

Pendulum-based vibration energy harvesting: Mechanisms, transducer integration, and applications

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ABSTRACT

Vibration energy harvesting is a promising approach to provide wireless sensors and portable electronics with sustainable power by converting ambient kinetic energy into expected electrical energy. As one of the most fundamental mechanical oscillators, pendulums are restored by gravity rather than elastic elements and have drawn a number of research interests in developing vibration energy harvesters in recent years due to their simple and reliable structures. This paper comprehensively reviews the state-of-the-art progress of the pendulum-based energy harvesting. The pendulum mechanisms for energy harvesting such as single-pendulum configurations, multi-pendulum configurations, and pendulums with modulation mechanisms are elaborated and discussed. The integrations of electromagnetic, piezoelectric, triboelectric, and hybrid transducers are characterized and compared. The applications of the pendulums in harvesting energy from ocean wave, vehicle motion, human motion, structural vibration, and flow-induced vibration are reviewed. Finally, the challenging issues and future trends of this technology are summarized based on the progress to date.

1. Introduction

With the intensification of energy crisis and environmental pollution, the harvesting of clean energy plays an increasingly critical role in the sustainable development of human beings [1–3]. Vibration energy harvesting which converts ambient kinetic energy into expected electrical energy is one of the attractive technologies, with promising applications in self-powered electronic devices [4–7]. For wireless sensors applied in infrastructure monitoring or electronic devices implanted into human body, chemical batteries are not sustainable and economical power sources because of the burden of frequent replacement or charging. Mechanical vibrations can be found in a number of ambient sources such as ocean waves [8], rotational machines [9], railroad tracks [10], vehicle suspensions [11], human motions [12], civil structures [13], and so on. By collecting the mechanical vibrations and generating electricity, energy harvesters are capable of serving as more environmental-friendly alternatives to the chemical batteries.

A vibration energy harvesting system typically consists of mechanical oscillators, optional modulation mechanisms, transducers, power electronic circuits, and electrical loads or storages [14]. When the housing of the energy harvester is excited by ambient vibrations, the

mechanical oscillators will generate linear or rotational motion relative to the housing. The kinetic energy of the mechanical oscillators can be converted into electrical energy by the transducers such as electromagnetic, piezoelectric and triboelectric types [15–17]. Sometimes customized modulation mechanisms are coupled to amplify or modulate the oscillator motion before inputting to the transducers [18]. The generated electrical energy are regulated with the power electronic circuits, and then can be either supplied to electrical loads or stored in batteries or capacitors.

It is apparent that the mechanical oscillators are the key components in the energy harvesting system for capturing vibration energy. The most fundamental mechanical oscillators can be categorized into spring-mass mechanism and pendulum mechanism. In the spring-mass mechanism, the oscillating mass is supported by an elastic element such as a mechanical spring, a magnetic spring or an elastic beam [19–21]. Mass gravity generally exerts adverse influence on the spring-mass mechanism. When the spring-mass mechanism is vertically installed, the mass gravity will cause a significant initial deformation of the spring, especially in low-frequency operation [22]. When the spring-mass mechanism is horizontally installed, the mass gravity will result in an additional friction which damps oscillation. In the pendulum

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mechanism, the oscillating pendulum is mostly restored by its gravity. Through comparison, it can be found that the pendulum mechanism has simpler and more reliable structure than the spring-mass mechanism. Moreover, the pendulum mechanism is capable of capturing vibrations with ultra-low frequency which is difficult for the spring-mass mechanism [23,24]. However, the pendulum mechanism typically has relatively large volume which poses challenges to achieve compact structure and high power density.

Researchers have presented a number of effective and innovative designs of the pendulum-based energy harvesters in the past few years. Pendulum mechanisms with various configurations such as horizontal-axis type [25], vertical-axis type [26], inclined-axis type [27] and gimbaled type [28] have been applied in vibration energy harvesting. Multi-pendulum mechanisms have been proposed to overcome the shortcomings of the energy harvesters using single pendulum [29,30]. Pendulum mechanisms combined with modulation mechanisms have also been reported to better adapt to random and broadband ambient excitations [23,31,32]. However, these works have not been comprehensively investigated and summarized.

There have been a number of excellent reviews on vibration energy harvesting. Literature [1,5], and [33] mainly focus on the performance improvement of the energy harvesters through various technologies such frequency tuning, nonlinear dynamics, amplification, and so on. Literature [2] reviews the available designs of piezoelectric energy harvesting tiles and literature [3] reviews the energy harvesting from the specific source of flow-induced vibration. Literature [4] summarizes the modeling methods and Literature [6] summarizes the architectural approaches of the vibration energy harvesters. The pendulum-based energy harvesting is usually included as a specific architecture in the existing reviews, and its designs and characteristics have not been thoroughly presented. According to statistics, there have been more than 130 journal publications about the pendulum-based energy harvesters. With the continuous growth of the related publications, it is necessary to make a comprehensive review on the recent progress of the pendulum-based energy harvesters.

This review focuses on the pendulum mechanisms and the transducer integration applied in vibration energy harvesting. The pendulum-based energy harvesters have inherent features such as low-frequency adaptability in comparison with the spring-mass type [24]. With deep insight into the characteristics of different pendulum mechanisms, it is helpful to adopt optimal configurations and parameters for certain excitations so as to enhance electrical output. In addition, the harvested energy will be significantly reduced when the actual excitation frequency is deviated from the natural frequency for the energy harvesters designed in resonant operation. Therefore, it is worth exploiting the nonlinearity in the pendulums as well as combined modulation mechanisms to achieve wide frequency bandwidth. This work also discusses the promising applications where the vibration excitations are suitable for the energy harvesting systems with pendulums.

The rest of this paper is organized as follows. Section 2 illustrates the common configurations of the mechanical oscillating system with one or more pendulums for energy harvesting. Section 3 elaborates and discusses the pendulums combined with the modulation mechanisms to improve energy harvesting performance. Section 4 characterizes and compares the integration approaches of the electromagnetic, piezoelectric, triboelectric, and hybrid transducers. Section 5 reviews and discusses the applications of the pendulums in harvesting energy from ocean wave, vehicle motion, human motion, structural vibration, flow-induced vibration, and so on. Finally, Section 6 summarizes the challenging issues and future research directions of the pendulum-based energy harvesting.

2. Pendulum mechanisms for energy harvesting

In a broad sense, a pendulum is a mass or an eccentric rotor which can rotate around an axis with a restoring torque generated by its

gravity. There have been a series of different configurations of the pendulum mechanisms utilized in vibration energy harvesting with the progress of this topic. Based on the pendulum number, the pendulum mechanisms are categorized into single-pendulum configuration and multi-pendulum configuration firstly. Furthermore, the single-pendulum configuration is classified based on the arrangements of the rotational axis, and the multi-pendulum configuration is classified based on the coupling modes of the pendulums, as shown in Table 1. More details about the pendulum configurations as well as their characteristics are presented as follows.

2.1. Single-pendulum configuration

(A) Horizontal-axis type

The pendulum rotating around a horizontal axis is the most common type. From the aspect of mechanism design, the horizontal-axis pendulum could be simply suspended by using a shaft as shown in Fig. 1(a) [47]. An innovative design is to constrain the motion of a rolling pendulum by using a spherical or cylindrical surface so that the pendulum is capable of rotating around the axis of the rolling surface similarly without a physical shaft as shown in Fig. 1(b) [48]. Smilek et al. also designed a rolling pendulum mechanism for energy harvesting consisting of a cylindrical proof mass installed inside a circular cavity in a Tusi couple configuration [49]. The pendulum-based energy harvesters with horizontal axes can be operated in direct resonance or parametric resonance [25]. When the direction of the input excitation is horizontal and orthogonal to the rotational axis, the dynamics of the pendulum can be expressed as

$$(m_h L_h^2 + I_h) \ddot{\theta}_h + C_h \dot{\theta}_h + m_h g L_h \sin \theta_h = m_h L_h A_{hd} \cos \omega_{hd} t \cos \theta_h \quad (1)$$

where m_h is the mass of the horizontal-axis pendulum, L_h is the distance between the pendulum centroid and the rotational axis, I_h is the moment of inertia of the pendulum, θ_h is the rotational angle relative to vertical, C_h is the damping coefficient caused by mechanical loss and energy harvesting, and A_{hd} and ω_{hd} are the acceleration amplitude and the angular frequency of the horizontal excitation. Applying small-angle approximation, the natural frequency of the pendulum is given as

$$\omega_{h0} = \sqrt{m_h g L_h / (m_h L_h^2 + I_h)} \quad (2)$$

In direct resonance when the natural frequency matches the excitation frequency, the pendulum will oscillate with significant amplitude and capture the excitation for energy conversion [32,50,51].

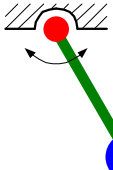
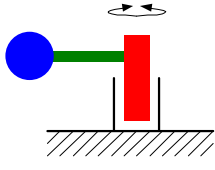
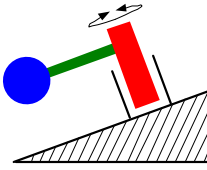
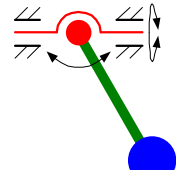
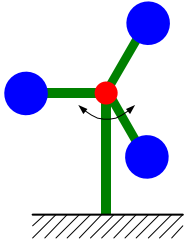
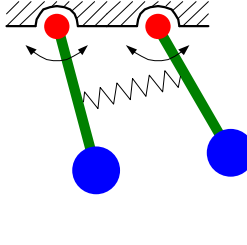
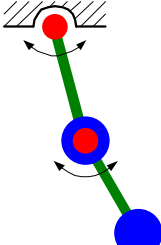
The parametric resonance is a more interesting phenomenon where the pendulum can rotate stably rather than swing back and forth [52–54]. The following equation governs the parametric excitation in vertical direction

$$(m_h L_h^2 + I_h) \ddot{\theta}_h + C_h \dot{\theta}_h + m_h L_h (g + A_{hp} \cos \omega_{hp} t) \sin \theta_h = 0 \quad (3)$$

where A_{hp} and ω_{hp} are the acceleration amplitude and the angular frequency of the vertical excitation. The primary parametric resonance occurs when the pendulum is subjected to excitation with angular frequency close to double of the natural frequency [55]. Once activated, the oscillatory amplitude growth of the parametric resonance will not saturate due to linear damping but be constrained by physical limits or nonlinearities at high amplitudes, which leads to large electrical power output [56–58]. However, there exists an initiation threshold which depends on damping and limits practical realization. Jia et al. explored two distinct design routes to passively minimize the required initiation threshold [25]. Dotti et al. addressed the quantification of damping including linear and quadratic terms in parametric pendulums for energy harvesting [59].

(B) Vertical-axis type

Table 1
Categories of pendulum configurations utilized in vibration energy harvesting.

Category	Schematic and description			
Single-pendulum configuration				
Multi-pendulum configuration	Horizontal-axis type [25,34,35]	Vertical-axis type [26,36,37]	Inclined-axis type [27,38]	Gimbaled type [28,39,40]
				
	Coaxial type [30,41]	Parallel type [42–44]	Series type [29,45,46]	

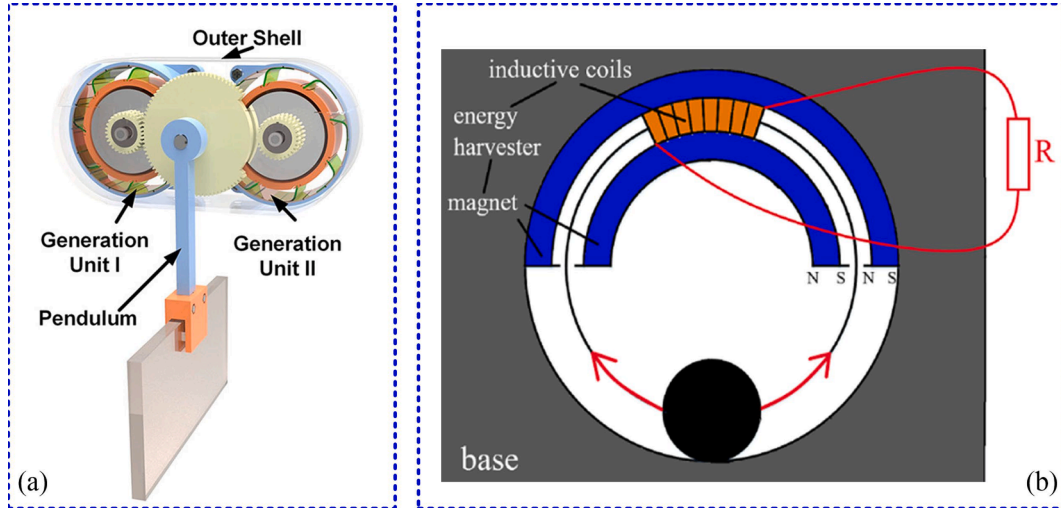


Fig. 1. Horizontal-axis pendulums using (a) a shaft [47] and (b) a rolling surface [48].

Fig. 2 shows two typical pendulum-based energy harvesters with vertical axes [26,60]. The pendulums are prone to rotate around the axes continuously in this configuration, especially when active control techniques are applied. Boren et al. designed a model predictive and

integral error controller for a vertical-axis pendulum energy harvester to enhance net power generation from ocean wave [61]. They also developed a scaled prototype and implemented experiments to evaluate how the net power output responded to varied wave environments and

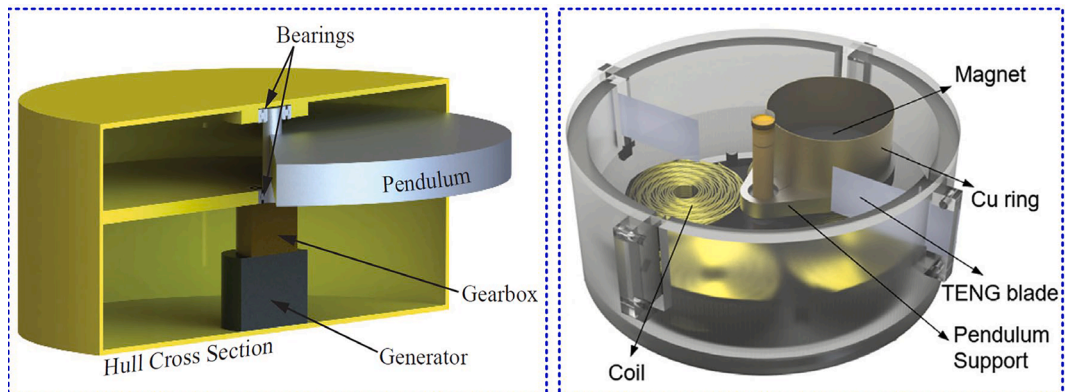


Fig. 2. Typical vertical-axis pendulums for energy harvesting [26,60].

operational conditions [37]. Since the vertical-axis pendulum mechanisms are symmetric with respect to their axes, they can be excited by translational vibration in horizontal plane or rolling vibration from arbitrary directions.

When the input excitation is translational in the horizontal plane, the dynamics of the pendulum can be expressed as

$$(m_v L_v^2 + I_v) \ddot{\theta}_v + C_v \dot{\theta}_v = m_v L_v A_v \cos \omega_v t \cos \theta_v \quad (4)$$

where m_v is the mass of the vertical-axis pendulum, L_v is the distance between the pendulum centroid and the rotational axis, I_v is the moment of inertia of the pendulum, θ_v is the rotational angle relative to the excitation direction, C_v is the damping coefficient caused by mechanical loss and energy harvesting, and A_v and ω_v are the acceleration amplitude and the angular frequency of the horizontal excitation. It can be seen from (4) that the pendulum motion is mainly caused by inertia force and the gravity has no effect in this case.

