion mechanisms should be focused on the efficiency enhancement.

4.4. Bio-inspired structures and metastructures

For further improving energy harvesting efficiency, bio-inspired structural designs attracted a lot of attention recently owing to the evolutive high-efficiency structures. Inspired by human fitness push-ups, Yang et al. [188] proposed a hexagonal skeleton structure in Fig. 23(a) to broaden the bandwidth of the EMEH. Fu et al. [189] developed a host-parasite structure for broadband vibration energy harvesting from low-frequency random vibration sources. The host-parasite structure in Fig. 23(b) is actually a mechanical plucking for frequency up-

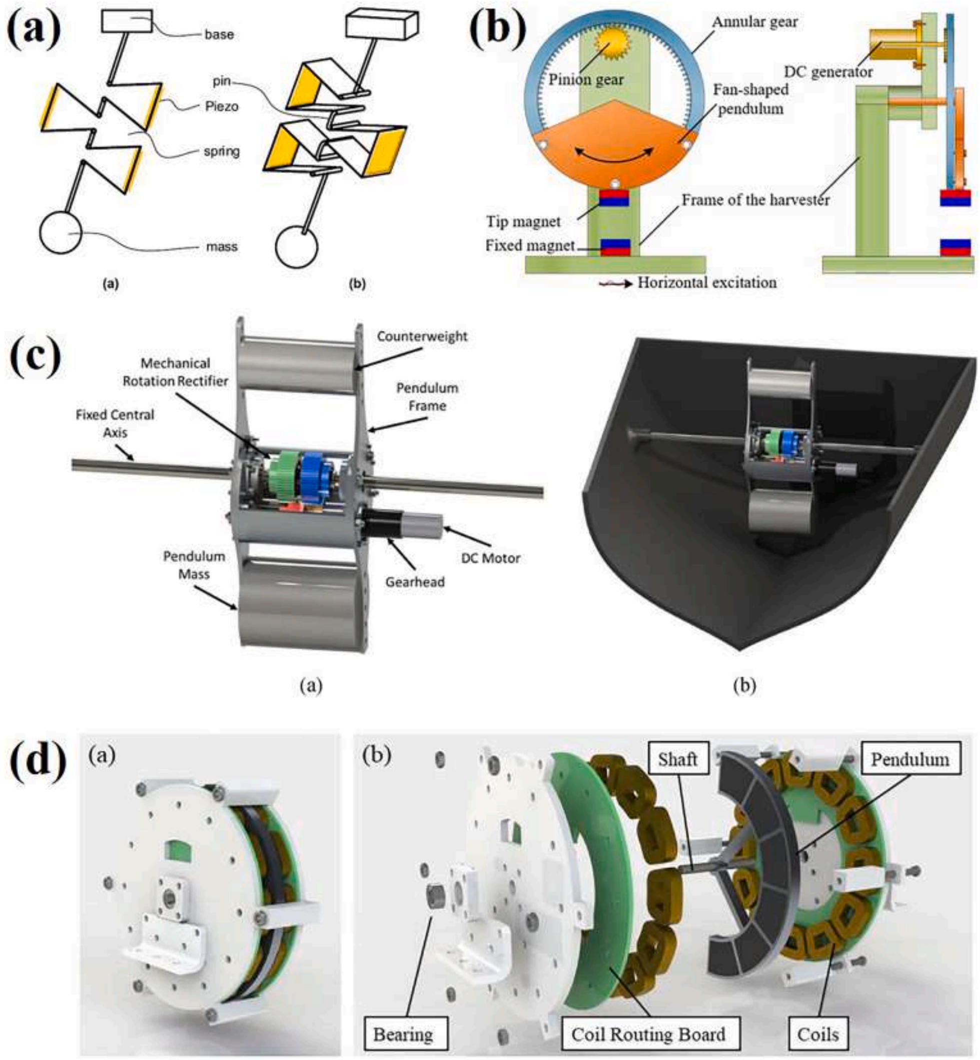

Fig. 21. (a) A binder clip pendulum PEH [13]; (b) schematic of pendulum-flywheel vibrational EMEH [180]; (c) a double mass pendulum EMEH for an unmanned surface vehicle [181]; (d) structure design of a low-frequency EMEH [182].

conversion. As shown in Fig. 23(c), an auxetic nonlinear PEH proposed by Chen et al. [190] is capable of enhancing both efficiency and bandwidth. By mimicking the dipteran wing, a bow-type bistable PEH [191] and TENG [192] in Fig. 23(d) were used for ultra-low frequency vibration energy harvesting. The corresponding parametric analysis of the PEH [191] shows that the light damping and large excitation benefit the energy output. An X-structured PEH [193] was shown to allow for the tuning of the working frequency range with various structural parameters in Fig. 23(e).

Inspired by auditory hair bundle structures, Kim et al. [194] proposed a compliant bistable mechanism as shown in Fig. 23(f) for low frequency vibration energy harvesting. Fish gills inspired parallel-cell TENG [195] in Fig. 23(g) can increase the contact surface of the layers. Whirligig-inspired intermittent-contact TENG [196] in Fig. 23(h) was used for ultra-low frequency vibration energy harvesting. Yang et al. [197] designed a double rocker TENG for applications targeting wave energy harvesting. With the aforementioned bio-inspired structural designs, ultra-low frequency vibration energy harvesting efficiency can be greatly improved or the effective bandwidth can be broadened. Proper structural design based on the evolutional bio-structures would benefit energy harvesting, but some theoretical analyses are still required to shed lights on the underlying mechanisms.

Metastructure/sonic crystal is an intentionally assembled periodic structure/lattice with multiple elements arranged in a repeating pattern. The arrangement scales are smaller than the target wavelength to influence the wave propagation. Apart from optical and acoustic waves, metastructures also show excellent performance for structure-borne wave manipulations. A properly arranged metastructure, like the parabolic acoustic mirror (PAM) proposed by Carrara et al. [198] in Fig. 24 (a), can focus the wave energy on the target point like the effect of ABH. Wave guiding or localization can be implemented with a specific arrangement of metastructures. Sugino and Erturk [199] analyzed the locally resonant metastructures with electromechanically coupled inductors in Fig. 24(b). The bandgap generates with a rather large wavelength than the lattice size and can be maintained even with optimal load resistance, which holds enormous potential for simultaneous low-frequency vibration energy harvesting and vibration suppression. Hu et al. [200] investigated the multi-cell metastructures analytically in Fig. 24(c) to implement simultaneous vibration suppression and energy harvesting. Since the different matching impedance for the optimal status of the two targets, the designed guideline with a tradeoff is required for specific applications.

4.5. Enhancing transducer properties

Structural design and optimization methods, as summarized in the above sections, are in charge of effectively transferring vibration energy into the electromechanical transducers to their maximum ability. A

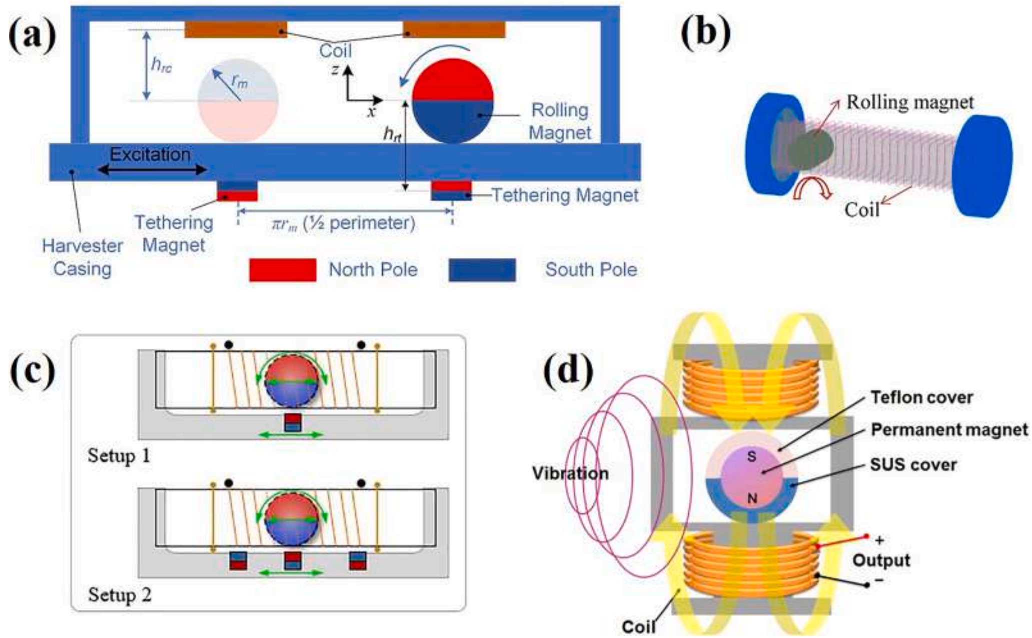

Fig. 22. (a) Schematic of the ultra-low frequency vibration energy harvesting using the rotary-translational motion of a magnet and system bistability [184]; (b) an EMEH with rolling magnets [185]; (c) a rolling magnets harvester with two setups [186]; (d) an EMEH with toly-poly like rolling magnets [187].

necessary following-up step is to convert the obtained vibration energy into electrical energy with a high conversion ratio, which requires specific properties of the transducers. This section reviews enhancing methods based on transducer property in three aspects: electromechanical coupling, interface circuits design, and material requirement. Representative case studies and analyses are categorized below.

