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Review Article

Research Progress of Acoustic Energy Harvesters Based on Nanogenerators

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In the wake of the rapid development of the Internet of Things (IoT) and artificial intelligence (AI) technology, a huge amount of wireless sensing nodes (WSNs) is urgently in demand in all aspects of daily production and living, such as smart cities, smart transportation, and intelligent monitoring. However, it has become one of the crucial challenges in the development of IoT technology to fulfill the requirements of energy consumption for enormous amounts of WSNs. Therefore, it not only possesses great potential to realize in situ power supply of WSNs by harvesting environmental energy but also can address the problems of durability, maintenance, and cost that exist in battery power supply. In particular, acoustic energy is ubiquitous in the environment but not efficiently utilized. Meanwhile, piezoelectric nanogenerators (PENG) and triboelectric nanogenerators (TENG) are capable of accomplishing efficient conversion of broadband, high entropy, and weak energy as the new energy conversion technology. Therefore, the basic principle of acoustic energy harvester based on nanogenerators (NGs) is firstly discussed. Then, the advances of acoustic energy harvesters based on NGs in the viewpoint of acoustic energy resonator structures are systematically reviewed for the first time. This review not only covers the working mechanism, structural design, and application scenarios of acoustic energy harvesters but also explores the advances in ultrasonic energy harvesting based on NGs. Finally, existing challenges and prospects for future development are systematically discussed, which will facilitate the development of acoustic energy harvesting based on NGs.

1. Introduction

In a time of rapid technological development, wireless communication technologies such as WiFi and Bluetooth, along with embedded and distributed systems, have reached maturity [1–3]. The use of IoT technology has effectively improved work efficiency across various industries, from national aerospace transport [4] to people's daily travel [5, 6]. The world is entering the era of the IoT, sensor networks, big data, robotics, and artificial intelligence [7–10]. Therefore, every moving object must be connected to the Internet and continuously monitored, to ensure their normal movement and status. Research shows that by 2025, more than 30 billion objects will be connected through the IoT, forming a vast network of sensors scattered over a geographical area and working in tandem [11, 12].

Literature research shows that the voltage requirements for some commercial low-power wireless sensors run the gamut from a few volts to tens of volts. The current drawn by these devices is about tens of μA, and the power consumption is about tens of μW [13]. Although the power consumption of WSNs is low, the quantity of them is numerous. Therefore, energy supply is one of the four most important challenges [14]. However, due to the high cost, complex distribution, electromagnetic interference, and power loss, the traditional cable power supply faces the challenge of supplying power to distributed wireless sensor nodes [15]. Alternatively, the battery as another power source, because of its limited life, needs to be charged or replaced by regular maintenance, which is a great difficulty in remote areas, enclosed spaces, and underwater environments [16, 17]. However, the working cycle of sensor networks is limited, and if the power support is lost, all sensors and artificial intelligence become useless, rendering 90% of the IoT unsustainable [18]. Moreover, more sensors are used in relatively complex and harsh environments, including some areas inaccessible to personnel. It is unrealistic and uneconomical to apply traditional charging methods to extend sensor life [19, 20]. Consequently, the technical problem of self-energy supply for sensor devices needs to be addressed urgently by effectively harvesting high-entropy energy from the environment and converting and storing it [21, 22].

A large amount of energy is distributed in people's production and life, such as solar energy [23], wind energy [24], wave energy [25], and tidal energy [26], but these energy sources mainly solve large-scale energy conversion and cannot meet the needs of wireless sensing nodes with lower and lower energy consumption. Therefore, researchers have focused on the ubiquitous nanoenergy [27], such as acoustic energy [28], vibration energy [29], and wind energy [30]. Among them, the acoustic energy widely distributed in the environment has attracted more and more attention. As a clean energy, it offers mild energy intensity and high collectability. Acoustic energy is widely found in daily environments such as road traffic, factories, and ship operations [31, 32]. At present, people use electromagnetic, piezoelectric, and triboelectric effects to carry out acoustic energy harvesting research. A practical method of converting heat into usable energy is offered by thermoacoustic power harvesting technology. Based on the thermal acoustic effect, it can convert heat energy into acoustic energy and generate electricity directly by the energy conversion equipment [33, 34]. It is a magical way to collect environmental energy [35]. The most developed form of power generation at the moment is the electromagnetic generator (EMG), which was developed on the basis of Faraday's discovery of the electromagnetic induction phenomena. However, due to the weak energy density of acoustic energy and the fast change of sound pressure, it is difficult to realize efficient acoustic energy conversion based on EMG. During the start-up process of the thermoacoustic generator, complex nonlinear factors such as frequency hopping and acoustic pressure saturation often occur, resulting in extremely unstable output power of the system, which limits the application of thermoacoustic technology. However, piezoelectric nanogenerator (PENG) and triboelectric nanogenerator (TENG) have the advantages of simple structure, low cost [36], high power density, and high sensitivity in acoustic energy harvesting [37, 38], and acoustic energy harvesting based on nanogenerators has become one of the most promising energy harvesting systems in different energy conversion modes [39, 40].

Piezoelectric is a Greek term that means to produce electricity through pressure [41]. French physicists Jacques and Pierre Curie made the discovery of the piezoelectric phenomenon in 1880. They discovered that under certain compression conditions, some crystal surfaces exhibit positive and negative charges. When the pressure was released, these charges vanished in proportion to the pressure that had been applied. The polar electricity phenomenon was identified by the Curie brothers as a direct piezoelectric action on tourmaline crystals [42]. Wang and Song [43] created the first PENG based on ZnO nanowire arrays in 2006 and found that the Schottky barrier formed between the metal tip and nanowire may produce an electrical current. In order to gather energy from the environment, Wang et al. [44] created a direct-current nanogenerator in 2007. Piezoelectric, vertically aligned ZnO nanowire arrays and ultrasonic waves were used to achieve this. In 2009, Yang et al. [45] packed ZnO piezoelectric fine wire onto a flexible substrate to develop a flexible power generator that generated an oscillating output voltage of roughly 50 mV. Since 2012, Fan et al.'s team [46] has shown that the triboelectric effect can be fully utilized by TENGs to transfer low-frequency mechanical energy from the environment—such as vibrations, wind, ocean waves, and human motions—into electricity. TENG is a distributed energy harvesting device based on Maxwell's theory of displacement currents. Maxwell originally put up the idea of displacement current in 1861, taking into account the coherence of the continuity equation for electric charge and the ampere law of magnetic field. The displacement current is not the same as the current that moves the free charge; instead, it is a time-varying electric field (in a vacuum or other medium) with the addition of a little movement of the bound charge within the atom due to the material's dielectric polarization [47]. Through the process of contact electrification, which occurs when one of the materials is separated from the other, electricity is produced. Electrons move from one material to the other when two different materials come into contact [48]. TENGs and PENGs have been successfully used for the harvesting of acoustic energy and have made a lot of progress in structural design, material selection, and performance improvement. In order to improve the collection efficiency of acoustic energy harvesting based on PENG and TENG [49], different resonance structures are applied, including the Helmholtz resonator, quarter-wavelength tube, and acoustic metamaterials. In addition, ultrasonic energy can also be used to supply power for implantable medical devices and underwater IoT devices. Ultrasonic waves are directly transmitted to PENG and TENG without resonance structure and are supplied to different application scenarios after energy conversion. In recent years, the harvesting and conversion of acoustic energy have attracted the research interest of scholars, and some important progress of the AEH based on different working principles have been proposed [28, 30, 50], which are of great importance for the development of AEHs. However, since the resonant structure is a very important part of acoustic energy conversion, therefore, as shown in Figure 1, the acoustic energy harvesting based on PENG and TENG according to different types of resonators is systematically reviewed for the first time. Finally, we propose challenges and prospects based on the development of structures, materials, and application scenarios in order to provide a useful reference for the development of AEH.