When the input excitation is the combination of rolling motion and heaving motion, the dynamics of the pendulum is written as [26]

$$(m_v L_v^2 + I_v) \ddot{\theta}_v + C_v \dot{\theta}_v + m_v L_v^2 \sin \theta_v \cos \theta_v \cdot \dot{\varphi}^2 + m_v L_v (g + \ddot{H}) \sin \theta_v \sin \varphi = 0 \quad (5)$$

where φ is the rolling angle and H is the heaving displacement. It can be seen from (5) that the gravity produces an effect in the term coupled with the rolling motion. Moreover, some vessels equipped with energy harvesters may undergo both pitching and rolling motions in wave environment. Yerrapragada et al. made use of the energy transfer between the pitching motion and the rolling motion with the frequency ratio of 2:1 to improve the electrical generation of a vertical-axis pendulum energy harvester [36]. In general, the output capability of the energy harvester with the vertical-axis pendulum is close to that with the horizontal-axis pendulum [60].

(C) Inclined-axis type

The inclined-axis configuration of the pendulum mechanism is an intermediate state between the horizontal-axis type and the vertical-axis type. In comparison to the horizontal-axis type, the influence of the pendulum gravity is reduced due to the inclination arrangement of the axis, which allows the parametric pendulum to achieve rotational response without active control involvement for low-amplitude vibration [27]. In addition, Dostal et al. experimentally verified that the

restoring torque caused by the gravity decreases with the inclination angle, and so does the natural frequency of the pendulum. In the researches of Ding et al. [62–64], a frequency tuning approach was developed for a pendulum energy harvester by adjusting the inclination angle of the rotational axis. Experimental results showed that resonant frequencies as low as 0.2 Hz, 0.25 Hz and 0.3 Hz were achieved with the inclination angles of 87 degrees, 86 degrees, and 85 degrees, respectively [63]. It can be seen that the inclined-axis configuration provides a more flexible alternative to the design of the pendulum mechanism.

(D) Gimbaled type

The aforementioned three types of pendulum configurations all only have one degree of freedom and are constrained to move in one plane, which limits the ability of harvesting the kinetic energy available when excited by multi-directional vibrations [65]. The gimbaled-pendulum energy harvesters can be introduced to overcome this limitation and fully utilize the potential of multiple degrees of freedom. As shown in Fig. 3, the gimbaled pendulums in energy harvesting can be suspended by a thread, a universal joint coupling or multiple coupled shafts. The gimbaled-pendulum mechanisms with the thread have the advantage of low damping and the disadvantage of small load capacity, so they are suitable for lightweight pendulums [66–68] or serving as auxiliary devices to produce internal resonance [69]. The gimbaled-pendulum mechanisms using the universal joint coupling or the multiple coupled shafts are essentially with the same structure, where the shafts are orthogonal to each other and the inner shaft rotates around the outer shaft. Wang et al. developed a hemisphere-pendulum energy harvester capable of rotating around two axes through a cross universal joint coupling [70,71]. A two-degree-of-freedom energy harvester composed of an eccentric dual-axis ring and electrical generators was also designed to acquire kinetic energy by mimicking biaxial hula-hoop motion [39]. The motions with respect to the coupled axes are not symmetrical, for the orientation of the outer shaft has unidirectional effect on the inner shaft.

The dynamics of the gimbaled pendulum is more complex in comparison with the pendulum with one degree of freedom. Taking the energy harvester with two axes horizontally arranged as an example, its dynamics can be governed by the following equations when excited by vibration accelerations $A_x \cos(\omega_x t)$ and $A_y \cos(\omega_y t)$ which are orthogonal in the horizontal plane.

$$(m_g L_g^2 + I_{g\alpha}) \ddot{\alpha} + C_\alpha \dot{\alpha} + m_g L_g^2 \dot{\beta}^2 \sin \alpha \cos \alpha + m_g L_g (g \sin \alpha \cos \beta + A_x \cos \omega_x t \cos \alpha - A_y \cos \omega_y t \sin \alpha \sin \beta) = 0 \quad (7)$$

$$(m_g L_g^2 \cos^2 \alpha + I_{g\beta}) \ddot{\beta} + C_\beta \dot{\beta} - m_g L_g^2 \dot{\alpha} \sin 2\alpha + m_g L_g \cos \alpha (g \sin \beta + A_y \cos \omega_y t \cos \beta) = 0 \quad (8)$$

rotational motion of the inclined-axis pendulum was possible even under low-to-moderate random excitation [38]. The dynamics of the inclined-axis pendulum under parametric excitation in vertical direction is given as

$$(m_i L_i^2 + I_i) \ddot{\theta}_i + C_i \dot{\theta}_i + m_i L_i (g \cos \gamma + A_i \cos \omega_i t) \sin \theta_i = 0 \quad (6)$$

where m_i is the mass of the inclined-axis pendulum, L_i is the distance between the pendulum centroid and the rotational axis, I_i is the moment of inertia of the pendulum, θ_i is the rotational angle, C_i is the damping coefficient caused by mechanical loss and energy harvesting, γ is the inclination angle of the rotational axis, and A_i and ω_i are the acceleration amplitude and the angular frequency of the vertical excitation.

It can be seen from the comparison between (3) and (6) that the

where m_g is the mass of the gimbaled pendulum, L_g is the distance between the pendulum centroid and joint coupling, α and β are the rotational angles, $I_{g\alpha}$ and $I_{g\beta}$ are the moments of inertia of the pendulum about its gravity center, and C_α and C_β are the damping coefficients caused by mechanical loss and energy harvesting. The dynamics of the gimbaled pendulum can also be modeled by taking the deflection angle relative to the vertical axis and the azimuth angle as variables [28]. Anurakpandit et al. made a simplified assumption that the perpendicular pivots were treated as two coupled references with geometric relationships [65]. Thus, the derived model was able to realistically identify the asymmetric characteristics between the two coupled references created by the gimbaled mechanism. From a new perspective, the gimbaled-pendulum energy harvester could be designed for threshold escape

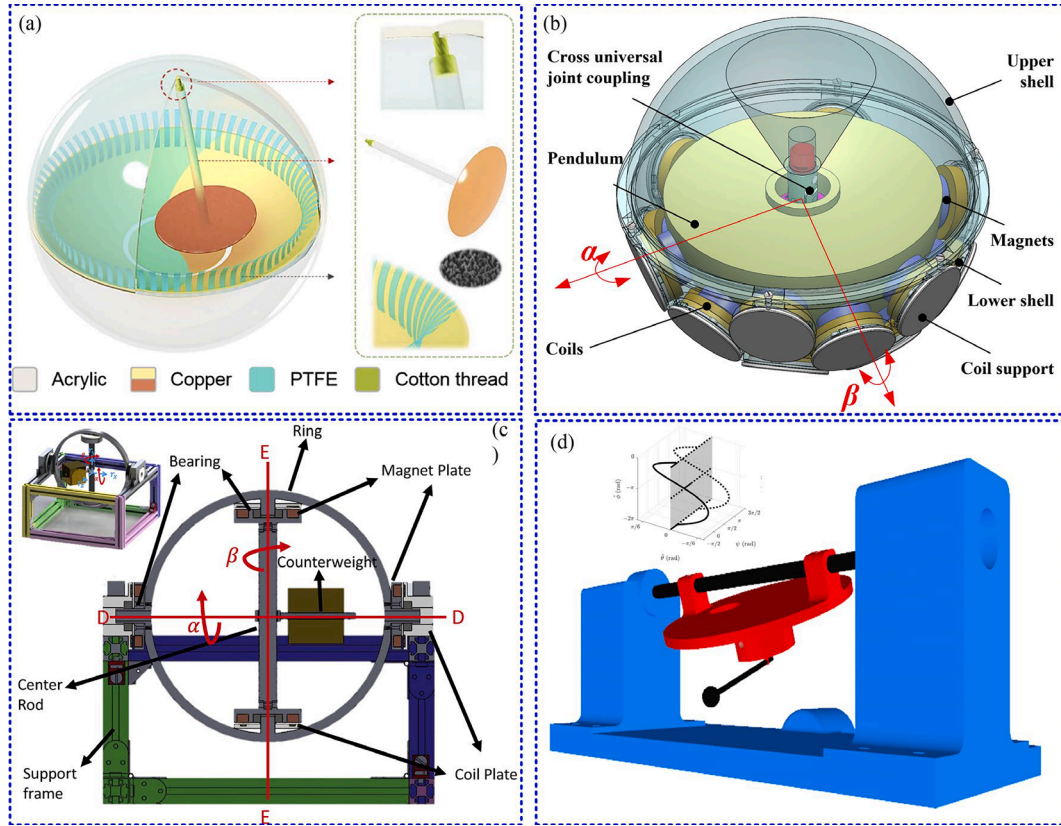


Fig. 3. Gimbaled-pendulum energy harvesters with (a) thread [68], (b) universal joint coupling [71], (c) and (d) multiple coupled shafts [39,72].

behavior in order to jump across stable attractors by excitation amplitude rather than frequency [40,72]. In general, the gimbaled pendulums provide the harvesting of vibration energy with richer dynamics and better adaptability at the cost of increased complexity in machine design.

2.2. Multi-pendulum configuration

(A) Coaxial type

The coaxial configuration of multiple pendulums aims to tune the natural frequency of the pendulum mechanism on the premise of compact volume. As presented in (2), the expression of the natural frequency becomes $(g/L_h)^{1/2}$ for a lumped-mass pendulum of which I_h can

be regarded as zero. Thus, the length of the pendulum rod is inversely proportional to the square of the natural frequency, which leads to large dimensions in harvesting low-frequency vibration such as ocean wave. Taking the excitation frequency of 0.5 Hz as an example, the required length of the pendulum rod is as long as 0.99 m for frequency match. By arranging a number of pendulums coaxially in the rotational plane, the moment of inertial is increased and the centroid distance to the pivot is decreased, resulting in the reduction of the natural frequency. Fig. 4 shows the schematic of the coaxial type with two equal-mass pendulums distributed in line. The corresponding expression of the natural frequency is given as

$$\omega_{d0} = \sqrt{\frac{g(l_1 - l_2)}{l_1^2 + l_2^2}} \quad (9)$$

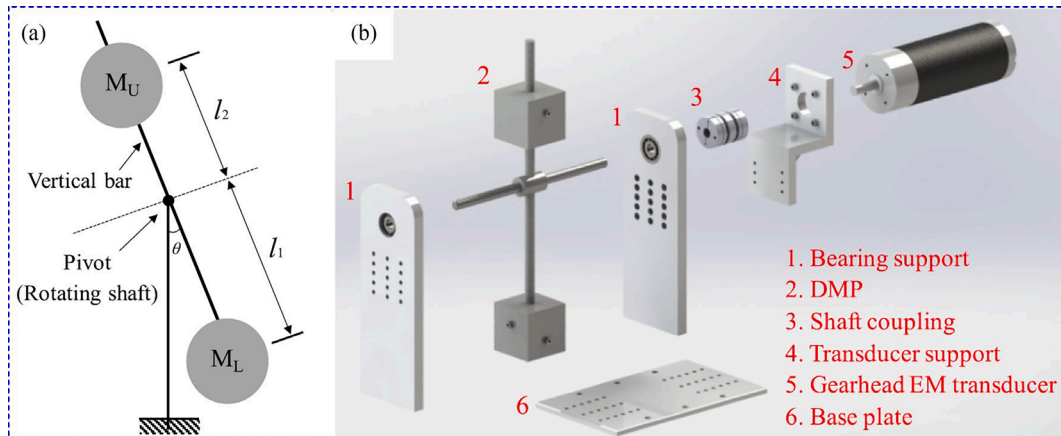


Fig. 4. Schematic of coaxial configuration with two pendulums. (a) Conceptual design. (b) Exploded view [73].

where l_1 and l_2 are the lengths of the two pendulum rods. It was shown that a tunable ultra-low natural frequency range from 0.2 Hz to 1.4 Hz could be achieved by using this configuration [73]. Graves et al. also developed a pendulum energy harvester with another mass as counterweight to reduce the natural frequency [74].

The coaxial configuration with arbitrary number of pendulums has also been investigated. Yurchenko et al. proposed the design of an N -pendulum energy harvester which not only allowed uncoupling the natural frequency of the pendulum from the rod length, but also provided convenient control of the frequency as well as the torque [30]. Moreover, an experimental study of the response to parametric excitation on a tri-pendulum energy harvester was presented in [75]. Nonlinear dynamic analysis such as bifurcation diagrams and basins of attraction was utilized to quantify the ability of an energy harvester with arbitrary number of concentric pendulums [76]. However, the mechanical damping due to the friction produced on the shaft also increases with the number of the pendulums using as counterweight.

(B) Parallel type

The parallel configuration mainly consists of multiple pendulums arranged in a row with independent rotational axes. In comparison with independent pendulums, the pendulums coupled in parallel through springs or magnets can enhance output power and frequency bandwidth during energy harvesting. However, this design may bring in physical constraints on the oscillating amplitude of the pendulums.

Malaji et al. conducted thorough investigation on this multi-pendulum mechanism. They analyzed the effect of mechanical coupling caused by springs on an energy harvester with two pendulums in parallel. It was found that the springs did not change the power curve under harmonic base excitation while two large peaks in the power curve appeared with particular value of coupling ratios under mistuned conditions [77]. The influence of the pendulum number was examined in [43]. The maximum output power saturated after a particular number of pendulums and further increase of the pendulum number did not lead to any significant enhancement. The combination of mechanical coupling and magnetic coupling was also applied in the parallel multi-pendulum configuration by attaching springs and magnets on the pendulums simultaneously. This system possessed rich dynamics including chaotic oscillation at large orbit, quasi-periodic motion, and periodic motion with low amplitude [42]. Results showed that 30.69 % increment of the power magnitude and 100 % enhancement of the bandwidth were achieved even under low-amplitude excitation [78]. Punyakaew et al. presented an energy harvester with two pendulums in parallel to exact the energy from two-frequency vibration. The resonant frequency of the pendulums could be adjusted online by controlling the position of

sliding blocks on the pendulums through proportional-integral-derivative controllers [44], but there was inevitable energy consumption in the electronic devices and the electrical actuators utilized in controlling.

(C) Series type

In the series configuration, one pendulum is arranged to rotate around the shaft assembled on another pendulum in sequence. This pendulum mechanism also shows complex dynamic behavior such as chaos due to increased degrees of freedom. The theoretical number of the pendulums in series can be large, but the existing researches focus on the configuration with two pendulums. Fig. 5 presents the schematic and prototype of a series-type pendulum energy harvester, where electricity is generated by the relative motion between the magnet attached on the second pendulum and the coils circularly distributed under excitation. The harvested power could be significantly enlarged when the pendulums underwent chaotic motion. Moreover, the energy harvesting system kept efficient in a broad spectrum of vibration frequency [29]. The series-type pendulum mechanism was also applied to a triboelectric-electromagnetic hybridized energy harvester to achieve high electro-mechanical energy conversion efficiency under low-frequency excitation. The authors pointed out that the lower pendulum started to motion while the upper pendulum swung and the motion track was chaotic and unpredictable [45]. Aiming at harvesting the kinetic energy of human motion, Izadgoshasb et al. compared three configurations of piezoelectric energy harvesters including with cantilever beam, with single pendulum and with two pendulums in series, and found that the two-pendulum configuration was capable of improving the efficiency of energy harvesting dramatically than the other two configurations [46]. Although the series configuration is prone to make the pendulum motion chaotic and easy to be harvested, it also has the disadvantage of large dimension along the direction of the pendulum rod, which decreases its power density.