4.5.1. *Structural optimization of transducers*

Owing to the possible arrangement of magnet arrays and coil windings, the electromechanical coupling enhancement is mainly concentrated on EMEHs. For the configuration involving opposing magnets in Fig. 25(a), Sun et al. [201] analyzed the damping improvement quantitatively by comparing it with other similar structures. The number of opposing magnets corresponds to the peak number of the radial magnetic flux density and also influences the peak value of the radial magnetic flux density. Both factors contribute to the electromechanical coupling coefficient. The magnetic flux density peak number increases with the opposing magnets pairs apparently, while the peak value decreases. Therefore, an optimal number of opposing magnet pairs should exist to achieve the maximum electromechanical coupling factor. Sun et al. [202] searched out the optimal configuration for maximum damping range with the same volume of magnets and coils. A similar magnet configuration for a planar EMEH [203] was investigated to achieve the highest electromechanical coupling and output voltage. The abrupt magnetic flux density change in a certain confined space can significantly enhance the output power density by over 20 times. This improvement was further validated by charging-capacitor experimental results.

Some magnetic flux path guiding materials have been used for maximizing the magnetic flux through coils. In Fig. 25(b), the non-resonant EMEH [204] with carbon steel for magnetic flux density guiding was verified with high performance for low frequency and large amplitude vibration energy harvesting. With proper magnet arrangement, Zou et al. [103,183] proposed two EMEHs with the magnetic field surrounding coils to enhance electromechanical coupling.

Recently, many researchers focused on the Halbach magnet array to increase the electromechanical coupling coefficient. Halbach magnet array is a specific arrangement of permanent magnets that concentrates the magnetic field on one side of the array while canceling the field to almost zero on the other side. One reported example of a low-profile, planar EMEH utilizing a Halbach array was the one proposed by Zhu et al. [205]. The built prototype in Fig. 26(a) with a concentrated magnetic field and low-profile structure can improve the output power of EMEHs. Salauddin et al. [102,206–209] developed a series of energy harvesters based on the Halbach magnet array for magnetic field enhancement. The prototype in Fig. 26(b) used a dual Halbach magnet array on a hybrid energy harvester through combining an EMEH and a TENG. Shahosseini and Najafi [210] analyzed several structural designs with a cylindrical Halbach magnet array for the EMEH as shown in Fig. 26(c) to compare their performance. As shown in Fig. 26(d), Li et al. [211] compared the performance of four types of EMEHs based on magnet arrays of alternating polarity and configuration: cubic-Halbach, cubic alternative, triangle-Halbach, and triangle-alternative.

Even with the developed energy harvesters, theoretical modeling of the Halbach magnet array is still scarce in the literature. Among existing efforts, Zhang et al. [212–214] provided analytical solutions for target structures with a Halbach magnet array. The circular Halbach magnet array in Fig. 26(e) is a specific case with the consideration of parameters such as the gap, magnetic shape, and distribution radius on the magnetic field. Theoretical modeling of harvesters with Halbach magnet array should be further investigated for a deep understanding of the advantages it might offer as well as possible drawbacks it might suffer. For the coil winding, the cylindrical coil is used for almost all the designs of harvesters in the literature. Some unconventional but effective coil windings of electric motors may be adopted for achieving high electromechanical coupling.

4.5.2. *Interface circuit tuning*

Besides the structural optimization of transducers, proper design and tuning of the interface circuit are contributive to improve energy harvesting efficiency. Huang et al. [215] used the complexification averaging method to analyze the energy harvesting performance theoretically with the consideration of a resonant interface circuit. The energy harvesting efficiency enhancement of a multistable energy harvester with a high-order odd stiffness coefficient was theoretically demonstrated. Yu et al. [216] explored a piezoelectric network with a negative capacitance circuit in Fig. 27(a) for enhanced coupling. Negative impedance could be used for the higher performance of

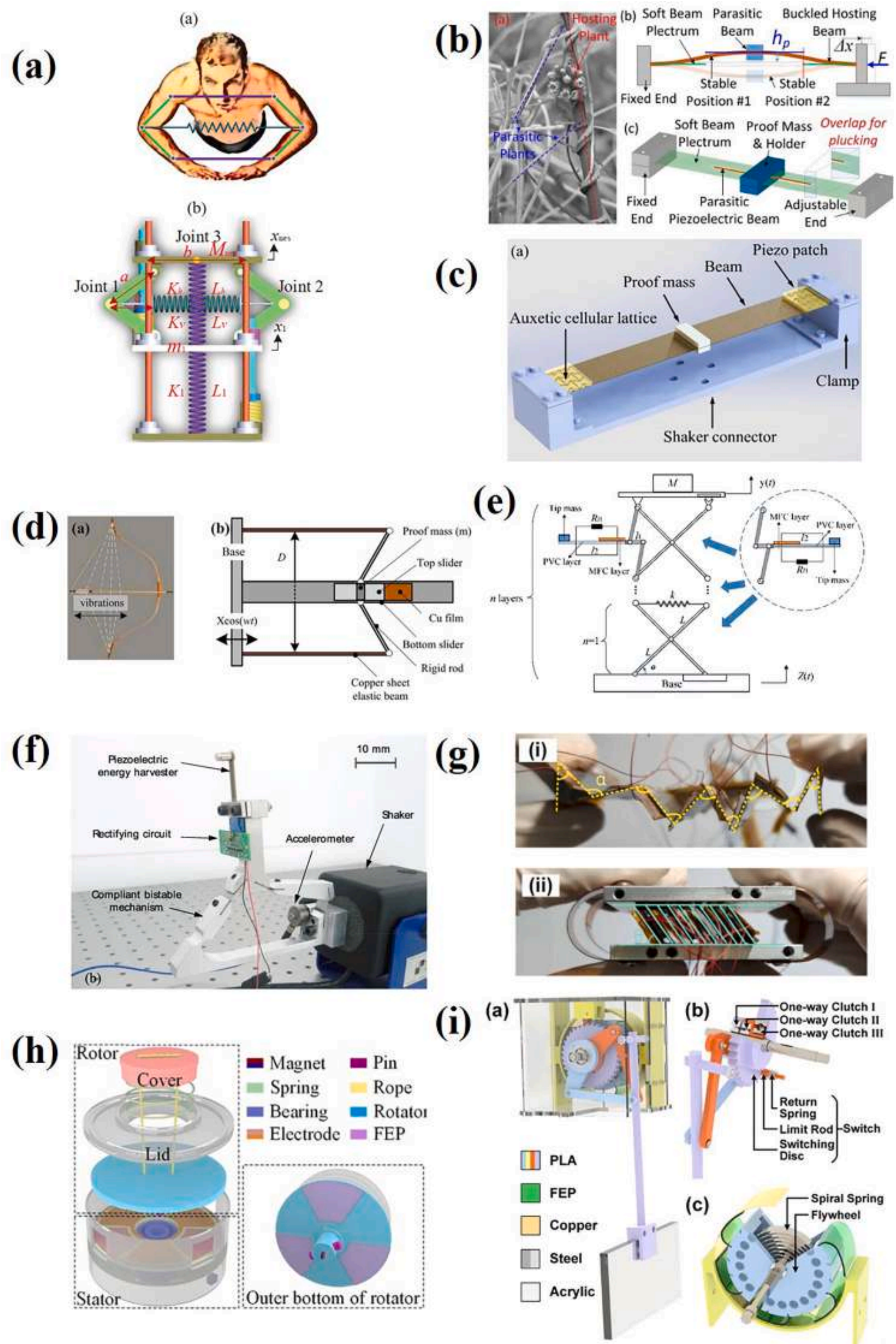

Fig. 23. (a) Bio-inspired hexagonal skeleton structure for an EMEH[188]; (b) host-parasite structure for broadband vibration PEH [189]; (c) auxetic nonlinear PEH [190]; (d) a bow-type TENG [192]; (e) X-structure based PEH [193]; (f) an auditory hair bundle structures inspired PEH with flexural joints [194]; (g) Z-TENG and PC-TENG [195]; (h) intermittent-contact TENG [196]; (i) overall structure, mechanical transmission structure, and generation unit of a double rocker-TENG [197].

electromagnetic transducers [217–219] than the ones with positive impedance. The equivalent negative resistance in Fig. 27(b) is a simplified circuit with the embodiment of a high-power operational amplifier. Mitcheson et al. [220] realized a switched-mode impedance to broaden the power frequency bandwidth of an EMEH. The corresponding H-bridge voltage source converter is shown in Fig. 27(c). Li and Zhu [221] utilized similar circuits to obtain a synthetic impedance for a self-powered EMSD. Cao et al. [222] proposed a feedforward and feedback DC-DC pulse-width modulation boost converter for EMEHs.

The shunt tuning technique is easier to be implemented with tunable electronic components. However, the system requires a power supply, including the microprogrammed control unit, operational amplifier, switch-mode rectifiers, etc. The tradeoff between the harvested energy and energy consumption of the electronic components involved should be considered while using the active or semi-active interface circuits.