2. Basis of Acoustic Energy Conversion (AEC)

The transmission of acoustic waves, or sound, in the air is a process where mechanical waves drive the elastic medium

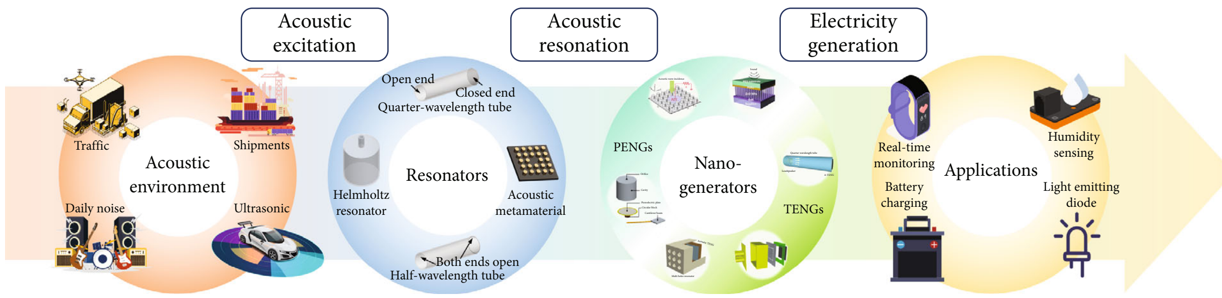


Figure 1: Schematic diagram of an acoustic energy harvesting system [13, 51, 52].

(i.e., air) to alternate between dense and sparse. From a macroscopic perspective, acoustic waves are characterized by dynamic changes in pressure. When the elastic medium is disturbed by acoustic waves in a particular area, the pressure in that area changes with time. The difference between the changing pressure and the equilibrium state pressure is known as sound pressure, which is typically measured in Pascals (Pa).

From an energy perspective, the process of acoustic wave transmission is actually a vibrational energy transfer process, including both the kinetic energy of the air medium moving back and forth in an equilibrium position and the deformation energy of the air medium as it squeezes and expands in local areas [53]. As the disturbance continues to propagate, acoustic energy is transferred as well. And the range of acoustic energy spans a vast range. For example, the acoustic power of speech communication is only about 10^{-5} W, while the acoustic power of a large rocket launch can reach 10^{9} W [54]. In addition, the subjective loudness perception produced by human hearing of acoustic energy is more closely related to the logarithm of acoustic intensity. Therefore, the logarithmic physical quantity, namely, sound pressure level (SPL) [55], is often used to scale the sound pressure, and its unit is dB. The SPL formula is defined as follows:

$$\mathrm{SPL} = 20\ \lg \frac{p}{p0}, \tag{1}$$

where p is the effective value of the measured acoustic pressure, $p0$ is the international reference sound pressure of 2×10^{-5} Pa, which corresponds to the sound pressure that normal hearing people can just hear against a sound with a frequency of 1000 Hz. The sound pressure level and frequency range of typical sound sources are shown in Table 1 [56].

The overall frequency spectrum recorded in the acoustical noise produced by these sources varies from 20 Hz to 20 kHz, and the sound pressure level (SPL) produced by these sources spans from 71.9 to 140 dB. Although these energies are small, they are ubiquitous, so harvesting these widely distributed micro-nanoenergy sources will provide a new way for the energy supply of WSNs in the era of IoT. The environmental acoustic level listed in Table 1 can effectively provide a good reference for acoustic energy harvesting.

2.1. Acoustic Energy Harvesters (AEH). Acoustic resonance cavities are commonly applied on acoustic energy harvesting devices, in order to amplify and enhance sound pressure. Most resonant cavity structures are hollow tubes or cavities where air vibrates within the cavity and generates fluctuating pressures when an acoustic wave is incident. The incident sound wave will vibrate at a higher amplitude at the resonant frequency of the resonant cavity, resulting in a strong excitation of the transducer structure and enhancing the transduction effect. These structures are used to concentrate the acoustic energy, increase the sound pressure in the sound field at specific frequencies, and eliminate unwanted frequency components from the system. When an acoustic resonance device is excited by an incident wave at its resonant frequency, the acoustic energy is collected inside the resonator in the form of a standing wave. Different structures of resonant cavities, such as the Helmholtz resonant cavities to collect and amplify incident acoustic waves and acoustic crystal resonant cavities to achieve the standing of incident acoustic waves, are used by AEH to focus and intensify the sound energy. The main types of acoustic harvesting and intensification devices commonly used today include the Helmholtz resonators, quarter-wavelength resonators, and structures coupled with acoustic metamaterials.

An acoustic band-stop filter known as a Helmholtz resonator [65, 66] consists of a cavity joined to a neck that has a much shorter length and smaller cross-sectional diameter than the cavity. The air in the cavity expands and contracts like a spring, and the Helmholtz resonator's viscous losses—which are brought on by friction between the oscillating air in the neck and radiation losses at the end of the neck—serve as a damper. The natural frequency of the device is established by the volume of the cavity and the size of the neck at low frequencies, when the acoustic wavelength is substantially wider than the Helmholtz resonator's dimensions. The relationship among the three is given by the following:

$$\omega = c\sqrt{\frac{S}{Leff\,V}}, \tag{2}$$

where $Leff$ is the effective resonator neck length and includes a correction factor for mass loading caused by air entrainment toward the neck extremities. S is the cross-

Table 1: Sound pressure level and frequency range of typical scene sound source.

