

Review

Frequency Up-Conversion for Vibration Energy Harvesting: A Review

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Abstract: A considerable amount of ambient vibration energy spreads over an ultra-low frequency spectrum. However, conventional resonant-type linear energy harvesters usually operate within high and narrow frequency bands, which cannot match the frequencies of many vibration sources. If the excitation frequency deviates a bit from the natural frequency of an energy harvester, the energy harvesting performance will deteriorate drastically. Because of the ultra-low frequency characteristic, it is challenging to reliably harvest energy from the ambient vibrations. To address this mismatching issue, the ultra-low frequency ambient vibrations are converted into high-frequency oscillations using certain mechanical mechanisms, which are termed frequency up-conversion techniques. This paper reviews the existing approaches that can realize frequency up-conversion for enhancing energy harvesting from low-frequency vibration sources. According to their working mechanisms, the existing methods are classified into three categories: impact-based, plucking-based, and snap-through-based approaches. The working principles of the three approaches are explained in detail. Representative designs from all categories are reviewed. This overview on the state-of-the-art frequency up-conversion technology would guide the better design of future kinetic energy harvesting systems.



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1. Introduction

Recent advances in perpetual sensing and pervasive computing systems put forward an urgent demand for getting rid of chemical batteries, which are not environmentally friendly and need to be recharged or replaced frequently [1]. Energy harvesting technology renders a solution of powering small electronics by harnessing energy from ambient energy sources, such as solar [2], radio frequency (RF) [3], thermal [4], and vibration [5,6]. The rapid development of micro-electronic and micro-electromechanical systems (MEMS) has dramatically reduced the power supply demand. For example, the power consumption of some up-to-date embedded micro-controllers in ultra-low-power mode has been reduced to about 30–250 nW [7,8]. Therefore, employing energy harvesting technology to provide a sustainable power supply has become possible in a wide range of applications, including wireless remote sensors for structural health monitoring [9], implanted sensors for medical devices, etc.

Kinetic energy is one of the most ubiquitous energy sources [10,11], existing in various forms in the ambient environment, including human activities (walking, running, finger tapping, heartbeat, and breathing), structural vibrations (industrial machinery, bridges, and transport vehicles); and fluid flows (wind, water, and ocean). Therefore, the development

of vibration energy harvesting systems has attracted immense research interest in recent years [12–18]. The development of an energy harvesting system requires domain knowledge across different disciplines, including mechanical engineering, electrical engineering, computer engineering, and material science. Therefore, to improve the performance of an energy harvesting system, sophisticated designs are often seen by considering issues from either the mechanical or electrical perspective, or both in some cases. To be more specific, on the one hand, using innovative mechanical structures can enhance the power output [19], and introducing nonlinear behaviours can widen the operation bandwidth [20–22]. On the other hand, utilizing advanced interface circuits, such as the synchronized switch harvesting on inductor (SSH) [23] or synchronous electric charge extraction (SECE) [24] interface circuits, the output power can be increased by 300–400% [25], compared with the case using the bridge rectifier standard energy harvesting (SEH) circuit [26].

These techniques have been well studied to date in the literature. There have been many example applications of using energy harvesting technology in powering various electronic devices. Energy conversion efficiency and operation bandwidth are the two main concerns in the design of any energy harvesting system. The operation bandwidths are normally in the relatively high-frequency range for most existing energy harvesters designed based on various transduction mechanisms, including piezoelectric, electromagnetic, triboelectric, etc. From the general mathematical formula of a typical energy harvester, it is learned that the maximum power of an energy harvester is proportional to the cube of the vibration frequency and drops dramatically at low frequencies [27]. When the excitation frequency deviates even a bit from the natural frequency of the energy harvester, the energy harvesting performance will deteriorate drastically. According to the literature, researchers have devoted numerous efforts to finding proper solutions addressing the aforementioned two issues. However, besides the above two concerns, in real-world application scenarios, most ambient vibration energies spread over an ultra-low frequency spectrum. For example, human gait motion is at around 1 Hz and wave heave motion is lower than 1 Hz. Therefore, the ultra-low frequency feature poses another issue to restrict the wide application of energy harvesters in practical circumstances [28–30]. The ultra-low frequency feature of most practical scenarios makes it challenging to achieve frequency matching for realizing optimal energy harvesting. The straightforward idea is to use frequency up-conversion mechanisms that are devised to address the above issue. In other words, when the external excitation frequency is quite low, e.g., at a few Hertz, a certain frequency up-conversion mechanism should be utilized to convert the low-frequency excitation into the high-frequency oscillation of the energy harvester. In this manner, the energy harvester could vibrate at its resonant state and produces desirable power output.

Although several articles have reviewed various topics of vibration energy harvesting from different aspects [9,10,28,31–38], attention has been paid on collecting and summarizing various broadband and power-boosting techniques. Only a recent comprehensive review has been conducted to focus on frequency up-conversion mechanisms for energy harvesting [39]. This article aims to provide a comprehensive overview of existing frequency up-conversion techniques for ultra-low frequency vibration energy harvesting. Moreover, according to the principles of frequency up-conversion mechanisms, the existing approaches are mainly classified into three categories, namely, impact, plucking, and snap-through-based energy harvesters. Representative designs and applications from all categories are discussed.