4.5.3. Enhancement through material selection

Manufactured material is another significant factor to be considered

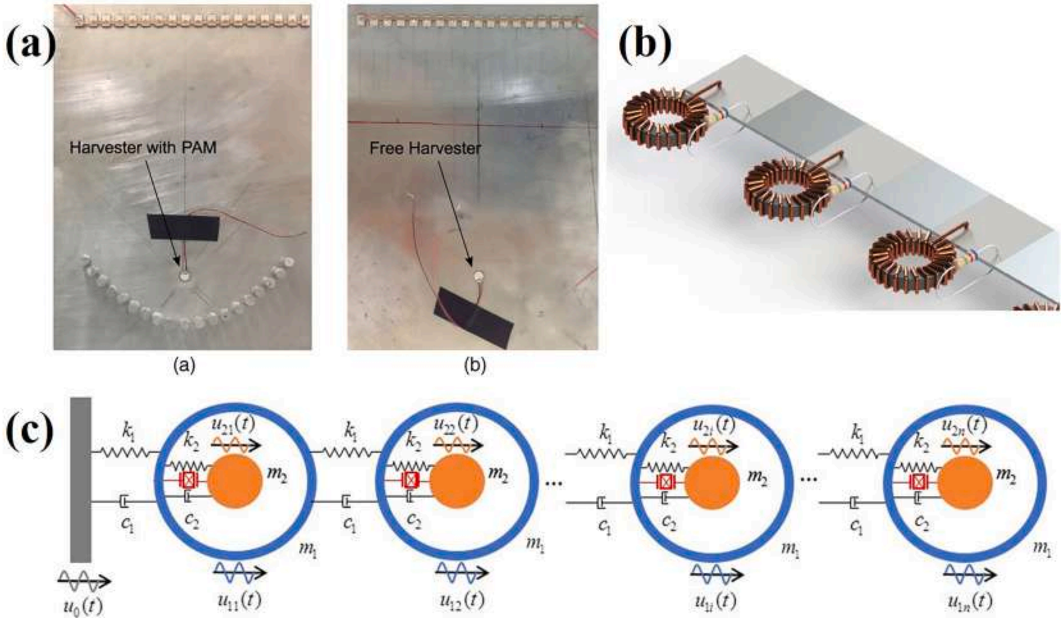

Fig. 24. (a) A metamaterial-inspired parabolic acoustic mirror [198]; (b) a locally resonant energy harvesting metastructure [199]; (c) multi-cell metastructure for simultaneous vibration suppression and energy harvesting [200].

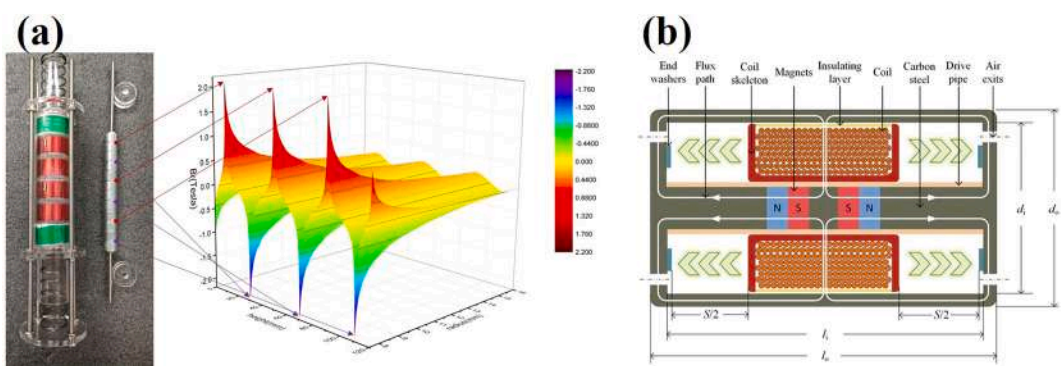

Fig. 25. (a) An EMEH with opposing magnets configuration [201]; (b) an EMEH with magnetic flux density guiding material [204].

in determining the performance enhancement of energy harvesting transducers. *NdFeB* magnets and copper coil wires have been widely used for decades and been proved effective for the EMEH fabrication. Current enhancement methods for EMEHs concentrate on structural optimization as illustrated in Section 4.5.1. More material enhancement methods are applied to PEHs and TENGs.

Piezoelectric materials can be used as sensors and harvesters. For the visualized vibration sensor in Fig. 28(a), the elasto-electro-chemical synergistic effect of piezoelectricity and electrochromism was utilized for the device development [223]. A buckled piezoelectric ribbon-substrate energy harvester in Fig. 28(b) was proposed by Bi et al. [224] for wearable electronics. The soft PEH can well suit the soft substrate to improve the energy harvesting performance. Since TENGs are based on the nano-scaled dissimilar thin films to generate electric charges, the material improvement has larger influence on TENGs than that on PEHs. Park et al. [225–227] explored several materials for enhancing the performance of TENGs, including nanocomposite-coated fabric, cobalt nano-porous carbon material, carbon nanotube fillers with different concentrations, etc. More material development is bound to benefit the performance and application fields of harvesters.

4.6. Hybrid harvesters

For increasing efficiency, hybrid harvesters were used by combining different types of harvesters as shown in Fig. 29. The hybrid harvesters combing types include PEH & EMEH [16], EMEH and TENG [228], PEH & TENG [229], PEH and Dielectric elastomer energy harvesters (DEEH) [230], EMEH and DEEH [231], tribo-piezo-pyroelectric hybrid energy harvester [232], etc. The applications are different, including human motions, ocean waves, wind, etc. The series of hybrid energy harvesters perform better with properly designed structures in both output energy and bandwidth than that of a single harvester. To improve the performance, more combinations and the corresponding efficiency improvement under specific applications should be investigated.

4.7. Exploration of nonlinearity

Most ultra-low frequency vibrations exhibit broadband characteristics, and corresponding harvesters contain complex nonlinearity, such as the bio-inspired structures. Actually, the principles and mechanisms of even a singular nonlinear factor can be very complex which deserves deep investigation. Zhou et al. [41] and Yang et al. [50] reviewed the design, principles, model analysis, and real applications, particularly about bistable and multistable energy harvesters. Three main nonlinear

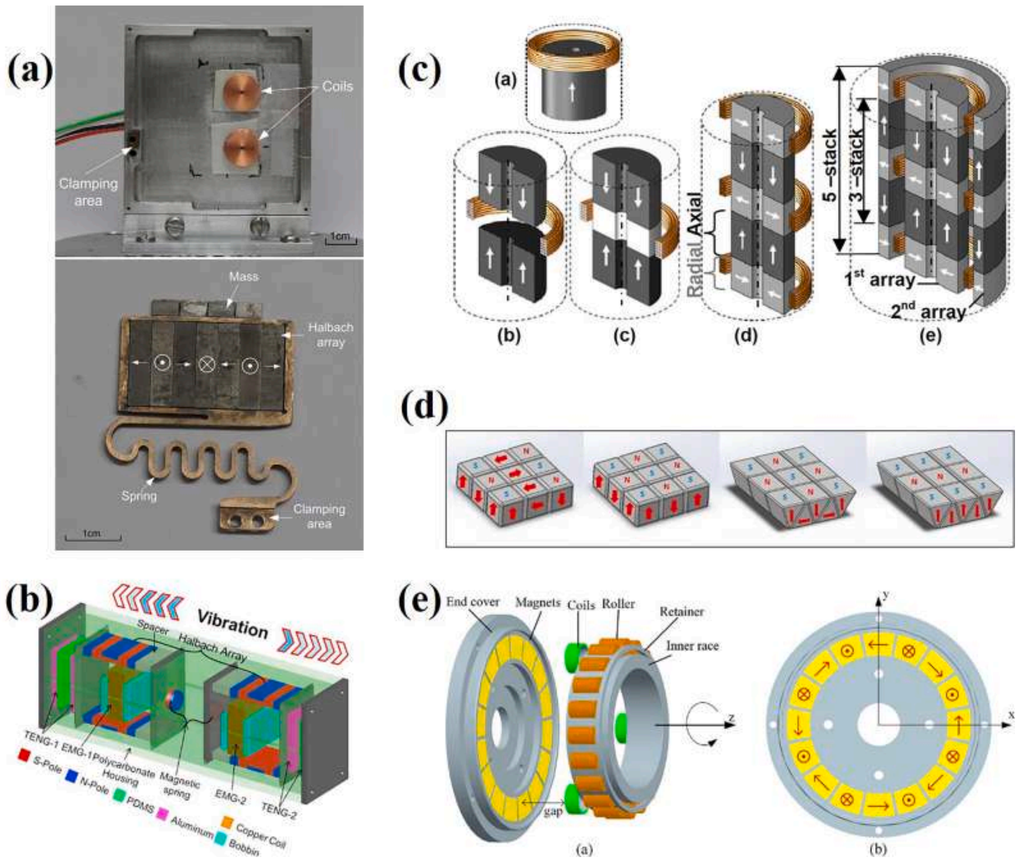

Fig. 26. (a) A planar EMEH with Halbach magnet array [205]; (b) schematic structure of handshaking vibration driven hybrid energy harvester using Halbach magnet array. [102]; (c) an EMEH with a single magnet, double opposing magnets, and Halbach array [210]; (d) the planar magnet array for a planar EMEH [211]; (e) schematic of a proposed novel EMEH and the corresponding arrangement mode of the magnets[212].

mechanisms of harvesters will be discussed in this section, including friction-based nonlinearity, structural nonlinearity, and magnetic force induced nonlinearity.

4.7.1. Friction-based nonlinearity

Coulomb friction is a non-negligible factor for moving mass and dissipates partial vibration energy into thermal energy. As shown in Fig. 30, three parametric models of harvesters considering the Coulomb friction effects were investigated by Mitcheson et al. [233], including two resonant harvesters: velocity-damped resonant generators and Coulomb-damped resonant generators, one non-resonant harvester: Coulomb-force parametric generator.