It is noticeable that the pendulum mechanisms may transit from periodic motion to chaotic motion due to their inherent nonlinearity. Simultaneously, the practical vibrations have the characteristics of randomness, multidirectionality and uncertainty, which are just consistent with the feature of chaos in the pendulum mechanisms. Researchers have performed a number of works exploring the chaotic dynamics of the pendulum mechanism from both of theoretical modeling and experimental verification to adapt the vibration characteristics [28,29,42,45,46,78,79]. Chaotic behaviors are prone to occur when the degrees of freedom are increased by using gimbaled pendulums, multiple pendulums in parallel, or multiple pendulums in series. With the help of the chaotic dynamics, the energy harvesters are expected to maintain output performance under the vibrations with wide frequency

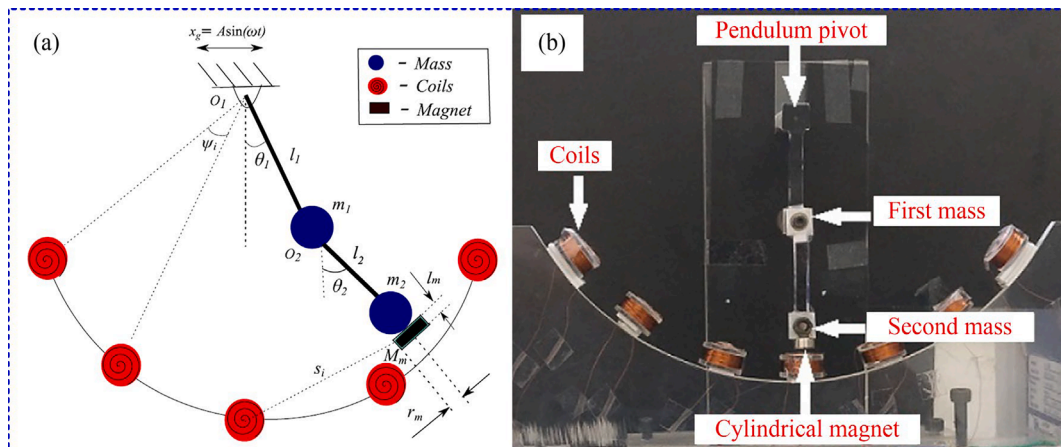


Fig. 5. An energy harvester with two pendulums in series. (a) Schematic. (b) Prototype [29].

spectrum and variable amplitude.

3. Combination of pendulum and modulation mechanism

The relative motion between the pendulums and the housing under excitation can be directly supplied to transducers for electromechanical energy conversion. However, sometimes the motion produced by the pendulums alone may be weak or undesired, and direct conversion may result in low electrical output and low efficiency. In this situation, modulation mechanisms are usually employed as auxiliary tools to enhance pendulum-based energy harvesting.

3.1. Pendulum with gear amplification mechanism

Since the pendulum-based energy harvesters are typically operated at low frequency, the angular velocity of the pendulum motion is relatively small. An effective approach is to connect the pendulum or its output shaft with a gear amplification mechanism, and then supply amplified motion to transducers. The gear mechanism generally consists of a set of gears with different number of teeth and a certain configuration to achieve desired transmission ratio. In the development of the pendulum-based energy harvesters, a number of researchers directly employed commercial products such as the planetary gearbox produced by Maxon with a transmission ratio as high as 103:1 [13,32,64,80,81]. The gear mechanism could also be assembled by discrete components through external gearing [24,47] or internal gearing [82]. Apparently, the friction in the gear mechanism has significant adverse effect on the efficiency of energy harvesting, especially when the number of the involved gears is large [83]. Therefore, it is a critical issue to adopt the gear mechanism with proper parameters in order to avoid that the frictional loss becomes too large to afford.

3.2. Pendulum with mechanical rectifier mechanism

In the arrangements of direct transmission or gear-amplified transmission, the electrical generator has to stop and reverse direction in response to the swing motion of the pendulum. Thus, it is helpful to incorporate a mechanical rectifier mechanism to maintain unidirectional rotation of the generator so as to improve energy conversion efficiency [84]. Fig. 6 shows the typical combinations of the pendulums and the mechanical rectifier mechanisms.

The function of mechanical rectification is mainly realized by using one-way clutches [89]. As shown in Fig. 6(a) and (b), two one-way clutches were mounted on the pendulum shaft in opposing directions, meaning that no matter the direction of the pendulum motion, at most one one-way clutch was engaged [85]. In this way, the bidirectional motion of the pendulum was rectified to unidirectional rotation. Moreover, due to the presence of the clutches, when the pendulum velocity was less than the generator velocity, the clutches would freewheel and allow the generator to continue running without being slowed along with the pendulum [32]. Fig. 6(c) and (d) show the mechanical rectifier with a ratchet and a plectrum, which can be regarded as an innovative form of the ratchet-type one-way clutch [86,87]. The ratchet-type clutch could also be applied in the pendulum-based energy harvesters [55,90]. Fig. 6(e) shows a string-driven mechanical rectifier where the clutch is engaged when the pendulum displacement is increasing and the clutch is disengaged when the pendulum displacement is decreasing [88]. Among the aforementioned mechanical rectifiers, it can be found that the time driving the generator in a period of the configuration using two clutches is doubled in comparison with the configuration using one clutch.

3.3. Pendulum with spring mechanism

Springs can be arranged with various configurations in the pendulum-based energy harvesters to achieve target functions such as generating internal resonance, providing additional restoring force or regulating energy storage. As shown in Fig. 7(a), the rigid pendulum rod was replaced with a piezoelectric spring based on a binder clip architecture so as to up-convert excitation frequency through internal resonance [23]. Jiang et al. designed an electromagnetic energy harvester using such a pendulum-spring mechanism with internal resonance [91]. Lin et al. installed an assisted spring on the pendulum rod of a triboelectric nanogenerator to realize a soft-contact mode which promoted durability and efficiency [67]. Literature [92] and [93] investigated the pendulum-spring mechanism whose pivot moved in a circular or elliptic orbit. Fig. 7(b) presents the configuration where two springs are symmetrically fixed on the pendulum rod at two sides. With the inclusion of the additional restoring force caused by the springs, the harvesting power attained high values for appropriate ranges of spring constants [94]. Martin et al. presented a biomechanical energy harvesting backpack with an inverted pendulum supported by linear springs [95]. Fig. 7(c) shows the third function of the springs in the pendulum-based energy

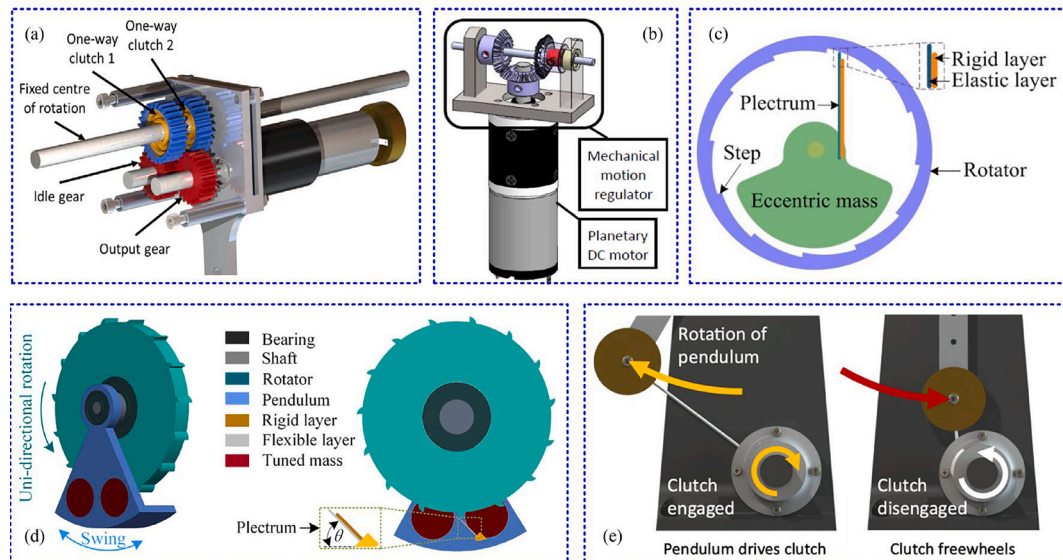


Fig. 6. Typical combination of pendulums and mechanical rectifier mechanisms. (a)(b) With two one-way clutches [32,85]. (c)(d) With a ratchet and a plectrum [86,87]. (e) With string and a one-way clutch [88].

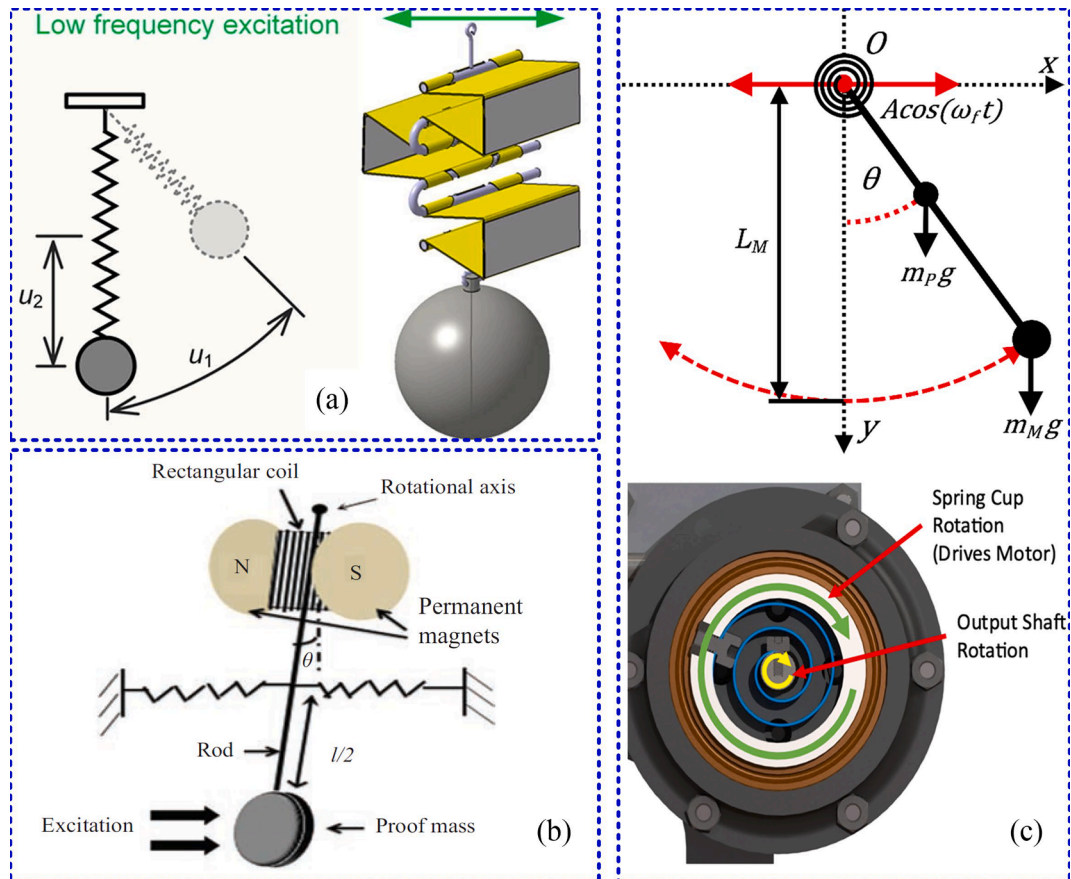


Fig. 7. Pendulum-based energy harvesters with spring mechanisms. (a) Generating internal resonance [23]. (b) Providing additional restoring force [94]. (c) Regulating energy storage [96].

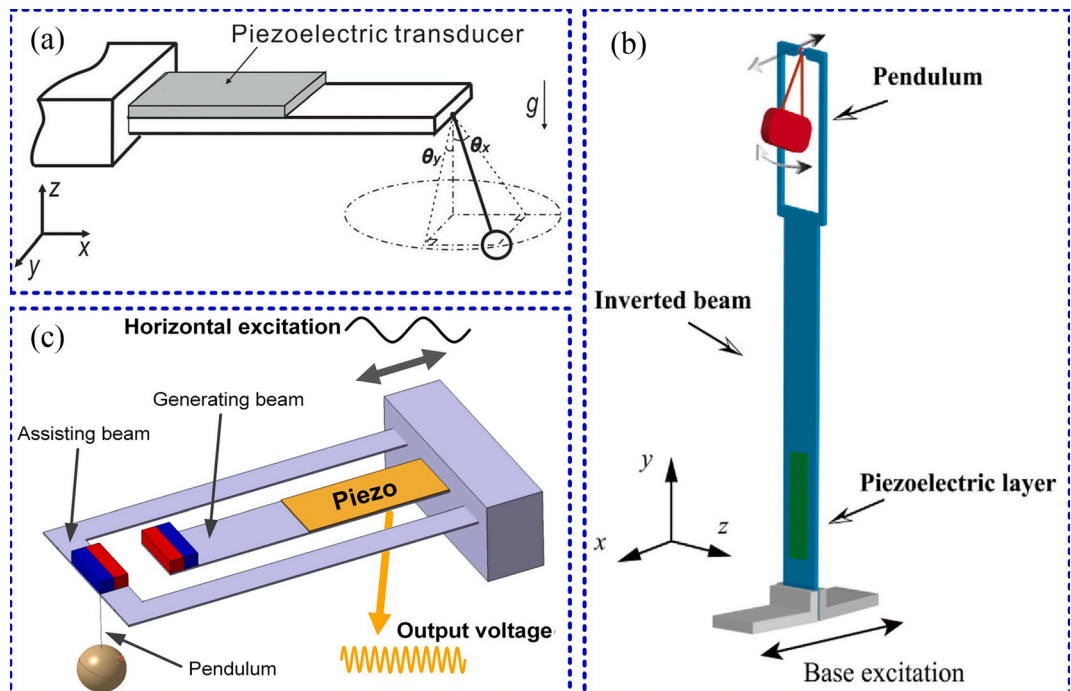


Fig. 8. Typical combinations of pendulums and elastic beams. (a) Horizontal beam [69]. (b) Inverted beam [99]. (c) Two beams with magnet pair [101].

harvesters as an energy storage regulator. The springs provide the benefits of smoothing the electrical output especially for sudden impacts [96]. Although the spring mechanism contributes to the improvement of energy harvesting, it should be noted that the introduction of additional mechanical elastic elements is disadvantageous to system reliability.

3.4. Pendulum with elastic beam mechanism

Elastic beams are also common-used elastic elements in energy harvesting, especially integrated with piezoelectric transducers. The modulation function of the elastic beams is to provide frequency up-conversion for the pendulum-based energy harvesters through internal resonance. In the combined mechanism, the pendulum usually acts as the oscillator with lower resonant frequency and the elastic beam acts as the higher one. Internal resonance will be induced and significant energy interchange between the two oscillators will be produced when their resonant frequencies are tuned to a certain ratio such as 1:2 [97].

Fig. 8 shows the typical combinations of the pendulums and the elastic beams. In Fig. 8(a), Xu et al. reported the conceptual design where the pendulum pivot was directly coupled to the tip of the horizontal beam fixed with piezoelectric transducers. Since the pendulum was the gimbaled type suspended by a thread, vibration energy in multiple directions could be transferred to the beam bending motion for energy conversion [69,98]. In Fig. 8(b), an inverted beam with large deformation was employed in the pendulum-based energy harvesting to improve the performance under weak excitation [99,100]. However, the pendulum motion in this configuration was constrained in a plane rather than in three dimensions. In Fig. 8(c), the pendulum pivot was fixed on the tip of the assisting beam which coupled the generating beam through repulsive magnet pair. In this way, two-stage frequency up-conversion was realized with the ratios of 1:2:6 [101].

3.5. Pendulum with magnetic mechanism

Magnets can serve as unconventional elastic elements with positive stiffness in repulsive arrangement or with negative stiffness in attractive

arrangement [102]. An interesting property of the magnets is that the magnetic force is usually nonlinear, so there will be more than one stable equilibriums when the magnets are added to the pendulum mechanism [103]. The multi-stability makes the oscillator snap through and offers an improvement of broadband performance.

Fig. 9 shows the typical configurations of the pendulum-based energy harvesters combined with different number of magnets. As shown in Fig. 9(a), two repulsive magnets were fixed on the pendulum bottom and the frame respectively to form a bi-stable configuration, which was beneficial to the enhancement of frequency bandwidth [82]. Castagnetti designed a tunable pendulum energy harvester by varying the equivalent stiffness of two magnets [31]. Bao et al. coupled two magnets to a pendulum-based piezoelectric energy harvester to widen its frequency bandwidth [104]. However, theoretical expression showed that the configuration using two magnets made the operation range move towards higher frequency [82]. To expand the frequency range towards lower frequency, a modified solution was to utilize three magnets of which one was fixed on the pendulum bottom and the others were arranged with attractive force at the two sides of the base as shown in Fig. 9(b) [105]. The multi-stable configuration could also be extended from two dimensions in plane to three dimensions in space [106]. Zhang et al. designed a novel autoparametric pendulum absorber-harvester where the pendulum was also attracted by magnetic forces from the two sides of its housing [107]. Fig. 9(c) shows a multi-stable energy harvester named as magnetic rolling pendulum by using four magnets. The magnetic pendulum could roll back and forth on the surface of the central magnet due to attractive magnetic force with low mechanical loss, and the other two magnets provided nonlinear repulsive force to achieve broad bandwidth [58,108].