Acoustic source	Acoustic pressure levels (dB)	Frequency (Hz)	Reference
Train moving with 200 km h^{-1} speed in a tunnel	140	—	[57]
Traffic highway	60-90	63	[58]
Hospital background in day time	72	—	[59]
Hair dryer	67	—	[60]
Dirt collector	80	500-1000	[60]
Telephone dial tone	80	450	[61]
Ship engine room	>100	31.5	[62]
Car air conditioning system	71.9	20-20 k	[63]
Electric generator	108.9	3-80 k	[64]

sectional area of the neck, c is the speed of sound, and V is the volume of the resonator cavity.

The periodic composite materials, sonic crystals and acoustic metamaterials [67, 68], exhibit many acoustic properties, and the propagation of elastic or acoustic waves in sonic crystals has attracted a lot of interest recently. Acoustic band gaps have been shown to be advantageous for sonic crystal applications such as acoustic filters, noise reduction, and transducers [69–71]. For instance, a point defect produced by removing a rod from a perfect sonic crystal can function as a resonant cavity [72]. In the sonic crystal's cavity at the resonance frequency, the incident acoustic wave is focused. Due to this phenomenon, piezoelectric materials may be used to convert acoustic energy into electric energy at the resonance frequency by being put in the cavity of a sonic crystal.

Since the longitudinal dimension of a straight tube resonator is not significantly less than the wavelength, it is impossible to represent it using lumped elements. Straight tube resonators come in two basic varieties: quarter wavelength [73] and half-wavelength resonators. A quarter wavelength resonator is a tube with an open end that is linked to the acoustic space where the unwanted noise is generated. The fundamental frequency at which the quarter wavelength resonator attenuates is determined by the length, and this frequency is given by

$$f = \frac{c}{4L}, \tag{3}$$

where L is the length of the resonator tube and c is the sound speed. A resonator tuned to noise with a wavelength of a quarter has a length that is proportional to that wavelength. The acoustic wave experiences a 180-degree phase shift that interacts with the incoming acoustic wave and destructively lowers the target noise after traversing half the wavelength and returning [74], so as to achieve the purpose of noise reduction.

In order to support characteristic frequencies with wavelengths that result in pressure nodes at each open end, the half-wavelength resonator is opened at both ends. The fundamental's wavelength is twice as long as the resonator's length. The half-wavelength resonator's lowest resonant frequency is provided by [75]

$$f = \frac{c}{2L}, \tag{4}$$

where L is the length of the half-wave resonator and c is the sound speed. Considering that each harmonic of the fundamental has a wavelength that satisfies the end criteria, each harmonic may propagate.

2.2. Basic Principle of AEC Based on PENG. A type of crystal material known as a piezoelectric material has a potential difference between its two sides under pressure and is capable of converting mechanical and electrical energy in concert. A polar surface, also known as a positive and negative charge surface, is created when an external force is applied to the material surface. To convert mechanical energy to electrical energy, these polar surfaces provide a piezoelectric potential that may be utilized to drive the motion of electrons in an external circuit [76–78]. The piezoelectric effect in a piezoelectric material is illustrated in Figure 2. The three main categories of materials are organic, inorganic, and composite piezoelectric materials. Polyvinylidene fluoride (PVDF) is the most typical organic piezoelectric material [79, 80]. PENG based on PVDF has the advantages of high durability, flexibility, strong sensitivity to small mechanical forces, and large electrical output with high energy conversion efficiency, which is treated as an ideal piezoelectric material. The development of PVDF-based nanocomposites has attracted much attention, and researchers have developed nanogenerators with high output performance and remarkable energy conversion efficiency based on such materials [81]. A variety of materials, including metals and polymers, have been given the capacity to self-heal or autonomously regain form. Both of these abilities can be attained in piezoelectric molecular crystals, according to Bhunia et al. Many long-desired technologies, like advanced microchips, accurate sensors, and miniature robots, are made possible by such materials. Future studies on these materials could result in the creation of self-healing fracture or scratch features for smart devices [82]. Piezoelectric single crystals and piezoelectric ceramics are examples of inorganic materials [83]. Biomaterials, from basic body components such as amino acids and proteins to tissues such as skin and bones, are also piezoelectric [84]. In the near future, flexible implantable bio-nanogenerators will be the choice of more

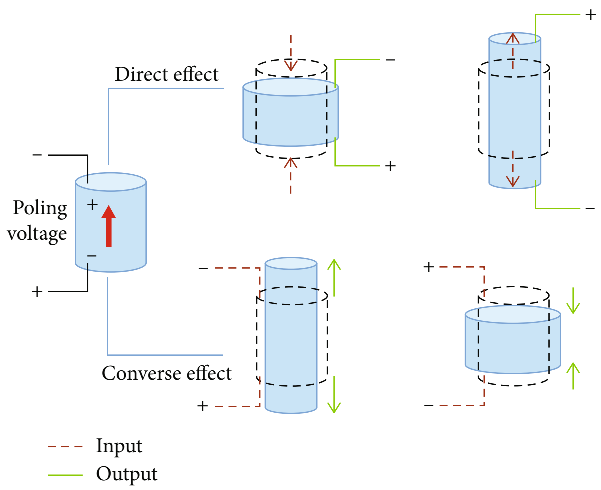


Figure 2: Energy conversion mechanism of PENG [87].

patients in the medical field, so biomaterials based on natural nontoxic biodegradable materials are very attractive. Researchers have used biodegradable spider silk fiber to create an incredibly flexible and mechanically durable biological PENG. The constructed SSB-PENG exhibits high output voltage and current, the highest instantaneous power density of 4.56 W/cm^2, and energy conversion efficiency of up to 66% [85]. Composite piezoelectric materials are inorganic piezoelectric materials with different shapes embedded in organic polymer matrix. Excellent output of piezoelectric nanogenerators is guaranteed by the flexibility and variety of architectures seen in the majority of piezoelectric materials [86]. Compared to TENG, PENG is more dependent on the natural piezoelectric action of the material. The following are the piezoelectric effect's constitutive equations:

$$D = dT + \varepsilon E(\text{Direct effect}), \quad (5)$$

$$X = sT + dE(\text{Converse effect}), \quad (6)$$

where D is the electrical displacement, d is the piezoelectric coefficient, T is the stress, ε is the material's permittivity, E is the electric field, X is the strain, and s is the mechanical compliance.