Theoretical analysis of these three models shows that the energy harvesting efficiency is dependent on two dimensionless ratios: amplitude ratio χ and frequency ratio γ:

$$\begin{cases} \chi = \dfrac{Z_l}{Y_0} \\ \gamma = \dfrac{\omega}{\omega_n} \end{cases} \tag{4}$$

where Z_l is the maximum possible amplitude of the mass-to-frame displacement; Y_0 is the source motion amplitude; ω is the excitation frequency and ω_n is the natural frequency. For the two resonant harvesters, resonance contributes to the energy harvesting efficiency of both harvesters with $\gamma = 1$ and $\chi > 1$. If the excitation frequency does not locate inside the resonance frequency range, the VDRG performs better when $\gamma > 1$, while the CDRG performs better when $\gamma < 1$. Moreover, when the excitation frequency is far away from the resonance frequency that $\gamma \neq 1$ and $\chi < 0.1$, the CFPG can harvest more power than the others. The above principles considering Coulomb friction for energy harvesting contribute to effective designs.

4.7.2. Structural nonlinearity

To broaden the effective frequency range, tactically designed nonlinear structures are utilized for vibration energy harvesters. With the possibilities of switching among various potential wells, BEHs and MEHs are capable of achieving high efficiency both in terms of working frequency range and output power.

Owing to the high static stiffness and low dynamic stiffness, a QZS harvester is perfectly matched for ultra-low frequency vibration energy harvesting and attracted more attention recently. As representative examples, Yang and Cao [234] proposed a QZS harvester with five springs that constituted geometric nonlinearity as shown in Fig. 31(a), which forms a tristable energy harvester. Yang et al. [235] analyzed a multi-stage oscillator and showed its suitability for simultaneous vibration control and energy harvesting. As shown in Fig. 31(b) and (c), a magnet aided QZS-TENG [236] and a QZS-based hybrid harvester by combining the EMEH and the TENG [237] were proposed for ultra-low frequency vibration energy harvesting. The corresponding theoretical modeling and analysis were demonstrated in detail. The results show that the proposed QZS springs can achieve ultra-low stiffness in a larger displacement region than that of a traditional QZS device. Margielewicz et al. [238] compared the QZS-PEH in Fig. 31(d) to a tristable PEH with the same dimension.

QZS structures are more complex and corresponding closed-form analytical solutions are more difficult to obtain. As a resort, approximate solutions are often used for performance prediction. More efforts are required to propose simplified but effective QZS structures as well as analysis models.

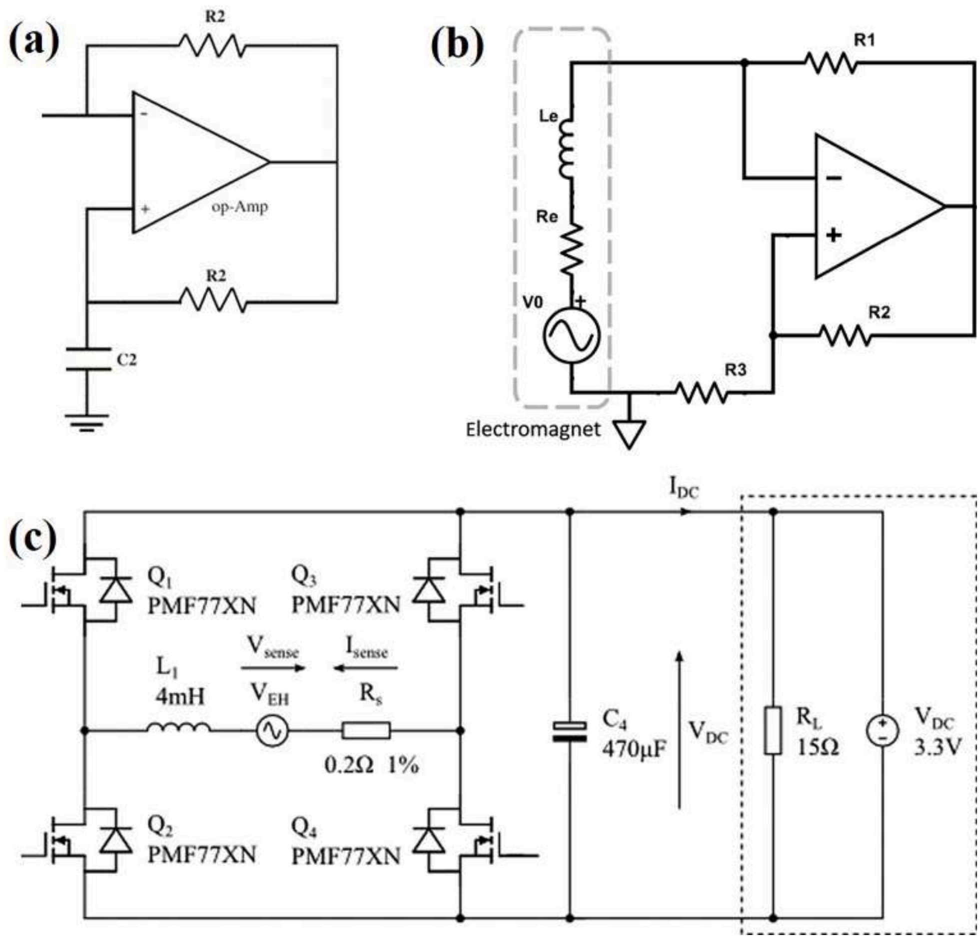

Fig. 27. (a) Negative capacitance for piezoelectric networks [216]; (b) an EMSD with negative resistance [218]; (c) H-bridge voltage source converter for an EMEH [220].

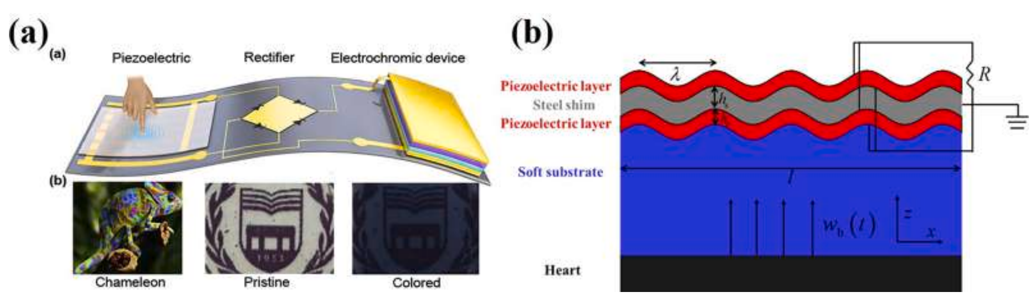

Fig. 28. (a) A visualized vibration sensor based on elasto-electro-chemical synergistic effect [223]; (b) a buckled piezoelectric ribbon-substrate energy harvester [224].

4.7.3. Nonlinear magnetic force

Most magnetic forces are nonlinear due to the divergent magnetic field between magnets. The repulsive magnetic force between the fixed magnets and moving magnets in Fig. 32(a) is nonlinear, which was commonly used for the EMEH. Liu et al. [239] designed a low-frequency handshaking EMEH based on this structure. Gao et al. [240] proposed a track-borne EMEH for powering sensors with the same magnetic levitation principle in the vertical direction. For the conventional EMEH with a linear spring in Fig. 32(b), the endmost magnets on both terminals are able to provide the attracting force to counteract the linear spring force so that a QZS zone appears in the system. Based on this principle, Fan et al. [241] developed an EMEH to harvest energy from low-frequency human motion. Linear EMEH, suspended EMEH, and monostable EMEH were compared to verify the natural frequency shifting phenomena.

By placing the repulsive EMEH into a large tube with two more repulsive magnets on both terminals like Fig. 32(c), a 2-DOF nonlinear EMEH is constructed for ultra-low frequency vibrations. Fan et al. [242] fabricated the nonlinear EMEH and experimentally verified the tunable natural frequency and output power improvement. Zhang et al. [243] used asymmetrically arranged magnets to generate the nonlinear repulsive force. Corresponding output power can be increased by three times and the resonance frequency can be decreased from 16.8 Hz to 14.6 Hz. Moreover, for the coils in Fig. 32(d) hung by elastic strings, the EMEH presents nonlinearity near the equilibrium point [244]. The working frequency range can be tuned by changing the length of elastic strings.