As another advantage of the magnets in vibration energy harvesting, the magnetic force is free of contact, which much benefits the system reliability in comparison with mechanical elastic elements. Thus, some frequency up-converting energy harvesters also employed magnet pair to couple the low-frequency oscillator and the high-frequency oscillator, and examples could be found in Fig. 8.

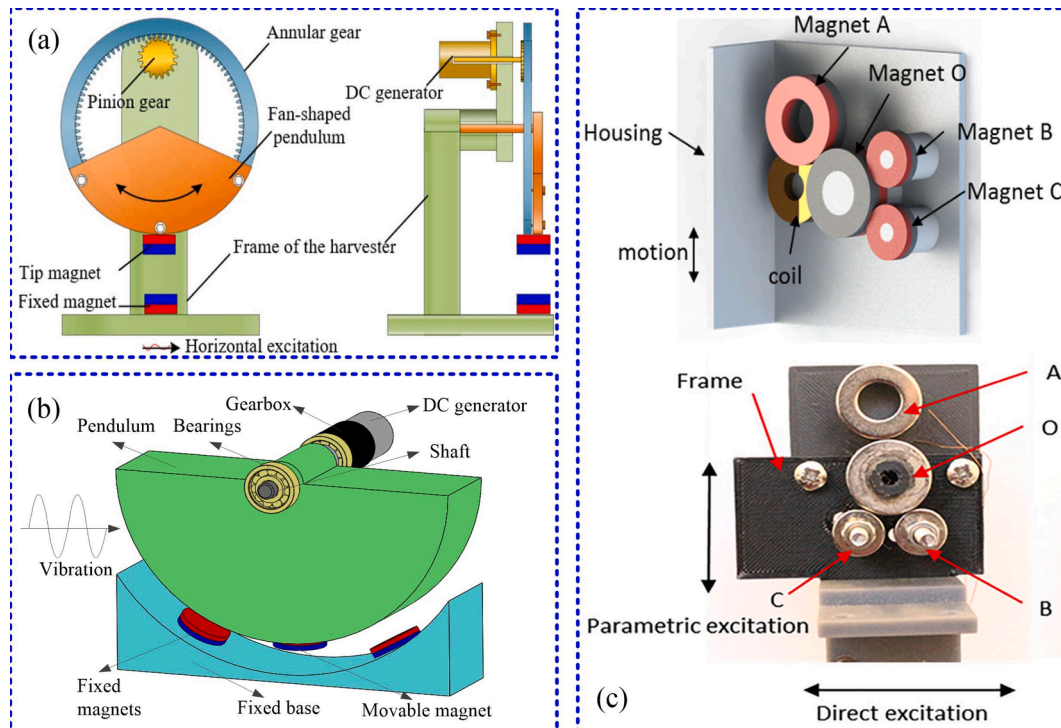


Fig. 9. Typical configurations of pendulum-based energy harvesters with magnetic mechanisms using (a) two magnets [82], (b) three magnets [105], and (c) four magnets [108].

Table 2

Comparison among pendulum-based energy harvesters with different modulation mechanisms.

Type	Performance improvement	Disadvantage
Gear amplification mechanism	Amplifying velocity output from pendulum shaft to improve transducer efficiency	Causing energy loss in gear transmission
Mechanical rectifier mechanism	Converting bidirectional motion of pendulum into unidirectional motion to improve transducer efficiency	Causing energy loss in mechanical rectification
Spring mechanism	Frequency up-conversion through internal resonance; Tuning frequency by introducing additional restoring force; Regulating energy storage to smooth electrical output	Requiring additional mechanical elastic element
Elastic beam mechanism	Frequency up-conversion through internal resonance	Requiring additional mechanical elastic element
Magnetic mechanism	Improving frequency bandwidth through multi-stability	Requiring magnetic compatibility of application environment

3.6. Comparative remarks

Table 2 summarizes the performance improvement and disadvantage of the modulation mechanisms applied in the pendulum-based energy harvesting. It can be seen that the modulation mechanisms generally have their specific targets on performance improvement. At the cost of

additional energy loss and more complex structure, the gear amplification mechanism aims to amplify the pendulum rotating velocity and the mechanical rectifier aims to regulate the pendulum rotating direction. Therefore, it requires tradeoff consideration between the improvement of the transducer efficiency and the energy loss due to the modulation mechanisms. Both of the spring mechanism and the elastic beam mechanism can be utilized to up-convert the frequency of the pendulum-based energy harvesters at the cost of additional elastic elements. The spring mechanism can also be utilized to tune the frequency and regulate the energy storage of the pendulums. Due to structural characteristics, the elastic beam mechanism is usually integrated with piezoelectric transducers. The magnetic mechanism is mainly employed to widen the frequency bandwidth of the pendulums. Although the magnetic mechanism is more reliable than the mechanical elastic elements, it requires the application environment to be compatible with magnetic field. These modulation mechanisms are not independent of each other. To comprehensively improve the performance of the pendulum-based energy harvesting, two or three modulation mechanisms can be adopted simultaneously.

4. Transducer integration and comparison

It is of significance to integrate the transducers with the pendulum mechanisms in an efficient and compact manner. The main types of the transducers applied in the pendulum-based energy harvesting include electromagnetic, piezoelectric, triboelectric, and hybrid transducers. Their characteristics and configurations are described and compared as follows.

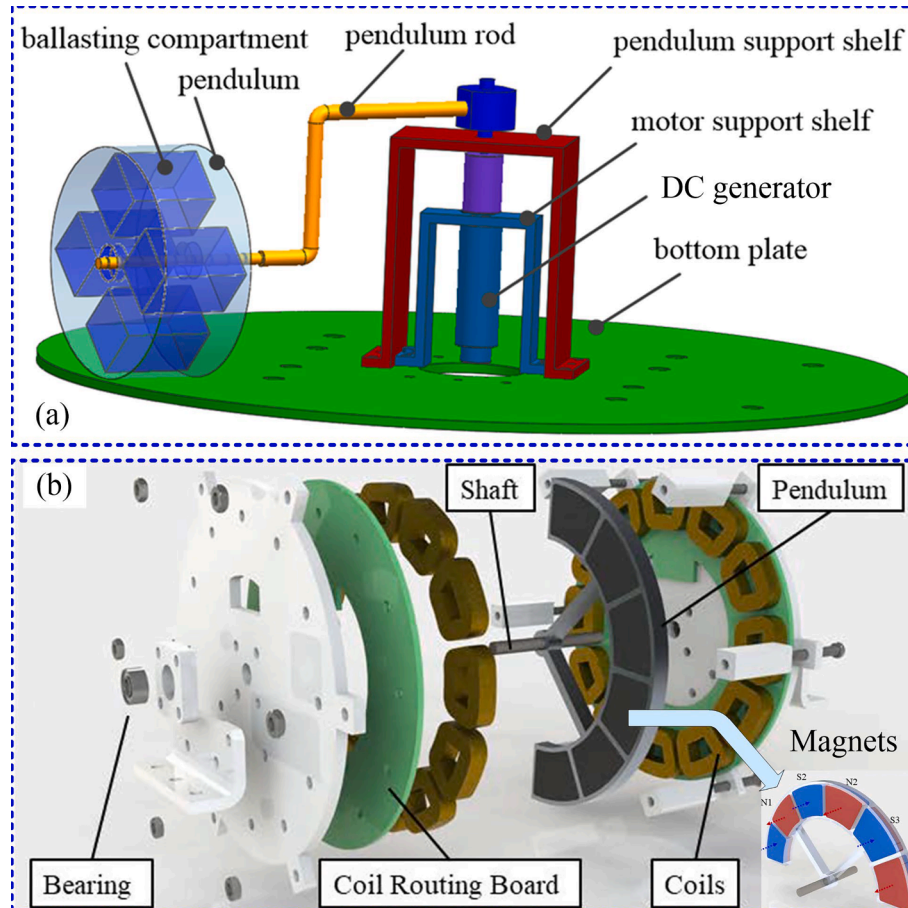


Fig. 10. Typical configurations of electromagnetic transducers in pendulum-based energy harvesters. (a) Integrated on shaft [63]. (b) Integrated on pendulum body [111].

4.1. Electromagnetic transducer

The theoretical basis of an electromagnetic transducer is the Faraday's law of electromagnetic induction. Its practical implementation is completed by the relative motion of coils in magnetic field. There are two typical configurations of the electromagnetic transducers in the pendulum-based energy harvesters. In Fig. 10(a), the first was to integrate an electrical generator on the shaft of the pendulum [63,90,109,110]. This configuration either utilized an assembled generator consisting of permanent magnets and coils or a commercial product. Iron core could be employed to enhance the magnetic flux density through the coils [24]. In Fig. 10(b), the second was to arrange magnets on the pendulum body and coils on the fixed boards to form a generator [111,112]. This configuration has the advantage of compact integration, but the coils must be coreless type which is disadvantageous to the magnetic flux density. The reason is that the pendulum will be hardly movable due to the attractive magnetic force if iron core is added. An unconventional integration should also be mentioned by using a linear electromagnetic transducer of which one end was hinged to the pendulum and another end was hinged to the frame [113].

4.2. Piezoelectric transducer

The piezoelectric transducer is based on piezoelectric effect which indicates the electric polarization generated by applied mechanical stress. The direction of the electric polarization can either be orthogonal or parallel to the direction of the applied mechanical stress, corresponding to 31-mode and 33-mode, respectively. Since the piezoelectric material has the property of low toughness and fragility, it is difficult to directly integrate the piezoelectric transducer with the pendulum mechanism. A common solution was to fix the piezoelectric material on elastic substrate material such as copper, and the swing pendulum periodically excited the tip of the piezoelectric beam operated in 31-mode as shown in Fig. 11(a) [114]. Ramezanpour et al. coupled a vertical-axis pendulum and a piezoelectric beam together through repulsive magnets to realize frequency up-conversion [115]. Besides non-contact coupling by magnetic force, an energy harvester with contact impact between a pendulum and two piezoelectric beams was also proposed in [116], but this design might be more prone to structural damage. Uzun et al. explored the displacement and velocity nonlinearities of a pendulum-based energy harvester where a piezoelectric beam also served as the pendulum rod [117]. Binder clips were employed as the elastic substrate layers to bond the piezoelectric transducer [23]. Fig. 11(b) shows another coupling solution where the pendulum excites the piezoelectric transducer operated in 33-mode with normal magnetic force [118]. Magnetostrictive material could be applied in the integration of the pendulum and the piezoelectric transducer to generate normal stress [119]. It can be noticed that additional

mechanisms such as elastic beams or magnets are usually required to integrate the piezoelectric transducer with the pendulum.

4.3. Triboelectric transducer

The triboelectric transducer which relies on the combination of triboelectrification and electrostatic induction has attracted an amount of attention in the last decade due to its advantages of light weight, low cost, and extensive material selection range [120]. In the triboelectric transducer, two materials with triboelectric charges in opposite polarization are subjected to separation and contact regularly by sliding motion or press/release motion to induce potential difference between two electrodes. Thus, it is flexible to integrate the triboelectric transducer with the pendulum mechanism.

Fig. 12 shows the typical configurations of the triboelectric transducers integrated in the pendulum-based energy harvesters. In Fig. 12(a), two multilayer-structured triboelectric transducers utilizing fluorinated ethylene propylene films were pressed and released by a bifilar pendulum [121]. The bifilar pendulum and the rectangle films could also be replaced by a gimbaled pendulum and ring films to harvest omnidirectional vibration energy [66]. In Fig. 12(b), the bottom and top sides of an eccentric pendulum were equipped with arc-shaped acrylic strips to contact/separate with fixed polytetrafluoroethylene brushes as triboelectric transducer during swing process [122]. In the structure shown in Fig. 12(c), the sectorial polytetrafluoroethylene films adhered with the pendulum could slide on the stator with copper electrode combs and produce potential drop when the pendulum was excited [123]. To maintain high surface charge density and low frictional loss, the triboelectric transducer was integrated with a two-degree-of-freedom pendulum where linear motion enabled contact/separate operation and rotational motion generated self-excitation effect [124]. Instead of being suspended by a shaft, Fig. 12(d) presents a triboelectric energy harvester with compact disk-track structure where the pendulum is supported by a rolling surface to maintain susceptible motion [125].

4.4. Hybrid transducers

In vibration energy harvesting, single energy conversion mechanism has its inherent advantages and disadvantages. For example, the triboelectric transducer outputs high voltage and low current, and the electromagnetic transducer outputs low voltage and high current in contrast because of different impedance property. Therefore, the hybridization of multiple transducers indicates an effective approach to achieve better output performance than single transducer [60]. Currently, the hybrid transducers applied in the pendulum-based energy harvesting mainly involve the triboelectric and the electromagnetic transducers due to their flexible integration and complementary performance [126].

As shown in Fig. 13(a), the energy harvester employed two

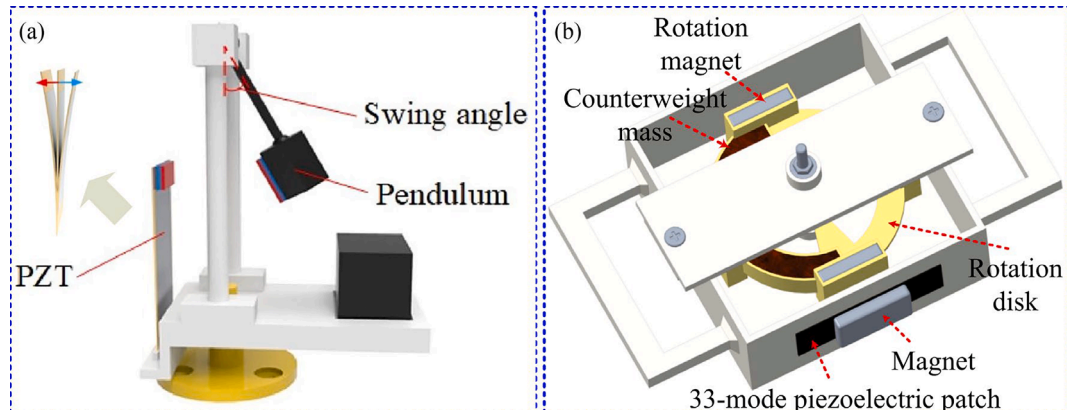


Fig. 11. Integrations of piezoelectric transducers and pendulums. (a) Operated in 31-mode [114]. (b) Operated in 33-mode [118].