2. Energy Conversion Mechanisms

Vibration energy harvesters can be classified into three main categories depending on their energy transduction mechanisms, namely, electromagnetic [40,41], electrostatic [42,43], and piezoelectric [44,45] types.

2.1. Piezoelectric Transduction

The piezoelectric transduction mechanism is based on the piezoelectric effect, which is the capability of certain materials to generate an electric charge on the surfaces in response to applied mechanical stress [46]. Piezoelectric transducers have the advantages of high-power density and ease of implementation, thus they are widely used for energy harvesting. Moreover, piezoelectric devices could be miniaturized and easily integrated with MEMS technology in a compact form. Therefore, piezoelectric transduction is a suitable choice to meet the miniaturization requirements of future self-powered devices.

2.2. Electromagnetic Transduction

The electromagnetic transduction mechanism refers to Faraday's law of induction: a voltage difference, sometimes called electromotive force, will be induced in a coil due to any change in the magnetic flux in which the coil is placed. Conventional power plants often realize this transduction mechanism for producing large-scale electricity. The difference is that the generators of power plants are driven by huge heat engines; while small-scale electromagnetic energy harvesters are driven by small ambient vibrations [41]. Electromagnetic vibration energy harvesters are suitable for scenarios where a relatively large amount of power is required. However, a major disadvantage of electromagnetic transduction is that the dimensions of the energy harvester assembly are usually large because of the need for different parts, such as coils and magnets.

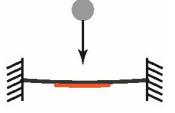
2.3. Electrostatic Transduction

The electrostatic transduction mechanism [43,47] could be understood through retrospection of the working principle of a parallel-plate capacitor. In a parallel-plate capacitor, its capacitance is proportional to the surface area of the conductor plates and inversely proportional to the separation distance between the plates. On the other hand, capacitance is the ratio of the change in electric charge on the conductor plates over the corresponding change in the electric potential. When the external excitation drives one of the conductor plates to vibrate, the separation distance between the plates would periodically vary. Therefore, if the capacitor is pre-charged with a constrained voltage, the variation of the separation distance between the conductor plates would lead to the generation of currents in the circuit shunted to the parallel-plate capacitor. Instead of pre-charging the electret materials, we can realize triboelectric energy harvesting by coupling the triboelectric effect and electrostatic induction [48]. Since triboelectric nanogenerators cannot realize energy transduction without electrostatic induction, they can also be deemed to belong to this category.

3. Frequency Up-Conversion Principles

As well-known, a typical linear energy harvester produces a substantial power output only around its natural frequency. However, ambient vibration energy usually spreads over a low-frequency spectrum. To address this challenge, efforts have been devoted to developing mechanical structures with low resonant frequencies for energy harvesting [49]. In general, there is still a limited number of low-frequency designs due to the challenge of space and size restrictions. Moreover, the aforementioned designs all belong to linear type energy harvesters that have narrow operating bandwidths. Instead of pursuing frequency matching, another idea is to achieve frequency up-conversion, i.e., to convert low-frequency vibrations into high-frequency oscillations. To this end, various means have been proposed in the literature, which can be mainly classified into the following three categories, as listed in Table 1. More detailed introductions of these means will be presented in the following sections.

Table 1. Classification of frequency up-conversion mechanisms. The orange-colored blocks denote piezoelectric transducers. The black slender blocks denote elastic beams. The dichromatic square blocks denote magnets. To facilitate the graphical illustration, only piezoelectric transduction-based designs are selected.

Mechanisms	Methodologies	Frequency Ranges	Representative Designs	References	Applications *	Features
Impact	Mechanical impact	1–50 Hz		Yang et al. [50] Halim et al. [51] Halim et al. [52]	• Small-scale wind • MEMS • Human-limb motion	• Simple • Unstable • Random output • Risk of fracture
Plucking	Mechanical plucking	10–50 Hz		Priya et al. [53] Pozzi et al. [54] Tan et al. [55]	• Wind flow • Knee-joint motion • Pavement harvesting	• Compact • Robust • Miniaturizable • Risk of fracture
	Magnetic plucking	10–100 Hz		Zhao et al. [56] Kulah et al. [57] Fan et al. [58] Kuang et al. [59]	• Windmill • MEMS • Human-limb motion • Knee-joint motion	
Snap-through		1–30 Hz		Ando et al. [60]	• Random vibration	• Miniaturizable • Large output • Minimum excitation requirement

* The applications indicate the applications in the references, rather than the only application scenarios of the methods in those categories.

3.1. Impact-Based Approach

A typical scenario where an impact phenomenon often occurs is a weight falling and striking a target object. During the falling period, with the increase of the falling speed, the gravitational potential energy of the weight is converted into kinetic energy. When impact occurs, the kinetic energy will be transferred to the targeted object in a short instant. Based on this mechanism, if the targeted object is designed as an energy harvester, it will be deformed in a short instant, and some initial energy is stored because of the impact. After the impact is released, the energy harvester starts to undergo an underdamped free oscillation at its natural frequency.

3.2. Plucking-Based Approach

As explained above, in the impact-based approach, the initial kinetic energy is injected by the impacts. After releasing, the energy harvester starts oscillation with an initial velocity. On the other hand, the plucking-based approach has a different mechanism. Plucking refers to the action of pulling an energy harvester forcibly away from its equilibrium by an external force. The external force can be applied through mechanical contact or magnetic coupling. According to the different forms of the applied external force, the plucking-based approach can be further classified into two sub-categories: the former is referred to as the mechanical plucking-based approach and the latter as the magnetic plucking-based approach [61]. In the plucking design, the plucker bends the structure, so as to input some initial potential energy to the energy harvester structure. After the plucker is released, the energy harvester starts to undergo an underdamped free oscillation at its natural frequency with an initial displacement.