If the central moving magnet is repulsed/attracted by

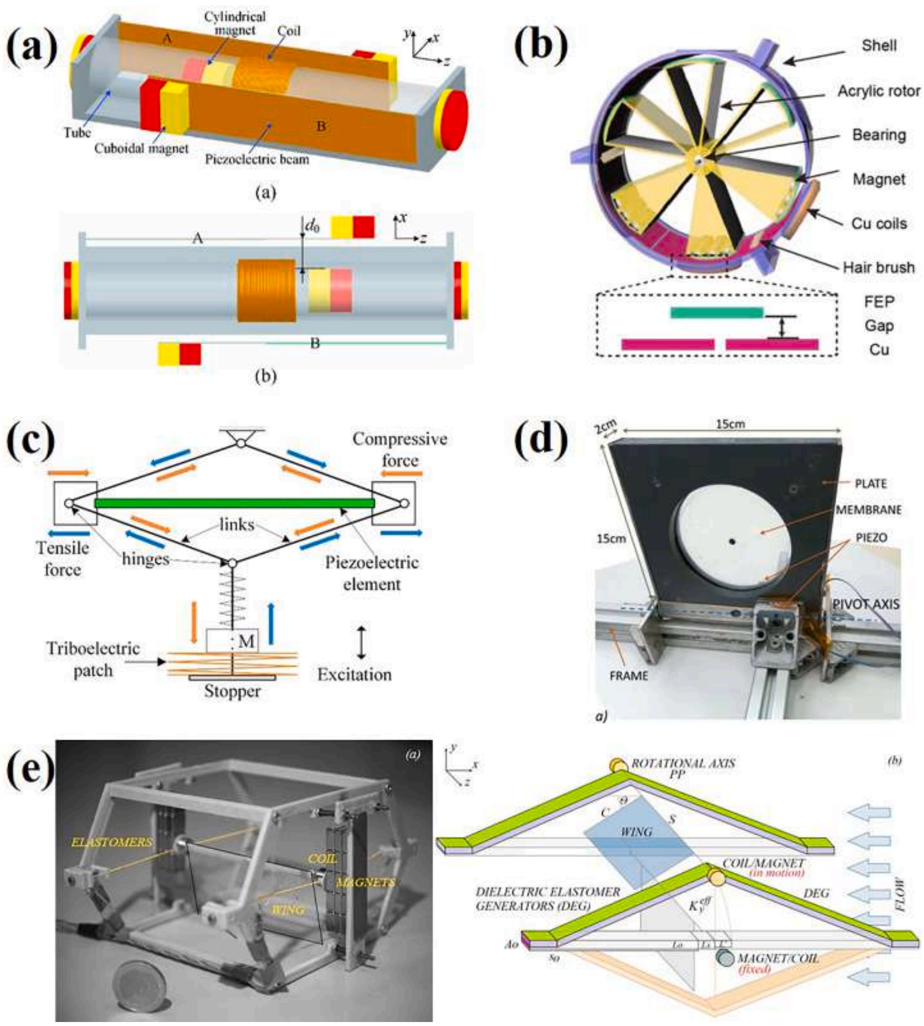

Fig. 29. Hybrid harvesters by combining (a) EMEH & PEH [16]; (b) EMEH & TENG [228]; (c) PEH & TENG [229]; (d) PEH & DEEH [230]; (e) EMEH & DEEH [231].

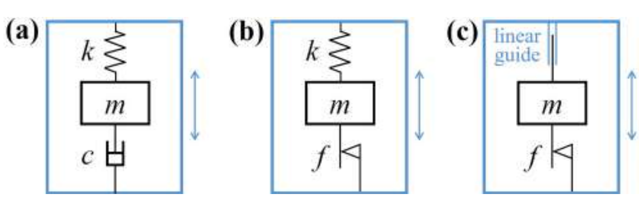

Fig. 30. Three models of vibration energy harvesters: (a) velocity-damped resonant generators; (b) Coulomb-damped resonant generators; (c) Coulomb-force parametric generator.

circumferentially distributed magnets as shown in Fig. 33(a) and (b), the proposed EMEH by Yan et al. [245,246] performs as a bistable energy harvester. When the moving magnet (PM^M1) in Fig. 33(a) locates at the plane determined by the central points of the three base magnets (PM^b1, PM^b2, PM^b3), the locating point is the high potential point in the vertical direction for the moving magnet. A bistable EMEH is applied to a 2-DOF harvesting system as shown in Fig. 33(b) to achieve broad bandwidth. A lower natural frequency of the DVA system contributes more to energy harvesting due to the higher output voltage in the second coupled mode.

The repulsive magnetic force on the central magnet in Fig. 32(a) is rather small when its location is near the equilibrium position and increases dramatically only the interval between the fixed and moving magnet is pretty small. The relationship between the small magnetic force and the large displacement is conducive to building QZS structures. The QZS springs in Fig. 31(b) and (c) utilize this property. The QZS spring with a similar structure in Fig. 33 was illustrated by Yan et al. [247]. More explorations about QZS structures with magnetic forces are worth investigating.

The nonlinear magnetic force has been widely used to generate bistable or multistable PEHs. Cantilever beams are the commonly used structures for ultra-low vibration frequency energy harvesting owing to their structural simplicity and tunable natural frequency. For the piezomagnetoelastic energy harvester in Fig. 34(a), Erturk and Inman [248] elaborated its theoretical modeling by combining an electromechanical-based bistable Duffing oscillator with piezoelectric coupling. Corresponding experiments verified the effectiveness of the above modeling. For the non-magnetic conduction beams like Fig. 34(b), a magnet is fixed at the free end of the cantilever beam that functions as both proof mass and repulsive/attractive magnetic force carrier. Gao et al. [249] compared the bistable PEHs when the end magnets are connected to the base with fixed support and elastic support. Their results show that the PEH with an elastically supported magnet is more conducive to keeping bistable oscillation even with low-intensity excitation and the corresponding magnet gap tuning is not required for random excitations.

Zhou et al. [250] proposed a theoretical model of the tristable PEH in Fig. 34(c) and demonstrated that the tristable PEH delivers wider working bandwidth and allows for easier maintenance on high-energy interwell oscillations than the bistable PEH. Moreover, the asymmetric tristable PEH efficiency enhancement with different unstable

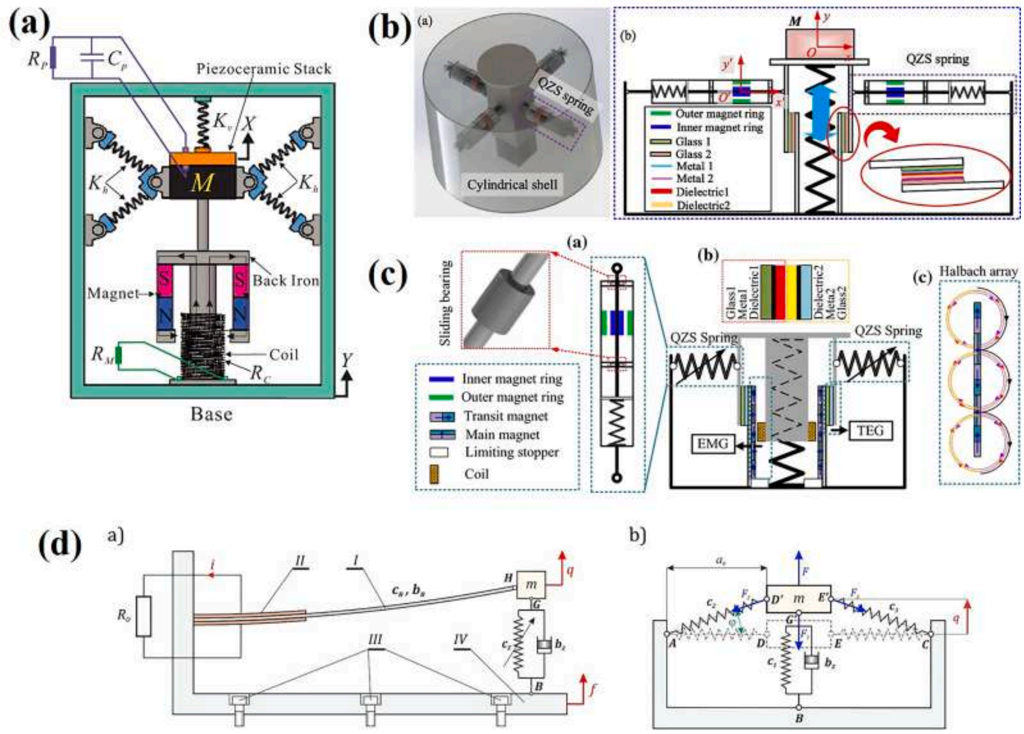

Fig. 31. (a) The physical model of multistage oscillators: from the first stage to the third stage [234]; (b) schematic model of the QZS-TENG [236]; (c) hybrid EMEH and TENG with a QZS spring [237]; (d) a QZS-PEH [238].

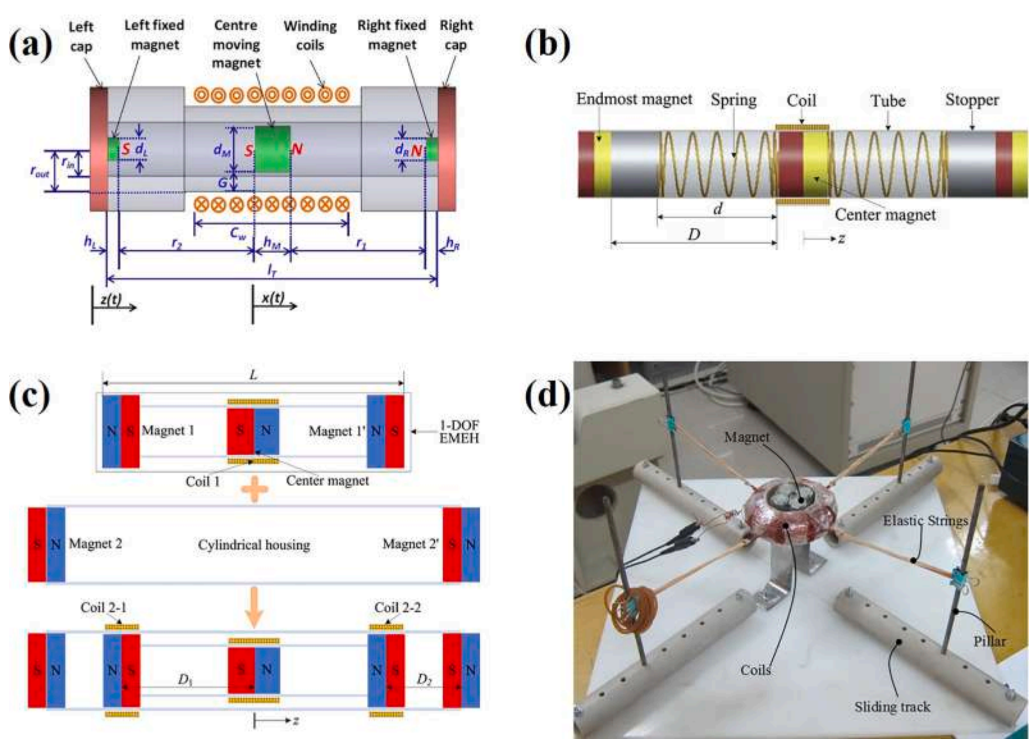

Fig. 32. (a) Schematic diagram of an EMEH device with nonlinear magnetic springs [239]; (b) schematic diagram of the monostable EMEH [241]; (c) structure of 2-DOF nonlinear EMEH [242]; (d) a nonlinear frequency tuning EMEH with elastic strings [244].

equilibrium positions was also theoretically explored by Zhou and Zuo [251], and Ma et al. [252]. The broad bandwidth and various potential wells of multistable energy harvesters provide possibilities for various applications. More investigations of multistable energy harvesters on both theoretical modeling and efficiency improvement are required for shedding light on the physical principles behind as well as developing design guidelines for targeted application scenarios.