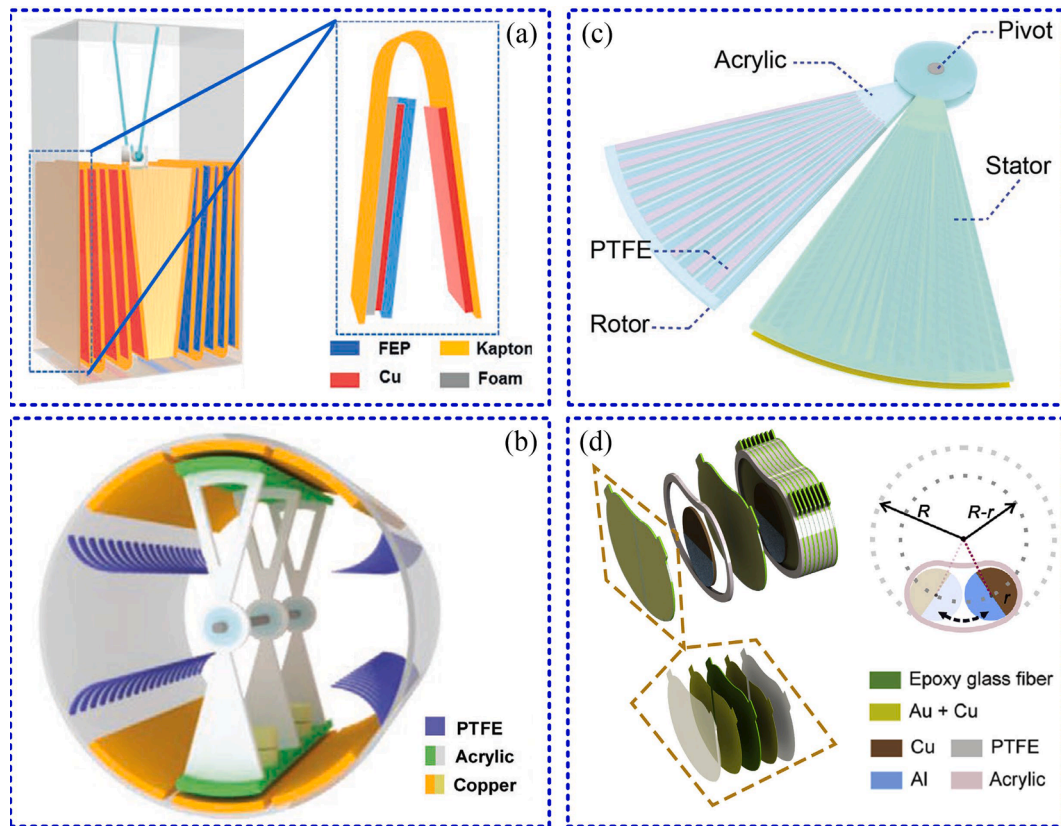


Fig. 12. Typical configurations of triboelectric transducers in pendulum-based energy harvesters. (a) Press/release triboelectric films [121]. (b) Contact/separate with triboelectric brushes [122]. (c) Slide on triboelectric layers suspended by a shaft [123]. (d) Slide on triboelectric layers supported by a rolling surface [125].

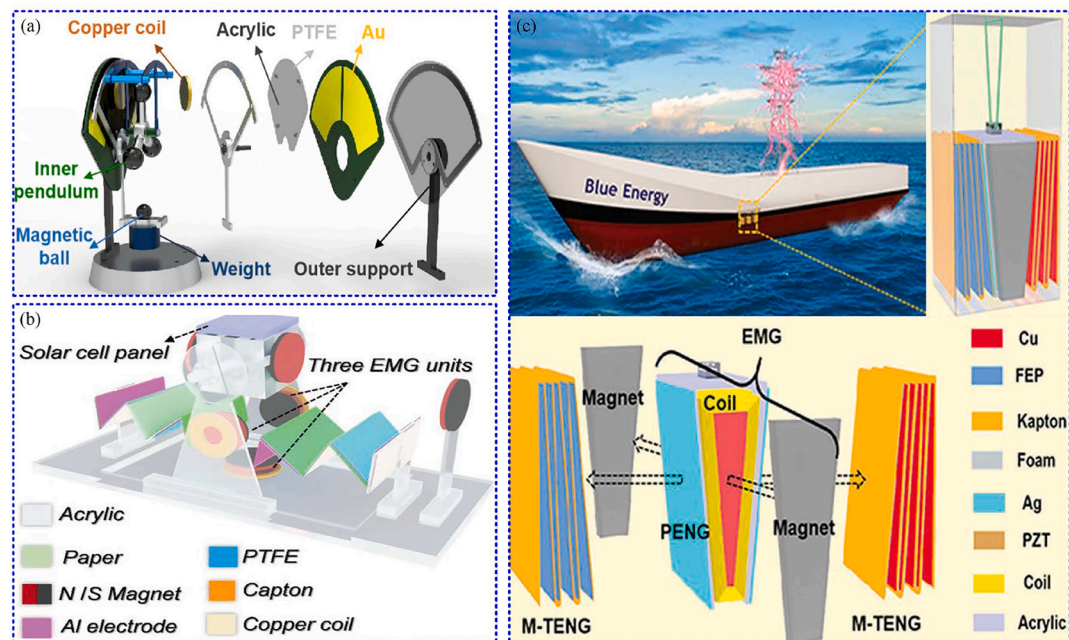


Fig. 13. Pendulum-based energy harvesting utilizing hybrid transducers. (a)(b) Hybridization of electromagnetic and triboelectric transducers [45,127]. (c) Hybridization of electromagnetic, piezoelectric, and triboelectric transducers [128].

pendulums in series, where the main pendulum was fixed with polytetrafluoroethylene films and electrodes to realize triboelectric energy conversion, and the inner pendulum was fixed with three magnetic balls to induce electromotive force on pasted coils. Results showed that the

maximum output power of the triboelectric and the electromagnetic transducers reached $15.21 \mu\text{W}$ and 1.23 mW respectively as triggered by wave vibration [45]. In Fig. 13(b), two zigzag multilayered triboelectric units and three magnet-coil units were coupled together on the

pendulum to harvest low-frequency kinetic energy simultaneously [127]. Furthermore, the pendulum-based energy harvester shown in Fig. 13(c) hybridized three transducers including electromagnetic, piezoelectric, and triboelectric types together to improve power take-off ability and space utilization rate [128]. This hybridization achieved a peak power density of 358.5 W/m^3 while the power density with single triboelectric transducer was 200 W/m^3 .

4.5. Comparison

In the pendulum-based energy harvesters, pendulum mechanisms and transducers are two critical components, of which the former capture vibration excitation and convert it into pendulum oscillation, and the latter convert the kinetic energy of the pendulums into electrical energy. Thus, they are desired to be integrated compactly to achieve high power density. Various configurations of the pendulum mechanisms are mainly developed to adapt the characteristics of vibration excitation such as direction, frequency bandwidth, and amplitude. However, no matter what configuration, the pendulum mechanisms typically include pendulum shafts, pendulum rods and pendulum bodies. The transducer integration has close relationship with the parts of the pendulum mechanisms rather than the configurations. Based on transducer principle and literature review, Table 3 gives the integration compatibility between the transducers and the parts of the pendulum mechanisms. The electromagnetic transducers are commonly constructed by installing magnets on the pendulum shafts or bodies and installing coils on the fixed housing. The suitable integration approach of the piezoelectric transducers is to directly attach piezoelectric material on elastic-type pendulum rods. For the triboelectric transducers, compatible integration with the pendulum mechanisms can be realized by setting two triboelectric materials on the pendulum bodies and the fixed housing, respectively.

Furthermore, Table 4 presents the data of typical pendulum-based energy harvesters with different types of transducers. It can be observed that the vibrations with frequency below 5 Hz are the main target sources. The electromagnetic and hybrid transducers are capable of generating relatively large output such as watt level, but large volumes are required simultaneously. The piezoelectric and triboelectric transducers supply electrical power of microwatt level, so the realization of high output power requires an array of transducers working together. The power density of the energy harvesters is heavily dependent on structure integration, and the hybrid transducers designed in [60] has the best performance. When the power density is normalized by dividing the square of the acceleration, the values of the electromagnetic transducers developed in [74] and [71] become higher.

The proportions of different transducers are presented in Fig. 14 by examining 131 literatures about the pendulum-based energy harvesters. It is found that the electromagnetic transducers occupy the largest proportion of 67.18 % and the hybrid transducers has the smallest proportion of 3.82 %. In general, the electromagnetic transducers are convenient to integrate with the pendulum mechanism and the electrical output can be designed in a wide range, so they attract relatively more

attentions in the pendulum-based energy harvesting. As emerging fields, the piezoelectric and triboelectric transducers combined with the pendulums have also received increasingly research interests.

5. Applications

Because of the outstanding adaptability to low-frequency excitations, the pendulum mechanism is capable of capturing the energy from a wide range of vibration sources. According to literature review, the typical sources for pendulum-based energy harvesting include ocean wave, vehicle motion, human motion, structural vibration, flow-induced vibration, and so on as shown in Fig. 15. The main applications are to provide wireless sensors and portable electronics with durable electrical power. More details are presented as follows.

5.1. Energy harvesting from ocean wave

Sustainable energy harvesting is with strong attraction because of the high cost of replacing or charging batteries in ocean environment. Wave energy is a widely distributed renewable resource with little dependence on time and weather condition, unlike solar energy and wind energy. Floating devices in wave such as buoys or ocean vehicles passively generate six-degree-of-freedom motions, which provide low-frequency (less than 1 Hz) vibration sources for harvesting. Researchers have contributed much efforts to this field. A pendulum-based energy harvester was developed to power an oceanic drifter which could be used in oil spill tracking, climate research, and rescue operation [137]. For oceanic vehicles, the harvested energy could be supplied to onboard sensors or employed as backup power source particularly for satellite phone calls or lighting in emergency [144]. Both types of electromagnetic and triboelectric energy harvesters with pendulums have been developed for wireless hydrological monitoring [129,151]. It can be found that ocean sensors and instruments are ideal candidates of utilizing pendulum-based energy harvesting. Besides small-power applications, the energy harvesters with large-size pendulums were also designed for large-scale wave generation [138,146,149,155].

5.2. Energy harvesting from vehicle motion

As effective tools of human beings, vehicles such as cars, buses and trains are equipped with an amount of sensors, which are employed to monitor the vehicle status such as tire pressure and temperature for safety. Energy harvesting provides a reliable and efficient solution for powering the sensors. Vehicles have multiple vibration sources such as wheels, carriages, suspensions, railroad tracks and sleepers during driving. Wang et al. designed a weighted pendulum to harvest energy from a rotating wheel for tire-pressure monitoring systems [9,139]. Nonlinear restoring forces and centrifugal effects were utilized to improve the bandwidth of the pendulum-based energy harvesters in rotating environment [140,154]. An inertial pendulum was coupled with a vehicle suspension to improve ride comfort and energy harvesting efficiency simultaneously [152]. Piezoelectric energy harvesters using pendulum mechanism were developed to power the inertial measurement units and acceleration sensors in driverless buses and trains for their safety and health monitoring [114,150]. The feasibility of harvesting the vibration energy of railroad tracks and sleepers by using pendulum systems was also evaluated and the results showed that the harvested energy was sufficient to feed a variety of rail-side devices such as wireless sensors or warning light systems [10]. With the development of intelligent transportation, additional sensors and electronics are required to percept the surrounding environment and realize autonomous operation, so the effect of the energy harvesting will become more significant.

Table 3

Integration compatibility between transducers and parts of pendulum mechanisms (more stars represents better compatibility).

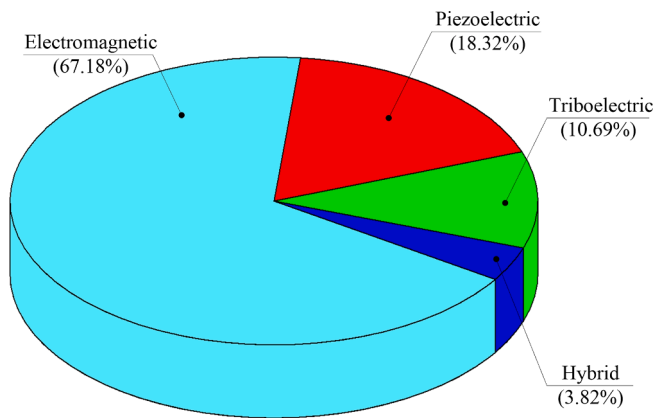
Transducers		Parts of pendulum mechanisms		
Type	Principle	Shaft	Rod	Body
Electromagnetic	Relative motion between coils and magnets	★ ★	★	★ ★
Piezoelectric	Mechanical stress applied to piezoelectric material	★	★ ★	★ ★
Triboelectric	Contact/separate motion of two triboelectric materials	★ ★	★	★ ★

Table 4

Performance comparison of typical pendulum-based energy harvesters with different transducers.

Literature	Transducer type	Frequency (Hz)	Acceleration (g)	Volume* (cm ³)	Output power (mW)	Power density (W/m ³)	Normalized power density (W/m ³ /g ²)
[74]	Electromagnetic	0.75	0.102	10,847	997	91.9	8835
[49]	Electromagnetic	3.45	0.4	50	1.4	28	175
[71]	Electromagnetic	2.2	0.18	3591	920	256	7907
[116]	Piezoelectric	2	0.04	47	0.01053	0.224	140
[23]	Piezoelectric	2.03	0.26	1156	13.29	11.5	170
[101]	Piezoelectric	1.71	0.19	10.4	2.07	199	5513
[121]	Triboelectric	2.31	0.6	180	28.8	160	444
[129]	Triboelectric	1.75	0.6	785	22.1	28.2	78.2
[125]	Triboelectric	1.2	0.75	3535	4.56	1.29	2.29
[60]	Hybrid	2	2.2	158	265.65	1681	347

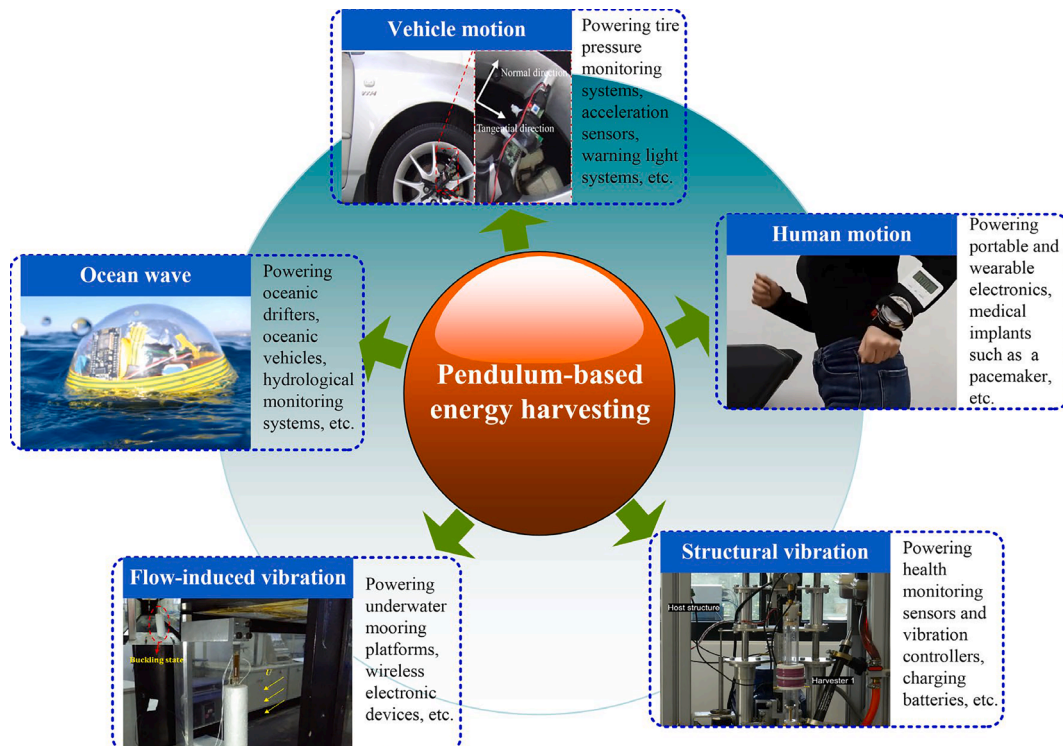
*The volumes are estimated according to the dimensional data provided in literatures.

**Fig. 14.** Proportions of different transducers in 131 literatures about pendulum-based energy harvesters [9,10,13,17,23–32,34–40,42–52,55,56,58–91,93–155].

5.3. Energy harvesting from human motion

With the growing demand of human body health monitoring, wearable electronics and medical implants have steadily gained importance. As a well-established power supply, batteries have the disadvantage of limited capacity and limited life span. Therefore, the vibration energy harvesting provides an alternative to power the wearable electronics and medical implants by capturing the kinetic energy from human motion, of which the frequency is generally less than 5 Hz [143].