Piezoelectric acoustic energy harvesters convert acoustic energy to electrical energy through the direct piezoelectric effect. When the incident sound wave passes through the piezoelectric material, the piezoelectric material will deform, and the polarization phenomenon will occur inside it. The polarization voltage formed by the polarization phenomenon promotes the directional flow of free charges in the piezoelectric material to generate electric energy. These harvesters typically consist of an acoustic resonance cavity and piezoelectric materials. Because of their simple structure, high power and voltage output, and ease of rectification [88, 89], piezoelectric-based acoustic energy harvesting devices have become an important method for acoustic energy collection.

2.3. Basic Principle of AEC Based on TENG. Maxwell's displacement current, which is brought on by a time-varying electric field and a medium polarization term, serves as the TENG's driving force principle. Triboelectric charges are created on surfaces in TENGs simply as a result of CE contact electrification between two different materials. Wang introduced an extra component ps, known as mechano-driven generated polarization, to displacement vector D in 2017 to account for the contribution provided by the contact electrification caused electrostatic charges in Maxwell's equations [90], that is,

$$D = \varepsilon 0.E + P + Ps. \quad (7)$$

Here, the presence of an external electric field causes the first term's polarization vector, and the extra term—which is mostly caused by the existence of surface charges—is caused by the relative movement of the medium and the absence of an electric field. Maxwell's equations with Eq. (7) substituted and define

$$D' = \varepsilon 0E + P. \quad (8)$$

The typical Maxwell's equations are applicable to fixed and stationary media with fixed borders and volumes. However, the equations must be enlarged for situations involving moving media and time-dependent configuration, such as the case in TENG. Wang has obtained the enlarged Maxwell's equations in differential form starting with the integral forms of the four physics laws and assuming that the medium is moving as a rigid translation object with acceleration. Maxwell's equation for a mechano-driven slow-moving media system is given by, assuming that the relativistic effect is neglected, for the space inside the moving medium or object [91, 92]:

$$\nabla \cdot D' = \rho f - \nabla \cdot Ps, \quad (9)$$

$$\nabla \cdot B = 0, \quad (10)$$

where the relative moving velocity (vr) of the point charge inside the medium with regard to the moving reference frame and the moving velocity v of the moving reference frame may be used to separate the unit charge's moving velocity into two portions.

Through triboelectrification and electrostatic induction effects, TENG can directly convert irregular mechanical energy into electrical energy output, with high voltage and low current output characteristics. The propagation of sound waves causes periodic changes in the pressure between the friction material and the electrode, resulting in repeated vibration of the friction material. The metal electrode film produces different degrees of separation and contact friction, resulting in a change in the balance between the surface friction charge and the induced charge, thereby driving the electrons to transfer through the external circuit, that is, forming a current to achieve the conversion of acoustic energy to electrical energy. In the field of acoustic energy capture, triboelectric nanogenerator technology shows broad application prospects. According to different structures and charge transfer principles, the working modes of TENG can be divided into vertical contact-separation mode [93], contact-sliding mode [94], single-electrode mode [95], and freestanding triboelectric-layer mode [96], as shown in Figure 3.

For the piezoelectric generator, the cantilever beam or spring is used as the motion drive of the acoustic signal conversion, which has good sensitivity to small disturbances. TENGs have wider adaptability in structural design and material use, enabling them to effectively respond to ambient sound waves in a wide frequency range (sound pressure level and sound frequency). Triboelectric nanogenerators driven by Maxwell's displacement current provide an efficient and disruptive technological path for harvesting ambient low-frequency acoustic energy.

The charge creation during the polarization change brought on by the persistent electric field is connected to the operation of PENG. Piezoelectric charges are produced close to the piezoelectric material's surface when it is exposed to an external mechanical force. The configuration of the electric dipoles, the applied stress, and the material's piezoelectric coefficient all affect the piezoelectric charge density or the polarization intensity [98]. The TENG, however, necessitates the use of no less than two materials for contact electrification. Every layer of the triboelectric material will produce polarized charges when it is in use. The triboelectric charge is induced to the electrode after the two materials are separated from one another, producing current [99]. Despite the advantages of both PENG and TENG, they also have flaws of their own [27, 100]. Therefore, we can make full use of the advantages and avoid the disadvantages of different NGs to provide good technical support for the development of the IoTs.

3. AEH Based on PENG

3.1. Helmholtz Acoustic Resonator-Assisted AHE Based on PENG. An acoustic resonator is typically required to raise the incident sound pressure and the resultant sound pressure. A traditional Helmholtz resonator is a good option for AEH use. However, it has been claimed that a resonance coupling strategy can further boost the power harvested. So, Yuan et al. presented an intriguing low-frequency band acoustic energy harvester [101], which is composed of the Helmholtz resonator, piezoelectric film, and mass block. The mass block can reduce the mechanical resonance frequency at the bottom of the device and increase the collected sound power. The acoustic resonance frequency of the Helmholtz resonator may be changed, and it is intended to amplify sound pressure. This device can be tuned in the bandwidth frequency range of 305 Hz to 376 Hz. Experimental results show that the acoustic energy harvesting device can generate 3.49 μW output power, and the energy conversion efficiency can reach 38.4% when the resonant frequency is matched under 100 dB.

Most of the previously fabricated and reported piezoelectric acoustic energy harvesters are narrow band, so the research on the low-frequency acoustic energy harvesting is becoming more and more important. A broadband, frequency-tunable acoustic energy harvester is developed by Izhar and Khan [13]. As illustrated in Figure 4(a), the developed energy harvester has a piezoelectric laminate plate and an improved conical Helmholtz resonator. Through analysis of the pressure acoustic module, under the same sound pressure level, the resonance sound pressure powered by the conical cavity is greater than that of the cylindrical cavity. Figure 4(b) shows that the device has three peaks at 1501 Hz, 1766 Hz, and 1890 Hz, corresponding to the three resonant frequencies of the collector. In addition, the device can generate a maximum power of 214.23 μW at 130 dB SPL and 1501 Hz frequency, as shown in Figure 4(c). When the device is operated in real sound conditions near household appliances, the output AC and DC voltage levels of about 250 mV and 265 mV are generated, respectively.

