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Rotational Energy Harvesting for Self-Powered Sensing

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Abstract

Advances in wireless sensors, biomedical devices and micro-robotics exert more pressure on creating reliable, miniaturized and self-sustained energy supply solutions for these micro-electromechanical systems. Rotational energy harvesting (REH) is one of the rapidly growing areas for self-powered electronics using available rotational energy or energy converted from other sources in the environment. This paper comprehensively reviews the state-of-the-art progress in REH in terms of the available energy characteristics, harvester categories, adopted methodologies and mechanisms and promising applications. Unique mechanisms and methodologies, such as using gravity and centrifugal force combined with other nonlinear mechanisms are discussed and characterized. In terms of applications, wearable and implantable devices, automotive, rotating machines, renewable energy systems and environmental sensing are discussed and reviewed to illustrate how rotational energy harvesters have been developed and adopted accordingly. Based on progress to date, the key developments, critical challenges and issues are summarized and discussed. Moving forward, an outlook is presented to outline potential research directions and opportunities in this area.

Context & Scale

Rotational energy has been a key element in many domestic and industrial areas from wristwatches to offshore wind turbines. It has been utilized on a large scale from megawatt-scale hydraulic power generators, to kilowatt-scale vehicles and rotating machines, to watt-scale hand-held tools, and to milliwatt (microwatt) rotational energy harvesters. The scope of this review is on milliwatt/microwatt-level harvesters (millimeter/centimeter-size) which are typically used to energize low-power electronics for long-term self-powered sensing applications in the era of the Internet of Things.

In order to enhance the structural smartness and perform autonomous condition-based maintenance, wireless, embedded and distributed sensors are increasingly introduced in critical infrastructure and systems, such as bridges, rotating machines and vehicles, to monitor their conditions in real time. However, these wireless sensors are mostly powered by on-board batteries which require regular recharging or replacement. Although an external power source is available in many applications, connection to this

may add undesirable cost and complication, particularly for retro-fitted sensors, and be impractical for sensors mounted on the rotating parts of the structure. Batteries are tolerable when the number of sensors is moderate, but their replacement or recharging will be excessively costly and inconvenient when thousands or millions of wireless sensors are adopted, particularly in remote or otherwise inaccessible locations. Miniature rotational energy harvesters can provide a self-sustained energy source for wireless sensors by converting rotational energy sources in the local environment into electricity. The major challenges are the energy harvesting capability, operating bandwidth, device miniaturization and system reliability in harnessing random, broadband and potentially low-frequency rotational energy sources. In this review, the available energy sources are characterized, and accordingly the designs of harvesters are categorized based on their operational principles. The fundamentals and methodologies adopted in rotational energy harvesting are discussed with the analysis of their contribution to effective energy harvesting. An application-orientated analysis is also provided to review the progress for different applications with the discussion of the advantages and disadvantages of different methods in those applications.

Keywords: Rotational Energy Harvesting, Energy Technology, Self-powered Sensing, Nonlinear Dynamics, Piezoelectric, Electromagnetic, Triboelectric, Condition Monitoring, Renewable Energy.

Contents

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1. Introduction

Rotational motion has been playing a fundamental role in the industrial development of humankind since the invention of the wheel. Archaeological excavation in Mesopotamia (now Iraq) has dated the oldest known wheel, as shown in Fig. 1(a), to 3500 BC. This period is known as the Bronze age and by that time people not only could plant crops and grow livestock but had also learnt how to make metal tools. Another wooden wheel with an axle was found in 2002 south of Ljubljana, and it is dated back to 3150 BC (Fig. 1(b)). The image of a wheeled cart on the surface of Bronocice pot in Fig. 1(c) confirmed the existence of the wheeled carts around 3000 BC. All these and other examples of prehistoric development of wheels can be found in Ref. [1].

By 2000 BC, people realised that wheels could be used for transportation and built primitive carts, wagons and chariots. Later the Egyptians learnt that the wheel can be made lighter when the inner part of the wheel is taken out and replaced by spokes. A pulley consisting of a wheel and an axle was invented around 2000 BC in ancient Egypt and was used for changing the direction and applied force of a taut rope when pulling or lifting weights [2]. Availability of the pulley around this time and its mechanical properties played a key role in building large structures by ancient civilizations without any machines. Later a number of important engineering inventions were made by ancient Greeks, some of which utilised intelligently the rotational motion.

Waterwheels were invented and used for converting the energy of falling or moving water to useful work, as shown in Fig. 1(d) [3]. Together with the watermills, the captured energy was used for conducting mechanical operations like milling or sawing. The Roman Hierapolis sawmill is one of the well-known examples. Later, watermills were used in a great variety of applications, including oil, corn and grain mills, cotton mills, slitting and stamp mills and as lifting mechanisms, as shown in Fig. 1(e). The first wind-driven organ machine was described by Hero of Alexandria, which was

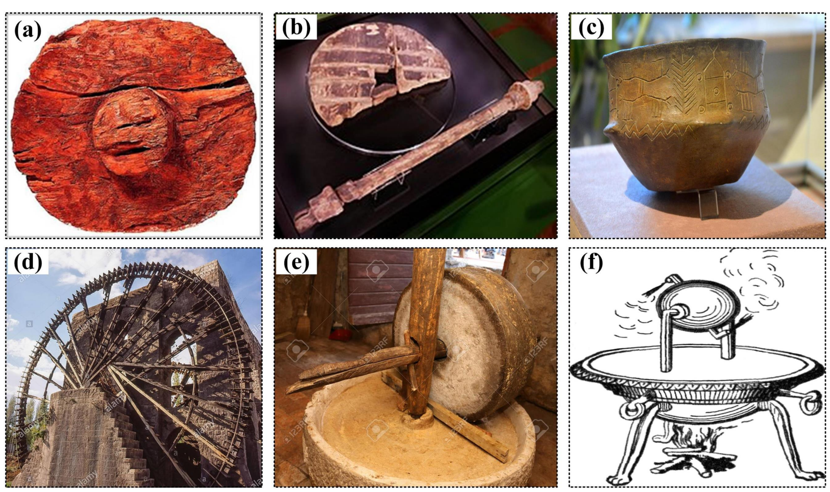

Figure 1: The oldest rotating systems and applications: (a) Mesopotamian wheel, (b) Ljubljana Marshes wheel, (c) Bronocice pot, (d) Norias of Hama water wheel, (e) the grinding wheel, and (f) steam engine.

reconstructed in the 19th century [4]. He was also given a credit for developing the first turbine, known as steam engine or Aeolipile, as shown in Fig. 1(f). The device comprised of a sealed bowl with water heated by the fire. On top of the device there is a sphere mounted on a shaft with two jet nozzles, which allow steam to exit the system, thereby creating a torque and forcing the sphere to rotate.

The next milestone in the usage of rotational motion was marked by the invention of the steam-operated pump by T. Savery and the first commercial steam engine by T. Newcomen. In 1776, J. Watt had critically improved the design of the steam engine, which basically marked the beginning of the first Industrial Revolution [5]. Discovery of electromagnetic induction by M. Faraday in 1832 led to the creation of the electrical generator and its derivatives, which utilise rotational motion to generate electricity [6]. Invention of the first Internal Combustion engine by E. Lenoir and presentation of its modified version by N. Otto in 1876 demonstrated how rotational motion can be generated without using water or wind flow. These and other inventions have further increased our dependence on rotational motion. To further visualise that, one should realise that the vast majority of power and transport systems utilise rotation.

Nowadays, rotational motion has been widely used in different sectors for various proposes, including engines for propulsion systems, wind turbines for renewable energy generation, wristwatches and vehicle wheels [7]. It is well-known that gas, hydro and nuclear power plants use turbines connected to electric generators to convert mechanical energy into electrical energy. In recent years, the rapid development of renewable energy technologies, including wind, marine and solar, and their volatile nature motivated scientists to think about energy storage technologies [8–10]. One such technology utilises rotational motion and is based on storing kinetic energy in Flywheel Energy Storage Systems (FESS), which can store hundreds of kJ with a relatively simple design and a reasonable size [11].

In the last decade, the advances in micro-robotics, distributed sensing and the Internet of Things have created a new area for rotational energy application in providing self-sustained power supply for low-power electronics. Wireless sensing has been widely adopted for monitoring the conditions of critical structures, machines or even human body. However, it currently has some recognised deficiencies, one of which is the power supply limitations [12]. Low-power electronics on robotics, machines and wearable/implantable devices are typically powered by batteries but the rechargeable batteries are not an effective solution when a high power demand is required for long-term monitoring; moreover, replacing or recharging batteries is impractical in cases where sensors are widely distributed or inaccessible (e.g. implants). Thus, energy harvesting of the available kinetic energy from the environment using miniaturized devices has been considered as an attractive alternative to batteries.

Energy harvesting has been under intensive development over the last 20 years. Nowadays it presents a well-formed multidisciplinary branch of science, which deals with the development of efficient devices capable of capturing and converting mechanical energy into electrical energy [13]. The harvested energy is used to energise low-power electronics and to fulfil the aim of self-powered sensing in health monitoring or condition monitoring of different applications, including vehicles, buildings, environments and humans. Because these vibrations are normally mitigated using passive and active means to avoid their harmful effect, the amount of energy available for harnessing is usually relatively low. To effectively capture these vibrations, linear, nonlinear and parametrically excited mechanical devices have been proposed and investigated. Different transduction mechanisms have been explored for different applications. Some fundamentals on energy harvesting can be found in Refs. [14–21]. The progress of energy harvesting in general can be tracked in several comprehensive reviews [22–26].

Although rotational energy has been widely adopted on different scales in various business sectors, REH for self-powered sensing is a relatively new research direction with a number of challenges. First, rotational motion is associated with high centrifugal and/or Coriolis forces when the operating frequency is high. These forces will push any moving unbalanced components of an energy harvesting device outwards radially or perpendicular to the rotating plane, basically obstructing or completely ceasing REH process. Second, the available spaces and mounting locations in rotating systems create physical limitations on the device size and usable mechanisms. Third, rotational energy can be random and low-frequency in many applications, which makes effective energy harvesting a challenge and requires the adaptation of different linear and nonlinear mechanisms. Another important limitation is that unlike vibrating harvesters, rotational energy harvesters often need bearings which do not scale well to miniature/micro dimensions and tend to be costly, especially when high-speed operation is needed. Consequently, creating an efficient REH device for harnessing rotational energy is an important and even more challenging task with a number of physical, mechanical and electrical constraints. However, with more efforts being contributed by this research community, self-powered wireless sensing can be achieved using available rotational energy sources in many applications, as shown in Fig. 2. Rotational motion is available or can be easily converted from many application scenarios, including Jet

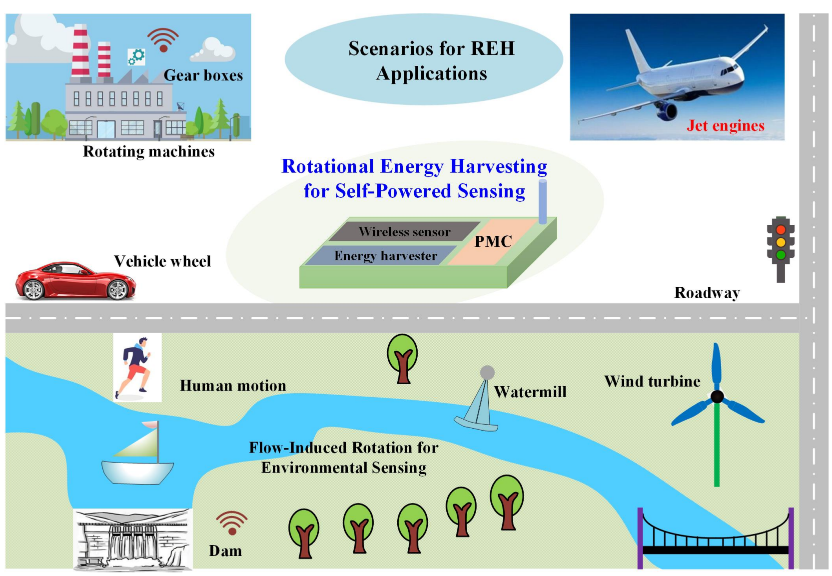

Figure 2: Self-powered sensing using rotational energy harvesting from different application scenarios, including rotating machines, human motion, environment, automotive, roadway and wind turbines.

engines, gear boxes, watermills, human motion, vehicle wheels, wind turbines, fluid flow motions etc. Combined with appropriate transduction mechanisms and power management circuits (PMC), rotational energy harvesters can convert those rotational energy sources into electricity to realize self-powered wireless sensing.

In this review, the focus is to critically assess and discuss the progress, challenges and potential opportunities in REH. To the best of the authors' knowledge, this is the first review paper focusing on REH. The rest of the paper is organized as follows: Section 2 discusses the types of rotational energy available and the corresponding energy harvester categories. Then, the maximum obtainable power and transduction mechanisms are discussed and analyzed. Different methodologies tailored for REH are reviewed and compared to enhance the harvesting capability in Section 3. The developed rotational energy harvesters in the literature are compared and categorized based on applications, including wearable and implantable devices, automotive and railway systems, rotating machines, renewable energy systems and environmental monitoring. Finally, the conclusions, challenges and potential opportunities are included in Section 5.

2. Classifications of motion and harvesters

REH on macro and micro scales has a number of complications associated with space and size constraints, as well as the type of energy source to harvest energy from. The nature and design of various rotating equipment and elements dictates the development of different energy harvesting concepts. In general, any energy harvesting device comprises two major elements - power take off and transduction mechanisms. Power take off is the mechanical system designed to absorb the given input as an external or parametric source of excitation [27]. Thus the mechanical system can be chosen as a discrete (n-degree-of-freedom lumped-mass) or continuous (rods and beams) systems, as well as it can be linear or intentionally nonlinear, due to prescribed geometrical constraints or material properties. In most cases, rotational energy sources fall into two categories, including continuous and non-continuous (reciprocating) motions. The following section will discuss the characteristics of these energy types and the associated energy harvesting solutions as well as the maximum obtainable power and the different transduction mechanisms.

2.1. Energy harvesting from non-continuous rotation

Reciprocating or oscillatory linear motion and fluid flow are the common sources of non-continuous motion and are typically converted to rotational motion using some mechanical rectification mechanisms. Rack and pinion (Fig. 3(a)) is the simplest mechanism that can convert a reciprocating motion to non-continuous rotational motion and vice versa. Bevel gears, ball-screw and worm gears are often used to amplify the motion or change the axis of rotation, as shown in Fig. 3(b) and 3(c). An application example is in shock absorbers, as shown in Fig. 3(d), for vibration suppression and ride comfort [28–30]. Converted reciprocating motion, similar to an oscillatory motion, will be non-continuous and bi-directional; therefore, it sometimes requires further mechanical rectification, to be efficient when connected to a conventional generator. A clutch or mechanical motion rectification (MMR) module, consisting of specifically

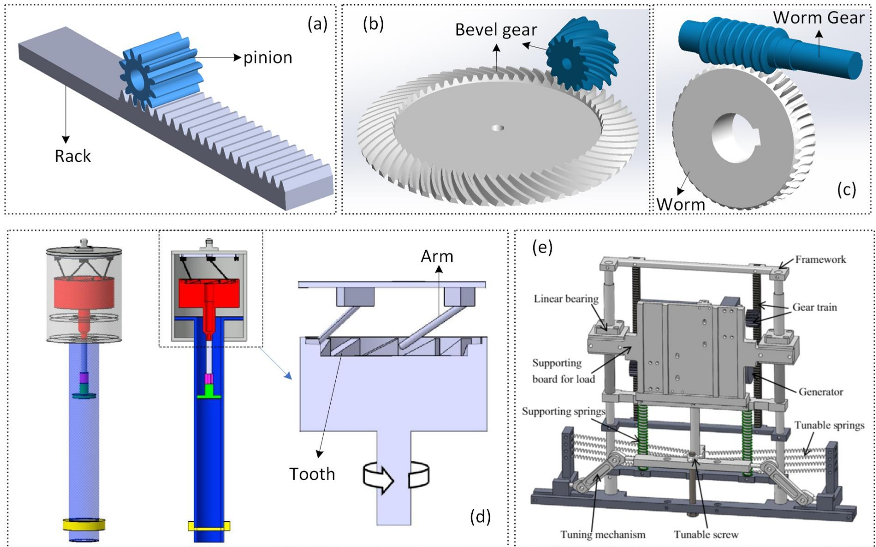

Figure 3: The rotational motion transmission and its application in energy harvesting: (a) Rack and pinion, (b) bevel gear, (c) warm gear, (d) bevel gear structure in a shock absorber [30], (e) rack and pinion structure for energy harvesting from backpack [31].

arranged gears, can be used for achieving unidirectional rotational motion. MMR has been used for energy harvesting in shock absorbers and backpacks [31], as shown in Fig. 3(e). Another rectification mechanism combined with electromagnetic energy harvesting design was proposed in Ref [32]. It should be stressed that various mechanical gears, screws and belt systems are difficult to be integrated in miniaturized devices in a cost effective manner, and therefore they should be avoided when possible. Direct drive mechanical systems can be used, allowing the torque to be converted to electricity without mechanical transmission. There are linear and rotational direct drive motors, which typically utilise electromagnetic principles for generating electricity.