Researchers have developed various pendulum-based energy harvesters for human application. In some designs, the devices were fixed on human wrists or ankles so as to harvest the swing energy of arms or legs during walking or running, and then power wearable electronics such as temperature sensors or pulse sensors [83,130,131,133]. Shukla et al. reported a piezoelectric pendulum-based energy harvester attached at the waistline to exploit the biomechanical energy available from human gait movement [148]. An energy harvesting backpack was developed to generate up to 0.22 W of electrical power from the oscillation of carried mass while walking [95]. Energy harvesting for medical implants has also been investigated besides wearable sensors. For

**Fig. 15.** Typical vibration sources and applications of pendulum-based energy harvesting [9,87,136,137,142].

example, a miniature pendulum could be utilized to harvest the kinetic energy from a beating heart as the power supply of a pacemaker [141]. In recent years, stretchable energy harvesters which can be applied on the deformable tissues of the human become emerging candidates [156]. The two types of energy harvesters can complement each other in converting biomechanical energy to electric energy for self-powered wearable electronics, for the pendulum-based energy harvesters have less flexibility and are capable of capturing more kinetic energy.

5.4. Energy harvesting from structural vibration

Vibration commonly exists in various engineering structures such as bridges, tall buildings, towers, turbines and tunnels due to earthquake, wind, vehicle driving, human activity, and so on. Large vibration will be dangerous when it compromises the stability of the structures, so conventional techniques utilize dissipative materials or tuned mass dampers for vibration mitigation. Instead of being dissipated, it is interesting to convert the structural vibration into electricity which can be supplied to health monitoring sensors or vibration controllers. To achieve energy harvesting and vibration mitigation simultaneously, an autparametric energy harvesting system has been proposed by coupling a pendulum-based energy harvester and a vibration absorber together [132,147]. The transducers could be either rotational type integrated with the pendulum shaft or linear type integrated with the pendulum rod [134,142,153]. Shen et al. investigated a regenerative tuned mass damper consisting of a pendulum mechanism, an electromagnetic damper and a harvesting circuit for a high-rise building [13]. Numerical results revealed that when wind velocity ranged from 8 m/s to 25 m/s, the harvested average power varied from hundreds of watts to kilowatts which could be stored in rechargeable batteries. A pendulum-based tuned mass damper with energy harvesting was also developed for the application of offshore wind turbines [113].

5.5. Energy harvesting from flow-induced vibration

The kinetic energy of fluid flow including both wind and water flow is also a remarkable source which can be easily found in natural environment and industrial piping. For irregular or weak flow, an effective approach instead of turbine generation is to make the flow self-excited and then harvest the vibration energy induced by the flow. Since the frequency spectrum of the flow-induced vibration typically locates at low level, the pendulum mechanism can serve as a suitable oscillator for energy harvesting. Zhang et al. developed an energy harvester comprised of a piezoelectric beam installed within a pendulum-type hollow cylinder [135]. When excited by wind, the cylinder and the piezoelectric beam would vibrate due to vortex and generate electricity for electronic devices. Aiming at improvement of efficiency and frequency bandwidth, additional nonlinear magnetic force was applied to the suspended cylinder subjected to wind [136]. As another typical application, an underwater mooring platform was anchored to the sea-floor and equipped with a series of sensors to acquire conductivity, temperature and salinity or detect acoustic sonars [145]. Since underwater current with velocity about 1 kn existed everywhere in ocean, the pendulum-based energy harvester could be installed inside the underwater mooring platform to harvest the flow-induced vibration energy and power the sensors with long endurance [62].

5.6. Discussion

According to the aforementioned description, it can be seen that the current researches on pendulum-based energy harvesting and related applications are conducted in an overlapping manner, that is, there are various pendulum mechanisms developed for a specific application field. By analyzing and matching the characteristics of applications and pendulum mechanisms, the most suitable pendulum mechanism in different situations can be selected. Since ocean wave has the feature of

multidirectionality, it is a good choice to adopt the gimbaled pendulum which can capture the vibrations from multiple directions. In addition, the chaotic dynamics of the gimbaled pendulum is consistent with the irregularity of ocean wave. For the application of rotating wheels in vehicles, the frequency of periodic excitation varies with the vehicle velocity. Therefore, the combination of a weighted pendulum and a magnetic multi-stable mechanism is a promising scheme to guarantee the output capability in a wide velocity range. The energy harvesters for human motion are generally worn on wrists, ankles or backpacks where low-frequency discontinuous vibrations occur. They are required with portable and lightweight structure to avoid extra burden on the daily operation of human body. To satisfy the demand of portability and sufficient output, the most suitable design is the horizontal-axis eccentric pendulum connected with a mechanical rectifier mechanism and a gear amplification mechanism. The excitation direction in shock absorbers is typically vertical, so energy harvesting can be realized by directly utilizing a horizontal-axis pendulum of which the base experiences parametric excitations. Furthermore, linear oscillators arranged along the pendulum rod are beneficial to the extension of operating bandwidth. In the application of flow-induced vibration, a suitable scheme is to suspend a horizontal-axis pendulum in water flow or wind and integrate a piezoelectric transducer on the pendulum rod. The inclined-axis pendulum can also be employed to tune the natural frequency of the energy harvester when the vibration frequency is very low. It should be noted that the recommended designs are based on the current research status and may change with the progress of energy harvesting field.

6. Conclusions and future trends

This work reviews the pendulum mechanisms as well as the transducers for vibration energy harvesting. According to the literatures, there have been a number of interesting and promising results. The inherent property of the pendulums makes them well adapt to low-frequency excitations. Furthermore, combined with modulation mechanism such as gears, mechanical rectifiers, elastic elements, and magnets, the pendulums are capable of generating mechanical motion suitable for efficient energy conversion. Various transducers including electromagnetic, piezoelectric, triboelectric and hybrid types can be integrated with the pendulums to capture kinetic energy from ocean wave, vehicle motion, human motion, structural vibration and flow-induced vibration, and provide effective power devices to wireless sensors, portable electronics, and even large-scale generation.

This work provides a reference for the design and performance enhancement of the pendulum-based energy harvesters. Firstly, the basic architecture and main parameters of the pendulum mechanism can be determined according to the characteristics of the vibration source. For example, the gimbaled pendulum can be employed when the vibrations come from multiple directions. The length of the pendulum rod is related with the frequency and the mass of the pendulum body is related with the harvestable power in practical application. Secondly, the pendulum motion can be modulated by mechanisms such as gear amplifiers or mechanical rectifiers to make the transducers work in high efficiency area. Broadband performance is expected when the vibration frequency locates in a wide range. Typical designs include multi-pendulum configurations in parallel or series, multi-stable equilibriums using nonlinear elastic elements, and so on. Thirdly, proper transducer is selected for the pendulum-based energy harvesting based on the match between the requirement of electrical loads and the impedance property of different transducers. Structural integration of the pendulum mechanism and the transducer can be implemented according to their characteristics to achieve compact structure and desired power density.

However, there also exist some challenging issues in the pendulum-based energy harvesting. Firstly, the pendulums require large dimensions while the extractable power is quite limited under low-

frequency excitation. In a lumped-mass pendulum, the rod length is inversely proportional to the square of its natural frequency. Although a counterweight can reduce the natural frequency, it increases the volume and weight of the pendulum system. On the other hand, the upper limit of the extractable power is proportional to the cubic of the vibration frequency [157]. Secondly, the space utilization of the integration of the pendulums and transducers is relatively low, which brings difficulty for portable and wearable applications. For examples, when the shaft of a pendulum is coaxially connected to an electrical generator, or when the pivot of a pendulum is coupled to the tip of a piezoelectric beam, the volumes of the energy harvesters will be much bulky, for the pendulums rotate in a plane or three-dimension space. Thirdly, it is desirable to further improve the adaptability of the pendulum-based energy harvesters to the vibration source with multiple directions, weak amplitude, or wide frequency spectrum so as to achieve reliable performance in practical environments.

To address the aforementioned challenges, more efforts on the pendulum mechanisms as well as transducer integration are suggested in the following aspects. 1) It is required to develop compact pendulum configurations such as a spherical shell pendulum, a deformable pendulum, or multiple pendulums arranged in array. 2) The integration schemes of the transducers with the pendulums can be investigated in depth to make use of the motion space and the inner space of the pendulums. Simultaneously, the energy conversion efficiency from the pendulums to the transducers needs to be optimized systematically. 3) Some works about the pendulum-based energy harvesting have explored the combination with multiple degrees of freedom, multi-stable mechanisms, frequency up-conversion, mechanical amplification, etc. However, there still exists space to innovate by introducing other existing performance enhancement technologies such as stochastic loading, mechanical stoppers, nonlinear extraction circuits, etc. [33]. 4) From the aspect of application, reliability study and experiments in practical environment such as sea trial are encouraged in addition to laboratory tests. To power stretchable sensing systems on human body, the combination of the pendulum-based energy harvesting and electrical storages such as batteries or micro-supercapacitors requires further investigation [158,159]. Moreover, it is worth exploring the application of the pendulum-based energy harvesters in other fields, such as the self-powered monitoring devices in industrial manufacturing and aerospace.

Declaration of Competing Interest

The author declares that he has 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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References

- [1] Maamer B, Boughamou A, Fath El-Bab AMR, Francis LA, Tounsi F. A review on design improvements and techniques for mechanical energy harvesting using piezoelectric and electromagnetic schemes. *Energy Convers Manage* 2019;199: 111973. <https://doi.org/10.1016/j.enconman.2019.111973>.
- [2] Sharma S, Kiran R, Azad P, Vaish R. A review of piezoelectric energy harvesting tiles: Available designs and future perspective. *Energy Convers Manage* 2022; 254:115272. <https://doi.org/10.1016/j.enconman.2022.115272>.
- [3] Ma X, Zhou S. A review of flow-induced vibration energy harvesters. *Energy Convers Manage* 2022;254:115223. <https://doi.org/10.1016/j.enconman.2022.115223>.
- [4] Wei C, Jing X. A comprehensive review on vibration energy harvesting: Modelling and realization. *Renew Sustain Energy Rev* 2017;74:1–18. <https://doi.org/10.1016/j.rser.2017.01.073>.
- [5] Tran N, Ghayesh MH, Arjomandi M. Ambient vibration energy harvesters: A review on nonlinear techniques for performance enhancement. *Int J Eng Sci* 2018;127:162–85. <https://doi.org/10.1016/j.iengsci.2018.02.003>.
- [6] Siang J, Lim MH, Salman LM. Review of vibration-based energy harvesting technology: Mechanism and architectural approach. *Int J Energy Res* 2018;42: 1866–93. <https://doi.org/10.1002/er.3986>.
- [7] Iqbal M, Nauman MM, Khan FU, Abbas PE, Cheok Q, Iqbal A, et al. Vibration-based piezoelectric, electromagnetic, and hybrid energy harvesters for microsystems applications: A contributed review. *Int J Energy Res* 2021;45(1):65–102.
- [8] Joe H, Roh H, Cho H, Yu SC. Development of a flap-type mooring-less wave energy harvesting system for sensor buoy. *Energy* 2017;133:851–63. <https://doi.org/10.1016/j.energy.2017.05.143>.
- [9] Wang YJ, De CC, Sung CK. System design of a weighted-pendulum-type electromagnetic generator for harvesting energy from a rotating wheel. *IEEE/ASME Trans Mechatron* 2013;18:754–63. <https://doi.org/10.1109/TMECH.2012.2183640>.
- [10] Dotti FE, Sosa MD. Pendulum systems for harvesting vibration energy from railroad tracks and sleepers during the passage of a high-speed train: A feasibility evaluation. *Theor Appl Mech Lett* 2019;9:229–35. <https://doi.org/10.1016/j.taml.2019.03.005>.
- [11] Guo S, Xu L, Liu Y, Guo X, Zuo L. Modeling and experiments of a hydraulic electromagnetic energy-harvesting shock absorber. *IEEE/ASME Trans Mechatron* 2017;22:2684–94. <https://doi.org/10.1109/TMECH.2017.2760341>.
- [12] Ylli K, Hoffmann D, Willmann A, Folkmer B, Manoli Y. Human motion energy harvesting: Numerical analysis of electromagnetic swing-excited structures. *Smart Mater Struct* 2016;25(9):095014.
- [13] Shen W, Zhu S, Xu Y-L, Zhu H. Energy regenerative tuned mass dampers in high-rise buildings. *Structural Control and Health Monitoring* 2018;25:e2072. <https://doi.org/10.1002/stc.2072>.
- [14] Zuo L, Tang X. Large-scale vibration energy harvesting. *J Intell Mater Syst Struct* 2013;24:1405–30. <https://doi.org/10.1177/1045389X13486707>.
- [15] Ren H, Wang T. Development and modeling of an electromagnetic energy harvester from pressure fluctuations. *Mechatronics* 2018;49:36–45. <https://doi.org/10.1016/j.mechatronics.2017.11.008>.
- [16] Cao D, Guo X, Hu W. A novel low-frequency broadband piezoelectric energy harvester combined with a negative stiffness vibration isolator. *J Intell Mater Syst Struct* 2019;30:1105–14. <https://doi.org/10.1177/1045389X19829835>.
- [17] Cheng P, Guo H, Wen Z, Zhang C, Yin X, Li X, et al. Largely enhanced triboelectric nanogenerator for efficient harvesting of water wave energy by soft contacted structure. *Nano Energy* 2019;57:432–9.
- [18] Zou H-X, Zhao L-C, Gao Q-H, Zuo L, Liu F-R, Tan T, et al. Mechanical modulations for enhancing energy harvesting: Principles, methods and applications. *Appl Energy* 2019;255:113871.
- [19] Wang T, Zhu Z, Zhu S. Comparison of vibration energy harvesters with fixed and unfixed magnetic springs. *Electron Lett* 2018;54:646–7. <https://doi.org/10.1049/el.2017.4769>.
- [20] Tang Q, Yang Y, Li X. Repulsively driven frequency-increased-generators for durable energy harvesting from ultra-low frequency vibration. *Rev Sci Instrum* 2014;85:1–6. <https://doi.org/10.1063/1.4870799>.
- [21] Fan Y, Ghayesh MH, Lu TF. A broadband magnetically coupled bistable energy harvester via parametric excitation. *Energy Convers Manage* 2021;244:114505. <https://doi.org/10.1016/j.enconman.2021.114505>.
- [22] Wang T, Zhu S. Resonant Frequency Reduction of Vertical Vibration Energy Harvester by Using Negative-Stiffness Magnetic Spring. *IEEE Trans Magn* 2021; 57:1–7. <https://doi.org/10.1109/TMAG.2021.3095589>.
- [23] Wu Y, Qiu J, Zhou S, Ji H, Chen Y, Li S. A piezoelectric spring pendulum oscillator used for multi-directional and ultra-low frequency vibration energy harvesting. *Appl Energy* 2018;231:600–14. <https://doi.org/10.1016/j.apenergy.2018.09.082>.
- [24] Li Y, Guo Q, Huang M, Ma X, Chen Z, Liu H, et al. Study of an electromagnetic ocean wave energy harvester driven by an efficient swing body toward the self-powered ocean buoy application. *IEEE Access* 2019;7:129758–69.
- [25] Jia Yu, Yan J, Soga K, Seshia AA. Parametric resonance for vibration energy harvesting with design techniques to passively reduce the initiation threshold amplitude. *Smart Mater Struct* 2014;23(6):065011.
- [26] Boren BC, Batten BA, Paasch RK. Active control of a vertical axis pendulum wave energy converter. In: *Proceedings of the American Control Conference*; 2014, 1033–8. <https://doi.org/10.1109/ACC.2014.6859459>.
- [27] Yurchenko D, Alevras P. Parametric pendulum based wave energy converter. *Mech Syst Sig Process* 2018;99:504–15. <https://doi.org/10.1016/j.ymsp.2017.06.026>.
- [28] Sommermann P, Cartmell MP. The dynamics of an omnidirectional pendulum harvester. *Nonlinear Dyn* 2021;104:1889–900. <https://doi.org/10.1007/s11071-021-06479-z>.
- [29] Kumar R, Gupta S, Ali SF. Energy harvesting from chaos in base excited double pendulum. *Mech Syst Sig Process* 2019;124:49–64. <https://doi.org/10.1016/j.ymsp.2019.01.037>.
- [30] Yurchenko D, Alevras P. Dynamics of the N-pendulum and its application to a wave energy converter concept. *Int J Dynam Control* 2013;1:290–9. <https://doi.org/10.1007/s40435-013-0033-x>.
- [31] Castagnetti D. A simply tunable electromagnetic pendulum energy harvester. *Meccanica* 2019;54:749–60. <https://doi.org/10.1007/s11012-019-00976-7>.