In recent years, high-speed railroad systems have attracted worldwide attention, but the noise pollution they generate cannot be ignored, especially in residential areas near the railroads. It is worth noting that noise is a renewable energy source that can be collected for power generation. So, it makes sense to conduct research on employing sound barriers to both reduce noise and produce power. Wang et al. [102] proposed an acoustic energy harvesting barrier that can absorb the noise of high-speed trains, as shown in Figure 4(d). The system is composed of honeycomb structural units that use a Helmholtz resonant cavity and PVDF film to convert the low-frequency noise energy of the high-speed rail into electrical energy. The electrical energy generated by the system is stored in the supercapacitor by the power module to supply power to small electronics beside the railroad, such as monitors. Experimental results show that the system has an instantaneous maximum output voltage of 74.6 mV at an ingress sound pressure of 110 dB, as demonstrated in Figure 4(e). Additionally, this research confirms the viability and efficacy of the indicated acoustic energy collecting method and sound insulation system in the application of renewable energy in high-speed railways. Noh [103] designed a piezoelectric acoustic energy acquisition system based on the Helmholtz resonator for the noise of high-speed trains and studied the main noise source characteristics of high-speed trains based on this system. According to the experimental findings, a big rectangular plate may create a voltage of around 0.7 V at a sound pressure level of 100 dB, and such a power level is sufficient to power various low-power electrical equipment.

In order to simultaneously reduce noise and generate power from the noise generated by the railway system, Li et al. [104] proposed a tunable low-frequency acoustic energy harvesting barrier (AEHB) to effectively use the significant acoustic energy present inside the subway tunnel and turn it into electrical energy for use in lighting and sensor systems along the rails. The noise harvesting input module, the Helmholtz resonator optimization module, the resonant frequency adjusting module, and the power generating module are the four components that make up the AEHB. The overall organizational structure of the AEHB is shown in Figure 4(f). The resonant frequency tuning component and the ideal energy harvesting unit are made to increase the unit's output power. In Figures 4(g) and 4(h),

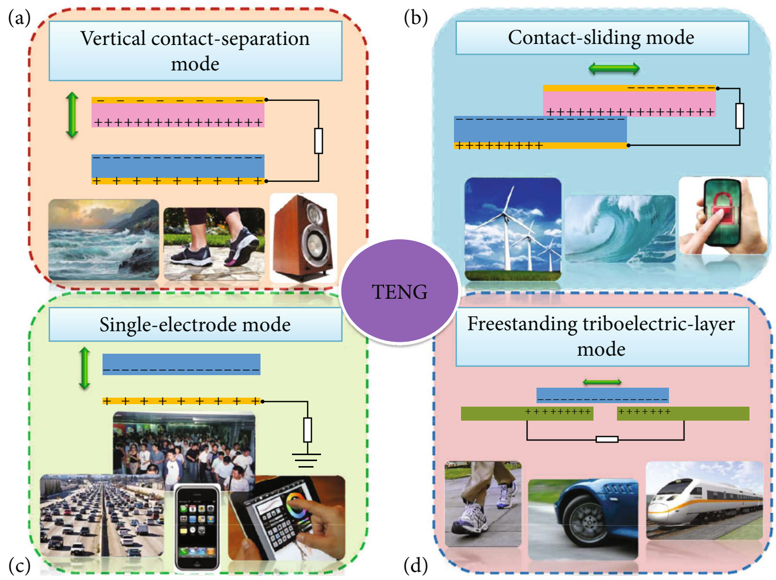


FIGURE 3: Four working modes of TENG [97] (copyright 2017, the Materials Research Society).

the energy conversion efficiency reaches its maximum when the mechanical resonant frequency is equal to the acoustic resonant frequency of the resonant cavity. The experimental results show that when the incident sound pressure level is 100 dB, one unit of the acoustic energy harvesting power generation system can generate an instantaneous voltage of 317.5 mV and an instantaneous maximum power of 100.8 μW, verifying the efficiency and practicability of the sound barrier. With great conversion efficiency, the device has a wide range of potential applications and can adapt to various tunnel environments, including high-speed rail tunnels, vehicular tunnels, and urban metro tunnels. The design and practical implementation of new multipurpose noise barriers in the future may benefit greatly from these findings.

3.2. Acoustic Crystals and Enhanced Material-Assisted AHE Based on PENG. There are additional structures than resonators that are used to contain acoustic waves. Acoustic crystals or acoustic metamaterials are composed of periodic arrangements of acoustic scatterers implanted in fluids or gases. The purpose is to control, direct, and modify sound waves. Because of its entire band gap, which prevents sound waves from propagating inside the crystal but instead causes them to be totally reflected by the crystal, it is ideal for applications like acoustic filters and vibration isolation for very precise mechanical systems. Acoustic energy harvesting by piezoelectric curved beams in the cavity of a sonic crystal is investigated by Wang et al. [105]. Point defects are formed by removing the centrally located bars from the PMMA cylindrical array. The acoustic wave causes the piezoelectric curved beam to vibrate while it is within the resonant cavity. Experimental results show that the maximum output power of the acoustic energy power generation device is 37 nW under the acoustic excitation with a sound pressure level of 80-90 dB and frequency of 4.2 kHz, which is 625 times that of the acoustic energy recovery when only PVDF film is used and not combined with acoustic crystal resonator.

Sun et al. [106] studied how the position of the metamaterial resonator flaw affected the effect of energy harvesting. They discovered that the ideal acoustic metamaterial plate's acoustic energy harvesting performance is enhanced by deleting the middle four resonators, so this study adopts this defect form. Figure 5(a) shows the architecture of the device. Utilizing silicone rubber cylinders mounted on an aluminum plate, a 6×6 metamaterial structure is executed. The graphs of peak output voltage and peak output power at 1340 Hz, 1329 Hz, and 1302 Hz for metamaterial plates that are 0.4 mm, 0.3 mm, and 0.2 mm thick are shown in Figures 5(b) and 5(c). Under ideal conditions, the peak power production of the metamaterial energy harvester is 195.52 W, corresponding to a plate with a thickness of 3 mm, which is 6 times and 331 times more than that of the metamaterial energy harvester with plate thicknesses of 0.4 mm and 0.2 mm, respectively. These discoveries will aid in the creation of high-performance acoustic energy harvesters based on metamaterials.