3.3. Snap-Through-Based Approach

Snap-through is a nonlinear phenomenon that can be observed in a bistable system and refers to the action when a bistable system snaps from one stable state to the other. The snap-through phenomenon often occurs along with a large-amplitude inter-well oscillation. As the power output of an energy harvester is normally proportional to the maximum displacement, the large-amplitude inter-well oscillation can significantly improve the energy harvesting performance. Since lots of typical vibration energy harvesters are designed

based on beam structures, and a post-buckled beam is convenient for the implementation of a bistable system, buckled piezoelectric beams with snap-through behaviours have been widely explored for vibration energy harvesting.

4. Impact-Based Energy Harvesters

The working principle of mechanical impact-based energy harvester is shown in Figure 1a. Firstly, the rigid ball is allowed to fall freely onto the centre of the clamped beam under the effect of gravity. After the collision, the kinetic energy of the rigid ball is transferred to the beam. As the sum of all momentums is conserved during collisions, the velocity of the beam becomes non-zero, and the beam starts to vibrate with an initial velocity. Due to the piezoelectric effect, the piezoelectric patch attached to the beam generates voltage output. Umeda et al. [62] developed an electrical equivalent model of this system to analyse the relationship between the input mechanical impact energy and the output electric energy. Later on, researchers designed various configurations based on the mechanical impact-based structures [52,63–66].

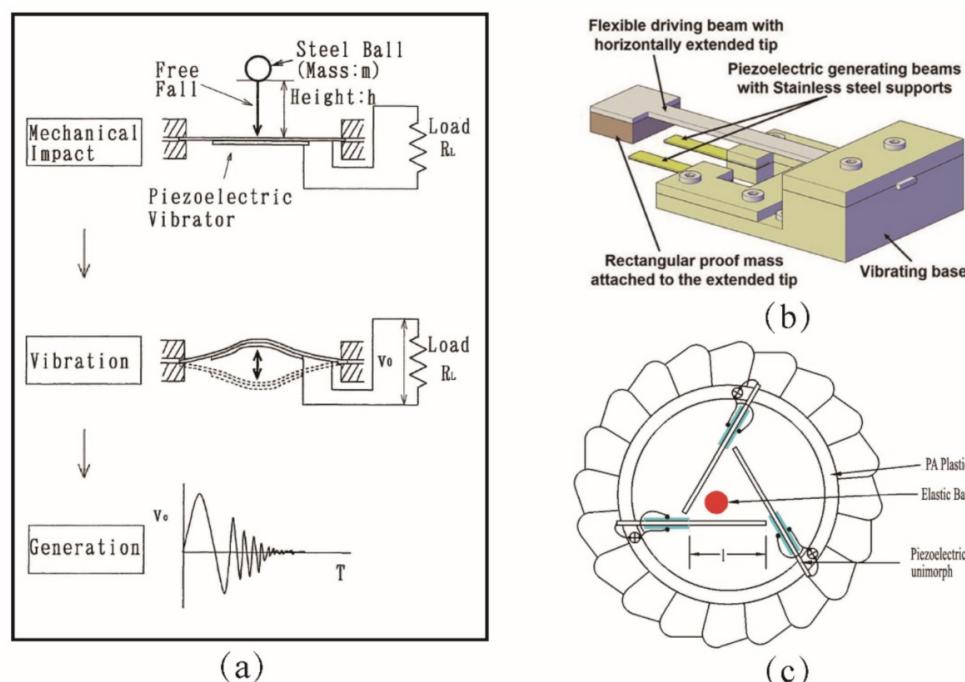


Figure 1. Mechanical impact-based energy harvesters. (a) The principle of mechanical impact [62]. (b) A mechanical impact-driven piezoelectric energy harvester [51]. (c) An impact-induced rotational piezoelectric wind energy harvester [50].

Figure 1b demonstrates a mechanical impact-based frequency up-conversion broadband piezoelectric energy harvester designed by Halim et al. [51,67]. A low-frequency driven beam with a horizontally extended tip mass simultaneously struck two high-frequency piezoelectric generator beams during its vibration. Hence, high-frequency voltage outputs were generated by the two piezoelectric beams. By utilizing impact-induced resonance, Yang et al. [50] proposed a small-scale energy harvester that could harness energy from winds. As shown in Figure 1c, when the wind drove the device to rotate, the ball struck the piezoelectric cantilevers; thus, electricity was generated by the piezoelectric transducers. The design enabled each bimorph to be struck in a similar area, but at different moments. It was proved that a relatively stable output frequency could be obtained by the proposed system.