One of the well-known examples of energy harvesting from non-continuous motion is the self-winding wristwatch, invented almost 100 years ago by J. Harwood. The energy harvesting is achieved there by oscillations of an unbalanced mass, which can be represented by a compound pendulum. In this case, the excitation amplitude is larger than the device dimensions, so resonant operation is not essential or even helpful in maximising power [33]. It has also been indicated that for systems with linear excitation, the power level of linear and rotational systems is equivalent when non-resonant motion is considered [33]. However, the resonant rotational motion of the unbalanced mass has higher power density, which is beneficial for energy harvesting purposes. Resonant oscillatory or rotational motion can be achieved in different ways, including gyroscopic and parametrically excited systems [34, 35]. Design and analysis of energy harvesting devices using bidirectional oscillations of a pendulum have been reported in a number of investigations, as shown in Fig. 4(a) and (b). This figure demonstrates the devices based on compound pendulums [36–39]. The main benefit of a compound pendulum over a mathematical (lumped-mass) pendulum is its compactness when a low natural frequency has to be attained; thus it is widely used for energy harvesting from human activities, which are typically below 5 Hz. Many devices for a restricted bidirectional motion have been developed for energy harvesting from human motion, where the devices are designed to be mounted on elbows, knees or other joints [40–47].

In other applications, a mathematical pendulum may be considered as a more appropriate choice; for example, such designs were reported in [48–50] and shown in Fig. 4(c) and (d). In Ref. [49], Marszal *et al.* proposed a ratcheting freewheel mechanism, which disengages when the input shaft rotates slower than the output shaft, as well as it prevents reversing of energy flow. To break the relationship between the pendulum length and its natural frequency, Alevras *et al.* and Ylli *et al.* [51, 52] studied pendulums with combinations of arms and elastic connections between them. Other designs that utilize pendulum-like motion were proposed in Refs. [53, 54].

2.2. Energy harvesting from continuous rotation

Compared to non-continuous rotation, continuous rotation is in some ways more straightforward to be harnessed. A good example is the conventional electromagnetic

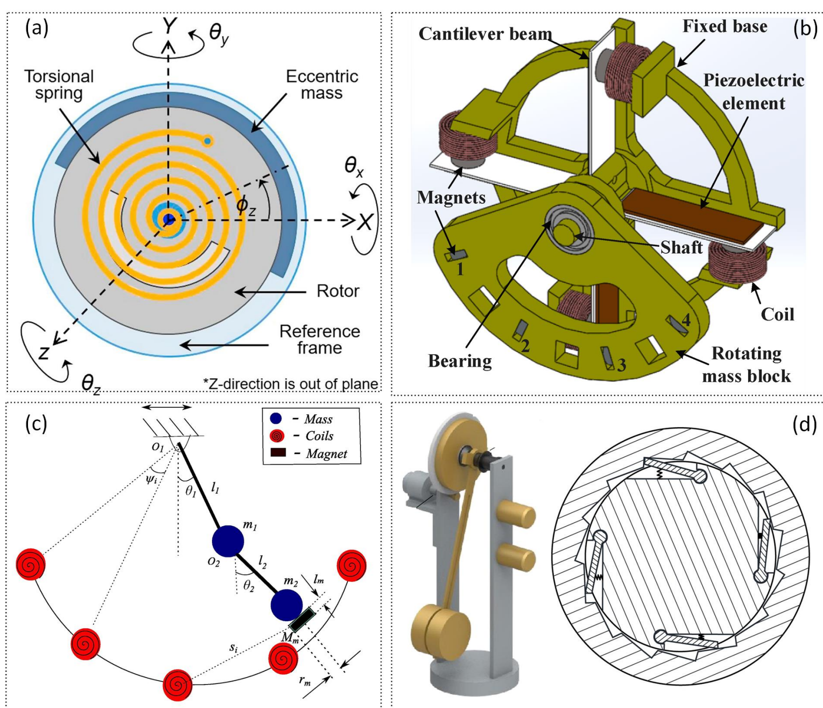

Figure 4: Compound energy harvesting devices used for energy harvesting from human activities in (a) eccentric rotor architecture for wearable sensors [39] and (b) hybrid piezo-electromagnetic energy harvesting using an unbalanced mass [38]. Pendulum energy harvesting devices: (c) pendulum-based electromagnetic harvester [48], (d) a parametrically forced pendulum [49].

generators used in wind or hydraulic power generation. However, all transduction mechanisms require a relative motion between transduction components (e.g. rotor & stator) to create, for example, the change in magnetic flux for excitation [41] or power generation [55]. Two anchors are typically used to create the necessary relative motion. For instance, in permanent magnet generators, magnets are mounted on the rotor, and coils are winded on the stator. However, due to the constraints in space and mounting location availability, anchors with relative motion cannot be accessed in many applications, such as rotating shafts. In such cases, harvesting from oscillating or otherwise varying rotation can use the inertia of the un-anchored component to create relative motion; this is not, however, possible for steady, continuous motion. Instead, most mechanisms have used gravity acting on the un-anchored component to create relative motion using just one anchor [55]. Also, in continuous rotation cases, the centrifugal force and the Coriolis force will influence the system dynamics significantly when the rotating frequency is high.

Based on the above description, REH devices can be divided onto 3 major categories: I. devices that utilises unbalanced and/or moving masses; II. beam-based devices; III. balanced or symmetric devices. The first category includes concepts with rotating pendulums or moving unbalanced masses, which are typically represented by levitating or rolling magnets, or eccentric proof masses. The second category contains devices based on oscillations of beams. These devices may or may not use magnets for enhancing multi-stability, and typically have single or double (bi-morph) piezoelectric layers. The devices in Category I and Category II mainly rely on the action of the gravity force in combination with other forces, such as the centripetal and magnetic forces, or rotation oscillation. The third category of devices consists of symmetric or balanced concepts, the vast majority of which have been developed for energy harvesting from a continuously incoming fluid flow.

Table 1 provides the visual representation of the existing concepts and devices grouped according to the presented classification, where the rows are organised based on the transduction mechanism. The last row includes mostly pendulum devices which were investigated for energy harvesting purposes but were not connected to any transduction mechanism. The table should be used to identify the publications in a particular category and with a particular transduction mechanism, as well as clearly indicating the empty spaces, with no publications. As expected and confirmed by this table, the electrostatic and triboelectric transduction mechanisms have been less explored. It can also be seen from this table that for beam-based devices, piezoelectric transduction

Table 1: Categories and Transduction of rotational energy harvesters in the literature

	Category I	Category II	Category III
Electromagnetic	[39, 48, 55–78]		[32, 71, 79–104]
Piezoelectric	[41, 105–109]	[110–153]	[111, 154–176]
Electrostatic	[177, 178]	[179]	[42, 180–185]
Triboelectric	[70]		[85, 86, 100, 165, 186–192]
Unspecified	[193–197]		[198]

is the dominant option due to the simplicity of integrating piezoelectric layers into beams, whereas for harvesters with unbalanced masses or symmetric structures, different mechanisms are all explored in the literature with piezoelectric and electromagnetic conversion being the major choices. Another important factor for transduction selection is device size. Piezoelectric conversion adds simplicity in micro-scale devices, whereas larger devices can use conventional electromagnetic transducers. According to Ref. [147], piezoelectric transducers are less affected by size scaling down. In terms of the percentage of the design in the literature, the balanced or symmetric harvesters are the highest among these categories, but the number of publications for unbalanced and beam-based harvesters has been increasingly presented for low-frequency random rotation conditions.

Some selected concepts from Category I can be found in Fig. 5. In Fig. 5(a) and (b), eccentric masses have been used to acquire energy from oscillatory host motions [61, 69]. With the assistance of gravity, the eccentric mass also fulfils the goal of creating relative motion using one anchor point. Similar designs using levitating magnets were studied for a rotational wheel motion in Fig. 5(c) [56, 64]. A pendulum design was tested for wave energy in Ref. [193] where the heave motion of waves was used as the excitation. Kuang and Zhu developed a parametrically excited nonlinear magnetic

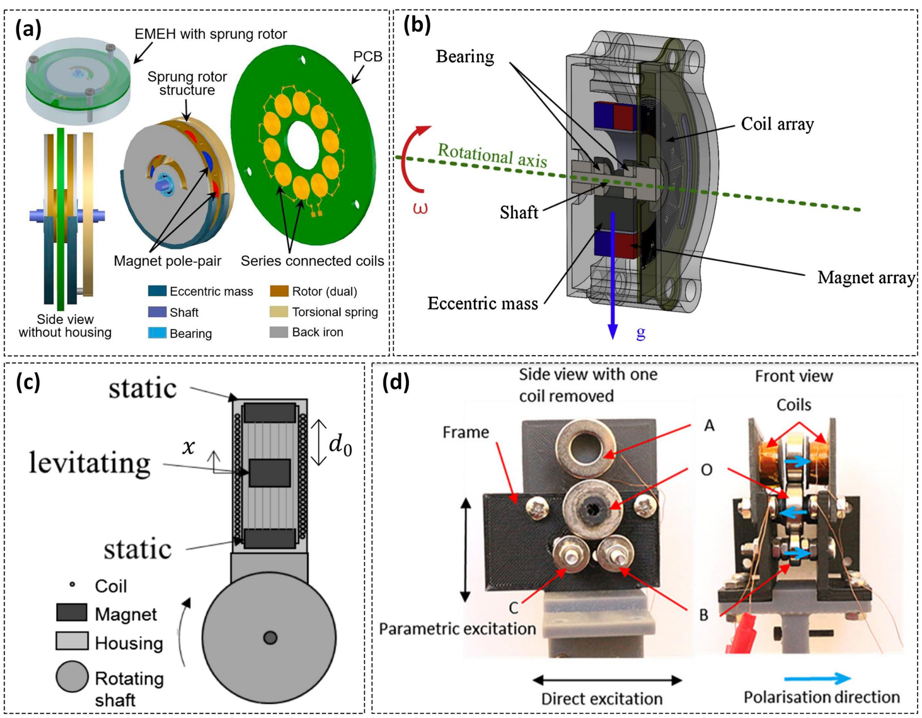

Figure 5: Category I devices: rotational energy harvester using unbalanced masses. (a) and (b) eccentric masses with electromagnetic conversion [39, 69], (c) levitating magnets on rotating hosts [64], (d) parametrically excited nonlinear magnetic rolling pendulum [66].

pendulum using the attractive and repulsive magnetic forces, as shown in Fig. 5(d) [66]. A broad operation range was obtained by converting the linear oscillation to the rotation of the pendulum structure.

Fig. 6 presents several typical beam-based harvesters in Category II. The majority of these work in the bending mode, rather than the compression/extension mode. Some of the presented devices use magnetic plucking forces to stimulate a piezoelectric beam to oscillate around its equilibrium positions, as shown in Fig. 6(a) and (b) [107, 117]. Based on this method, Fu and Yeatman introduced bi-stability into the plucking harvester by introducing a fixed magnet above the beam tip magnet, as shown in Fig. 6(c) [149]. This method requires two anchors for the rotating driving magnets and for the static piezoelectric beams. In order to enhance the energy generation capability, a number of permanent magnets can be arranged to create the multi-stability of the beam which is covered in Section 3. The harvesters in Fig. 6(d) and (e) are arranged vertically and use gravity to create the beam bending [112, 116]. The advantage is that only one anchor is required.

As can be seen, the devices in the first two categories have some asymmetries in their design, and therefore at relatively high rotational speeds the high centripetal force will introduce a bias-force on the beams, potentially keeping a device in an equilibrium position and affecting the energy harvesting capability. One should also not forget about the Coriolis force which acts on a moving body within a rotational frame reference, but its action will be perpendicular to the axis of rotation. This force may cause an object to be pushed to one side of a housing, creating much higher friction or completely forcing the object to stop. Thus, the third category of balanced or symmetric rotational energy harvesters, presented in Fig. 7, may have an advantage over the others when a relatively high rotational speed is considered for energy harvesting.

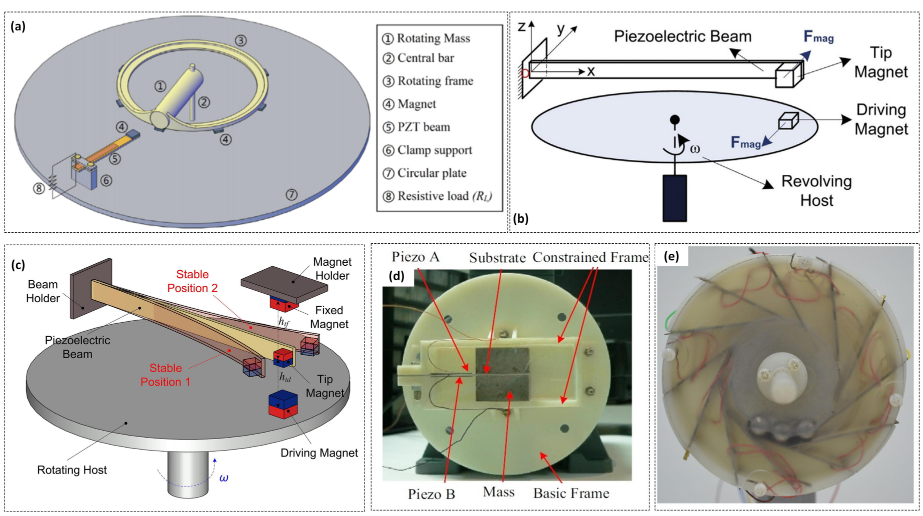

Figure 6: Category II beam-based rotational energy harvesters: (a) and (b) magnetic plucking excited beam structures [107, 117]; (c) bi-stable plucking harvester using piezoelectric transduction [149]; (d) and (e) gravity-excited beam structures [112, 116].

Fig. 7(a) and (b) represent a group of devices, which use the alternating repulsive and attractive magnetic forces to bend piezoelectric beams. The motion sources can be directly from rotation [163] or converted from other sources, such as fluid flow using micro-turbines [155]. A relatively different concept based on compressing a piezoelectric material is shown in Fig. 7(c), where the magnetic force is applied to flextensional transducers on the stator by the driving magnets on the rotor [99]. It is worth noting that such configurations create loading torque peaks on the rotor. This will be an issue for conditions where the driving torque is limited. The cogging effect and high cut-in speeds may result due to the concentrated load peaks. Turbines can also be classified as symmetric rotational energy harvesters and operate at different frequencies on different size scales. Fig. 7(d) is one example of a horizontal-axis wind turbine combined with electromagnetic transduction [81]. Electrostatic transduction is especially convenient from the manufacturing point of view on micro-scale with the advantage of simplicity. Fig. 7(e) illustrates the common layout of such devices in harnessing rotational energy [199]. Triboelectric conversion is also explored in harnessing continuous rotation energy, but the frequent contacts and friction between materials may result in component failure and reduce the system reliability. Therefore, this mechanism is more favorable to low-frequency motion conditions, and additional considerations need to be applied to avoid material degradation and enhance system robustness and reliability [200].