High-density acoustic energy harvesting is one of the Internet of Things' energy-supplying options for wireless sensor network nodes. To improve the efficiency of acoustic energy harvesting, combining multiple resonant structures to form a multiresonant structure coupling is an effective method. Yang et al. [107] placed a Helmholtz resonant cavity with a flexible piezoelectric composite film in the center of a locally resonant sonic crystal, forming a coupled resonance mode of the Helmholtz and sonic crystal, as shown in Figure 5(d). The device's acoustic coupling resonance is highest when the Helmholtz resonator and the acoustic crystal resonator have the identical resonant frequency. The functional relationships between both the suggested coupled resonance structure and the EMHR structure's output voltage and frequency were tested and computed. Experimental results show that at a load of 4.4 kΩ and the input sound pressure level of 110 dB, the maximum output power of the transducer is 429 μW, the maximum open-circuit voltage

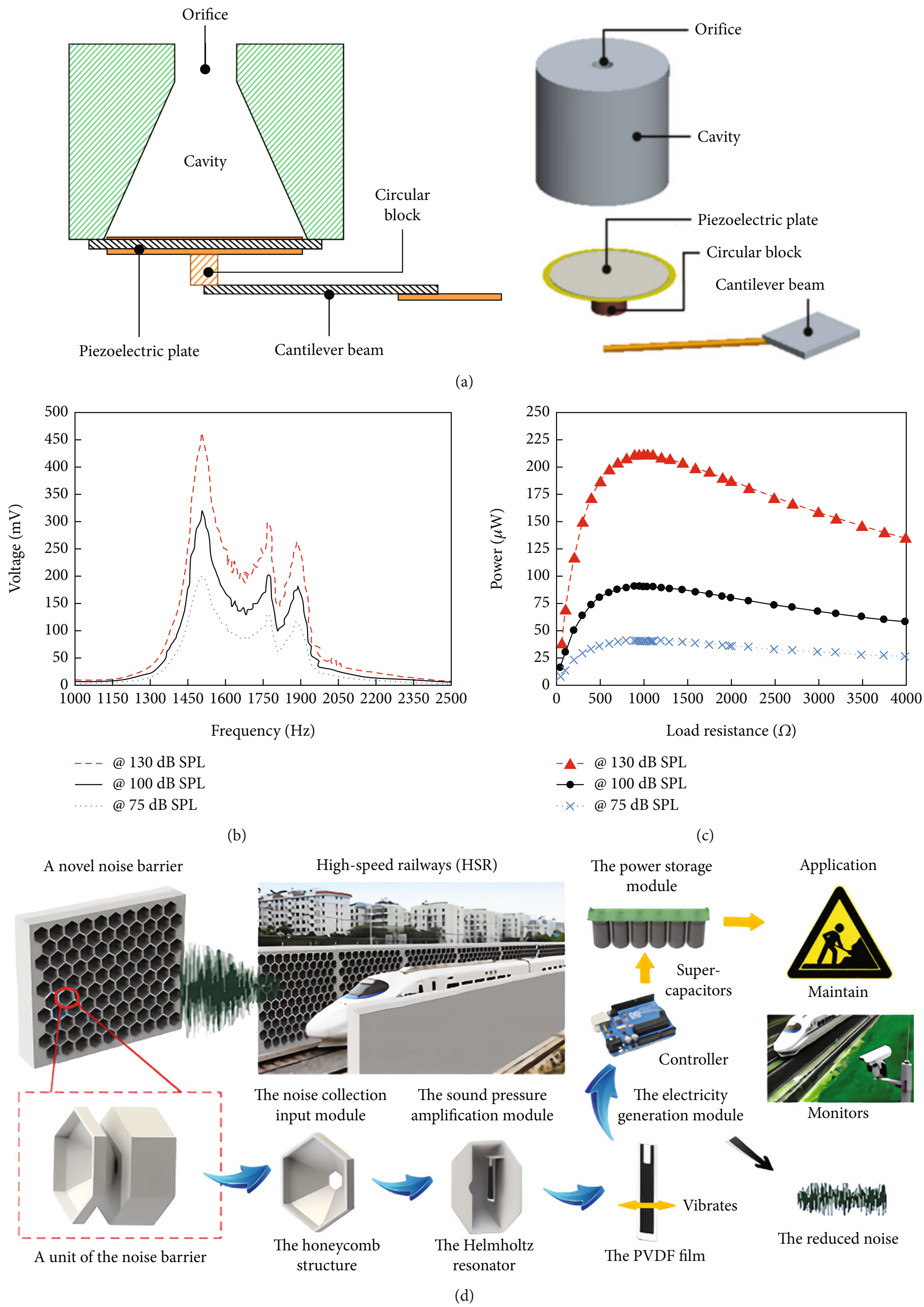
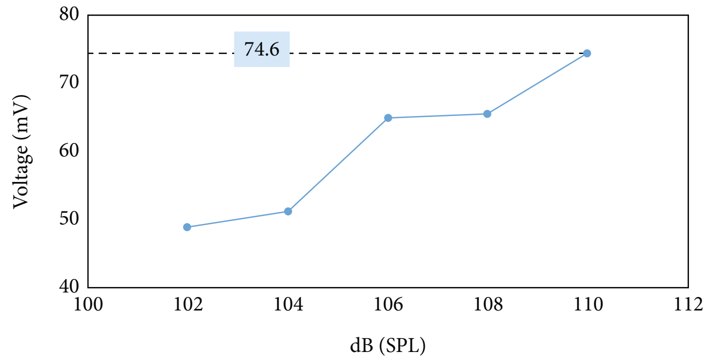


FIGURE 4: Continued.



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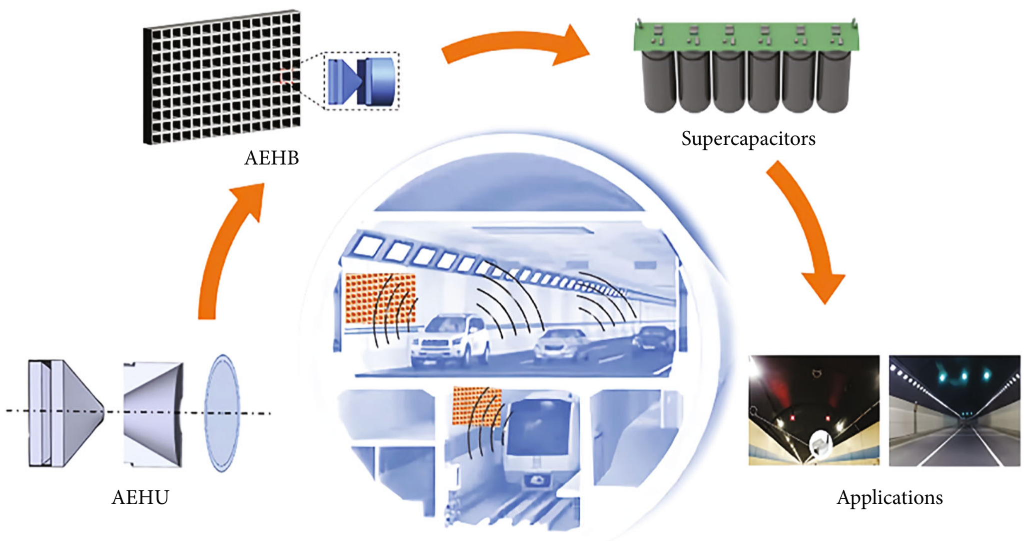