5. Plucking-Based Energy Harvesters

5.1. Mechanical Plucking

Rotational vibration energy harvesting has received extensive attention in recent years. Priya [53] designed a piezoelectric windmill consisted ten piezoelectric bimorphs, as shown in Figure 2a. The structure and framework of the piezoelectric windmill are similar to that of a conventional windmill, except the blades are made of piezoelectric materials. The piezoelectric blades oscillate to produce electricity as the wind flows through the windmill. Janphuang et al. [68] proposed a piezoelectric microelectromechanical system (MEMS) harvester. It consisted of an atomic force microscope-like piezoelectric cantilever and a rotating gear with a series of teeth. During the rotation of the gear, the piezoelectric cantilever was plucked by the teeth of the gear. Thus, voltage output was consequently produced. A geometrically nonlinear plucking-based framework to achieve frequency up-conversion for piezoelectric energy harvesting is presented in [69]. Fang et al. [70] designed a music-box-like extended rotational plucking energy harvester with multiple piezoelectric cantilevers, as shown in Figure 2b. Fu et al. [71] proposed a theoretical model of a plucking piezoelectric energy harvester by using Hertzian contact theory to describe the involved impact. In order to convert the impulsive excitation to the plucking force for helping the harvester jump to the high-energy orbit, Fang et al. [72] also proposed an asymmetric plucking-based bistable energy harvester with a rotary structure and plectrum.

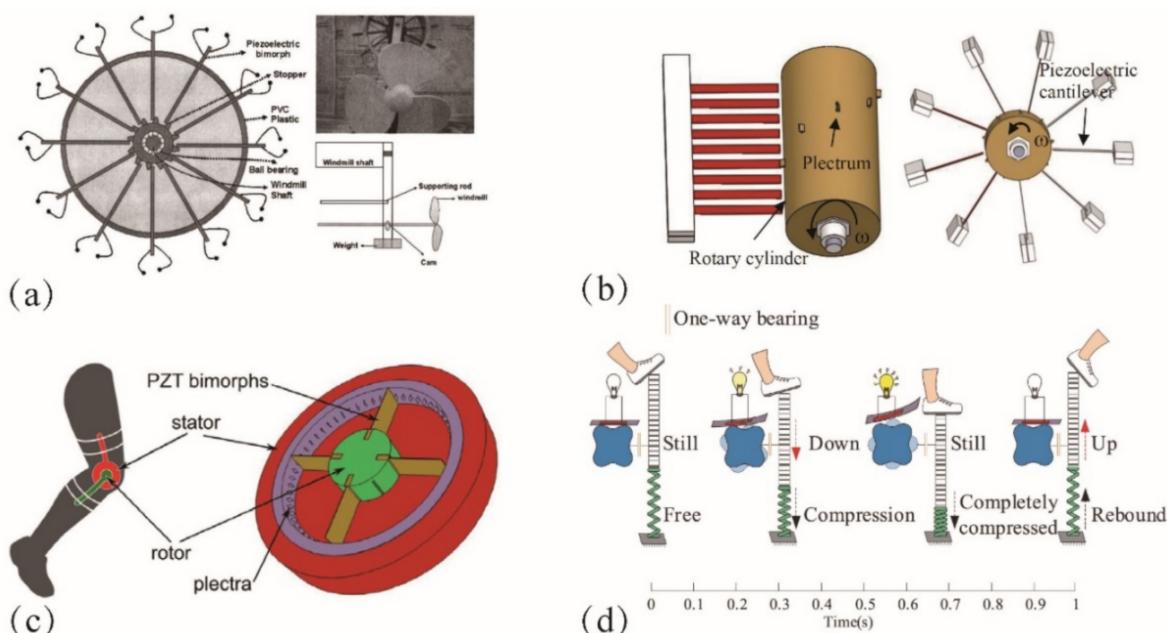


Figure 2. Mechanical plucking-based energy harvesters. (a) A piezoelectric windmill harvester [53]. (b) A music-box-like extended rotational plucking energy harvester [68]. (c) A knee-joint energy harvester [54]. (d) A double-frequency up-conversion harvester for gathering ultra-low-frequency human walking in public squares [55].

Given the rapid development of smart wearables and IoT devices, harnessing energy from human motions shows great potential in replacing traditional batteries and providing sustainable energy. This idea has attracted lots of interest from academic and industrial communities [73]. According to the research, the peak power stored in walking motion can be up to 275 W [74]. Various on-body and off-body type energy harvesters have been developed for human motion energy harvesting. Figure 2c shows a knee-joint piezoelectric harvester [54,75,76], which was designed to harvest the kinetic energy from knee-joint motion. It was worn on the outer side of the knee and fixed by braces and comprised a hub that carried a series of bimorphs. The ring-mounted plectra plucked the bimorphs as

the joint rotated during walking. On-body type energy harvesters are fixed around the knees or shoes and affect normal human motion to some extent. Unlike them, off-body type energy harvesters do not influence human movement and show a greater potential for practical application. Tan et al. [55] proposed a double-frequency up-conversion harvester for gathering ultra-low-frequency human walking in public squares. Figure 2d shows that the harvester is mainly composed of a gear rack and a multi-leaf cam. The rack acts as the first frequency up-conversion mechanism for low-frequency walking. The multi-leaf cam carries out the second frequency up-conversion operation. After the two-stage conversion, the low-frequency input signal from walking is significantly increased.

Liu et al. [77,78] proposed a piezoelectric energy harvester with a wide operating frequency range by incorporating a high-frequency piezoelectric cantilever, a low-frequency piezoelectric cantilever, and a metal base as the bottom stopper. Figure 3a illustrates that frequency up-conversion of the energy harvester is realized when the low-frequency piezoelectric cantilever scrapes through the high-frequency piezoelectric cantilever. The advantages of the proposed harvesters include: restricting the large displacement of the compliant driving beam, improving the power density, and being especially suitable for a compact MEMS device, as shown in Figure 3b [78]. Gu et al. [79,80] also designed a similar impact-driven vibration energy harvester that consisted of a compliant driving beam and two rigid generating beams.