2.3. Maximum achievable power

The low power generation capability is the major reason limiting the adoption of REH technologies in many applications. Therefore, it is critical to examine the theoretically achievable power upper bounds for typical rotational energy harvesters. These

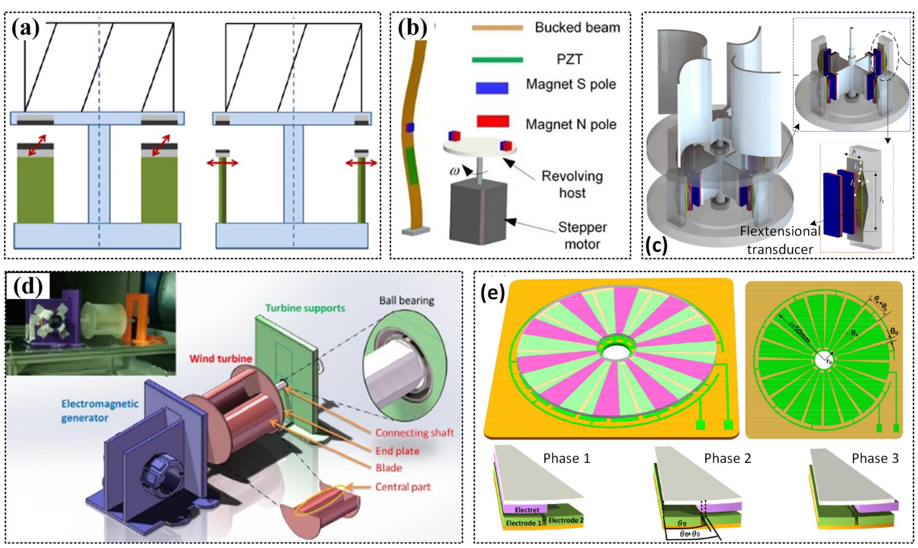

Figure 7: Category III - symmetric or balanced devices. (a) and (b) balanced devices with piezoelectric beams [155, 163], (c) flextensional piezoelectric transducers for REH [99], (d) turbine-based energy harvester with electromagnetic transduction [81], (e) electrostatic rotational energy harvester [199].

power limits can also provide means to evaluate how the output power varies with key design and operational parameters. According to the energy harvester categories in Section 2, the obtainable power limits are analyzed for unbalanced and balanced harvesters operating at non-resonant and resonant modes under non-continuous, continuous rotation and linear oscillation excitation conditions.

2.3.1. Unbalanced non-resonant harvester under non-continuous rotation

Fig. 8(a) presents a generalized unbalanced harvester (eccentric mass) working at the non-resonant mode under non-continuous rotation excitation. A good example of such devices is the self-powered wristwatches developed by Seiko Corp. to harness energy from human motion [201]. As there is no stiffness component in such a system, this type of device typically operates in a non-resonant mode. According to Ref. [33], the equation of motion for the model in Fig. 8(a) can be expressed as

$$I\ddot{\theta} = D\left(\dot{\Omega} - \dot{\theta}\right), \tag{1}$$

where $I = mR^2/4$ is the mass moment of inertia of the half disc, m is the mass, R is the radius, D is the damping coefficient that represents the velocity-dependent transduction mechanism, and θ and Ω are the angular displacement of the half disc and the oscillating host, respectively. The instantaneous power obtained by the transduction can be

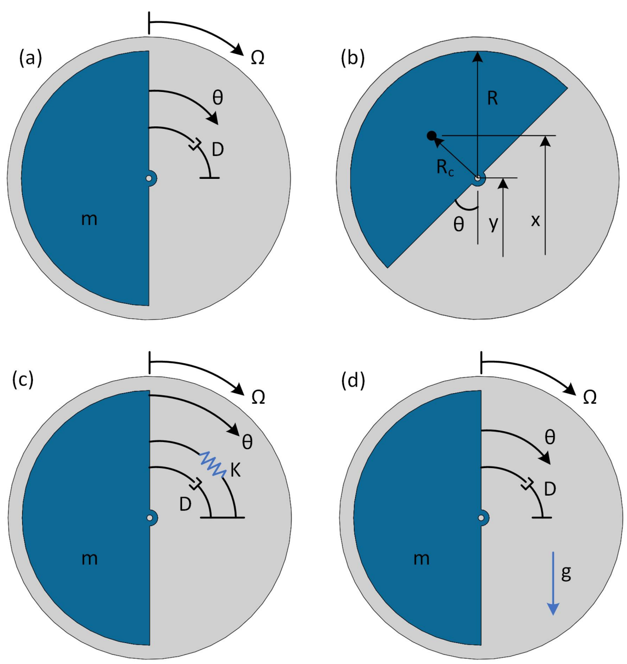

Figure 8: Models for unbalanced/balanced rotational energy harvesters (e.g. eccentric mass or beams on a rotating host). (a) non-resonant harvester operating under non-continuous rotations; (b) non-resonant harvester operating under linear oscillation (y direction); (c) resonant harvester operating under non-continuous rotations; (d) non-resonant harvester operating under continuous rotations with gravity as the counter force.

written as

$$P_{ins} = D\left(\dot{\Omega} - \dot{\theta}\right)^2 = \left(\frac{I\ddot{\theta}}{D}\right)^2. \tag{2}$$

For a harmonic non-continuous excitation $\Omega(t) = \Omega_0 \sin(\omega t)$, $\ddot{\theta} = -\omega^2\theta$ and $\theta(t) = \theta_0 \sin(\omega t + \phi)$. Using the Laplace analysis, Eq. (1) can be rewritten as

$$\frac{\theta_0}{\Omega_0} = \frac{D}{\sqrt{D^2 + \omega^2 I^2}}. \tag{3}$$

$$\phi = \arccos(\theta_0/\Omega_0). \tag{4}$$

Based on Eqs. (2)-(4), the average output power can be obtained as

$$P_{avg} = \frac{I^2\omega^4\theta_0^2}{2D} = \frac{I\omega^3\Omega_0^2}{2}\frac{D/\omega I}{1 + (D/\omega I)^2} \tag{5}$$

Therefore, the maximum power is obtained when $D = \omega I$, and it is written as (using $I = mR^2/4$)

$$P_{max} = \frac{I\omega^3\Omega_0^2}{4} = \frac{m\omega^3\Omega_0^2 R^2}{16}, \tag{6}$$

where $\phi = \pi/4$ and $\theta_0 = \Omega_0/\sqrt{2}$. According to Eq. (6), the excitation frequency ω and amplitude Ω_0 have significant impacts on the maximum obtainable power. From the harvester design perspective, the mass has less influence than the radius. In terms of how to obtain the maximum power, the source of motion is required to be significantly large in amplitude to obtain a phase difference $\phi = \pi/4$ between the harvester motion and source motion. Therefore, this type of harvester is ideal for large-amplitude low-frequency motions, such as arm swing or turbine blade rotation. It is worth mentioning that this maximum obtainable output power in Eq. 6 is similar to the maximum obtainable power of a linear vibration harvester ($P_{max} = 1/2 Y_0 Z_l \omega^3 m$ [22], where Y_0 is the excitation amplitude, Z_l is the maximum internal displacement.).

2.3.2. Unbalanced non-resonant harvester under linear oscillation

Unbalanced harvesters can also be used in collecting linear motion energy. Therefore, a linear harmonic motion $y(t) = Y_0 \sin(\omega t)$ is adopted in this analysis, as shown in Fig. 8(b). The linear position of the eccentric mass is then $x(t) = y(t) + R_c \sin(\theta(t))$, where R_c is the radius of the mass center. According to Ref. [33], the equation of motion for the eccentric mass can be obtained

$$I\ddot{\theta} + mR_c^2\cos^2(\theta)\ddot{\theta} - mR_c^2\sin(\theta)\cos(\theta)\dot{\theta}^2 + D\dot{\theta} = -m\ddot{y}R_c\cos(\theta). \tag{7}$$

As the system described in Eq. (7) is non-linear, it is difficult to get an explicit expression for $\theta(t)$. However, the maximum power can be estimated using the input power $\mathrm{d}U = F_y\mathrm{d}y = m\ddot{x}\,\mathrm{d}y$ on the eccentric mass. If the relative motion between the eccentric mass and the host is $z(t)$, then $z(t) = x(t) - y(t)$, and $\ddot{x} = \ddot{y} + \ddot{z}$. Therefore, $\mathrm{d}U/m = \ddot{y}\, dy + \ddot{z}\, dy$. Integrating the instantaneous power over an excitation cycle is the energy obtained by the energy harvester in that cycle. The $\ddot{y}\, dy$ term can be neglected since the integration is zero. $z(t)$ can be rewritten as $z(t) = \sum z_n \sin(n\omega t + \phi_n)$. The instantaneous power then can be expressed as

$$\mathrm{d}U = -m\omega^3 Y_0 \sum n^2 z_n \sin(n\omega t + \phi_n)\cos(\omega t)\mathrm{d}t. \quad (8)$$

Since the range of $z(t)$ is within $\pm R_c$, R_c can be approximated as the maximum of $\sum n^2 z_n \sin(n\omega t + \phi_n)$. The maximum achievable power can be then estimated as

$$P_{max} \cong \frac{1}{2} m\omega^3 Y_0 R_c. \quad (9)$$

Similar to the unbalanced harvester for non-continuous rotation, the linear motion excited harvesters are also affected significantly by the operating frequency ω. The motion range limits $\pm R_c$ and the excitation amplitude Y_0 are also the contributing factors.

2.3.3. Resonant harvester under non-continuous rotation

Similar to linear vibration energy harvesters which typically operate at their resonance, rotation energy harvesters (balanced or unbalanced) can also be designed to be resonant devices by coupling an angular spring and a damper, as shown in Fig. 8(c). Beam-based harvesters mounted on a rotating host are another type of resonant-based harvester. The equation of motion can be expressed as [33]

$$I\ddot{\theta} = D\left(\dot{\Omega} - \dot{\theta}\right) + K(\Omega - \theta). \quad (10)$$

Based on Eq. (10) and the Laplace Transformation, the internal angular displacement of the eccentric mass Ψ_0 at resonance can be written as

$$\Psi_0 = \Omega_0 \left(\frac{I\omega}{D}\right). \quad (11)$$

If the parasitic damping (D_p) and the electrical damping (D_e) are considered, the obtainable power by the transduction can be written as

$$P_e = \frac{I^2\omega^4\Omega_0^2}{2D_e}\frac{D_e^2}{(D_e + D_P)^2}. \quad (12)$$

When $D_e = D_p$, the maximum obtainable power can be achieved

$$P_{e(max)} = \frac{I^2\omega^4\Omega_0^2}{8D_e}. \quad (13)$$

From Eq. (13), it is obvious that the resonant oscillating harvester can obtain a higher maximum power at the resonant condition. This type of harvester is ideal to be used in conditions where the excitation frequency is constant, whereas for random and broadband excitation conditions, the non-resonant harvesters are favorable. Another important limitation in resonant oscillating harvesters is to develop a miniature rotational spring with a large rotation range which has not been demonstrated in MEMS to the authors' knowledge.

2.3.4. Unbalanced non-resonant harvester under continuous rotation

Continuous rotation is available in many applications, such as rotating shafts or transmission systems. Using gravity as the counter force is the typical method to create relative motion between the rotating host and the harvester, as shown in Fig. 8(d). The equation of motion can be written as

$$I\ddot{\theta} = D\left(\dot{\Omega} - \dot{\theta}\right) - mgR_c\cos(\theta). \tag{14}$$

The energy output is related to the relative speed $(\dot{\Omega} - \dot{\theta})$ between the rotating host and the eccentric mass. Maximum output power can be obtained when the eccentric mass is static, ie. $\ddot{\theta} = \dot{\theta} = 0$. The maximum obtainable power then is

$$P_{max} = D\dot{\Omega}^2 = mgR_c\dot{\Omega}. \tag{15}$$

The maximum output power depends on the gravitational force of the eccentric mass and the relative angular velocity. To increase the relative velocity, the gravitation torque $T_g = mgR_c\cos(\theta)$ is critical. In addition, due to the use of an eccentric mass, the centrifugal force might be an issue at high rotational speeds.

Table 2 summarizes the maximum obtainable power for different types of rotational energy harvesters under different operating conditions. It is worth noting that the maximum obtainable powers are significantly different among the types. The selection of energy harvester type depends on the practical applications and their corresponding constraints. For instance, resonant non-continuous harvesters have high power generation capability, but are only ideal for narrow-band excitation frequency conditions, whereas non-resonant unbalanced harvesters are ideal for low-frequency and large-amplitude non-continuous motions.

2.4. Transduction mechanisms

Transduction mechanisms typically include piezoelectric, electromagnetic, electrostatic or triboelectric phenomena, as well as their combinations, as shown in Fig. 9. Device size and layout and the application features dictate the most effective transduction mechanism. For example, often piezoelectric beams are equipped with bulk permanent magnets to achieve multi-stability, which enhances the energy harvesting potential. Electrostatic devices, which require a bias voltage, are combined with triboelectric or piezoelectric devices capable of generating that essential voltage. The

Table 2: Maximum obtainable power for different types of rotational energy harvesters.

Harvester Type	Harvester Proof Mass	Operation Mode	Maximum Power	Key Factors	Comments & Notes
Unbalanced	Non-continuous	Non-resonant	$I\omega^3\Omega_0^2/4$	ω, Ω_0, R	Large-amplitude Low-frequency
Unbalanced	Linear motion	Non-resonant	$m\omega^3 Y_0 R_c/2$	ω, Y_0	High-frequency
Unbalanced/ Balanced	Non-continuous rotation	Resonant	$\frac{I^2\omega^4\Omega_0^2}{8D_e}$	ω, Ω_0	Resonant condition
Unbalanced	Continuous rotation	Non-resonant Gravity-driven	$mgR_c\dot{\Omega}$	m, R_c, $\dot{\Omega}$	Low-frequency large eccentric mass

majority of the above-mentioned beam structures utilise piezoelectric energy harvesting, whereas relatively high speed of rotational motion is beneficial for electromagnetic energy harvesting by balanced concepts. Unfortunately, the choice is often not obvious, since other factors may also play a key role on the device. For completeness, the fundamentals are presented here briefly.

2.4.1. Piezoelectric effect

The piezoelectric effect was first identified by the Curie brothers in 1880 [202]. For small-scale energy harvesters, the piezoelectric effect is widely used due to the advantages of high energy density, simple structure and compact size. In general, the linear piezoelectric effect is governed by the following constitutive equations [25].

$$\begin{bmatrix} \sigma \\ D_c \end{bmatrix} = \begin{bmatrix} s^E & d^t \\ d & \varepsilon^T \end{bmatrix} \begin{bmatrix} T \\ E \end{bmatrix} \tag{16}$$

where Eq. (16) connects the mechanical domain (strain σ and stress T) with the electrical domain (electric displacement D_c and electric field E). s, d and ε are the elastic compliance, dielectric constant and piezoelectric coefficient, respectively. The superscript t is the transpose.

The beam-type harvester via the 31-mode in Fig. 9(a) is most commonly adopted, and the corresponding designs can be found in Refs. [116, 121, 133, 203]. In addition, piezoelectric energy harvesters designed as flextensional structures also have attracted lots of attention, in which the greatest strength is to increase the reliability of the harvester compared with the beam-type harvester. The outstanding structures and applications have been reported in Refs. [99, 142, 162, 167].