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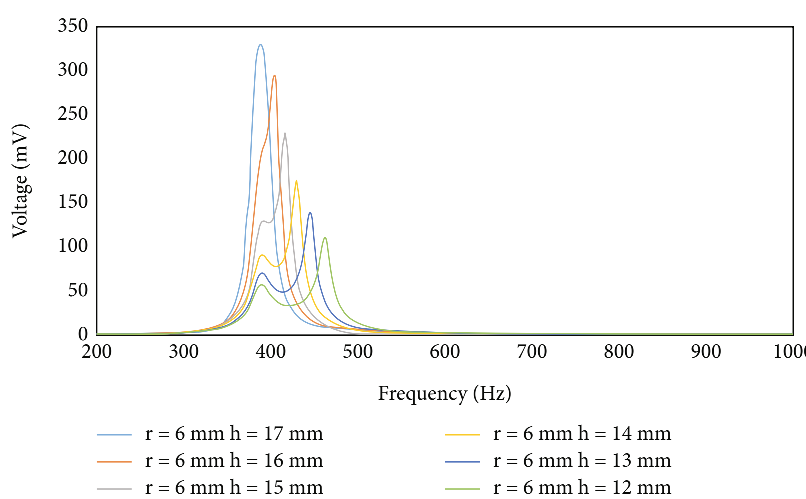

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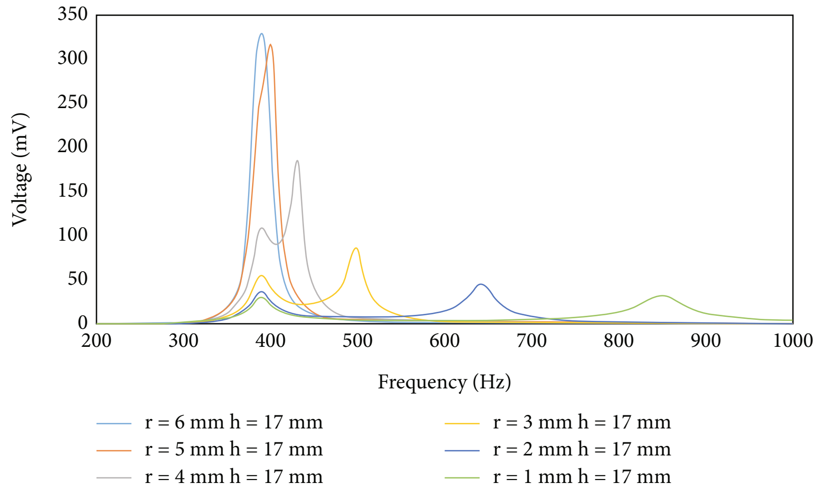
Figure 4: Continued.



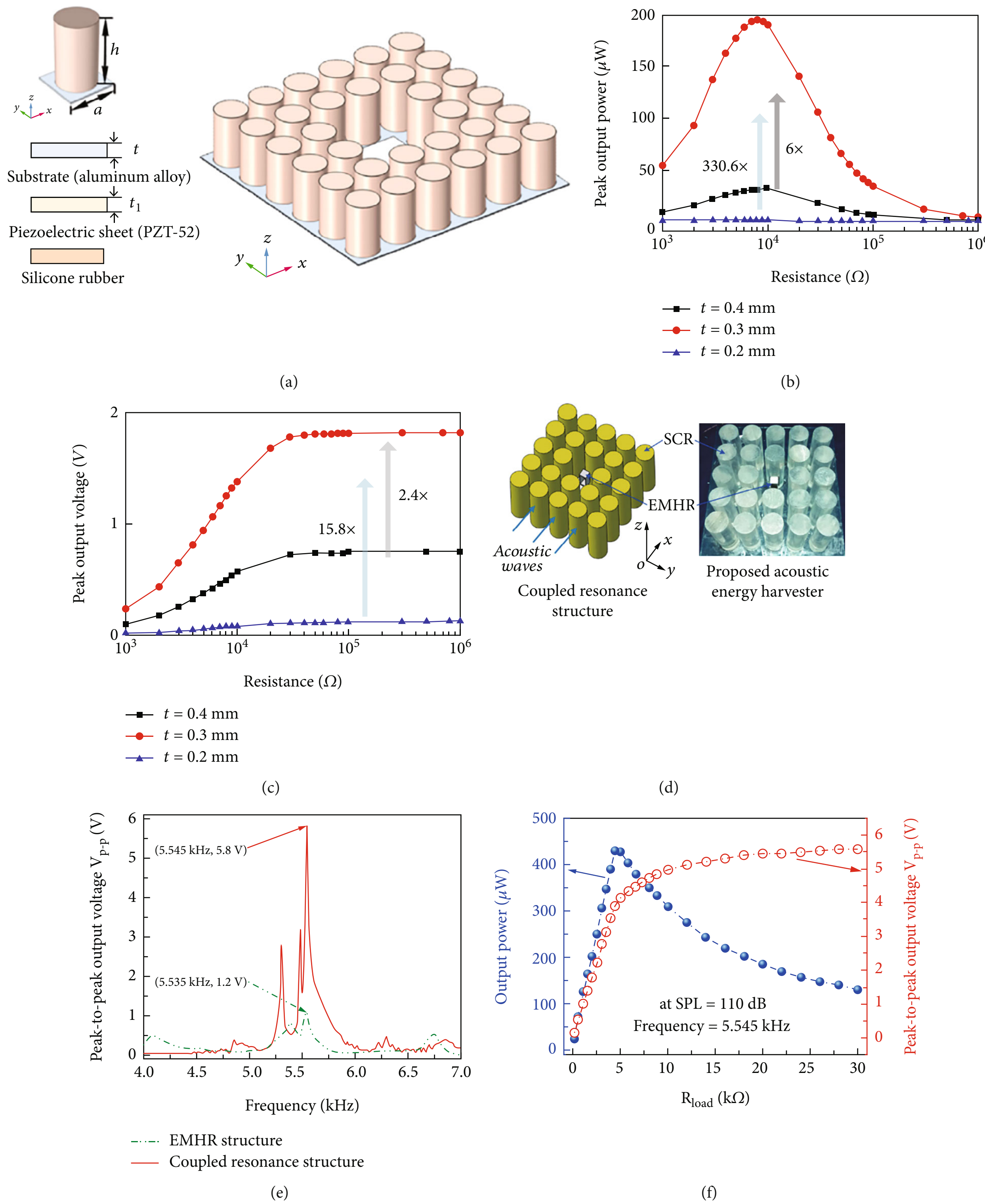
(h)