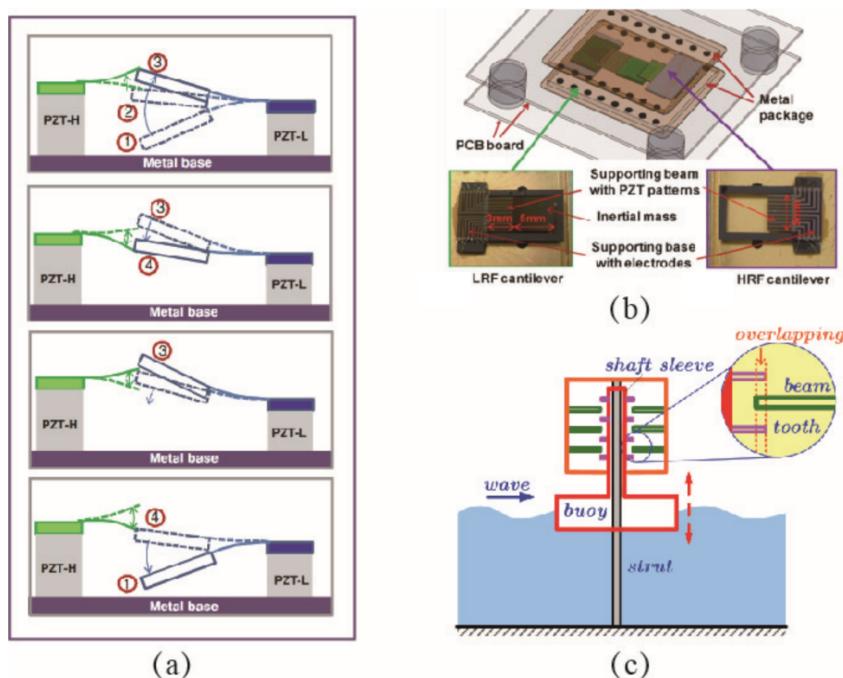


Figure 3. Impact plucking-based harvesters. (a) The operating mechanism of the proposed scrape-through piezoelectric energy harvester [77]. (b) Schematic drawing of MEMS harvester system and fabricated cantilevers [78]. (c) An impact-driven wave energy harvester [81].

Figure 3c presents an impact-driven harvester designed by Lin et al. [81] for wave energy harvesting. It is constituted by a cylindrical buoy, a series of beams, and a shaft sleeve with teeth. The device could adapt a conventional harvester that operates at a frequency higher than hundred hertz to capture the energy from the slow (frequency ~ 0.1 Hz) wave motion. The authors also established a mathematical model to describe and predict the dynamics of the proposed harvester. More relevant studies can refer to these further studies [82–84].

5.2. Magnetic Plucking

Figure 4a,b, respectively, show the schematic and the prototype of a MEMS-based magnetic plucking vibration energy harvester [57,85]. Low-frequency ambient vibrations were converted to higher frequency oscillations through a mechanical frequency up-converter. The diaphragm with a magnetic had a low natural frequency that matched the ambient excitation frequency. A series of Parylene cantilevers with high resonant frequencies were installed beneath the diaphragm. During the vibration of the diaphragm, the attached magnet pulled the Parylene cantilevers up to a certain position, then released them at another position. After being released, the cantilevers started to vibrate at their resonant frequencies. Coils were located on the top surface of the cantilevers. Currents were induced in the coils during the vibration. Since the oscillating frequencies of the cantilevers were high, the energy conversion efficiency was increased. Galchev et al. [86,87] designed a parametric frequency-increased generator, as shown in Figure 4c. A large inertial mass harnessed the kinetic energy from the ambient vibration and transferred a portion of the energy to two frequency-increased generators through magnetic force coupling. The two generators converted the kinetic energy into electrical energy via either electromagnetic induction [86] or piezoelectric transduction [87].