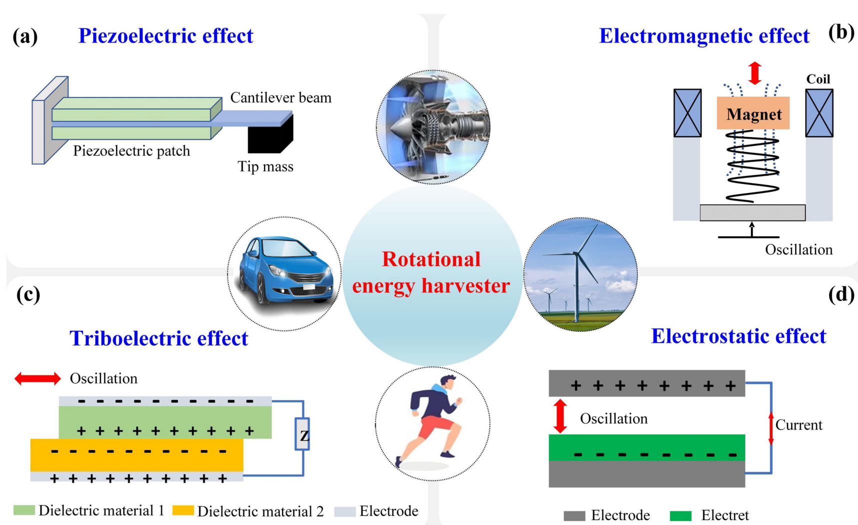

Figure 9: Transduction mechanisms for rotational energy harvesting in applications such as rotating machinery, vehicle wheel, human motion, wind turbine by (a) piezoelectric effect, (b) electromagnetic effect, (c) triboelectric effect, (d) electrostatic effect.

2.4.2. *Electromagnetic effect*

The electromagnetic effect has long been the dominant conversion mechanism for conventional power generators. This mechanism has also been popular for rotational energy harvesting, as shown in Fig. 9(b). The rotational motion is regarded as the base excitation which results in the relative movement between the magnet and coils. According to Faraday's Law, the voltage induced in the coils can be expressed as [204]

$$\varepsilon_v = -\frac{d\Phi_B}{dt} \tag{17}$$

where ε_v is the induced voltage and Φ_B is the linked magnetic flux. For electromagnetic transduction, the power generation capability is highly related to the operation frequency and device dimensions ($P \propto L^5\omega^2$ [147]). It is therefore ideal for this type of harvester to operate at high frequencies and large dimensions.

2.4.3. *Triboelectric effect*

In the last decade, triboelectric transduction has attracted widespread interests in REH [205]. The most common mode is vertical contact-separation mode whose working mechanism is shown in Fig. 9(c). When rotation is applied to material 1, it becomes electrically charged after contacting with another material. Because of the continuous rotational motion, the electric pulses can be generated. In order to reveal the mechanism of power generation, Wang reformulated Maxwell's displacement current as [206]

$$J_D = \varepsilon\frac{\partial \boldsymbol{E}}{\partial t} + \frac{\partial \boldsymbol{P_s}}{\partial t} \tag{18}$$

where the second term $\frac{\partial \boldsymbol{P_s}}{\partial t}$ contributes to the output current of triboelectric nanogenerators (TENGs) and is related to the driving force. Recently, various TENGs have been investigated to derive low-powered electronic and to realize self-powered systems, such as a wind-driven wireless temperature sensor [165, 189, 190], a fluid-driven wireless speed sensor [100, 191] and a MEMS plasma switch for conditioning TENG [207].

2.4.4. *Electrostatic effect*

For the electrostatic effect in Fig. 9(d), charges with the opposite sign are induced on the counter-electrode by the electrostatic field of the electrets [208–210].The electromechanical transduction is given by [211]

$$I = \alpha_e \dot{u} - c_e \dot{V} \tag{19}$$

where α_e is the force factor. c_e is the shunting capacitance. An electrostatic rotational energy harvester was designed to harvest human motion energy [184, 185]. Later, the synchronized switch harvesting on inductor (SSHI) with a dual-stage design was applied to enhance energy harvesting performance [211].

The transduction mechanisms for energy harvesting in rotational motion have been introduced in the above subsections. Each method has its own advantages, and to combine these respective merits various hybrid generators have been developed, as shown in Fig. 10. Toward practical application in harsh environments, a waterproof triboelectric-electromagnetic hybrid harvester was reported, as shown in Fig. 10(a)

[212]. In this design,a freestanding triboelectric nanogenerator (TENG) and a rotating electromagnetic generator (EMG) are integrated together. When the rotational motion is provided, such as flow-induced, the rotor will rotate. According to the electromagnetic effect, the EMG can generate the voltage, at the same time the friction of TENG between the polymer film and the electrode can also generate voltage based on the triboelectric effect. The experimental results demonstrate that the hybrid energy harvester can be a self-powered wind speed sensor to detect wind speed as low as 3.5 m/s. Similarly, a triboelectric-electromagnetic hybrid harvester was investigated as shown in Fig. 10(b), and the experimental results illustrated that the designed harvester is a promising way to drive an electronic thermometer and achieve a self-powered water-temperature sensing system [100]. As presented in Fig. 10(c), a bimorph-based piezoelectric harvester was integrated into triboelectric harvester to form a hybrid harvester for high-efficient mechanical rotational energy harvesting [165]. At wind speed of 14 m/s, it could power 50 LEDs in parallel connection.

For hybrid energy harvesters in rotational motion, the output power can be improved by adopting multiple transduction mechanisms [213]. However, how to use the device space of an energy harvester effectively is critical in terms of increasing the device power density. Also, in some cases, energy may be available in different forms, such as solar, vibration, or thermal. Hybrid energy harvesters can convert different types of energy into electric energy in one device. For example, if a hybrid REH is used to provide power for wireless sensors of wind turbine, solar and rotational energy

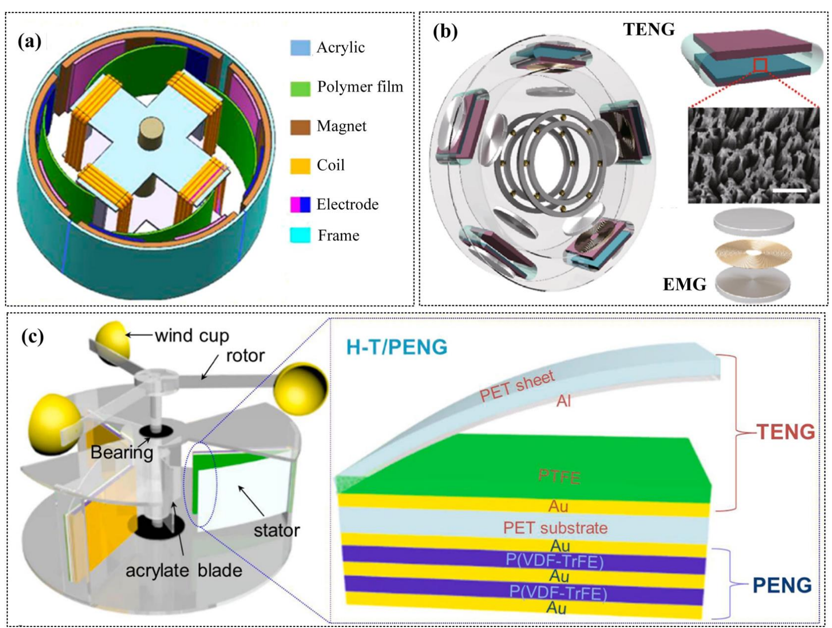

Figure 10: Hybrid generator for harvesting rotational energy to realize self-powered sensor: (a) An ultra-low-friction triboelectric-electromagnetic hybrid nanogenerator [212]; (b) tribo-electromagnetic hybrid generator [100]; (c) hybrid piezo-triboelectric generator for harvesting rotational energy [165].

can be harvested in a hybrid device. Such a device provides a more robust power source even if one type of energy source is not available. Therefore, enhancing the robustness of power supply is another advantage of hybrid rotational energy harvesters.

3. Methodologies and mechanisms

This section focuses on methodologies and mechanisms that have been tailored for REH. An in-depth analysis is provided to review the advantages and uniqueness of each method in effectively harnessing rotational energy.

3.1. Frequency up-conversion

Rotational energy can be characterized as low-frequency and random in many situations, such as flow-induced rotation, pendulum oscillation and turbine blade rotation, where electromagnetic conversion might be ineffective due to its poor scaling-down performance in operating frequency. It is the same for resonant-based piezoelectric transducers, as the resonant frequency of the transducers is high due to the miniaturized dimensions, and there is large discrepancy between the low excitation frequency and the high resonant frequency.

In this context, frequency up-conversion (FREUC) has been adopted to address the low-frequency random REH challenge. FREUC is a method to intermittently stimulate the piezoelectric transducers either by direct impact [40, 106, 161, 164, 168] or magnetic plucking [41, 68, 107, 117, 160, 163, 169, 214] using low-frequency random energy sources, as shown in Fig. 11(a). After being stimulated, the transducer (typically in beam or disc shapes) can vibrate freely at its resonance before the next stimulation force appears. Therefore, the transducer can always operate at its resonant frequency for any low-frequency random input excitation.

Fig. 11(b) presents the implementation of the FREUC method into rotational energy harvesters. For the direct impact method, multiple plectra are fixed on the edge of a rotor, and piezoelectric beams are mounted on a stator [168]. The relative motion between the rotor and the stator causes impact between the plectra and the beams, transferring kinetic energy into the beams. The beams then oscillate at their resonant frequency, as shown in Fig. 11(c). Another method to implement FREUC is magnetic plucking. Instead of using moving plectra, driving magnets are mounted on the rotor and piezoelectric beam with tip magnets mounted on the stator or vice versa [41]. The magnetic forces applied by the driving magnets on the piezoelectric beams realize the plucking effect and transfer the kinetic energy. In the multi-beam configuration, as shown in Fig. 11(b), the beams normally vibrate with phase differences. In order to avoid the charge cancelling-out effect, bridge rectifiers are required for each beam.

It is worth mentioning that there are pros and cons for both the direct impact method and the magnetic plucking method. For direct impact, the impact duration is typically much shorter than the magnetic force while the impact force could be higher, as shown in Fig. 11(d). The shorter duration and the higher impact force are ideal to stimulate the beam and obtain higher power output, especially when the rotational frequency is ultra-low (e.g. bellow 1 Hz). However, the direct impact or excessive applied load may cause material degradation and is detrimental to the long-term reliability of the

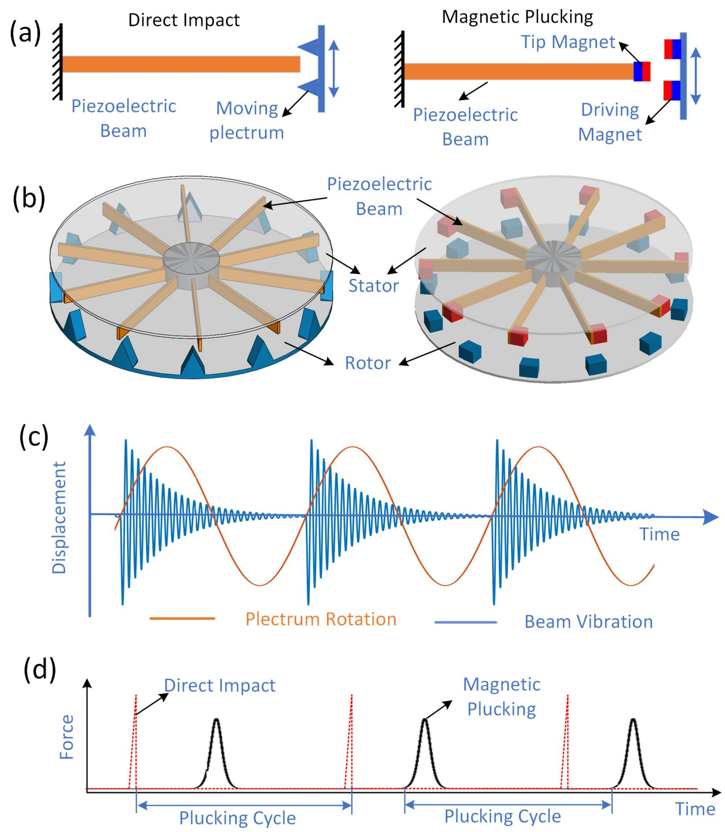

Figure 11: Frequency up-conversion (FREUC). (a) FREUC methods including direct impact and magnetic plucking, (b) implementation of FREUC in rotational energy harvesters, (c) displacement of piezoelectric beam under plucking, and (d) comparison of the forces introduced by direct impact and magnetic plucking.

system [215]. Appropriate protecting mechanisms need to be introduced to address this concern when using direct impacts.

Another significant difference is that the magnetic plucking force is continuous and much easier to control the amplitude by adjusting the gaps or dimensions of magnets, while the direct impact force is more difficult to control and the impact force is highly depended on the contact between the plectra and the beams. In cases where the rotor angular momentum is limited compared to the momentum transferred by each impact, the rotor's smooth motion will be affected and the rotation could be event be stalled. A good example would be REH from airflow using micro-turbines. The impact or plucking force determines the cut-in speed of the micro-turbine [157].

One important aspect for FREUC is the output power fluctuation at high excitation frequencies [107, 117, 164]. With increase of the excitation frequency, the excitation cycle is not long enough for the beam to ring down fully, as shown in the comparison between Fig. 12(a) and (b). At high excitation frequencies, the beam still vibrates when the subsequent excitation force appears, resulting in output power fluctuation due to the phase variation between the driving plucking force and the beam vibration. This effect narrows the operating frequency range. The frequency of the fluctuation peaks correlates to the resonant frequency f_r of the transducers and is given by [117]

$$f_i = \frac{f_r}{n \cdot i}, \tag{20}$$

where i (= 1,2,3,...) is the sequence of the peaks and n is the number of driving magnets on the rotor or plucking events per cycle. Solutions to alleviate the fluctuation issue have been investigated. Increasing the transducer's electromechanical damping is one possibility. Assuming the beam's initial vibration voltage after plucking is V_0, the beam ring-down dynamics can be expressed as [149]

$$V_d(t) = \underbrace{V_0 \cdot e^{-\pi f_r \cdot t/Q}}_{\text{Amplitude}} \cdot \underbrace{\cos(\omega_d t + \Phi_0)}_{\text{Frequency}}, \tag{21}$$

where $Q = 1/(2\zeta_b)$ is transducer's quality factor, ζ_b is system overall damping ratio, ω_n is the transducer's damped resonant frequency, and Φ_0 is the initial phase of beam vibration. It can be seen from Eq. (21) that the ring-down percentage is determined by the 'Amplitude' factor. Therefore, in order to allow enough time for the beam to ring

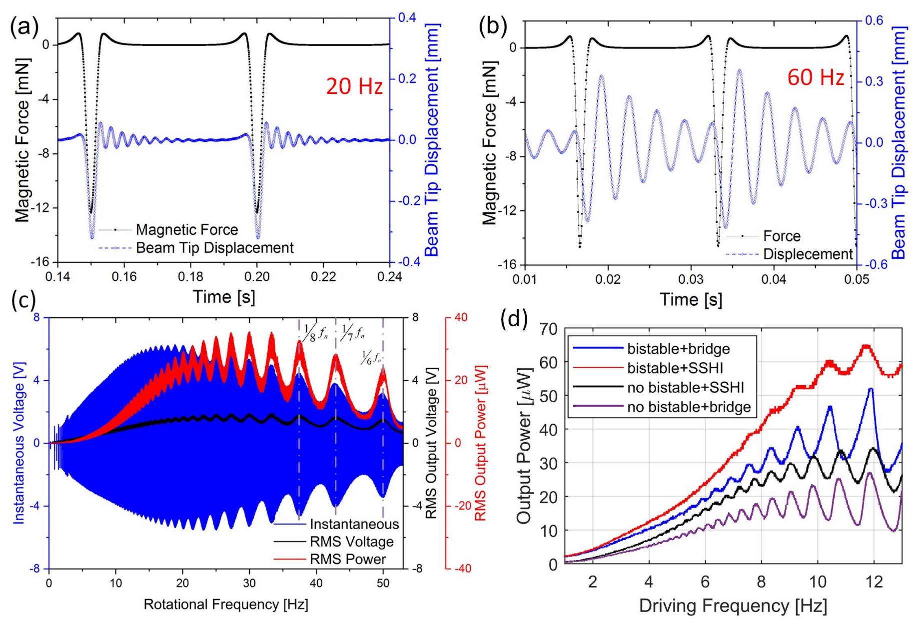

Figure 12: FREUC harvester dynamics under different excitation frequencies and the illustration of the output power fluctuation issue. (a) Beam displacement and magnetic force at 20 Hz and (b) at 60 Hz, (c) output power fluctuation with the increase of excitation frequency [117], and (d) nonlinear dynamics to address the fluctuation issue and to increase the output power [148].

down to a certain percent k, the upper limit for the driving frequency is

$$f_e^u = -\frac{1}{\ln k}\frac{\pi}{Q} \cdot f_r. \tag{22}$$

The upper limit of the excitation frequency f_e^u is a function of the transducer resonant frequency f_r and the quality factor of the energy harvesting system. A lower quality factor Q (namely higher transducer damping) is beneficial to increase the upper limit f_e^u. However, increasing the mechanical (parasitic) damping will reduce the recovered useful energy from each ring-down cycle. Different nonlinear dynamics have been investigated to enhance the damping ratio, including bi-stability and synchronized switch harvesting on inductors (SSHI) [127, 148–150, 163]. Fig. 12(d) illustrates the effects of bi-stability, SSHI and their coupled method in alleviating the power fluctuation issue [148].