- [32] Graves J, Kuang Y, Zhu M. Scalable pendulum energy harvester for unmanned surface vehicles. *Sens Actuators, A* 2020;315:112356. <https://doi.org/10.1016/j.sna.2020.112356>.
- [33] Yildirim T, Ghayesh MH, Li W, Alici G. A review on performance enhancement techniques for ambient vibration energy harvesters. *Renew Sustain Energy Rev* 2017;71:435–49. <https://doi.org/10.1016/j.rser.2016.12.073>.
- [34] Niroomand M, Foroughi HR. A rotary electromagnetic microgenerator for energy harvesting from human motions. *J Appl Res Technol* 2016;14:259–67. <https://doi.org/10.1016/j.jart.2016.06.002>.
- [35] Lee BC, Chung GS. Design and analysis of a pendulum-based electromagnetic energy harvester using antiphase motion. *IET Renew Power Gener* 2016;10:1625–30. <https://doi.org/10.1049/iet-rpg.2015.0396>.
- [36] Yerrapragada K, Ansari MH, Karami MA. Enhancing power generation of floating wave power generators by utilization of nonlinear roll-pitch coupling. *Smart Mater Struct* 2017;26:94003. <https://doi.org/10.1088/1361-665X/aa7710>.
- [37] Boren BC, Lomonaco P, Batten BA, Paasch RK. Design, Development, and Testing of a Scaled Vertical Axis Pendulum Wave Energy Converter. *IEEE Trans Sustainable Energy* 2017;8:155–63. <https://doi.org/10.1109/TSTE.2016.2589221>.
- [38] Dostal L, Pick MA. Theoretical and experimental study of a pendulum excited by random loads. *Eur J Appl Math* 2019;30:912–27. <https://doi.org/10.1017/S0956792518000529>.
- [39] Wang YJ, Lee CK. Dynamics and power generation of wave energy converters mimicking biaxial hula-hoop motion for mooring-less buoys. *Energy* 2019;183:547–60. <https://doi.org/10.1016/j.energy.2019.06.135>.
- [40] Sequeira D, Little J, Mann BP. Investigating threshold escape behavior for the gimbal horizontal pendulum system. *J Sound Vib* 2019;450:47–60. <https://doi.org/10.1016/j.jsv.2019.03.008>.
- [41] Najdecka A, Kapitaniak T, Wiercigroch M. Synchronous rotational motion of parametric pendulums. *Int J Non Linear Mech* 2015;70:84–94. <https://doi.org/10.1016/j.ijnonlinmec.2014.10.008>.
- [42] Malaji PV, Ali SF. Analysis and experiment of magneto-mechanically coupled harvesters. *Mech Syst Sig Process* 2018;108:58–72. <https://doi.org/10.1016/j.ymssp.2018.02.025>.
- [43] Malaji PV, Ali SF. Broadband energy harvesting with mechanically coupled harvesters. *Sens Actuators, A* 2017;255:1–9. <https://doi.org/10.1016/j.sna.2016.12.003>.
- [44] Punyakaew S, Parnichkun M. Vibration energy harvesting for low frequency using auto-tuning parametric rolling pendulum under exogenous multi-frequency excitations. *Theor Appl Mech Lett* 2020;10:448–55. <https://doi.org/10.1016/j.taml.2020.01.059>.
- [45] Chen X, Gao L, Chen J, Lu S, Zhou H, Wang T, et al. A chaotic pendulum triboelectric-electromagnetic hybridized nanogenerator for wave energy scavenging and self-powered wireless sensing system. *Nano Energy* 2020;69:104440.
- [46] Izadgoshasb I, Lim YY, Tang L, Padilla RV, Tang ZS, Sedighi M. Improving efficiency of piezoelectric based energy harvesting from human motions using double pendulum system. *Energy Convers Manage* 2019;184:559–70. <https://doi.org/10.1016/j.enconman.2019.02.001>.
- [47] Xu Y, Yang W, Lu X, Yang Y, Li J, Wen J, et al. Triboelectric Nanogenerator for Ocean Wave Graded Energy Harvesting and Condition Monitoring. *ACS Nano* 2021;15(10):16368–75.
- [48] Lu Z-Q, Zhao L, Ding Hu, Chen L-Q. A dual-functional metamaterial for integrated vibration isolation and energy harvesting. *J Sound Vib* 2021;509:116251.
- [49] Smilek J, Hadas Z, Vetiska J, Beeby S. Rolling mass energy harvester for very low frequency of input vibrations. *Mech Syst Sig Process* 2019;125:215–28. <https://doi.org/10.1016/j.ymssp.2018.05.062>.
- [50] Borowiec M, Litak G, Rysak A, Mitcheson PD, Toh TT. Dynamic response of a pendulum-driven energy harvester in the presence of noise. *J Phys Conf Ser* 2013;476:012038.
- [51] Mitcheson PD, Toh TT, Wong KH, Burrow SG, Holmes AS. Tuning the resonant frequency and damping of an electromagnetic energy harvester using power electronics. *IEEE Trans Circuits Syst II Express Briefs* 2011;58:792–6. <https://doi.org/10.1109/TCSII.2011.2173966>.
- [52] Avanço RH, Tusset AM, Suetake M, Navarro HA, Balthazar JM, Nabarrete A. Energy harvesting through pendulum motion and dc generators. *Latin Am J Solids Struct* 2019;16:1–12. <https://doi.org/10.1590/1679-78255013>.
- [53] Najdecka A, Narayanan S, Wiercigroch M. Rotary motion of the parametric and planar pendulum under stochastic wave excitation. *Int J Non Linear Mech* 2015;71:30–8. <https://doi.org/10.1016/j.ijnonlinmec.2014.12.008>.
- [54] Reguera F, Dotti FE, Machado SP. Rotation control of a parametrically excited pendulum by adjusting its length. *Mech Res Commun* 2016;72:74–80. <https://doi.org/10.1016/j.mechrescom.2016.01.011>.
- [55] Marszał M, Witkowski B, Jankowski K, Perlikowski P, Kapitaniak T. Energy harvesting from pendulum oscillations. *Int J Non Linear Mech* 2017;94:251–6. <https://doi.org/10.1016/j.ijnonlinmec.2017.03.022>.
- [56] Dostal L, Korner K, Kreuzer E, Yurchenko D. Pendulum energy converter excited by random loads. *ZAMM Zeitschrift Fur Angewandte Mathematik Und Mechanik* 2018;98:349–66. <https://doi.org/10.1002/zamm.201700007>.
- [57] Vaziri V, Najdecka A, Wiercigroch M. Experimental control for initiating and maintaining rotation of parametric pendulum. *Eur Phys J: Special Topics* 2014;223:795–812. <https://doi.org/10.1140/epjst/e2014-02141-y>.
- [58] Kuang Y, Zhu M. Parametrically excited nonlinear magnetic rolling pendulum for broadband energy harvesting. *Appl Phys Lett* 2019;114(20):203903.
- [59] Dotti FE, Reguera F, Machado SP. Damping in a parametric pendulum with a view on energy harvesting. *Mech Res Commun* 2017;81:11–6. <https://doi.org/10.1016/j.mechrescom.2017.02.009>.
- [60] Hou C, Chen T, Li Y, Huang M, Shi Q, Liu H, et al. A rotational pendulum based electromagnetic/triboelectric hybrid-generator for ultra-low-frequency vibrations aiming at human motion and blue energy applications. *Nano Energy* 2019;63:103871.
- [61] Boren BC, Batten BA, Paasch RK. Model Predictive and Integral Error Tracking Control of a Vertical Axis Pendulum Wave Energy Converter. *Marine Energy Technology Symposium (METS)*; 2014.
- [62] Ding W, Cao H, Zhang B, Wang K. A low frequency tunable miniature inertial pendulum energy harvester. *J Appl Phys* 2018;124(16):164506.
- [63] Ding W, Song B, Mao Z, Wang K. Experimental investigations on a low frequency horizontal pendulum ocean kinetic energy harvester for underwater mooring platforms. *J Mar Sci Technol (Japan)* 2016;21:359–67. <https://doi.org/10.1007/s00773-015-0357-7>.
- [64] Ding W, Mao Z, Cao H, Wang K. Performance evaluation of a two-directional energy harvester with low-frequency vibration. *Smart Mater Struct* 2020;29(5):055006.
- [65] Anurakpandit T, Townsend NC, Wilson PA. The numerical and experimental investigations of a gimbal pendulum energy harvester. *Int J Non Linear Mech* 2020;120:103384. <https://doi.org/10.1016/j.ijnonlinmec.2019.103384>.
- [66] Zhang C, He L, Zhou L, Yang Ou, Yuan W, Wei X, et al. Active resonance triboelectric nanogenerator for harvesting omnidirectional water-wave energy. *Joule* 2021;5(6):1613–23.
- [67] Lin Z, Zhang B, Xie Y, Wu Z, Yang J, Wang ZL. Elastic-Connection and Soft-Contact Triboelectric Nanogenerator with Superior Durability and Efficiency. *Adv Funct Mater* 2021;31:1–8. <https://doi.org/10.1002/adfm.202105237>.
- [68] Lin Z, Zhang B, Guo H, Wu Z, Zou H, Yang J, et al. Super-robust and frequency-multiplied triboelectric nanogenerator for efficient harvesting water and wind energy. *Nano Energy* 2019;64:103908.
- [69] Xu J, Tang J. Multi-directional energy harvesting by piezoelectric cantilever-pendulum with internal resonance. *Appl Phys Lett* 2015;107(21):213902.
- [70] Wang T, Lou H, Zhu S. Prototyping and Electromagnetic Analysis of a Biaxial-Pendulum Wave Energy Harvester. *Oceans Conference Record (IEEE)* 2021; 2021-Sept:2–6. <https://doi.org/10.23919/OCEANS44145.2021.9706060>.
- [71] Lou H, Wang T, Zhu S. Design, modeling and experiments of a novel biaxial-pendulum vibration energy harvester. *Energy* 2022;124431. <https://doi.org/10.1016/j.energy.2022.124431>.
- [72] Sequeira D, Mann BP. Potential well hopping and performance of ocean energy harvesters. *J Sound Vib* 2020;465:115008. <https://doi.org/10.1016/j.jsv.2019.115008>.
- [73] Cai Q, Zhu S. Applying double-mass pendulum oscillator with tunable ultra-low frequency in wave energy converters. *Appl Energy* 2021;298:117228. <https://doi.org/10.1016/j.apenergy.2021.117228>.
- [74] Graves J, Kuang Y, Zhu M. Counterweight-pendulum energy harvester with reduced resonance frequency for unmanned surface vehicles. *Sens Actuators, A* 2021;321:112577. <https://doi.org/10.1016/j.sna.2021.112577>.
- [75] Alevras P, Brown I, Yurchenko D. Experimental investigation of a rotating parametric pendulum. *Nonlinear Dyn* 2015;81:201–13. <https://doi.org/10.1007/s11071-015-1982-8>.
- [76] Dotti FE, Virla JN. Nonlinear dynamics of the parametric pendulum with a view on wave energy harvesting applications. *J Comput Nonlinear Dyn* 2021;16:1–6. <https://doi.org/10.1115/1.4050699>.
- [77] Malaji PV, Ali SF. Analysis of energy harvesting from multiple pendulums with and without mechanical coupling. *Eur Phys J: Special Topics* 2015;224:2823–38. <https://doi.org/10.1140/epjst/e2015-02591-7>.
- [78] Malaji PV, Ali SF. Magneto-mechanically coupled electromagnetic harvesters for broadband energy harvesting. *Appl Phys Lett* 2017;111:1–6. <https://doi.org/10.1063/1.4997297>.
- [79] Chen J, Bao B, Liu J, Wu Y, Wang Q. Piezoelectric energy harvester featuring a magnetic chaotic pendulum. *Energy Convers Manage* 2022;269:116155. <https://doi.org/10.1016/j.enconman.2022.116155>.
- [80] Hasnain S, Kallu KD, Nawaz MH, Abbas N, Pruncu CI. Dynamic response of an inverted pendulum system in water under parametric excitations for energy harvesting: A conceptual approach. *Energies* 2020;13. <https://doi.org/10.3390/en13195215>.
- [81] Simeone L, Ghandchi Tehrani M, Elliott S. Level-dependent load in a pendulum like energy harvester. *Mech Syst Sig Process* 2019;119:244–54. <https://doi.org/10.1016/j.ymssp.2018.08.013>.
- [82] Wang Y, Gao M, Ouyang H, Li S, He Q, Wang P. Modelling, simulation, and experimental verification of a pendulum-flywheel vibrational energy harvester. *Smart Mater Struct* 2020;29(11):115023.
- [83] Xie L, Menet CG, Ching H, Du R. The automatic winding device of a mechanical watch movement and its application in energy harvesting. *J Mech Des, Trans ASME* 2009;131:0710051–7. <https://doi.org/10.1115/1.3151803>.
- [84] Le CD, Vo CP, Vu DL, Nguyen TH, Ahn KK. Water electrification based triboelectric nanogenerator integrated harmonic oscillator for waste mechanical energy harvesting. *Energy Convers Manage* 2022;251:115014. <https://doi.org/10.1016/j.enconman.2021.115014>.
- [85] Liang C, Wu Y, Zuo L. Broadband pendulum energy harvester. *Smart Mater Struct* 2016;25:95042. <https://doi.org/10.1088/0964-1726/25/9/095042>.
- [86] Fan K, Wang C, Chen C, Zhang Y, Wang P, Wang F. A pendulum-plucked rotor for efficient exploitation of ultralow-frequency mechanical energy. *Renew Energy* 2021;179:339–50. <https://doi.org/10.1016/j.renene.2021.06.139>.