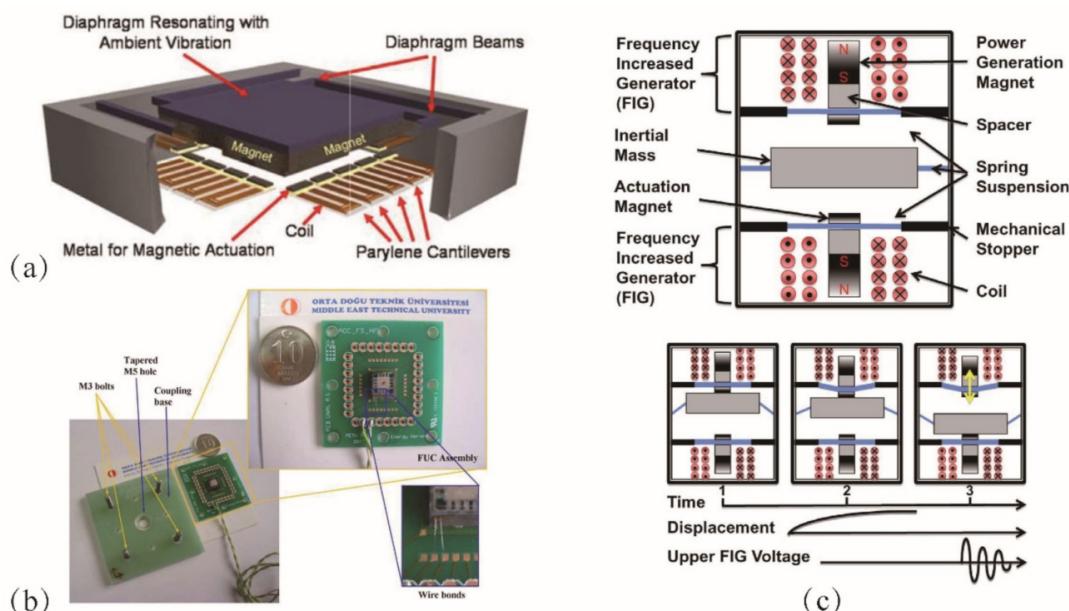


Figure 4. Magnetic plucking-based micro-scale harvesters. (a) 3D view of the MEMS-based electro-magnetic vibration-to-electrical power generator [57]. (b) Components of the micro-generator [85]. (c) Illustration of the method of magnetic plucking operation [86].

Wind energy is widely available in nature. Recent research has shown that it is also an ideal renewable energy source for energy harvesting [88,89]. Unlike wind farms with giant dimensions, wind energy harvesters are expected to be miniaturized and only produce small-scale power outputs for low-power-consumption electronics [90]. Piezoelectric transducers are more efficient than electromagnetic transduction at small scales [91], and piezoelectric wind energy harvesters can efficiently capture wind energy at low and variable wind speeds [92]. Karami et al. [93] proposed a novel piezoelectric energy harvester, as shown in Figure 5a. The rotation of the blades could induce the large oscillations of piezoelectric beams. The magnetic force applied on the piezoelectric beams depended on the relative distance between the piezoelectric beams and the magnets on the rotating blades. During rotation, the parameters in the governing equations of the piezoelectric beams varied. Thus, the piezoelectric beams were parametrically excited. Figure 5b presents a piezoelectric windmill for harvesting wind energy from low-speed air flows [94,95]. Its

cut-in wind speed was as low as about 1 m/s, and the robustness could be maintained under high-speed winds up to 20 m/s. Fu et al. [96] designed a turbine-like piezoelectric energy harvester with self-regulation ability. The plucking mechanism was implemented by setting up a magnetic coupling between the magnets installed on the turbine rotor and a piezoelectric beam. The magnetic coupling could be self-regulated, and the harvester could produce considerable output over a broad wind speed range. Figure 5c shows the hybrid water-proof wind energy harvester designed by Zhao et al. [56]. The rotational motion of the blades could drive the separately installed piezoelectric beams to vibrate through magnetic coupling. A force amplification structure was adopted to enhance the energy conversion efficiency. More relevant studies can be found in [97–99].

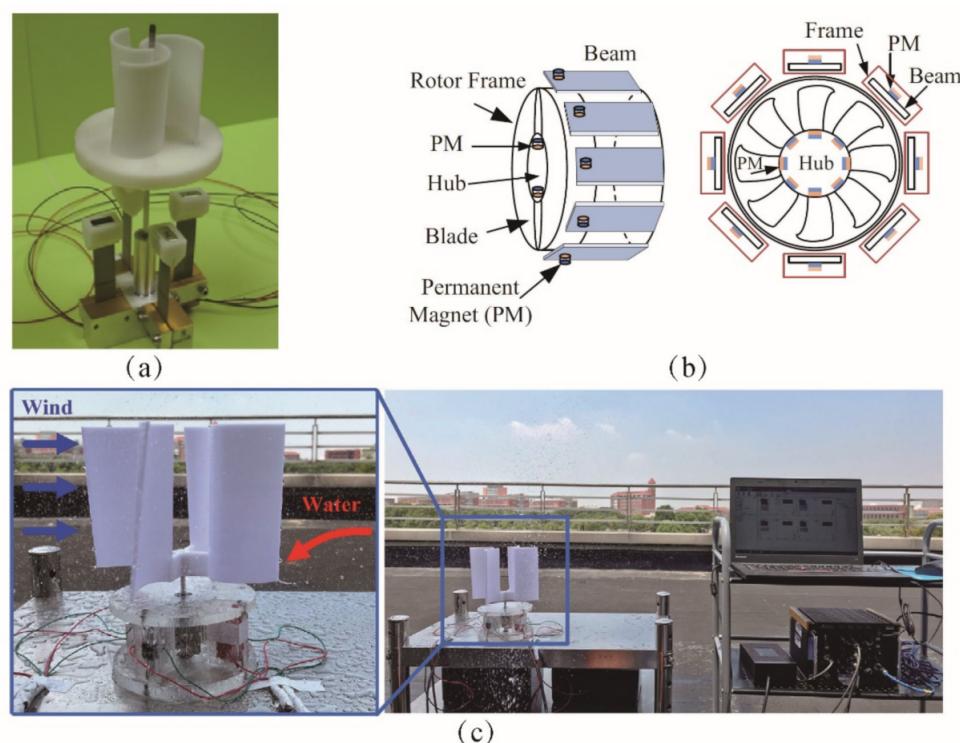


Figure 5. Magnetic plucking-based wind energy harvesters. (a) A bistable structure wind energy harvester [93]. (b) A micro-power wind energy harvester from low-speed air flows [94]. (c) A water-proof hybrid wind energy harvester [56].