3.2. Multi-stability

It is well known that inter-well oscillation from one potential well to another one enhances beam deformation, therefore, higher output power can be obtained. The challenge in REH is to realize inter-well oscillation in low-frequency excitation. To broaden the frequency bandwidth of energy harvesting, magnetically coupled multi-stability has been widely adopted, and theoretically and experimentally validated in Refs. [133–137, 216]. When energy harvesters with multi-stability are applied to a rotational environment, the potential energy of the beam-type harvester is time-varying in one rotating cycle due to the change of gravitational potential energy. The whole potential energy can be calculated using

$$U = \frac{1}{2}K_e x^2 + M_e g x \sin\theta + \int F_m \, dx \tag{23}$$

where F_m is the nonlinear magnetic force, K_e is the equivalent stiffness of the piezoelectric beam. x is the transverse deformation of the piezoelectric beam. $\theta = \int_0^t \dot{\theta}(t)dt$ is the angular displacement of the rotational motion. In Ref. [138], the nonlinear magnetic force F_m and the elastic force of the piezoelectric beam are rewritten as the equivalent restoring force F_r. Thus, Eq. (23) can be rewritten as

$$U = M_e g x \sin\theta + \int F_r \, dx, \tag{24}$$

where F_r is determined by the parameters of the magnetically coupled configuration and the number of external magnets. Depending on the magnet configuration (magnet magnetization and number), the harvester can be mono-stable [139], bi-stable [133, 134, 216], tri-stable [135, 140] or multi-stable [136, 137]. For these nonlinear harvesters, the typical characteristic is that a tip magnet is mounted at the free end of a cantilever beam, and there will be different number of fixed magnets arranged near the tip magnet with either attractive or repulsive forces. If there is only one fixed magnet paired with the tip magnet to generate the attractive force, as shown in Fig. 13(a), the harvester is mono-stable with one potential well in the potential energy plot. If the magnetization direction is reversed and the magnetic force is repulsive, bi-stability with two

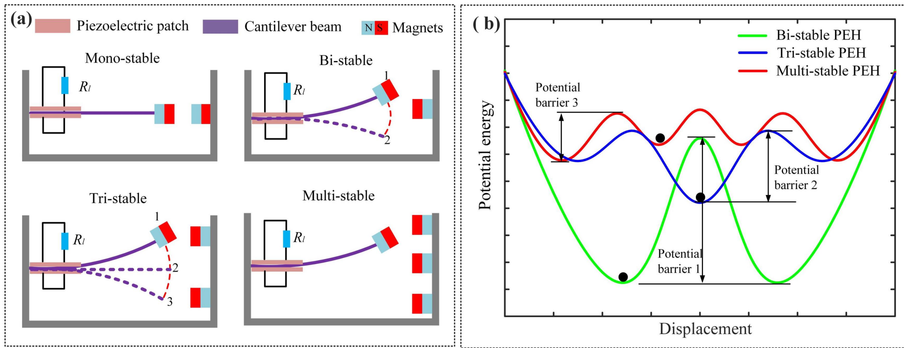

Figure 13: Magnetically coupled multi-stability: (a) typical configuration of mono-stable, bi-stable, tri-stable and multi-stable harvesters, (b) corresponding potential energy of different configurations.

stable equilibrium positions will appear in the potential well, as shown in Fig. 13(b). If there are two external magnets with repulsive forces, tri-stability with three stable equilibrium positions will appear. If more external magnets with either attractive or repulsive forces are adopted, multi-stability can be realized. From Fig. 13(b), it can be observed that with the increase of stable positions, normally the potential barrier among two stable positions will decrease. In addition, when these harvesters are employed in rotational motion, it can be noticed that the gravity component from Eq. 24 contributes to the time-varying potential wells as explained in Fig. 14(c), which means that even low rotational excitation from wind turbines or low-speed rotational machines can trigger the inter-well oscillation for rotational energy harvesters.

Some research works utilized multi-stability to enhance energy harvesting in rotational motion. Zhang *et al.* explored a bi-stable energy harvester on the rim of a vehicle wheel, and they experimentally investigated the influence of the rotational radius on the energy harvesting performance in real-vehicle tests [119]. In addition, stochastic resonance was used to improve the efficiency of energy harvesting in rotational motion. Later, Mei *et al.* proposed a symmetric tri-stable energy harvester to harness rotational energy with the aim to power a Tire Pressure Monitoring System (TPMS), as shown in Fig. 14(b) [123]. In order to address the issue of efficiency energy harvesting at ultra-low frequencies, the same authors developed a quad-stable harvester, as shown in Fig. 14(c) [152]. Compared with the bi-stable and tri-stable energy harvester, the performance was dramatically boosted especially at 60 - 180 rpm (1 – 3 Hz). The reason is that the low potential barrier of the multi-stable energy harvester makes it easier to achieve inter-well oscillations via time-varying potential wells. In summary, combining the multi-stability and time-varying potential wells caused by rotational motion is an effective way to improve the efficiency of energy harvesting in rotational motion.

3.3. Gravitational field

For REH, the gravitational field can be used as a continuous exciting force especially for the beam-type harvesters or harvesters using eccentric proof mass. When a harvester is installed in a non-horizontal plane, the piezoelectric beam is subjected to

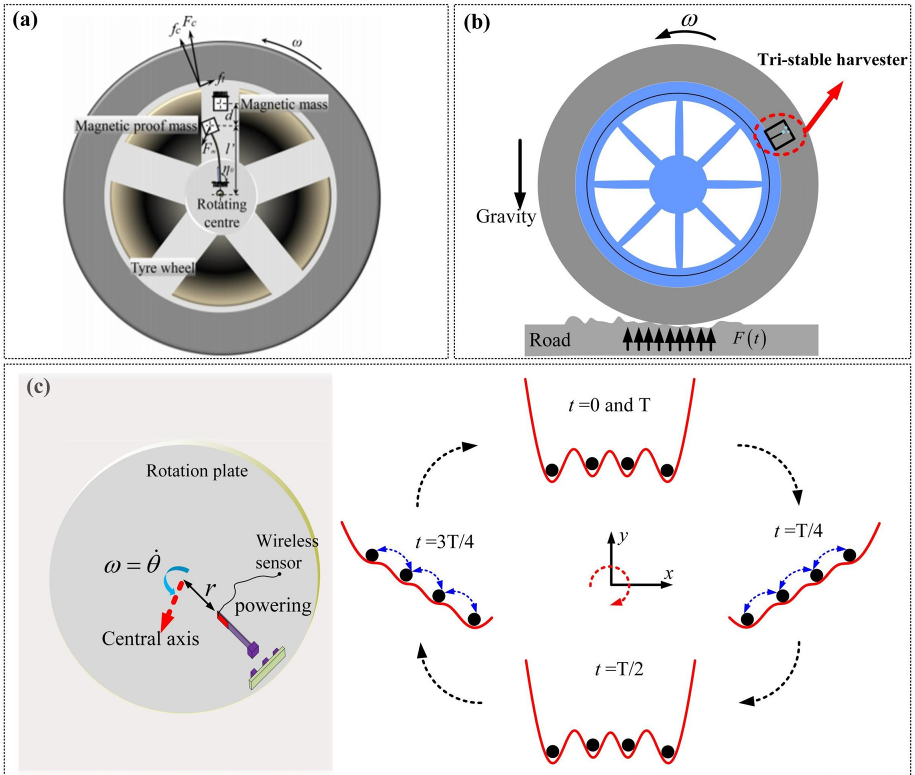

Figure 14: Harvesting rotational energy via multi-stability, (a) a bi-stable energy harvester installed on rim of vehicle wheel [119], (b) a tri-stable energy harvester in tire for powering TPMS [123], (c) enhancing the output power in low-frequency rotational motion via quad-stability [152].

periodic vibration excitation from the gravity field acting on the tip mass. The governing equation can be written as [123]

$$M_e\ddot{x}(t) + C\dot{x}(t) + (K_e + K_c\dot{\theta}^2)x(t) + \chi\ddot{\theta} - \vartheta_p v(t) + F_m = -\Gamma g \sin(\dot{\theta}t) \tag{25}$$

$$C_p\dot{v}(t) + R_l^{-1}v(t) + \vartheta_p\dot{x}(t) = 0 \tag{26}$$

where M_e, C, K_e are the equivalent mass, mechanical damping and equivalent stiffness of the piezoelectric beam, respectively, K_c is the coefficient related to the centrifugal force, χ is the coefficient related to the angular acceleration, C_p and ϑ_p are the capacitance and electromechanical coupling coefficient, respectively, $v(t)$ is the output voltage, R_l is the load resistance, F_m is the magnetic force corresponding to multi-stability and Γg is the gravity-related excitation term.

Four representative structures of energy harvesting in rotational motion are illustrated in Fig.15. When a plate rotates in the vertical plane, the gravitational force on the tip mass of a cantilever beam mounted on the rotating plane acts as a periodic excitation force to enforce the beam vibration, as shown in Fig.15(a). Based on this idea, Khameneifar *et al.* developed a beam-type piezoelectric harvester for rotary motion applications [111]. 6.4 mW output power was obtained at 138 rad/s using a PZT beam with the dimension of $51 \times 38 \times 0.13$ mm. Febbo *et al.* proposed a two-degrees of freedom (2DoF) beam-type energy harvester, as shown in Fig.15(b) [125], in which the gravity of tip mass enforces the beam. An output power of 26-105 μW over the range of 50-150 rpm was obtained. Fig.15(c) shows a disk-swing driven energy harvester proposed by Nezami *et al.* [68]. When the rotational speed is low, the orientation of the gravity-induced disk is toward the ground, but the orientation of the piezoelectric beam is changing due to the rotational motion. Thereby the relative motion between them enforces the harvester to generate electrical energy. As shown in Fig. 15(d), Wang *et al.* investigated a flex-compressive energy harvester aiming to power a wireless sensor in jet engines [142]. The periodic force from the gravity is the exciting force to compress the piezoelectric structure to generate electrical energy.

In addition, for the magnetically coupled nonlinear energy harvesters in rotational motion, the magnetic force may result in multi-stable potential functions. As stated

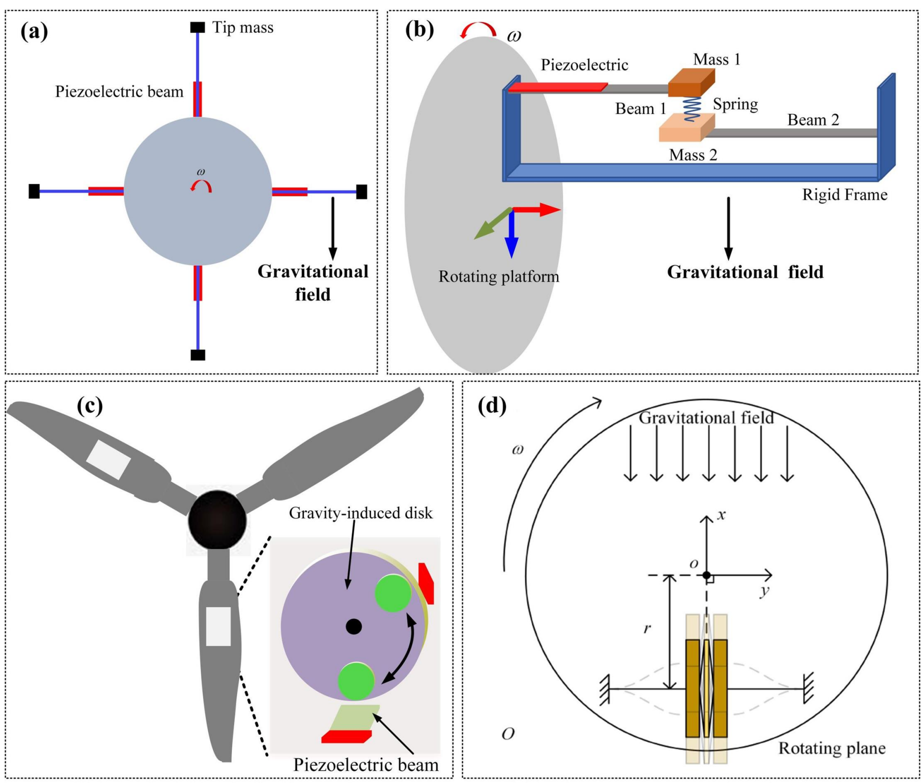

Figure 15: Harvesting rotational energy via gravitational field, (a) a linear energy harvester in rotational motion, (b) a 2DoF cantilever beam-type energy harvester in rotational motion aiming to power wireless sensor in a wind turbine [125], (c) a gravity-induced energy harvester in wind turbine [68] (© IOP Publishing. Reproduced with permission. All rights reserved), (d) a flex-compressive energy harvester aiming to power a wireless sensor in jet engines [142].

in Section 3.2, the gravity field can lead to time-varying potential wells which are beneficial for inter-well oscillations, resulting in high output voltage. Related work combining the advantages of the gravitational field and multi-stability can be found in Ref. [121]. In summary, the gravitational field can be a periodic excitation force to realize the rotational energy harvesting in the vertical plane, and the excitation frequency is equal to the rotational frequency.

3.4. Centrifugal and Coriolis forces

The centrifugal force acting on a rotating device is always oriented outwards in the radial direction. This force is proportional to the square of the rotational speed and can influence the dynamic performance and the harvesting capability, especially at high rotational speeds. When the plane rotates at a rotational speed $\overrightarrow{\omega}$, the centrifugal force F_c can be defined by

$$F_c = -M_e \cdot \overrightarrow{\omega} \times (\overrightarrow{\omega} \times \overrightarrow{r}) \tag{27}$$

where M_e is the equivalent mass, and $\overrightarrow{r}$ is the mounting position vector of the harvester.

In addition, when the energy harvester has the relative motion in the rotational reference frame, the Coriolis force also appears. The Coriolis force was firstly revealed in 1835 by the French scientist Gaspard-Gustave de Coriolis when investigating water wheels [217]. This force is perpendicular to the rotational angular velocity and to the velocity of the objects in the rotational reference frame. The Coriolis force F_{cor} can be calculated by

$$F_{cor} = -2M_e \cdot \overrightarrow{\omega} \times \overrightarrow{v} \tag{28}$$

According to Eqs. (27) and (28), it can be concluded that the centrifugal force F_c depends on the position vector $\overrightarrow{r}$ of the energy harvester, while the Coriolis force F_{cor} is decided by the harvester velocity $\overrightarrow{v}$ measured in the rotational reference frame. Typically, $\overrightarrow{v}$ is relatively small compared to the rotation velocity, and the resulted Coriolis force is less dominant compared to the centrifugal force.