In real applications, the nonlinearity is more complicated than the three analyzed nonlinear factors (friction-based nonlinearity, structural nonlinearity, nonlinear magnetic force). However, figuring out the

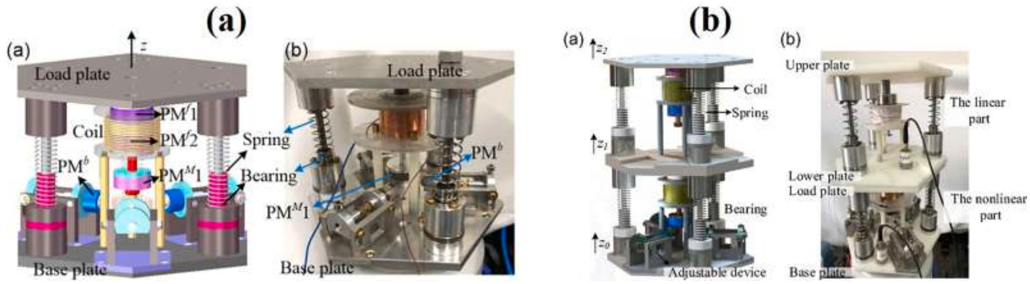

Fig. 33. Configuration and prototype of (a) SDOF EMEH [245]; (b) 2-DOF bistable EMEH [246].

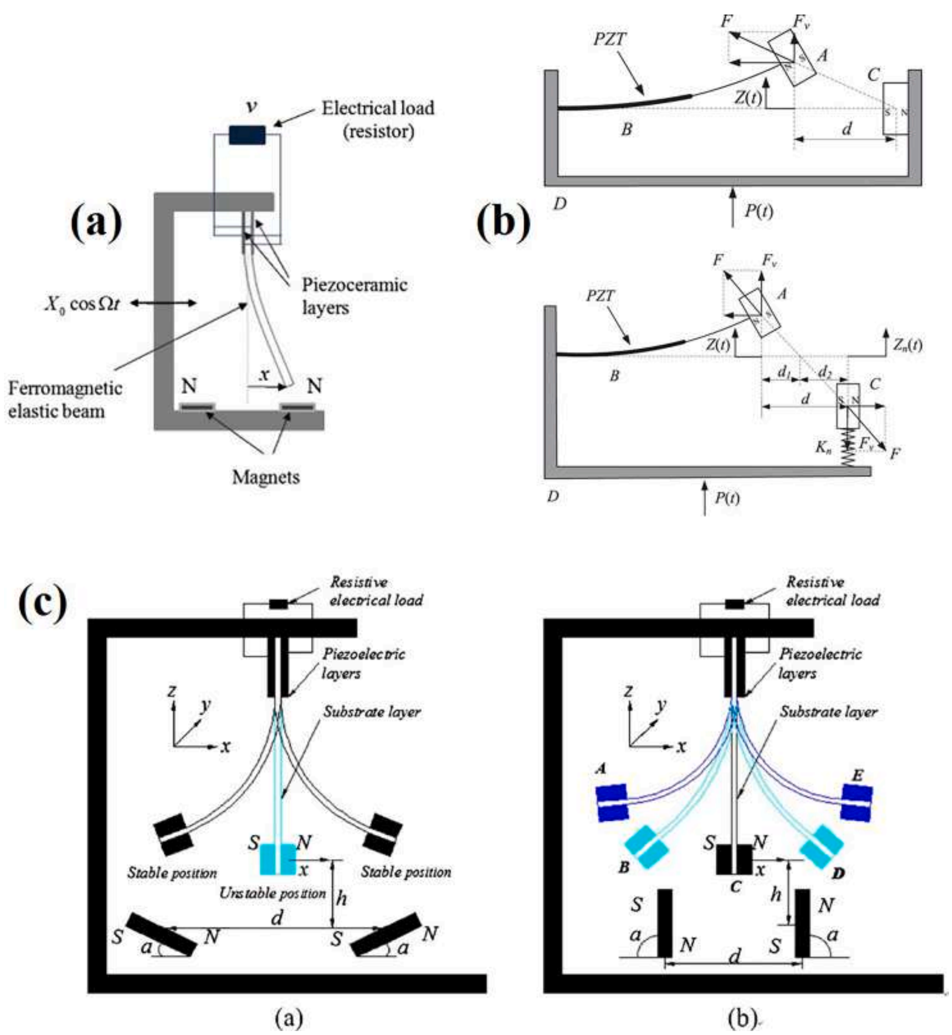

Fig. 34. (a) A bistable PEH [248]; (b) a bistable magnet repulsion PEH with a rigid support (top) and an elastic support (bottom) [249]; (c) nonlinear PEHs with bistability (left) and tristability (right) [250].

principles of the three nonlinear factors from the above literature is beneficial to the proper utilization of nonlinearity for target energy harvester design with nonlinearity. Moreover, the nonlinearity of singular factor is difficult to describe. Even with the efforts from the above literature, the research with specific nonlinear factors still need investigations for the principles revealing.

5. Scaling laws

For vibration isolation or suppression, frequency response function is commonly used to estimate the performance of a designed isolation system. To quantify the harvested energy and to evaluate the performance of harvesters, universal scaling laws are required. Currently, there is no determinist and detailed scaling law for evaluating the energy harvesting results. The existing scaling laws for both electromechanical coupling and output power are listed and compared in this section.

5.1. Electromechanical coupling

For an EMEH with simultaneous functions of shunt damping and energy harvesting, the electromechanical coupling efficiency is a vital metric for the transducer performance improvement. Elliott et al. [253]

fitted the nondimensional electromagnetic coupling coefficient of the EMEH, as follows:

$$C_{em} = \frac{(Bl)^2}{R_m R_e} \approx \left(\frac{M_T}{M_0}\right)^{0.35} \quad (5)$$

where B is the magnetic flux density; l is the length of the wire moving in the field; R_m is the mechanical resistance; R_e is the coil's internal resistance; M_T is the total mass of the transducer and M_0 is a reference mass. Compared with the PEH with a mass-independent coupling factor, the electromagnetic coupling coefficient of the EMEH is positively related to the transducer mass in Eq.(5). With the proposed scaling laws by Gardonio et al. [254] for the EMEH and the PEH on seismic vibration energy harvesting, a similar principle about the electromechanical coupling coefficient was acquired. Overall, the effective electromagnetic coupling coefficient should be properly considered when using an EMEH.

5.2. Output power

For scaling the harvested energy by the EMEH, Moss et al. [255] provided the upper limit to estimate the maximum power, as follows:

$$P_{max} = 1.9V^2 f_r^2 \quad (6)$$

where V is the transducer volume in m^3 and f_r is the resonant frequency in Hz. For performance comparison, the power density with different metrics is considered: volume, frequency, acceleration, and mass.

Since there is no uniform standard for quantifying the harvested energy from the literature, direct power density comparison with the aforementioned enhancement methods is rather difficult. Even for a specific harvester, the evaluation index is still not clear. For the EMEH, various parameter scaling laws are considered: volume, mass, moving mass, frequency, acceleration, displacement amplitude, exciting force, and even various combinations of several parameters above, etc. For example, Fu et al. [189] calculated the power density with consideration of piezo-material volume and square of acceleration; Moss et al. [255] used different standards, including volume, frequency, acceleration square, and mass; Zou et al. [40] and Shen et al. [204] weighted the power density with volume, etc. The unclear evaluation index of the power density makes the comparison among previous works rather difficult. The evaluation index for specific types of harvesters is worthy of exploration.

For further comparison with different standards, the available experimental performance statistics of small-scale and *meso*-scale/large-scale energy harvesters are listed in Table 2 and Table 3 respectively. To distinguish the small-scale from the *meso*-scale, a demarcation value of the harvester volume is set as 1000 mm^3. Therefore, the small-scale energy harvesters are mainly used for MEMS, *meso*-scale and large-scale energy harvesters are useful to charge wearable electronics, sensors, or batteries. It is important to reiterate, however, the dividing threshold value is a relative term, since there is no rigorous definition for small-scale or large-scale.

Seven key parameters pertinent to representative harvesters are listed and compared in Table 2 and Table 3: maximum output power (P_{max}), excitation frequency (f_{ex}), excitation amplitude (A) in displacement/acceleration/force, output voltage (U_{out}), matching resistance (R_{mat}), volume/mass/surface area of moving parts ($V/M/S$) and harvester type. The items with a dot in front, like "• 7.85 mm^3" in the first line, mean that corresponding data are calculated with the parameters from the literature or estimated from the corresponding figures provided in the literature. Another explanation to avoid possible confusion is concerned with the use of the letter "g" in the two different columns: the amplitude A and volume/mass/surface area of moving parts (V/M/S) column. For the amplitude A, "g" means the gravitational acceleration (9.8 $\mathrm{m/s}^2$). For the mass of moving parts, "g" denotes the mass unit in gram.