Magnetic plucking mechanisms have also been widely employed for harvesting energy from low-frequency human motions [100,101]. Pillatsch et al. [102] built a frequency up-converting energy harvester, as shown in Figure 6a, to collect energy from human bodies. It consisted of an eccentric proof mass that carried a magnet and a piezoelectric beam. When the proof mass swung and the magnet passed by the tip of the piezoelectric beam, the piezoelectric beam deflected under the magnetic force. After the magnet passed over, the deflected piezoelectric beam started to vibrate around its natural frequency. The energy conversion efficiency of this frequency up-converting energy harvester was then further improved by using synchronous switch harvesting circuits and bistable mechanical structures [103–107]. Figure 6b shows an energy harvester for harnessing energy from knee-joint motions through a magnetic plucking mechanism [59,108]. Magnetic plucking avoided direct contact between the piezoelectric beam and the plectrum, thus increasing the service life and reducing the noise. Figure 6c demonstrates an impulse-excited energy harvester for collecting energy from human bodies [109]. A cylindrical proof mass actuated an array of piezoelectric beams through magnetic attracting force. After the initial excitation, those piezoelectric beams were left to vibrate at their resonant frequencies. A similar design was proved to be capable of harnessing energy from both sway and bi-directional

vibrations [110]. Another similar device was developed to harvest energy from low-frequency motions, then power a transmission circuit for wireless sensing [111].

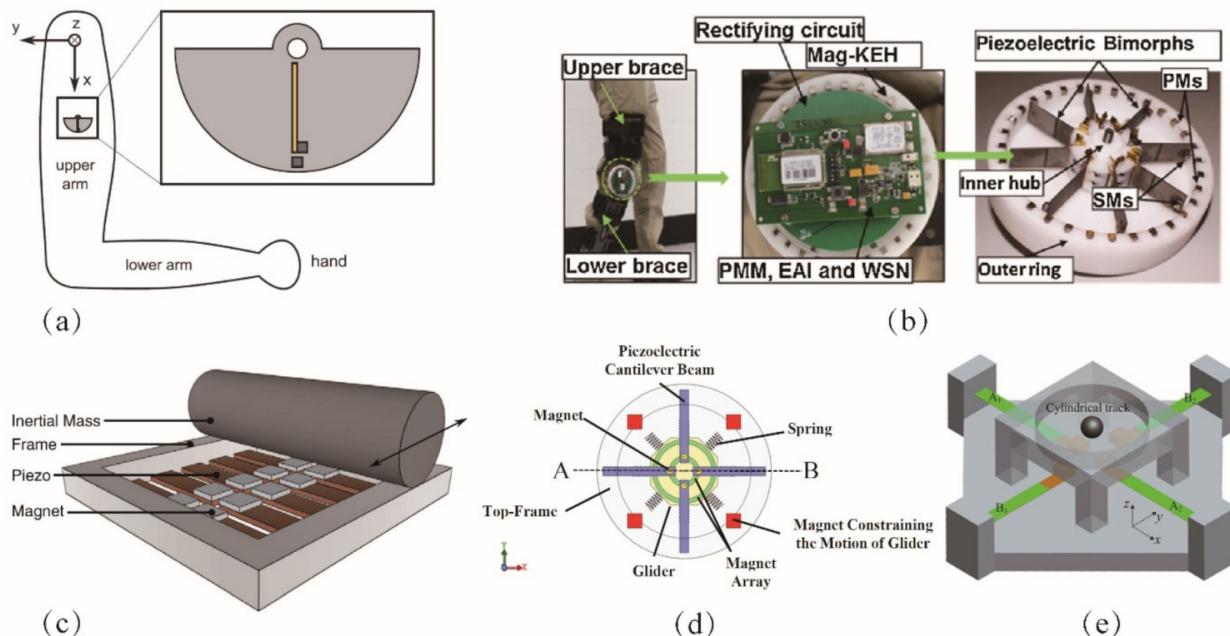


Figure 6. Magnetic plucking-based motion harvesters. (a) A human motion energy harvester with rotating proof mass [102]. (b) A magnetic plucking-based knee-joint energy harvester [59]. (c) An impulse-excited motion harvester [109]. (d) A 3-axial frequency-tunable piezoelectric energy harvester [112]. (e) A magnetic-force-configured harvester for various mechanical motions [58].

Chung et al. [112] proposed a frequency-tunable piezoelectric energy harvester, as shown in Figure 6d. Due to the magnetic-force configuration, the harvester could convert three-axial mechanical vibration into electrical outputs. Moreover, the frequency mismatching issue was addressed by the plucking mechanism. In addition, the device avoided mechanical wear-out problems since the plucking was realized through magnetic couplings. Fan et al. [58] also designed a similar nonlinear piezoelectric energy harvester, as shown in Figure 6e. It was able to harvest energy from the sway motion in different directions on the horizontal plane. Other relevant articles on the topic of magnetic plucking energy harvesting can be found in [113,114].