In the literature, the centrifugal force is mostly associated with beam-based rotational energy harvesters (Category II). When these harvesters are mounted on a rotational host, the centrifugal force acting on the tip mass of the harvester always points outward in the radial direction. For different installation configurations, such as the forward configuration, inverse configuration or angular mounting configuration, the centrifugal force can alter the resonant frequency of the piezoelectric beam to achieve a self-tuning energy harvester, but the mechanical functions are different. To reveal the mechanism of tunable stiffness, two different configurations including a forward harvester and an inverse harvester are selected and shown in Fig. 16(a) and (b) respectively. Here L is the length of the piezoelectric beam; r is the rotational radius from the installation mount to the rotating centre; θ is the angle between the direction of the centrifugal force acting on the tip mass when the beam is deformed and the length direction of the beam when it is not deformed. This angle is generated by gravity and the centrifugal force applied on the beam. The centrifugal force F_c is divided into the transverse component F_{c1} and axial component F_{c2}. For both forward and inverse configurations, the transverse component F_{c1} contributes to the transverse vibration of the piezoelectric beam. In addition, for the forward configuration the axial component

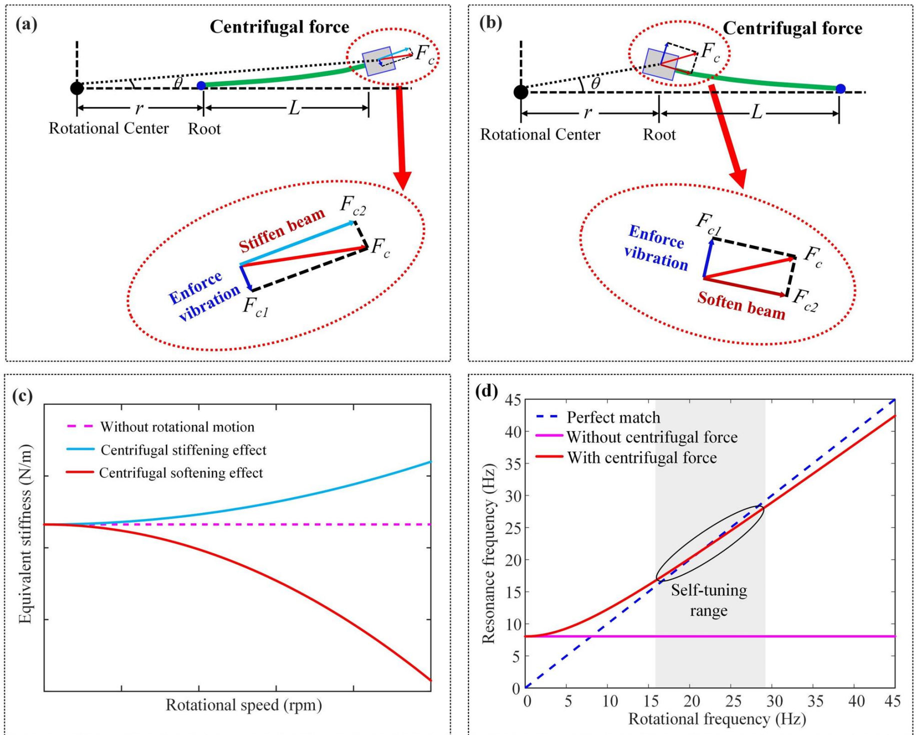

Figure 16: Use of the centrifugal force to enhance energy harvesting performance. (a) the centrifugal force in forward harvester configuration [218], (b) the centrifugal force in inverse harvester configuration[218], (c) the variation of beam's equivalent stiffness via centrifugal stiffening effect and centrifugal softening effect , and (d) the principle of self-tuning by centrifugal stiffening effect.

F_{c2} can stiffen the piezoelectric beam corresponding to the centrifugal stiffening effect, however, for the inverse configuration the axial component F_{c2} can soften the piezoelectric beam corresponding to the centrifugal softening effect. Fig. 16(c) illustrates the effect of centrifugal force on changing the equivalent stiffness of the piezoelectric beam via the centrifugal stiffening effect and centrifugal softening effect, respectively.

Recently, many studies employing the centrifugal force have been conducted to broaden the effective frequency range or to enhance the energy harvesting performance in low-frequency rotational motion. The utilization of centrifugal stiffening effect has been applied to obtain a passively self-tuning harvester. The principle of self-tuning by the centrifugal stiffening effect is shown in Fig. 16(d). The increase of the rotational speed (increased centrifugal force) contributes to increasing the resonance frequency of the beam-type harvester simultaneously. When the configuration parameters are designed at optimized values, a self-tuning range can be obtained, enhancing the harvester operational frequency range. The underlying mechanism is that when the rotational speed increases, the centrifugal force increases proportionally; the equivalent beam stiffness is enhanced consequently. Thus, the corresponding resonant frequency is increased, and self-tuning is obtained. For example, Gu and Livermore developed a passively-tuned beam-type harvester as shown in Fig. 17(a) [106]. With increasing rotational speed, the beam's stiffness increases to ensure the harvester operates at or near its resonance frequency, and their experimental results demonstrated the passive-tuned frequency range is 11 Hz. Later, Mei *et al.* proposed a theoretical guidance for designing nonlinear harvesters using the centrifugal force [138]. They experimentally validated that the rotational radius can alter the self-tuning range. An impact self-tuning harvester consisting of a piezoelectric beam and a flexible drive beam was proposed by Gu and Livermore as shown in Fig. 17(b) [126]. The axial component of the centrifugal force stiffens the flexible beam to tune its resonant frequency; thus, the resonance frequency can track the driving frequency to achieve the self-tuning effect. The deformation of flexible beam impacted the piezoelectric beam to effectively harvest energy over a wide frequency range. Liu et al. [143] designed a self-tuning harvester employing the centrifugal force and a stretchable spring. A schematic is presented in Fig. 17(c) to illustrate the mechanism. This centrifugal force changed the length of a string in the harvester, leading to changing the equivalent length of a beam. The resonance frequency was then passively changed. Although the self-tuning effect enhanced the effective frequency range, the drawback of this design is that in order to retain the gap for the slider motion, the piezoelectric patch cannot be installed at the

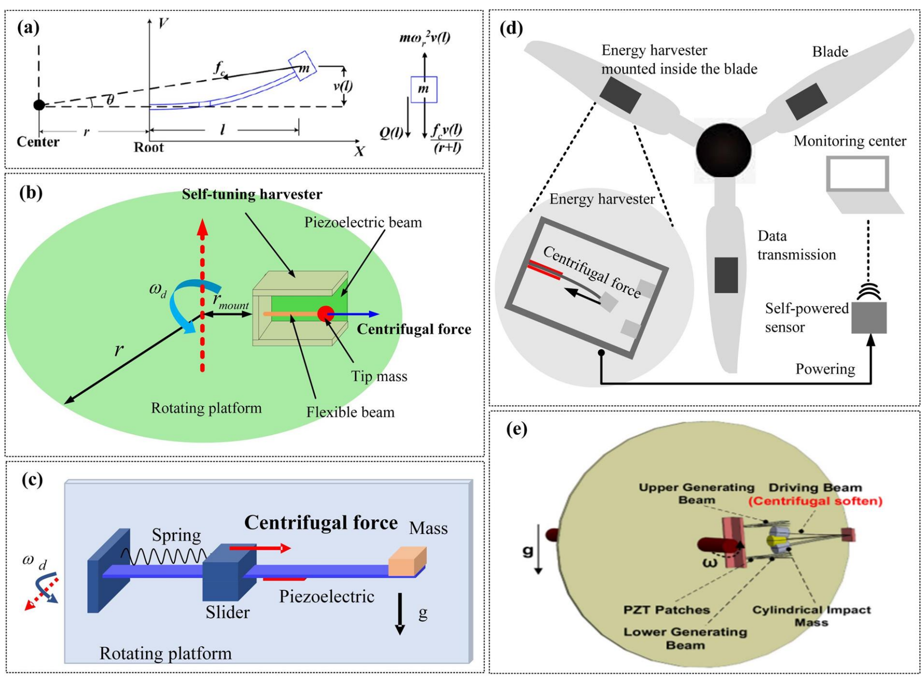

Figure 17: Self-tuning effect using the centrifugal force. (a) a passive-tuned energy harvester [106], (b) an impact energy harvester with self-tuning effect [126] (© IOP Publishing. Reproduced with permission. All rights reserved), (c) a string-model self-tuning energy harvesting, (d) an inverse energy harvester for ultra-low frequency REH via the centrifugal softening effect [218], (e) an impact energy harvester using the centrifugal softening effect [145].

end of the beam, which in turn reduces the output voltage.

On the other hand, the centrifugal softening effect is also an effective alternative to increase output power. To enhance energy harvesting performance under ultralow-frequency rotational motion, an inverse harvester was reported by Mei *et al.* [218]. A comprehensive theoretical model was established to explain the centrifugal softening effect. The experimental results illustrated that due to the centrifugal softening effect, the output voltage was enhanced significantly over the speed range of 75-120 rpm (1.2-2 Hz). Later, Fang *et al.* [145, 146] developed an impact piezoelectric harvester via the centrifugal softening effect as shown in Fig. 17(e), in which the deformation of the driving beam caused by gravity and the centrifugal force impacts the upper and lower generating beams, thus, the rotational energy was converted into electrical energy. Similarly, Zou *et al.*[162] explored a magnetically coupled 2DoF harvester to harvest rotational energy, in which the gravity and centrifugal force both promote energy conversion for a pair of inverse piezoelectric beams.

3.5. Flow-induced rotational energy harvesting

Rotational motion can be converted from fluid flow, as is widely used in large hydro-power generators and wind turbines. For REH, miniaturized turbines have been developed using different conversion mechanisms. Two classes of turbines have been studied: the Horizontal Axis Wind Turbine (HWAT) and the Vertical Axis Wind Turbine (VWAT). It is well-known that the incoming flow power can be expressed as

$$P_f = \frac{1}{2}\rho A V^3 \tag{29}$$

where ρ is the fluid density, A is the area facing the flow and V is the incoming free-stream velocity. The wind power is proportional to the area and proportional to the cube of its velocity. Thus, the larger the device and the incoming flow speed, the higher its intrinsic power. For a conventional HWAT or VWAT, the generated power is

$$P_e = \frac{1}{2}C_p \eta \rho A V^3 \tag{30}$$

where C_p is the power coefficient, which is associated with the turbine efficiency, and η is the efficiency of the entire system including gearboxes, generators and other components. The theoretical maximum value of $C_p = 16/27$, according to the Betz limit. Besides the similar issues faced by large and mega-scale turbine, such as start-up speed, mechanical and electrical losses, the small devices face also the issue of scaling, which brings the turbines efficiency down due to higher viscous losses.

Table 3 present some information on investigated HAWTs and VAWTs. Electromagnetic transduction is most popular for the HAWT design, although some concepts utilised piezoelectric beams, electrostatic and triboelectric transduction. The number of blades for small-scale HAWTs is an important parameter for device performance. In [91], Bansal *et al.* have shown that the peak performance depends on the number of blades; moreover, for the considered design, a higher number of blades led to a low value of the peak performance velocity. The VAWT concepts presented in the second part of Table 3 utilise the Savonius turbine, for which the maximum power can be estimated by Eq. 29 where $A = width \times height$. Han *et al.* [81] used different orientations of

Table 3: Small-scale HAWT and VAWT for low-induced rotation energy harvesting.

HWAT					
Reference	Year	Transaction mechanism[a]	Dimensions[b] (mm)	Air speed (m/s)	Maximum Power (mW)
Federspiel & Chen [92]	2003	EM	⌀100	2.5	8
Hirahara *et al.* [93]	2005	EM	⌀500	9.4	2965
Holmes *et al.* [94]	2005	EM	⌀7.5	40	1.1
Priya *et al.* [173]	2005	PE	$60 \times 20 \times 0.5$	4.47	10.2
Priya [154]	2005	PE	$60 \times 20 \times 0.6$	4.47	7.5
Rancourt *et al.* [95]	2007	EM	⌀42	11.8	130
Myers *et al.* [174]	2007	PE	$96 \times 254 \times 127$	4.5	5
Bansal *et al.* [91]	2009	EM	⌀20	4.3	10
Xu *et al.* [96]	2010	EM	⌀152	4.5	18
Carli *et al.* [97]	2010	EM	⌀63	16.8	10
Howey *et al.* [80]	2011	EM	⌀32×50	7	2.5
Kishore *et al.* [219]	2014	PE	$100 \times 80 \times 65$	1	0.45
Fu & Yeatman [157]	2015	PE	⌀37×18	4	0.74
Perez *et al.* [181]	2016	ES	40×10	10	1.8
Nezami *et al.* [68]	2019	PE	⌀102	40 rpm	2.2
Zhang *et al.* [177]	2020	ES	⌀30	4	0.71
VWAT					
Reference	Year	Transduction mechanism	Width & Height (cm× cm)	Air speed (m/s)	Maximum Power (mW)
Karami *et al.* [155]	2013	PE	16×17.5	2.0	4
Avirovik *et al.* [156]	2015	PE	16.5×23	4.0	3
Bethi *et al.* [75]	2019	N/A	⌀ 50×2.5	18	88471

[a] EM - Electromagnetic; PE - Piezoelectric; ES - Electrostatic.
[b] The dimension information was collected from the literature with some dimensions not reported.

the Savonius turbine, geometric parameters and a number of blades, and demonstrated that the turbines with 3 blades performed better than those with 2 or 4 blades.

3.6. Other mechanisms

Some concepts and mechanisms which are not included in previous sessions are discussed here. Various mechanisms have been proposed to harvest ultra-low frequency and multi-direction kinetic energy, as shown in Fig. 18. A vortex-induced-vibration harvester was developed to realized self-powered sensing for structural health monitoring of a marine riser, as shown in Fig. 18(a) [198]. Ocean currents and waves excite the impeller to generate the rotational motion. The rotational motion was then converted into electricity using electromagnetic transduction. A novel pendulum-type triboelectric energy harvester in Fig. 18(b) was proposed to power a sensor for water quality monitoring using ocean wave energy [191] . The operational principle is that the ocean wave enforces the swing motion of a mass block which is connected with a rotor, thus the friction between the rotor and stator can generate electric energy based on the triboelectric effect. Fig. 18(c) shows a rolling mass driven energy harvester consisting of a metal ball and four piezoelectric beams with a tip magnet at the beam's free end [220]. Since the metal ball can move in any direction, the magnetic force acting on the ball leads to the vibration of the piezoelectric beams. A tunable rotational energy harvester,

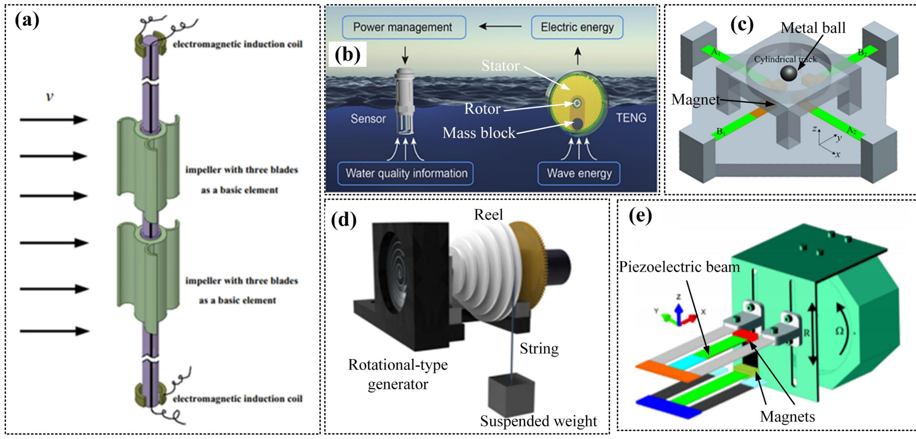

Figure 18: Other mechanisms for energy harvesting: (a) Ocean current energy conversion [198], (b) Ocean wave energy harvesting for powering wireless sensors [191], (c) an energy harvester for various mechanical motions [220], (d) a tunable energy harvester for low frequency vibration [197], (e) E-shape multi-beam energy harvester [129].

as presented in Fig. 18(d), was reported to harness translational base excitation with low frequency and large amplitude [197]. The translational motion of the suspended weight can be converted into rotational motion to generate electric power. Additionally, by manipulating the reel's size, the harvester resonant frequency can be altered. In order to solve the challenge in harnessing ultra-low frequency rotation (0.5 to 3 Hz), an E-shape multi-beam piezoelectric energy harvester with nonlinear characteristics was numerically and experimentally studied, as shown in Fig. 18(e) [129]. The interaction between the piezoelectric beams can broaden the whole frequency range, as each beam has its own effective frequency range. Additionally, this structure also utilizes the centrifugal softening effect and multi-degrees of freedom to further enhance the energy harvesting performance.