- [87] Fan K, Hao J, Wang C, Zhang C, Wang W, Wang F. An eccentric mass-based rotational energy harvester for capturing ultralow-frequency mechanical energy. *Energy Convers Manage* 2021;241:114301. <https://doi.org/10.1016/j.enconman.2021.114301>.
- [88] Graves J, Zhu M. Design and experimental validation of a pendulum energy harvester with string-driven single clutch mechanical motion rectifier. *Sens Actuators, A* 2022;333:113237. <https://doi.org/10.1016/j.sna.2021.113237>.
- [89] Yang Y, Yu X, Meng L, Li X, Xu Y, Cheng T, et al. Triboelectric nanogenerator with double rocker structure design for ultra-low-frequency wave full-stroke energy harvesting. *Extreme Mech Lett* 2021;46:101338.
- [90] Behnke C, Klassen A, Schomburg WK. Energy Harvesting Employing a Drive Similar as a Clock Unit. *Energy Harvesting and Systems* 2017;4:137–41. <https://doi.org/10.1515/ehs-2017-0004>.
- [91] Jiang W, Han X, Chen L, Bi Q. Improving energy harvesting by internal resonance in a spring-pendulum system. *Acta Mechanica Sinica/Lixue Xuebao* 2020;36: 618–23. <https://doi.org/10.1007/s10409-020-00945-4>.
- [92] Abohamer MK, Awrejcewicz J, Starosta R, Amer TS, Bek MA. Influence of the motion of a spring pendulum on energy-harvesting devices. *Appl Sci (Switzerland)* 2021;11. <https://doi.org/10.3390/app11188658>.
- [93] He C-H, Amer TS, Tian D, Abolila AF, Galal AA. Controlling the kinematics of a spring-pendulum system using an energy harvesting device. *J Low Frequency Noise Vibration and Active Control* 2022;41(3):1234–57.
- [94] Kadje AN, Wofo P. Effects of springs on a pendulum electromechanical energy harvester. *Theor Appl Mech Lett* 2014;4(6):063001.
- [95] Martin JP, Li Q. Design, model, and performance evaluation of a biomechanical energy harvesting backpack. *Mech Syst Sig Process* 2019;134:106318. <https://doi.org/10.1016/j.ymssp.2019.106318>.
- [96] Graves J, Kuang Y, Zhu M. Pendulum energy harvester with torsion spring mechanical energy storage regulator. *Sens Actuators, A* 2022;339:113505. <https://doi.org/10.1016/j.sna.2022.113505>.
- [97] Rocha RT, Balthazar JM, Tusset AM, Piccirillo V. Using passive control by a pendulum in a portal frame platform with piezoelectric energy harvesting. *JVC/J Vibration Control* 2018;24:3684–97. <https://doi.org/10.1177/1077546317709387>.
- [98] Xu J, Tang J. Modeling and analysis of piezoelectric cantilever-pendulum system for multi-directional energy harvesting. *J Intell Mater Syst Struct* 2017;28: 323–38. <https://doi.org/10.1177/1045389X16642302>.
- [99] Pan J, Qin W, Deng W, Zhang P, Zhou Z. Harvesting weak vibration energy by integrating piezoelectric inverted beam and pendulum. *Energy* 2021;227:120374. <https://doi.org/10.1016/j.energy.2021.120374>.
- [100] Pan J-N, Qin W-Y, Deng W-Z, Zhou H-L. Harvesting base vibration energy by a piezoelectric inverted beam with pendulum. *Chin Phys B* 2019;28(1):017701.
- [101] Wu Y, Qiu J, Kojima F, Ji H, Xie W, Zhou S. Design methodology of a frequency up-converting energy harvester based on dual-cantilever and pendulum structures. *AIP Adv* 2019;9(4):045312.
- [102] Hadas Z, Kurfurst J, Ondrusek C, Singule V. Artificial intelligence based optimization for vibration energy harvesting applications. *Microsyst Technol* 2012;18:1003–14. <https://doi.org/10.1007/s00542-012-1432-1>.
- [103] Cottone F, Vocca H, Gammaitoni L. Nonlinear energy harvesting. *Phys Rev Lett* 2009;102:1–4. <https://doi.org/10.1103/PhysRevLett.102.080601>.
- [104] Bao B, Zhou S, Wang Q. Interplay between internal resonance and nonlinear magnetic interaction for multi-directional energy harvesting. *Energy Convers Manage* 2021;244:114465. <https://doi.org/10.1016/j.enconman.2021.114465>.
- [105] Wang T, Zhu S. Analysis and Experiments of a Pendulum Vibration Energy Harvester with a Magnetic Multi-Stable Mechanism. *IEEE Trans Magn* 2022;58(8):1–7.
- [106] Wang T, Lou H, Zhu S. Bandwidth enhancement of a gimbaled-pendulum vibration energy harvester using spatial multi-stable mechanism. *Appl Energy* 2022;326:120047. <https://doi.org/10.1016/j.apenergy.2022.120047>.
- [107] Zhang A, Sorokin V, Li H. Energy harvesting using a novel autoparametric pendulum absorber-harvester. *J Sound Vib* 2021;499. <https://doi.org/10.1016/j.jsv.2021.116014>.
- [108] Kuang Y, Hide R, Zhu M. Broadband energy harvesting by nonlinear magnetic rolling pendulum with subharmonic resonance. *Appl Energy* 2019;255. <https://doi.org/10.1016/j.apenergy.2019.113822>.
- [109] Ma T, Zhang H. Enhancing mechanical energy harvesting with dynamics escaped from potential well. *Appl Phys Lett* 2012;100(11):114107.
- [110] Ma T, Zhang H. Reaping the potentials of nonlinear energy harvesting with tunable damping and modulation of the forcing functions. *Appl Phys Lett* 2014; 104(21):214104.
- [111] Li M, Deng H, Zhang Y, Li K, Huang S, Liu X. Ultra-low frequency eccentric pendulum-based electromagnetic vibrational energy harvester. *Micromachines* 2020;11:1–14. <https://doi.org/10.3390/mi1111009>.
- [112] Ambroziewicz B, Litak G, Wolszczak P. Modelling of electromagnetic energy harvester with rotational pendulum using mechanical vibrations to scavenge electrical energy. *Appl Sci (Switzerland)* 2020;10:1–14. <https://doi.org/10.3390/app10020671>.
- [113] Jahangiri V, Sun C. Integrated bi-directional vibration control and energy harvesting of monopile offshore wind turbines. *Ocean Eng* 2019;178:260–9. <https://doi.org/10.1016/j.oceaneng.2019.02.015>.
- [114] Zhang T, Tang M, Li H, Li J, Zou Y, Pan Y, et al. A Multidirectional Pendulum Kinetic Energy Harvester Based on Homopolar Repulsion for Low-Power Sensors in New Energy Driverless Buses. *Int J Precision Eng Manuf - Green Technol* 2022; 9(2):603–18.
- [115] Ramezanpour R, Nahvi H, Ziaei-Rad S. Electromechanical behavior of a pendulum-based piezoelectric frequency up-converting energy harvester. *J Sound Vib* 2016;370:280–305. <https://doi.org/10.1016/j.jsv.2016.01.052>.
- [116] Fan G, Wang Y, Tian F, Hao M, Wen Y, Xu Y, et al. Impact-driven piezoelectric energy harvester using a pendulum structure for low-frequency vibration. *J Intell Mater Syst Struct* 2021;32(17):1997–2005.
- [117] Uzun Y, Kurt E, Hilal KH. Explorations of displacement and velocity nonlinearities and their effects to power of a magnetically-excited piezoelectric pendulum. *Sens Actuators, A* 2015;224:119–30. <https://doi.org/10.1016/j.sna.2015.01.033>.
- [118] Bao B, Wang Q, Wu N, Zhou S. Hand-held piezoelectric energy harvesting structure: Design, dynamic analysis, and experimental validation. *Meas: J Int Meas Confederation* 2021;174:109011. <https://doi.org/10.1016/j.measurement.2021.109011>.
- [119] Dai X. An vibration energy harvester with broadband and frequency-doubling characteristics based on rotary pendulums. *Sens Actuators, A* 2016;241:161–8. <https://doi.org/10.1016/j.sna.2016.02.004>.
- [120] Lee S, Lee Y, Kim D, Yang Ya, Lin L, Lin Z-H, et al. Triboelectric nanogenerator for harvesting pendulum oscillation energy. *Nano Energy* 2013;2(6):1113–20.
- [121] Zhang C, Zhou L, Cheng P, Liu Di, Zhang C, Li X, et al. Bifilar-Pendulum-Assisted Multilayer-Structured Triboelectric Nanogenerators for Wave Energy Harvesting. *Adv Energy Mater* 2021;11(12):2003616.
- [122] Jiang T, Pang H, An J, Lu P, Feng Y, Liang Xi, et al. Robust Swing-Structured Triboelectric Nanogenerator for Efficient Blue Energy Harvesting. *Adv Energy Mater* 2020;10(23):2000064.
- [123] He C, Chen BD, Jiang T, Xu L, Han CB, Gu GQ, et al. Radial-Grating Pendulum-Structured Triboelectric Nanogenerator for Energy Harvesting and Tilting-Angle Sensing. *Adv Mater Technol* 2018;3(4):1700251.
- [124] Li W, Wan L, Lin Y, Liu G, Qu H, Wen H, et al. Synchronous nanogenerator with intermittent sliding friction self-excitation for water wave energy harvesting. *Nano Energy* 2022;95:106994.
- [125] Zhong W, Xu L, Wang H, Li D, Wang ZL. Stacked pendulum-structured triboelectric nanogenerators for effectively harvesting low-frequency water wave energy. *Nano Energy* 2019;66:104108. <https://doi.org/10.1016/j.nanoen.2019.104108>.
- [126] Hao C, He J, Zhang Z, Yuan Y, Chou X, Xue C. A pendulum hybrid generator for water wave energy harvesting and hydrophone-based wireless sensing. *AIP Adv* 2020;10(12):125019.
- [127] Yang H, Deng M, Tang Q, He W, Hu C, Xi Yi, et al. A Nonencapsulative Pendulum-Like Paper-Based Hybrid Nanogenerator for Energy Harvesting. *Adv Energy Mater* 2019;9(33):1901149.
- [128] Zhang C, Yuan W, Zhang B, Yang Ou, Liu Y, He L, et al. High Space Efficiency Hybrid Nanogenerators for Effective Water Wave Energy Harvesting. *Adv Funct Mater* 2022;32(18):2111775.
- [129] Rui P, Zhang W, Zhong Y, Wei X, Guo Y, Shi S, et al. High-performance cylindrical pendulum shaped triboelectric nanogenerators driven by water wave energy for full-automatic and self-powered wireless hydrological monitoring system. *Nano Energy* 2020;74:104937.
- [130] George A, Moline D, Wagner J. A mobile energy harvesting autowinder – Build and test. *Renewable Energy* 2020;146:2659–67. <https://doi.org/10.1016/j.renene.2019.08.106>.
- [131] Liu H, Hou C, Lin J, Li Y, Shi Q, Chen T, et al. A non-resonant rotational electromagnetic energy harvester for low-frequency and irregular human motion. *Appl Phys Lett* 2018;113(20):203901.
- [132] Kecik K, Borowiec M. An autoparametric energy harvester. *Eur Phys J: Special Topics* 2013;222:1597–605. <https://doi.org/10.1140/epjst/e2013-01948-2>.
- [133] Wu Z, Tang J, Zhang X, Yu Z. An energy harvesting bracelet. *Appl Phys Lett* 2017; 111(1):013903.
- [134] Kecik K. Assessment of energy harvesting and vibration mitigation of a pendulum dynamic absorber. *Mech Syst Sig Process* 2018;106:198–209. <https://doi.org/10.1016/j.ymssp.2017.12.028>.
- [135] Zhang M, Hu G, Wang J. Bluff body with built-in piezoelectric cantilever for flow-induced energy harvesting. *Int J Energy Res* 2020;44:3762–77. <https://doi.org/10.1002/er.5164>.
- [136] Zhang LB, Abdelkefi A, Dai HL, Naseer R, Wang L. Design and experimental analysis of broadband energy harvesting from vortex-induced vibrations. *J Sound Vib* 2017;408:210–9. <https://doi.org/10.1016/j.jsv.2017.07.029>.
- [137] Carandell M, Toma DM, Carbonell M, Del Rio J, Gasulla M. Design and testing of a kinetic energy harvester embedded into an oceanic drifter. *IEEE Sens J* 2020;20: 13930–9. <https://doi.org/10.1109/JSEN.2020.2976517>.
- [138] Serena A, Molinas M, Cobo I. Design of a direct drive wave energy conversion system for the sequest concept. *Energy Procedia* 2012;20:271–80. <https://doi.org/10.1016/j.egypro.2012.03.027>.
- [139] Wang JY, De CC, Sunga CK. Design of a frequency-adjusting device for harvesting energy from a rotating wheel. *Sens Actuators, A* 2010;159:196–203. <https://doi.org/10.1016/j.sna.2009.12.007>.
- [140] Roundy S, Tola J. Energy harvester for rotating environments using offset pendulum and nonlinear dynamics. *Smart Mater Struct* 2014;23(10):105004.
- [141] Zurbuchen A, Pfenniger A, Stahel A, Stoek CT, Vandenbergh S, Koch VM, et al. Energy harvesting from the beating heart by a mass imbalance oscillation generator. *Ann Biomed Eng* 2013;41(1):131–41.
- [142] Kecik K, Mitura A. Energy recovery from a pendulum tuned mass damper with two independent harvesting sources. *Int J Mech Sci* 2020;174:105568. <https://doi.org/10.1016/j.ijmecsci.2020.105568>.
- [143] Zhou N, Hou Z, Zhang Y, Cao J, Bowen CR. Enhanced swing electromagnetic energy harvesting from human motion. *Energy* 2021;228:120591. <https://doi.org/10.1016/j.energy.2021.120591>.

- [144] Wang YJ, Yu JH. Enhancement of rolling energy conversion of a boat using an eccentric rotor revolving in a hula-hoop motion. *Ocean Eng* 2016;116:21–31. <https://doi.org/10.1016/j.oceaneng.2016.02.008>.
- [145] Ding W, Wang K, Mao Z, Cao H. Layout optimization of an inertial energy harvester for miniature underwater mooring platforms. *Mar struct* 2020;69: 102681. <https://doi.org/10.1016/j.marstruc.2019.102681>.
- [146] Crowley S, Porter R, Taunton DJ, Wilson PA. Modelling of the WITT wave energy converter. *Renew Energy* 2018;115:159–74. <https://doi.org/10.1016/j.renene.2017.08.004>.
- [147] Felix JLP, Balthazar JM, Rocha RT, Tusset AM, Janzen FC. On vibration mitigation and energy harvesting of a non-ideal system with autoparametric vibration absorber system. *Meccanica* 2018;53:3177–88. <https://doi.org/10.1007/s11012-018-0881-8>.
- [148] Shukla R, Bell AJ. PENDEXE: A novel energy harvesting concept for low frequency human waistline. *Sens Actuators, A* 2015;222:39–47. <https://doi.org/10.1016/j.sna.2014.11.016>.
- [149] Pozzi N, Bracco G, Passione B, Sirigu SA, Mattiazzo G. PeWEC: Experimental validation of wave to PTO numerical model. *Ocean Eng* 2018;167:114–29. <https://doi.org/10.1016/j.oceaneng.2018.08.028>.
- [150] Cho JY, Jeong S, Jabbar H, Song Y, Ahn JH, Kim JH, et al. Piezoelectric energy harvesting system with magnetic pendulum movement for self-powered safety sensor of trains. *Sens Actuators, A* 2016;250:210–8.
- [151] Li M, Zhang Y, Li K, Zhang Y, Xu K, Liu X, et al. Self-powered wireless sensor system for water monitoring based on low-frequency electromagnetic-pendulum energy harvester. *Energy* 2022;251:123883.
- [152] Hajidavalloo MR, Cosner J, Li Z, Tai WC, Song Z. Simultaneous Suspension Control and Energy Harvesting through Novel Design and Control of a New Nonlinear Energy Harvesting Shock Absorber. *IEEE Trans Veh Technol* 2022; 9545:1–15. <https://doi.org/10.1109/TVT.2022.3159734>.
- [153] Kecik K. Simultaneous vibration mitigation and energy harvesting from a pendulum-type absorber. *Commun Nonlinear Sci Numer Simul* 2021;92:1–12. <https://doi.org/10.1016/j.cnsns.2020.105479>.
- [154] Zhang Y, Zheng R, Nakano K, Cartmell MP. Stabilising high energy orbit oscillations by the utilisation of centrifugal effects for rotating-tire-induced energy harvesting. *Appl Phys Lett* 2018;112:2–7. <https://doi.org/10.1063/1.5019907>.
- [155] Nicola P, Giovanni B, Biagio P, Antonello SS, Giacomo V, Giuliana M, et al. Wave Tank Testing of a Pendulum Wave Energy Converter 1: 12 Scale Model. *Int J Appl Mech* 2017;09(02):1750024.
- [156] Zhou H, Zhang Y, Qiu Ye, Wu H, Qin W, Liao Y, et al. Stretchable piezoelectric energy harvesters and self-powered sensors for wearable and implantable devices. *Biosens Bioelectron* 2020;168:112569.
- [157] Tiwari S, Vyasarayani CP, Chatterjee A. Performance limit for base-excited energy harvesting, and comparison with experiments. *Nonlinear Dyn* 2021;103:197–214. <https://doi.org/10.1007/s11071-020-06145-w>.
- [158] Zhang C, Chen H, Ding X, Lorestan F, Huang C, Zhang B, et al. Human motion-driven self-powered stretchable sensing platform based on laser-induced graphene foams. *Appl Phys Rev* 2022;9(1):011413.
- [159] Zhang S, Zhu J, Zhang Y, Chen Z, Song C, Li J, et al. Standalone stretchable RF systems based on asymmetric 3D microstrip antennas with on-body wireless communication and energy harvesting. *Nano Energy* 2022;96:107069.