The comparison between Table 2 and Table 3 shows that PEHs are more frequently used as small-scale vibration energy harvesters than EMEHs. The output power of TENGs is limited by the high internal impedance. Some high power output samples utilize the EMEHs with heavy proof mass. A proper selection of the harvester should be made on a need basis to ensure a better performance.

6. Challenges

Despite the persistent effort made in the past, including the aforementioned enhancement methods for ultra-low vibration energy harvesters, several challenging issues deserve deeper investigations, five of which are listed below which hopefully can inspire further research.

6.1. Efficient up-conversion mechanisms

The frequency gap between the ultra-low frequency vibration energy sources and the efficient working frequency range of harvesters is the primary challenge to be tackled. As mentioned in Section 4, various frequency up-conversion mechanisms were introduced to handle this

Table 2
Performance statistics of small-scale vibration energy harvesters.

Method	Refs.	P_{max}(μW)	f_{ex}(Hz)	A	U_{out}(V)	R_{mat}(Ω)	$V/M/S$	Type
Resonant	[122]	5.625×10^{-5}	11	>0.2 g	0.0075	1 M	• 7.85 mm^3	PEH
	[123]	0.0233	68	0.25 $\mathrm{m/s}^2$	–	–	0.11 mm^3	PEH
	[124]	249	16	0.4 $\mathrm{m/s}^2$	6.5	550 k	1.29 g	PEH
natural frequency tuning	[133]	47.23	0–10	< 1 g	–	–	25 g	PEH
	[135]	700	13.2	1 g	13.5	–	2.2 g	PEH
	[140]	0.26	58	0.5 g	4	5.5 M	1.84 g	PEH
impact	[152]	613	• 3.3	31 mm	13	20 k	• 53.76 g	PEH
	[154]	203	4.9	2 g	0.9	43	3.9 cm^3	EMEH
	[156]	42.56	• 0.33	1 *m*	261.2	–	• 0.0528 mm^3	PEH
plucking	[159]	247	13.5	0.4 g	6.65	180 k	4.36 g	PEH
	[147]	430	8.2	0.4 g	0.43	228 k	8 g	PEH
	[160]	50	3	0.6 g	–	–	3 g	PEH
	[166]	8.1×10^{-3}	10	0.6 g	18	10 k	14.44 mm^3	EMEH
Snap-through	[167]	7	12	2 g	6	5 M	• 6.11 g	PEH
	[168]	193	10	4 g	–	8.2 k	–	PEH
Rolling	[187]	9.03	20	3 g	0.0455	80	• 179.6 mm^3	EMEH
Bio-inspired	[189]	10.6	23	0.25 g	–	–	7.95 mm^3	PEH
transducer	[205]	150	45	0.5 g	1.6	4.4 k	0.7 g	EMEH
	[223]	0.61	4	–	20	165 k	–	PEH

Table 3
Performance statistics of mesoscale/large-scale vibration energy harvesters.

Method	Refs.	P_{max}(mW)	f_{ex}(Hz)	A	U_{out}(V)	R_{mat}(Ω)	$V/M/S$	Type
DVA	[130]	930.3	1.033	0.05 g	17.1	34	17.6 kg	EMEH
	[131]	5.2	11.5	–	–	20	0.048 kg	EMEH
natural frequency tuning	[132]	78	1	• 3.95 m/s^2	–	15	1.047 kg	EMEH
	[137]	325	• 3.3	• 130.28 m/s^2	330	0.33	• 1131 mm^3	EMEH
	[138]	2.5	148	4.92 m/s^2	6	15 k	30.8 g	PEH
impact	[153]	11.58	15	20 m/s^2	1.52	50	4.36 g	EMEH
plucking	[161]	4.42	0.5	1 g	1	1.1 k	121 g	EMEH
	[162]	13.13	3	–	0.74	24.6	1809 mm^3	EMEH
string-suspended	[169]	12.3	2.6	23 mm	1.2	25	• 4241 mm^3	EMEH
	[170]	9.4	3	8 mm	1.3	45	• 4241 mm^3	EMEH
	[171]	6.5	4	13 mm	1.35	30	• 4241 mm^3	EMEH
ball-screw	[172]	6	0.1	0.1975 m/s	1.55	85	• 3534 mm^3	EMEH
	[175]	1150	1.2	20 mm	10	35	–	EMEH
rack-pinion	[176]	12,000	2	6 mm	11	10	80 kg	EMEH
	[177]	3290	2.12	–	–	10–15	13.6 kg	EMEH
	[178]	7.68	3	4.5 N	0.52	36	–	EMEH
array	[179]	106.5	5	16 mm	–	300	–	EMEH
pendulum	[13]	13.29	2.03	0.26 g	• 40	54.2 k	2.03 kg	PEH
	[180]	16.3	10	15 mm	–	–	1.102 kg	EMEH
	[181]	997	0.75	0.102 g	–	–	• 12.3 kg	EMEH
	[182]	54.2	2	0.1 g	–	–	–	EMEH
	[183]	0.29	10	20 mm	4.3	440	549.5 mm^3	EMEH
rolling magnets	[185]	1.02	3.1	1 g	1.1	2 k	–	EMEH
	[186]	40.6	8	0.2 g	–	450	• 50.27 mm^3	EMEH
bio-inspired	[188]	0.91	5–15	0.08 g	–	–	1.05 kg	EMEH + PEH
	[190]	0.12265	• 30	0.1 g	• 3.8	60 k	2400 mm^3	PEH
	[191]	0.143	4	0.7 g	–	2063 k	4.2 g	PEH
	[192]	0.64	5	15 mm	• 300	110 M	2.6 g	TENG
	[193]	0.084	2.42	0.1 g	5	300 k	10 g	PEH
	[194]	0.0018	7	1 m/s^2	0.6	–	2 g	PEH
	[195]	1.294	4	30 mm	143	8.8 M	–	TENG
	[196]	1.24	1.8	10 mm	• 370	111 M	–	TENG
	[197]	11	<1	–	450	• 10 M	602 g	TENG
meta-structure	[198]	1.51	55 k	–	• 2	1.3 k	–	PEH
transducer	[204]	23.2	4.5	3.25 g	–	168	27 g	EMEH
	[102]	11.75	5	0.5 g	–	1.39 k	600 mm^3	EMEH + TENG
	[206]	2.92	6	0.5 g	1.28	62	10.2 g	EMEH
	[207]	1.093	11	0.5 g	0.545	44	12.1 g	EMEH
	[208]	12.51	6.5	0.5 g	–	617	12.1 g	EMEH + TENG
	[209]	10.07	4.5	0.6 g	–	710	12.2 g	EMEH + TENG
	[210]	15	5	1 mm	–	900	2331 mm^3	EMEH
	[211]	35.5	24	1 g	20	200	127.68 g	EMEH
	[212]	131.1	• 16.67	–	4.59	• 46	• 1.6 cm^3	EMEH
	[214]	46.7	5	–	–	46	• 113.1 cm^3	EMEH
	[225]	3.69	4.5	8 N	510	4.5 M	4 cm^2	TENG
hybrid	[16]	• 1.59	6	1.5 g	–	9/180 k	4.8 g	EMEH + PEH
	[228]	4.8	0.1	10 cm	3/640	300/150 M	• 258,643 mm^3	EMEH + TENG
	[229]	19.6	2.5–10	1 g	58.4/60	150 k/1 M	110 g	PEH + TENG
nonlinear	[235]	0.8	7	4 m/s^2	0.14	10	100 g	EMEH
	[239]	0.57	6.7	1 g	• 0.25	10	1.23 g	EMEH
	[240]	119	3–7	1.2 mm	1.16	45	50 g	EMEH
	[241]	1.15	9	0.8 g	0.26	12	11.29 g	EMEH
	[242]	2.58	7.5	0.5 g	• 0.75	12	• 27.82 g	EMEH
	[244]	550	80	5 m/s^2	–	10 k	27.4 g	EMEH
	[245]	28	• 15.8	0.6 g	7.5	2 k	0.5 kg	EMEH
	[248]	8.45	8	0.35 g	–	60 k	–	PEH

problem. Halim et al. [153] proposed a ball impacted frequency up-conversion design as shown in Fig. 13(b) to harvest the reciprocating vibration energy in the vertical direction. Fang et al. [158] analyzed the dynamic plucking force of a rotational PEH in Fig. 14(b) and the related parameters affecting output power, including the load resistance, the overlapped length, and the structural stiffness. Dauksevicius et al. [163] used non-contact magnetic plucking to convert the low-frequency vibration energy of a rotational disk into the higher frequency range of a PEH. The snap-through method always contains pre-pressed potential energy that can lead to a fast status switch when an external disturbance occurs. As shown in Table 1, frequency up-conversion can be implemented with the aforementioned four types of methods. With a satisfactory matching between the harvesting transducers and up-converted vibration input, the harvested energy increases and should exceed that without frequency up-conversion [147,148,155]. However, the power conversion efficiency is not high enough due to the energy loss when impact or plucking occurs. Both the deformation of the contact pieces and generated thermal energy might reduce the energy harvesting efficiency. More explorations with efficient frequency up-conversion are therefore required for high energy output and a broad working frequency range.

For the motion conversion mechanism, typically from translational motions to rotational motions, the frequency up-conversion is implemented simultaneously with a proper transmission ratio. While transferring the elastic potential energy of the string into kinetic energy of the rotor, the working frequency of the string suspended rotor is significantly improved for high energy output [169-171]. The theoretical modeling of this string-based frequency up-conversion mechanism may still need further exploration. For the commonly used mechanical motion conversion mechanisms, like the ball-screw [175], the rack-pinion [176], the magnet array [179], and the pendulum [181], the output motion frequency is still low that additional gearboxes are required for frequency up-conversion. However, the redundant mechanical parts are bound to increase the parasitic damping that the energy loss is intensified.