Differing from the beam-type rotational energy harvesters, this subsection reviews some energy harvesters designed for ultra-low frequency or irregular motions. The above-discussed harvesters provide inspiration in designing more effective or high-efficiency energy harvesters. Also, these harvesters provide guidance for harvesting other types of motion, such as translational motion, multi-direction motion, flow-induced motion.

4. Applications and discussions

Self-powered sensing is expected to be the ultimate solution for many Internet of Things applications. REH has been gaining increasing attention in providing sufficient power for different sensing applications. In this section, applications on wearable devices [70, 101, 102, 187], automotive and railway systems [119, 151, 170, 221], rotating machinery and renewable energy systems [68, 111, 125, 142, 172] and environmental monitoring [76, 86, 86, 88, 157] will be reviewed and discussed in details in terms of how REH has been tailored for these applications. The variation and characteristics of the different energy sources will be analyzed.

4.1. *Wearable & implantable devices*

There are abundant energy sources from human motion, such as arm swing, shock excitation, heart motion etc [59, 72, 222]. In terms of wearable or implantable devices, the major considerations are the dimensions and weight of the harvester in addition to the energy harvesting capability. Moreover, human motions are typically of random low-frequency form which is challenging for micro-devices to adapt to. The energy that can be converted from the human body by energy harvesting devices could be very limited, which means more efficient conversion mechanisms are critical to fulfil the application requirements. Fig. 19 summarises some developed rotational harvesters in harnessing human motion.

Using pendulum structures to covert human random motions into rotation is one of the popular mechanisms, as shown in Fig. 19(a), (b) and (e). Different conversion mechanisms including piezoelectric [41], electromagnetic [39, 101] and electrostatic mechanisms [184, 224] have been integrated with the pendulum structures. Piezoelectric transducers are typically stimulated either by non-contact magnetic forces from the pendulum [41] or by direct impacts due to the relative motion between different body parts [40, 223]. Piezoelectric transducers are typically simple in structure and ideal for low-frequency applications when combined with the frequency up-conversion mechanism, as discussed in Section 3.1. For electromagnetic harvesters, the low output voltage (around or below 1 V, creating difficulties for rectification) due to the low-rotational frequency of the pendulum is a challenge in wearable device applications. This issue has been reported in Refs. [39, 101, 104]. Fu *et al.* developed a rotational energy harvester using footstep-induced airflow and a micro-turbine with an electro-

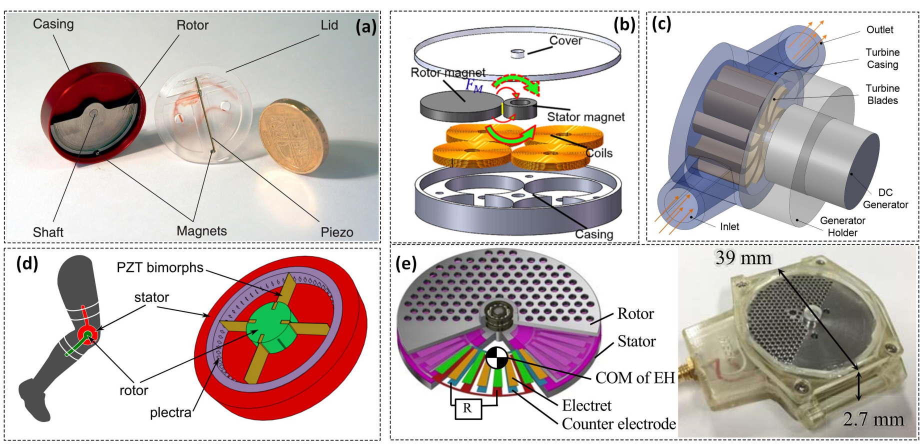

Figure 19: Typical rotational energy harvesters used for wearable devices. (a) Pendulum-based piezoelectric energy harvester [41], (b) pendulum-based electromagnetic energy harvester [101], (c) micro-turbine energy harvester using footstep-induced airflow [43], (d) Impact-based energy harvester using upper and lower leg relative motions [223], and (e) pendulum-based electrostatic energy harvester [224].

magnetic generator [43], as shown in Fig 19(c). The low output voltage issue is avoided due to the high airflow speed generated by footstep impacts on air cushions in shoes. Similarly, Xie and Cai adopted a special trapezoidal slider mechanism (equivalent to the rack and pinion mechanism) to amplify the foot-strike motion into high frequency rotation [225]. Although the system reported is quite complex, significant amounts of power (about 1 W) were obtained. Electrostatic conversion is ideal in developing micro-systems. Electret-based harvesters have been reported in REH, as shown in Fig. 19(e). Electrets are mounted on the pendulum and charges can be generated on the electrodes on the harvester stator [184, 224]. High-performance electret fabrication and harvester assembly could be the challenges for using electrostatic conversion in harnessing low-frequency human motions.

For self-powered sensing, monitoring motion accelerations (e.g. body motion [46, 72], footsteps [43]) and temperature [46] are the straight-forward application scenarios. This information can be useful in detecting health conditions, but more biomedical information can be collected by self-powered wearable devices with the development of the current technology. Miniaturization, power generation capability and system-level development are the major challenges in lifting the current research impacts to the next level.

4.2. Automotive and railway systems

Rotational energy is widely acquirable in automotive and railway applications, where many sensing functions are in demand, including monitoring conditions of engines [226], transmission systems [227] or driver safety [228]. Rotational energy in such systems normally presents at high frequencies with a wide bandwidth, and system dimensions are not the major constraints in many scenarios. However, due to the high power consumption of sensing functions typically required for precise condition monitoring, the power generation capability is one of the major design priorities in energy harvesting for these applications.

Fig. 20 provides several representative rotational energy harvester designs for automotive and railway system applications. Tire pressure monitoring systems (TPMS) are one of the widely studied areas where rotational motions, periodic deformation, centrifugal force and gravity are available for energy harvesting, as shown in Fig. 20(b), (d) and (e). Guo *et al.* developed a hexagon-shaped triboelectric energy harvester and used the periodic deformation of tires to generate electricity, as shown in Fig. 20(b) [85]. One of the challenges of using triboelectric-based structures in such applications is the system long-term durability. Roundy and Tola developed an offset pendulum-based energy harvester for TPMS, as shown in Fig. 20(e) [108]. Piezoelectric transduction was combined with nonlinear dynamics to directly power an RF transmission every 60 s over a wide speed range (10 to 155 kph). Tornincasa *et al.* presented a wideband energy harvester for TPMS using magnetic levitation [56]. Zhang *et al.* introduced a bistable piezoelectric harvester into a rotating wheel and used the centrifugal force and gravity associated with rotation to stimulate the harvester to create stochastic resonance [151]. Wu *et al.* used a seesaw structure with magnets mounted on the wheel hub and a fixed magnet mounted on the brake caliper to create alternating forces on the seesaw structure due to rotation, as shown in Fig. 20(d) [105]. The system operated effectively over a wide speed range (36 μW peak at 26-115 km/h). Rui *et al.* developed a

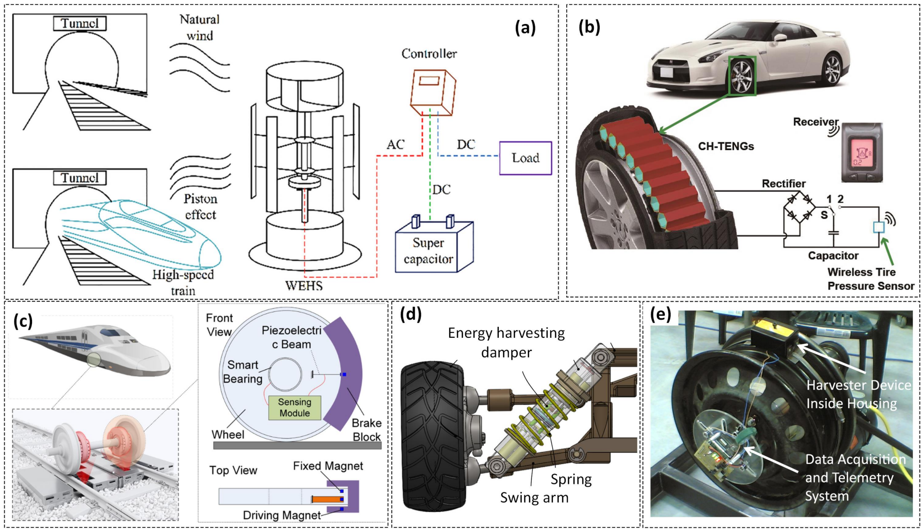

Figure 20: Typical rotational energy harvesters used for automotive and railway systems. (a) Wind energy harvester using train-induced airflow [103], (b) triboelectric rotational energy harvester for tires [85], (c) coupled electromechanical nonlinear dynamics for rotational energy harvester on train wheels [148], (d) energy harvesting from suspension systems using a ball-screw structure [229], and (e) offset pendulum-based nonlinear harvester for TPMS [108] (©IOP Publishing. Reproduced with permission. All rights reserved).

three-beam impact-driven piezoelectric harvester for self-powered TPMS [230]. Gravity combined with rotational motion was used to create impact events among beams to effectively harness low-frequency rotational energy sources.

There are many publications in the literature to harness rotational energy for TPMS to collect tire deformation energy [141, 170, 175, 176, 231], and to harvest rotation from wheels using self-tuning or other nonlinear mechanisms [60, 132, 153]. Since this paper focuses only on REH, more publications on energy harvesting in general for TPMS can be found in these comprehensive reviews [232, 233]. It is worth mentioning that although self-powered TPMS are important to ensure vehicle safety over the long term, current battery technology can already support typical TPMS for a duration long enough for the lifetime of tires [234]. Therefore, power supply is not a critical bottleneck for TPMS. However, self-powered sensing is still in urgent demand in many other automotive systems [235, 236], such as conditions of transmission systems, engines or emission systems, where more detailed operational conditions are required to be recorded. As shown in Fig. 20(d), Xie *et al.* developed an energy harvesting damper using a ball-screw structure to covert the translational motion of the suspension system into rotation [229]. This device not only fulfils the function of energy recovery, but also passively dampens the vehicle vibrations.

Compared to automotive applications, rail trains are also ideal hosts for rotational energy harvesters to realize self-powered monitoring. Fig. 20(a) presents an airflow energy harvester using turbines to collect wind energy induced by high-speed trains. A Savonius vertical-axis wind turbine was adopted and installed alongside the rail tracks to generate electricity when trains pass by and to power either tunnel lighting or sensing electronic components. Fu *et al.* proposed a solution to use the relative motion between train wheels and the brake block to excite a piezoelectric transducer using magnetic plucking, as shown in Fig. 20(c), and the harvested power could be used for monitoring the conditions of rolling bearings in wheels [148]. Gao *et al.* adopted the pendulum structure with a gear train and electromagnetic transduction in rail applications to harness low frequency train vibrations (around 3 Hz) [78]. A self-powered sensing unit including a brake pressure sensor and an accelerator was implemented.

Due to the energy and space availability in both automotive and rail transport applications, REH solutions for self-powered sensing are more practical yet are still at an early stage of development. Such solutions could be of great importance in enhancing operational safety and reducing maintenance costs. Therefore, this field is expected to have a promising future in the coming decade.

4.3. Rotating machinery and renewable energy systems

Rotating machines, including electric motors, drilling or cutting machines, and wind turbines, require real-time and long-term monitoring to fulfil condition-based maintenance [237]. Harnessing the available energy in such cases to power embedded sensors will provide sustainable power supply solutions for long-term monitoring. Rotational energy in such applications typically distributes at frequencies relevant to the operation frequency of the machines, but the harvester dimensions or mounting locations can be limited. In addition, it might be difficult to find locations where anchor points enabling the necessary relative motion (rotor vs stator) are accessible.

Different rotational energy harvesters have been developed for rotating machinery and renewable energy systems, and the representative designs are illustrated in Fig. 21. Nezami *et al.* developed a piezoelectric-based rotational energy harvester for rotating turbine blades using gravity and the magnetic plucking method, and the collected energy can be used to monitor the structural integrity of wind turbines [144]. Such a gravity-driven system is deal for situations where the rotational speed and rotation radius are small enough that the generated centrifugal force is comparable to the gravitational force [55], whereas when the rotational speed is increased significantly, the force variation on the oscillating mass due to the gravity will be marginal, and the mass oscillation will be reduced. Using a similar idea, Zou *et al.* used two magnetically coupled piezoelectric beams with free ends pointing to the rotating shaft central axis [130], as shown in Fig. 21(a). The centrifugal force, gravity and the magnetic forces are combined to create nonlinear dynamics ideal for broadband operation, as discussed in Section 3. Fu *et al.* used the rotary-translational motion acquired from ultra-low frequency turbine tower motions (<1 Hz) to implement effective energy harvesting for condition monitoring, as shown in Fig 21(b) [238]. Bi-stability was obtained by introducing two tethering magnet underneath the rolling path of a ball magnet.

For high rotating speed cases, electromagnetic conversion has its advantage, especially when there are less demanding dimensional constraints [147]. Trimble *et al.* adopted an electromagnetic energy harvester similar to conventional electromagnetic generator with magnets on the rotor and coils on the stator to harvest rotational oscillations [79]. Also using electromagnetic conversion, Zhang *et al.* developed a smart bearing which has an embedded rotational energy harvester, as shown in Fig 21(c) [83]. A Halbach ring was adopted to enhance the magnetic flux density within the harvester.

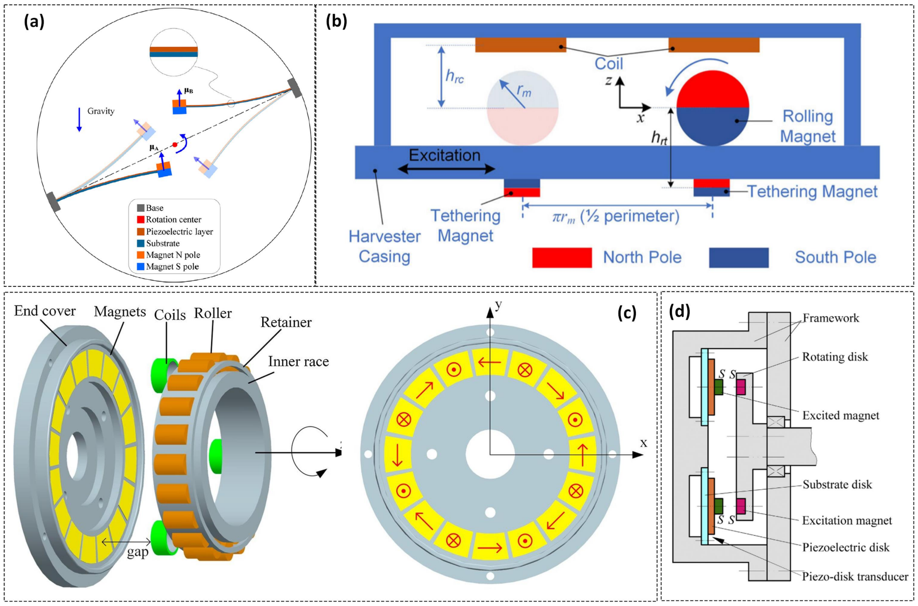

Figure 21: Typical rotational energy harvesters used for rotating machinery and renewable energy systems. (a) rotating energy harvesting using two inverted piezoelectric beams [130], (b) ultra-low frequency energy harvesting from turbine tower motion using rotary-translational motion [238], (c) smart bearing with an electromagnetic generator [83], and (d) piezo-disc rotational energy harvester using rotary magnets [160].