6. Snap-Through Based Energy Harvesters

The working principle of snap-through can be easily understood by referring to the lumped parameter model that consists of two inclined springs and a mass presented in [115]. Snap-through motion occurs in a bistable structure with two equilibrium states. The rapid transition between the two equilibrium states is referred to as the snap-through motion. Under a large excitation, the bistable system undergoes large-amplitude intra-well oscillation [6]. Jung et al. [116] designed a snap-through-based piezoelectric energy harvester, as shown in Figure 7a. The bi-stability was achieved by a buckled bridge structure. A piezoelectric beam was attached to the proof mass of the bistable system. The natural frequency of the piezoelectric beam was higher than the buckled bridge. A single snap-through motion generated an impulse-like excitation to the piezoelectric beam, making it vibrate almost freely at its natural frequency. A similar energy harvester consisting of a buckled bridge and an attached piezoelectric beam was built and investigated by Speciale et al. [117]. Instead of attaching the piezoelectric beam to the proof mass of the bistable structure, Ando et al. [60] placed the piezoelectric beam at the lateral sides of the proof mass, as shown in Figure 7b. When the bistable system snapped from one equilibrium state to the other, the proof mass rapidly crashed on the lateral piezoelectric beam. The

impact was converted to the free vibration of the lateral piezoelectric beam, thus producing an electrical output. The above work all employed piezoelectric transductions. Panigrahi et al. [118] developed a frequency un-conversion electromagnetic harvester based on the snap-through mechanism. Figure 7c demonstrates the schematic of the electromagnetic harvester. The bi-stability was formed by the combination of the linear spring and the magnets. The magnet also played the role of inducing the current in the coil during the vibration. The experimental result demonstrated that the response frequency could be increased more than 25 folds due to the employment of the snap-through mechanism. More related work using similar design strategies, as introduced above, can be found in [119–121]. It is worth noting that the snap-through phenomenon itself does not realize frequency up-conversion. The snap-through phenomena are designed to be induced by low-frequency vibrations for producing impulse-like large-amplitude excitations. Harvesters with high resonant frequencies are attached to or placed near the snap-through systems for harnessing impulse-like excitations.

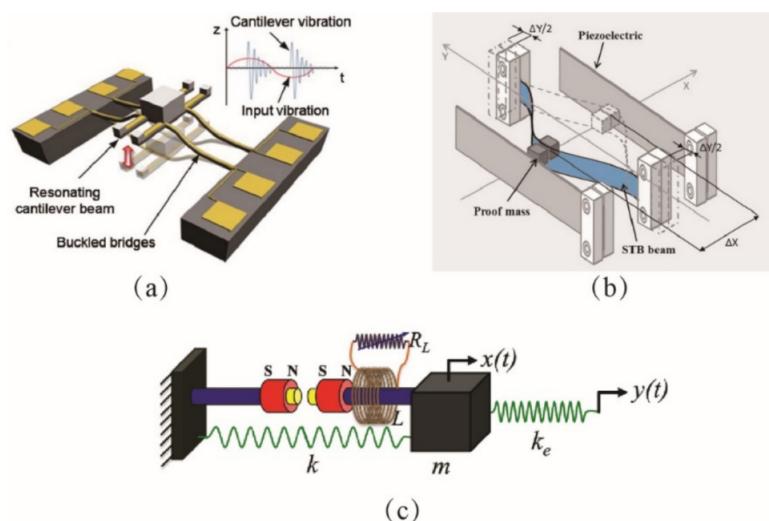


Figure 7. Snap through-based vibration energy harvesters. (a) A snap-through-based piezoelectric energy harvester [115]. (b) A frequency up-converting energy harvester based on snap-through and impact [60]. (c) A frequency un-conversion electromagnetic harvester based on the snap-through mechanism [116].

7. Conclusions

This paper has presented a review on the state-of-the-art frequency up-conversion mechanisms for energy harvesting and the corresponding designs under low-frequency vibration excitations. The existing frequency up-conversion approaches have been classified into three categories according to their working principles.

The first approach, impact-based frequency up-conversion, is realized by instantaneously pre-charging an energy harvester with initial kinetic energy then releasing it for free vibration at its natural frequency with an initial velocity. The kinetic energy transfer is completed during the impact in a relatively short time. The second approach is often referred to as plucking. The plucking-based approach pre-charges an energy harvester with initial potential energy. Plucking refers to the action of pulling an energy harvester forcibly away from its equilibrium by an external force. The potential energy of the harvester is increased during the plucking process. After releasing, it induces a free vibration at the natural frequency with an initial displacement. The third approach is based on the snap-through phenomenon of a bistable system. The snap-through motion refers to the rapid transition between the two equilibrium states of the bistable system. Usually, a piezoelectric beam with a high natural frequency is attached to or placed near the bistable system. Under a low-frequency excitation, the snap-through motion can generate impulse-like excitation to

the piezoelectric beam. Thus, it can vibrate almost freely at its natural frequency, converting the low-frequency ambient excitation to high-frequency voltage outputs.

Most existing researches that adopted the above three approaches have been summarized and discussed. The plucking-based approach is the most widely employed method for energy harvesting from low-frequency vibrations. It is envisioned that researchers in this field can be inspired by this literature review and develop novel frequency up-conversion approaches or innovative energy harvesting systems based on the techniques reviewed in this article. Furthermore, hybrid design has become a new research trend in recent years. It is expected that more innovative designs can be proposed by combining different transduction mechanisms and frequency up-conversion principles to improve energy harvesting performance further.

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