As an indispensable part of ultra-low frequency vibration energy harvesting, frequency up-conversion plays an important role in high-energy output. Based on the analyses of the frequency up-conversion mechanism, energy loss is inevitable but may be minimized with proper designs and optimizations. More explorations on this target should be extensively investigated in future research.

6.2. Structural designs for response amplification

Amplified vibration response contributes to the harvested energy with the coupling between the excitation and resonance frequency. On the premise of knowing the excitation frequency, the predesigned energy harvesters will perform effectively with either a single resonance peak [120] or multi resonance peaks [124]. However, the inconstant energy sources in real applications will reduce the performance of harvesters. The adjustment of structural parameters that affect the resonance frequency is beneficial to maintain the efficient energy harvesting status, like the effective length [131,132], the preload value [133,134], etc. Moreover, the real-time adaptive frequency tuning methods without manual intervention perform better in the target frequency range with specific structural design and dynamic analyses [135-138].

The response amplification with resonance phenomena is effective but limited by the working frequency. Adaptive frequency tuning methods prove to be effective to follow the exciting frequency without additional energy consumption. However, the related investigation is largely insufficient and only limited to some specific cases. The adaptive frequency tuning methods should be considered as an important research direction for ultra-low frequency vibration energy harvesters.

Moreover, some emerging energy trapping methods, exemplified by the ABH effect [146] and metastructures [198], perform well at higher frequencies rather than low frequencies. If similar energy concentration methods can be materialized in the low or even ultra-low frequency range, the harvested energy can be improved significantly. Possible methods include the exploration of new cross-frequency energy transfer mechanisms through intentional mechanical or electromechanical nonlinearity [143,144], new motion conversion mechanisms as well as proper parameter adjustments, etc. Therefore, the effective utilization of the energy concentration methods in the low frequency range is a different yet very promising path for output power enhancement.

6.3. Optimizations with multi-functionalities

For the systems with humans involved, multi- or at least dual functionalities of vibration suppression, energy harvesting, and self-sensing should be considered seriously. The tolerable vibration amplitude is more significant to avoid human uncomfortableness when the harvesters are applied on the offshore platform, vehicle suspensions, tall buildings, etc. More challenging, the resonance frequency range of the human body and different organs is lower than 10 Hz which overlaps with the typical range of most ultra-low frequency vibration energy sources. An optimized design to accommodate both targets in terms of achieving high energy output and maintaining lower vibration of the structures, is an urgent and challenging problem to be solved in the future. The self-sensing functionality of alerting the over-amplitude vibration of the target system can also be developed with the harvester itself.

With the impedance added to the interface circuit of the applied transducers, structural damping always comes along with the energy harvesting process. The generated damping can suppress the vibration amplitude and affect the harvesting performance. Simultaneous vibration control and energy harvesting are then should be deeply investigated for target systems. Some experimental studies were conducted in various systems like bridge stay cables [70], DVA systems [131], vehicle suspension [256], etc. Sugino et al. [199] and Hu et al. [200] theoretically analyzed the simultaneous functionalities with metastructures. Results show that the optimal status of both targets is not able to be achieved with the same set of parameters. Therefore, a tradeoff is required for a specific target. While in some properly designed systems, bi-objective optimal design or adjacent optimal status may exist that requires further demonstration. Moreover, compared with theoretical analyses and simulations, experimental studies are still scarce and need to be enriched in the future to verify the predicted performance on one hand, and to increase the credibility of the technology and influence the public for its potential use in practice.

6.4. Electromechanical coupling enhancement for large-scale energy harvesters

Like the issue relating to the response amplitude for vibration control, the output power is the ultimate goal to pursue for researchers who focus on energy harvesting. The output power in Table 2 with small-scale energy harvesters is usually at μW level that may be enough to power MEMS electronics. However, the harvested power of *meso*-scale or large-scale harvesters in Table 3 with several mill-watts is still insufficient to power high-powered appliances or emergency power supply. Even with heavy proof mass [130,176,177], the peak output power is only several watts. The ultra-low frequency vibration energy sources contain high power, particularly for the energy source with large amplitude. The wave motions or tall building vibration also have enormous potential to implement the high power output via efficient harvesters. The electromechanical coupling coefficient enhancement of harvesters provides a possibility to enhance the output power density that can supply the high-powered appliances.

As demonstrated by Moss et al. [255], the electromechanical coupling coefficient of EMEHs increases with the dimension size, which is much more suitable for large-scale energy harvesting. Corresponding structural designs and optimizations are proposed for electromechanical coupling enhancement, including opposing magnet configurations [201-203], applications of magnetic flux density guiding materials [204], and the magnetic field concentration using Halbach magnet array [102,205-214], etc. By far, most related investigations are simulations and small-scale prototype tests. When scaled up to large structures, many problems may emerge, such as the friction-based parasitic damping increase, the effects on the primary systems, the installation volume, etc. Corresponding harvester designs and real-scale experimental tests are therefore required for field tests and real applications. In addition, the simplest cylindrical coils are directly used for the EMEH design, the coil winding optimization is still scarce for electromechanical coupling enhancement. More explorations should be conducted on the coil winding optimization.

6.5. Real applications

The field performance of any proposed idea is the most meaningful metric to evaluate a harvester. For all harvesters cited from the open literature, simulations or laboratory experiments are mostly conducted to verify the claimed properties of the harvesters. There is an obvious lack of field experiments to test the onsite performance of the proposed energy harvesting devices in the in-situ environment. Some well-performed harvesters in laboratory tests may not be able to cope with the hostile natural environment; or the other way around, nature may not be able to offer the ideal environment in terms of energy supply as the one prescribed by the models.

The environmental source may only be able to provide intermitted excitations [257] and time-limited harmonic excitations [258], etc. As a result, real structural responses might be quite different from the harmonic and swept-sinusoidal excitations, which may adversely compromise the harvesting effectiveness. The laboratory test of harvesters is usually performed with a single direction excitation, while the real environmental excitation is usually multi-directional, even rotational with unequal distributions. Typical examples are abundant such as ocean waves in both translational and vertical directions, human motions with both reciprocations and rotations, wind flowing from every possible direction, etc. The adaptability of designed harvesters should be tailored to cope with real-life excitations so that expected energy harvesting efficiency be maintained. Meanwhile, other practical issues should be considered when the harvesters are applied to field applications, such as the changeable exciting frequency, installations on primary structures, and fluid–structure interactions when harvesting marine energy and wind energy, etc.

The adaptability to the environmental excitation should be optimized for specific harvesting applications, such as railway tracks, ocean waves, human motions, etc. Related theoretical analyses and onsite tests are required for further research when the harvesters are under field excitations.

7. Discussion and prospects

Ultra-low frequency vibration offers high potential for energy harvesting, mainly because of the high amplitude vibration involved. However, the effective working frequency band of existing harvesting transducers is predominantly located at a high frequency range. This dilemma, as well as the attraction from the abundant environmental energy sources, triggered extensive interest in the scientific community, evidenced by the increasing efforts in developing and analyzing new designs and optimizations of ultra-low frequency energy harvesters. This paper provides a state-of-the-art review on the topic with particular attention to the related enhancement methods for energy harvesting efficiency improvement. Existing energy sources are first introduced from the perspective of both frequency spectrum and energy levels. Then, commonly used energy harvesting transducers are briefly discussed for a better understanding of the corresponding energy conversion mechanisms. The emphasis of this review is on the discussion of existing and future possible methods for enhancing both the effective frequency range and the energy harvesting efficiency of ultra-low frequency vibration energy harvesters. Typical structural designs, their modeling, analyses, performance and limitations are discussed in detail. Moreover, available experimental results arising from different enhancement methods are listed for scaling comparison. Existing challenges are identified. Discussions and suggestions of several investigation topics and related new themes for future studies of ultra-low frequency vibration energy harvesters are provided, summarized as follows.

An efficient frequency up-conversion mechanism is vital to compensate for the frequency gap between the energy harvesting transducers and energy sources. The harvesters with frequency up-conversion mechanisms proved to be more efficient than those without the mechanisms through experiments. For further enhancement of harvested energy, efficient frequency up-conversion mechanisms with minimized energy loss hold promising prospects for ultra-low frequency vibration energy harvesting.

The response amplitude of harvesters plays a key role in energy harvesting, especially due to the lower kinetic energy contributed by the low frequency component. The real-time adaptive resonance frequency tuning mechanism deserves further investigations to maintain high-energy output with changeable excitation frequencies.

Human-involved systems require simultaneous vibration control and energy harvesting. This applies to applications in vehicles and other civil or mechanical systems like buildings. Therefore, a balanced design based on a compromised tradeoff between different considerations is needed, which shall be an interesting avenue to be explored.

Moreover, with the enhanced electromechanical coupling efficiency, the output power of large-scale energy harvesting systems should be improved significantly. Corresponding modeling and analysis tools, as well as real-scale measurements, are required to verify the predicted performance. Meanwhile, we should pay attention to improving the output power density of harvesters for real applications.

Finally, as the most common energy source is from the natural environment, ultra-low frequency vibration offers high potential green energy. This promising avenue definitely deserves more attention from both scientific communities and the grand public. Successful stories would help showcase the technology and influence the public and governmental opinion to promote its further exploration and eventually its real-life applications.

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.

Data availability

No data was used for the research described in the article.

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