87.5mW output power was obtained at 600 rpm with a ⌀70 mm magnetic rings and three ⌀12 mm × 23 mm coils. The output power is sufficient to energize a wireless sensor to monitor the bearing vibrations or temperature. Kan *et al.* used a similar idea and integrated piezoelectric transducers into a rotational energy harvester instead of coils, as shown in Fig 21(d) [160]. A simpler structure is realized using piezoelectric discs. This solution would be useful in cases where available system dimensions are limited. In engine or gear train shafts where torque oscillations are abundant, using the inertia of the un-anchored component to create relative motion is a potential solution; this is not, however, possible for steady, continuous motion. Instead, most mechanisms have used gravity acting on the un-anchored component to create relative motion using just one anchor.

In rotating machines and renewable energy systems, one of the challenges lies in schedule-driven maintenance which is costly and inefficient. Exploiting the rotational energy in these settings to power distributed or embedded sensing electronics will enable a paradigm shift from schedule-driven to a condition-based maintenance. The available energy is likely to be distributed at frequencies related to the operational frequencies and these frequencies are relatively high compared to those in other applications. Anchor locations to mount the harvester and create the needed relative motions for energy harvesting could be the challenge in some cases, where rotors and stators are not closely spaced, especially at high rotating speeds.

4.4. Environmental monitoring

Rotational energy is not directly exploitable in most cases in the natural environment. However, it can be converted from other forms which can be abundant, including airflow and wave motion. Therefore, structures, such as pendulums or micro-turbines are suitable choices. Due to the randomness of environmental energy sources, it is more challenging to effectively harvest those types of energy. On the other hand, the sensing requirement in environmental monitoring is not as demanding as in other applications. Therefore, self-powered sensing using rotational energy harvesters are achievable in environmental monitoring.

Some example work has been summarized in Fig. 22. Wu *et al.* introduced a miniaturized windmill-based harvester for self-powered monitoring of forest fire, as shown in Fig. 22(a) [88]. An average output power of 3 mW was obtained at 3 m/s airflow speed. Similarly, Deng *et al.* developed a multi-source energy harvesting system with a vertical axis energy harvester [239]. A sound monitoring system was fully powered by the developed harvester. Similarly, Wang *et al.* integrated triboelectric and electromagnetic transduction in the harvester to implement a self-powered wind speed sensor, as shown in Fig. 22(c) [86]. A humidity/temperature sensor was powered by converting wind energy at 5.7 m/s. Karami *et al.* developed a low-speed wind energy harvester using a vertical turbine combined with mangetic coupling and piezoelectric transduction, as shown in Fig. 22(d) [155]. Bi-stability was used to enhance the harvester performance over a wide wind speed range. Fu and Yeatman developed an airflow energy harvester using a micro-turbine with piezoelectric transduction, as shown in Fig. 22(e) [157]. A reduced cut-in speed was obtained using a self-regulating mechanism, and the harvester can be used to monitor conditions in ventilation systems in smart building.

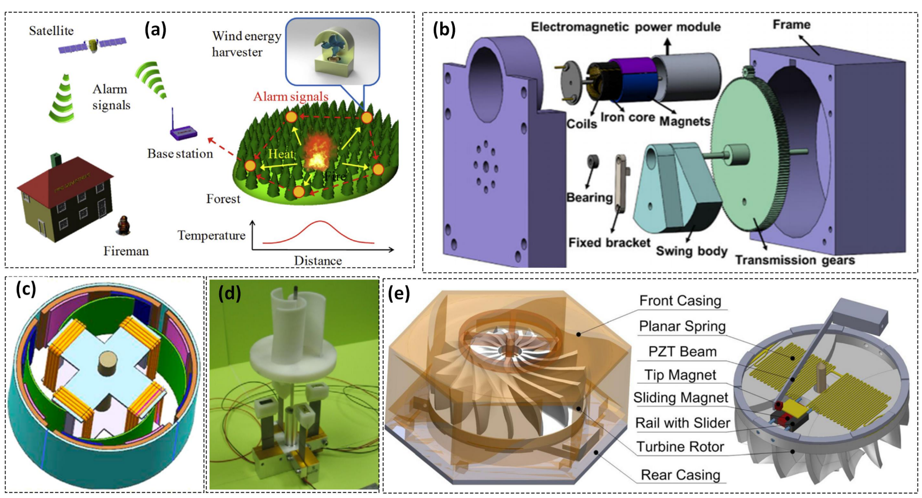

Figure 22: Typical rotational energy harvesters used for environmental sensing. (a) Forest fire monitoring using turbine-based rotational energy harvester [88], (b) ocean wave energy harvester using a pendulum structure for ocean condition monitoring [76], (c) triboelectric and electromagnetic hybrid harvester for wind speed sensing [86], (d) parametrically excited nonlinear piezoelectric turbine [155], and (e) airflow energy harvesting using micro-turbine with piezoelectric transduction [157].

Other turbine-based airflow energy harvesters were reported using electrostatic [181] and electromagnetic transduction [80].

Ocean waves are a possible energy source for self-powered sensing applications. Li *et al.* developed an ocean wave energy harvester using a pendulum structure and a gear train, as shown in Fig. 22(b) [76]. 0.13 W output power was obtained from ultra-low frequency wave motions, and the output power was used to monitor ocean conditions and power warning lights. Other systems have been reported in the literature using a ball-and-rail mechanism [109] and a rack-and-pinion mechanism [240]. Ultra-low frequency wave motion is the challenge, but the dimensions can be increased to implement more complicated mechanisms and to enhance the output power.

Due to the differences in various environmental conditions and lack of direct access to rotational energy, different mechanisms are necessary to tailor harvesters for specific applications, which may result in the lack of generality in different solutions. In addition, compared to other applications, harvesters developed for environmental sensing are limited. This shows the potential of further investigation in this area.

4.5. Comparison and discussions

It is worth comparing the characteristics and existing solutions for different applications of rotational energy harvesters. Based on the discussion in the above-mentioned applications, a comparison is provided in Table 4. In terms of the energy availability,

Table 4: Performance comparison for energy sources and developed rotational energy harvesters for different applications.

Characteristics	Wearable Devices	Automotive & Railway	Rotating Machinery	Environmental Sensing
Available Energy	Low-frequency 1-2 Hz; random; Non-continuous	Broadband; High acceleration	Narrowband; Abundant usable energy; continuous	Random; Not directly available; unstable
Dimension Requirement	Require miniaturization	Application-specific	Miniaturized	less confined
Anchor Availability	One Mounting Location	Rotor & stator available	Rotor & stator available	One
Harvesting Mechanisms & Configurations	Pendulum; Frequency up-conversion; Multi-stability	Multi-stability Micro-turbine; Translational-to-rotational conversion	Rotor & stator configuration; Gravity-based excitation	Micro-turbine; Pendulum
Ideal Transduction	Piezoelectric Electrostatic Triboelectric	Piezoelectric Electrostatic Electromagnetic	Piezoelectric Electrostatic Electromagnetic	All; Application-dependant
Estimated Output Power[a]	µW to mW	1 to 10 mW	10 to 100 mW	µW to mW
Relevant Publications	[41, 43, 101] [40, 184]	[103, 148, 151] [85, 229]	[68, 79, 130] [83, 160]	[76, 86, 88] [157, 239]

[a] These values are summarized from the literature, but specific designs can be out of these ranges.

the energy sources from automotive, railway and rotating machinery applications are abundant. However, in the automotive and railway applications, the frequency range of the available energy is more broadband, whereas the energy is more concentrated in certain frequencies in rotating machinery applications. In both the wearable devices and the environmental sensing applications, the available energy is in a random and low-frequency form, and it is more challenging to harvest energy from these cases.

In terms of device dimensions, wearable devices are the most size-sensitive, and miniaturization is necessary in most cases. In rotating machinery, sometimes dimensions are also a big concern when the available spaces are limited in systems including engines, and transmission systems where the assembly has already been compacted. In automotive and environmental sensing applications, the size constraints are different depending on specific application scenarios. Another important feature to compare is the anchor availability. For conventional electromagnetic generators, two mounting positions, for one rotor and one stator, are necessary to create relative motion between magnets and coils. However, this requirement would be impossible in some cases, where direct relative motion is inaccessible in a confined space. Human motions and environmental energy sources such as wave motions are examples. Inertial devices can be used to replace one anchor point, but only for cases of oscillating or otherwise variable rotation.

Based on the energy characteristics in different applications, different mechanisms, configurations and transduction types have been investigated and tailored for different operating conditions. The pendulum structure and frequency up-conversion are beneficial in low-frequency and random conditions including wearable devices and environmental sensing. Translational-to-rotational conversion mechanisms are useful to convert linear motions into rotation. This method can be applied in most cases where space constraints are less strict. Gravity and centrifugal force-based harvester designs are typically ideal for applications where the rotational speeds are in a range that those forces play equally important roles in system dynamics rather than one of them is dominant. Micro-turbines are useful in cases where fluid-flow are available. In general, multi-stability is useful in cases where broadband operation is required.

In terms of transduction, electromagnetic conversion is ideal for high-frequency conditions, because the output voltage at low frequencies might be too small to pass through bridge rectifier circuits. Triboelectric conversion is typically used in low-frequency cases. As triboelectric transduction requires two components to be in contact, there are risks of material damage or degradation at high operating frequencies. Piezoelectric and electrostatic transduction have a broader frequency operating range, and they are especially ideal for micro-scale devices due to their simplicity in structure and good compatibility with micro-fabrication. However, there are also concerns of material degradation of piezoelectric harvesters and requirement of electrets for electrostatic harvesters. The harvester output power in different applications varies significantly due to the difference in space availability and energy source characteristics. For instance, the output power from wearable energy harvesters ranges from μW to mW, whereas in automotive applications, the output can be as high as tens of mW. Some typical developments for each application are also provided in Table 4.

Looking forward, there are also many potential and critical applications for REH, including smart implants, micro/nano-robotics and embedded smart structures. Biomedical devices, such as pacemakers and drag delivery implants require reliable power supply for long-term operation. However, the current battery solution or the energy harvesting technology would not be able to fulfil the aim of long-term autonomous operation. In order to facilitate those applications, more efforts on developing high-efficiency function materials, innovate conversion mechanisms, ultra-low power electronics are required for the coming decade.

5. Conclusions and future directions

This paper provides a comprehensive review of the state-of-the-art progress on rotational energy harvesting, which has been drawing substantial and increasing attention from both academia and industry over the past decade. Self-powered wireless sensing is the most promising application for rotational energy harvesting, with a wide range of application areas and associated available rotation sources. Continuous and non-continuous rotations are the major categories of sources either directly available or converted from other types of motion, such as linear oscillation or fluid flow.

The major challenges witnessed in REH include energy harvesting capability, operating bandwidth, device miniaturization and system reliability in harnessing random, broadband, and potentially low-frequency energy sources. Another identified limitation is the requirement of using micro-bearings which do not scale down well and tend to be costly, especially at high rotating speeds. Different types of harvesters, including unbalanced harvesters using eccentric proof masses, beam-based harvesters and symmetric or balanced harvesters, have been reported in the literature to harness various energy sources with distinct characteristics. The theoretically maximum obtainable power for different harvester types are analyzed with the indication of the key operational and design factors to enhance the energy harvesting performance and the appropriate application areas. The basic concepts for major transduction mechanisms, including piezoelectric, electromagnetic, electrostatic and triboelectric transduction, are briefly reviewed with the key governing equations.

Methodologies and mechanisms tailored for rotational energy harvesting are reviewed for addressing different challenges in various application areas. Frequency up-conversion is ideal for low-frequency and random rotational energy; multi-stability provides a solution to enhance the performance of beam-based harvesters operating in continuous rotating conditions. The centrifugal force is mainly used to create a tuning force to adjust the resonant frequency of harvesters either by softening or hardening effects. The gravitational field provides a unique source of excitation for rotational energy harvesters. Other methods, such as pendulums and micro-turbines also provide means to harvesting other types of energy sources using a rotational energy harvester.

Major and promising application areas for rotational energy harvesting are reviewed, including wearable/implantable devices, automotive and railway systems, rotating machines and renewable energy systems, and environmental sensing. The motion characteristics and the corresponding energy harvesting solutions are quite different, showing the necessity for application-oriented design and optimization when one designs a harvester. Metrics to compare harvester performance are not straightforward to obtain due to the differences in application areas and harvester operation conditions. In terms of methodology and structure for different applications, pendulum structures and frequency up-conversion are ideal for low-frequency and random excitation conditions in wearable devices and environmental sensing. Gravity and centrifugal-force based harvesters are normally adopted in applications, such as automotive and machinery, where rotating speeds are in a range that those forces exert equal impact on system dynamics. Micro-turbines are useful in harnessing fluid-flow energy sources in environmental sensing.

Enhancing the power generation capability and reducing the sensing power requirement are the directions to implement self-powered sensing in the era of the Internet of Things. The practical exploitation of this technology requires developments not only in energy harvester design, but also power management circuits, energy storage and low-power sensing systems. Although extensive work has been reported, commercialized self-powered solutions enabled by rotational energy harvesting are still limited. In addition to the power generation capability, considerations on system reliability (avoiding material degradation), performance stability, cost, and compatibility with the applications are of equal importance in order to promote rotational energy harvesting to the next level, especially for long-term self-powered sensing applications. The power generation capability of energy harvesters varies significantly from μW to mW in different applications from wearable devices to automotive monitoring. The final aim is to obtain energy budget balance between power generation capability and sensing power demands to eventually achieve self-powered sensing.

Moving forward, more efforts are required in the following areas to tackle the exciting challenges and to realize self-powered sensing using REH. (1) The development of generic designs which can be easily adapted to multiple application scenarios would aid significantly in making these solutions practical and cost effective. (2) System-level study and evaluation of self-powered sensing is necessary to enhance and optimize energy harvesting capability by co-designing energy harvesters, power management circuits and energy storage in a holistic manner. (3) Feasibility and suitability need to be properly addressed to create tailored and practical solutions for targeted applications. Factors include bandwidth, device size, cost, robustness, mounting requirement (number of required anchors), and impact of the harvester on the rotating host (rotor balance). (4) The fundamentals of REH. Theoretically investigation of the phenomena (energy transfer, centrifugal effect, impact) in REH may be interesting, and can be verified via numerical simulation and experiments. (5) Self-powered sensing is the ultimate target. This will require more efforts in energy budget balance analysis between energy harvesting capability and sensing power demands. More successful demonstrations from both academia and industry are urgently needed to boost the confidence of the general public to this technology.

In summary, rotational energy harvesting can be seen as one of the enabling technologies in implementing self-powered sensing in the era of the Internet of Things. This technology has a great potential to be integrated with other types of transducers, such as micro-robotics or smart actuators to allow for energy self-sufficient operation. More investigations and efforts are expected in the coming decade to facilitate energy self-sustained sensing and actuation in a variety of applications, including wearable devices, smart robotics, biomedical electronics, structural condition monitoring, and environmental sensing.

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