FIGURE 4: Piezoelectric acoustic harvesters based on Helmholtz resonator. (a) Cross-sectional view and exploded view of developed improved AEH. Output values of the harvester (b) load voltage and (c) load power (copyright 2018, Korean Society for Precision Engineering and Springer-Verlag GmbH Germany). (d) Architecture of the honeycomb acoustic energy harvesting noise barrier. (e) Comparison of experimental and simulated output voltages with the noise acquisition input module. (2018 Elsevier). (f) The overall organizational structure of the AEHB. (g) The voltage response curves with the resonant frequency when the device radius is held constant. (h) The voltage response curves with the resonant frequency when the device height is held constant.

is 3.89 V, and the resonance frequency is 545 Hz, as shown in Figures 5(e) and 5(f). Compared to the single resonator structure, the coupled resonant structure of multiple acoustic resonators had a larger sound pressure amplification factor, with 23 times the efficiency of the Helmholtz resonator and 262 times that of the local resonance phononic crystal. Furthermore, the interrelated resonant structure of such numerous acoustic resonators may be applied in a variety of applications, including the harvesting of acoustic energy, noise elimination, acoustic filtering, acoustic focus, and the placing of powerful acoustic waves, among others.

An acoustic energy harvester's performance cannot be increased by adopting only one method of energy harvesting, such as phononic crystal/metamaterial or the Helmholtz resonator. In order to boost the harvesting efficiency, certain researches on developing the hybrid design of the phononic crystal and the Helmholtz resonator were presented. Ma et al. [108] introduced a novel type of metamaterial and Helmholtz coupled resonator (MHCR) that enhances acoustic energy density through energy focusing and pressure amplification, as illustrated in Figure 5(g). Figure 5(h) depicts the variation of output voltage and output power of MHCR energy harvester with external electrical resistance at the resonance frequency. The peak output voltage of the acoustic energy harvesting device using the coupled resonant cavity is 528.60 mV, and the output power is 93.13 μW. This is approximately 3.5 times the highest voltage produced by the metamaterial energy gathered system. Field testing found that the highest transmission ratio of MNCR in a mechanical noise environment is 30.83 mV/Pa, which is 48 times that of the metamaterial energy harvester in a sound environment. These results validate the MHCR's ability to collect and convert acoustic energy, making it a promising and efficient green energy capture device with broad application prospects. For the design of acoustic harvesters that increase energy density, MHCR can offer helpful direction.

3.3. Quarter Wavelength Tube-Assisted AHE Based on PENG. Li et al. [109] studied an acoustic energy harvesting system combining a quarter-wavelength resonator and a piezoelectric material, as shown in Figure 6(a). In this study's acoustic energy harvester, a piezoelectric cantilever plate made of lead zirconate titanate (PZT) is housed inside a quarter-wavelength straight tube resonator. The enhanced sound pressure within the tube causes the vibration oscillation of the piezoelectric plate when the tube resonator gets energized by an external sound wave at its acoustic resonance wavelength, producing electrical energy. The PZT plates are stacked in the tube to boost the total voltage and power. The number of PZT plates that optimize voltage and power is constrained because of their interference with air particle movement. It is found that placing the piezoelectric patch in the first half of the pipe is more conducive to sound collection and energy conversion than placing it along the whole pipe. Calculated and experimental displacement and sound pressure and voltage of 8 piezoelectric plates placed along the tube are recorded in Figures 6(b) and 6(c). The measured output voltage is 3.79 V when the incident sound pressure level is 100 dB. With a single piezoelectric plate positioned at various points along the tube, different voltage and power outputs are produced. The output voltage and power drop as the piezoelectric plate travels near the closed tube end. Calculated and experimental displacement and sound pressure and voltage of 7 piezoelectric plates placed in the first half of the tube are recorded in Figures 6(d) and 6(e). The measured output voltage is 5.089 V when the incident sound pressure level is 100 dB. The output voltage has a linear relationship with the input



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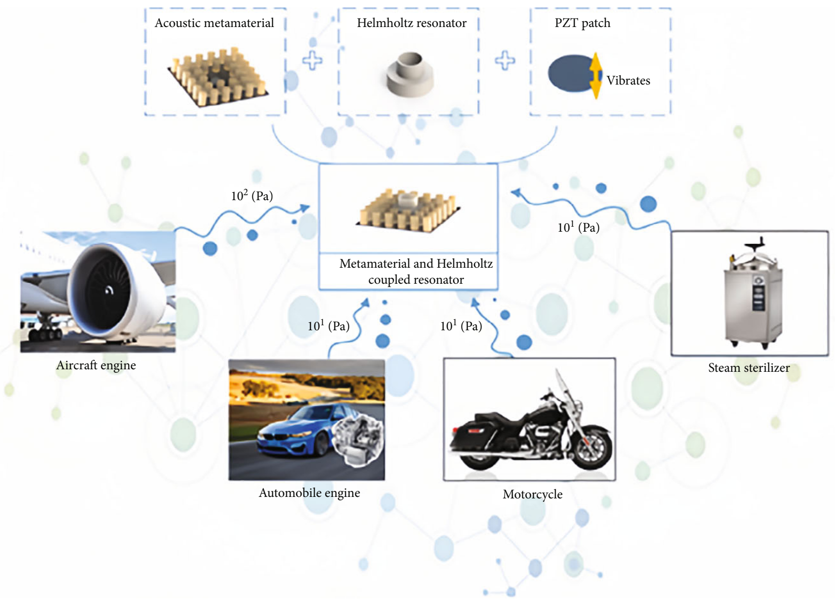

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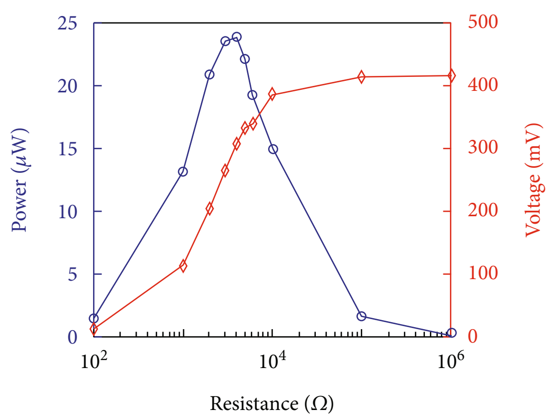
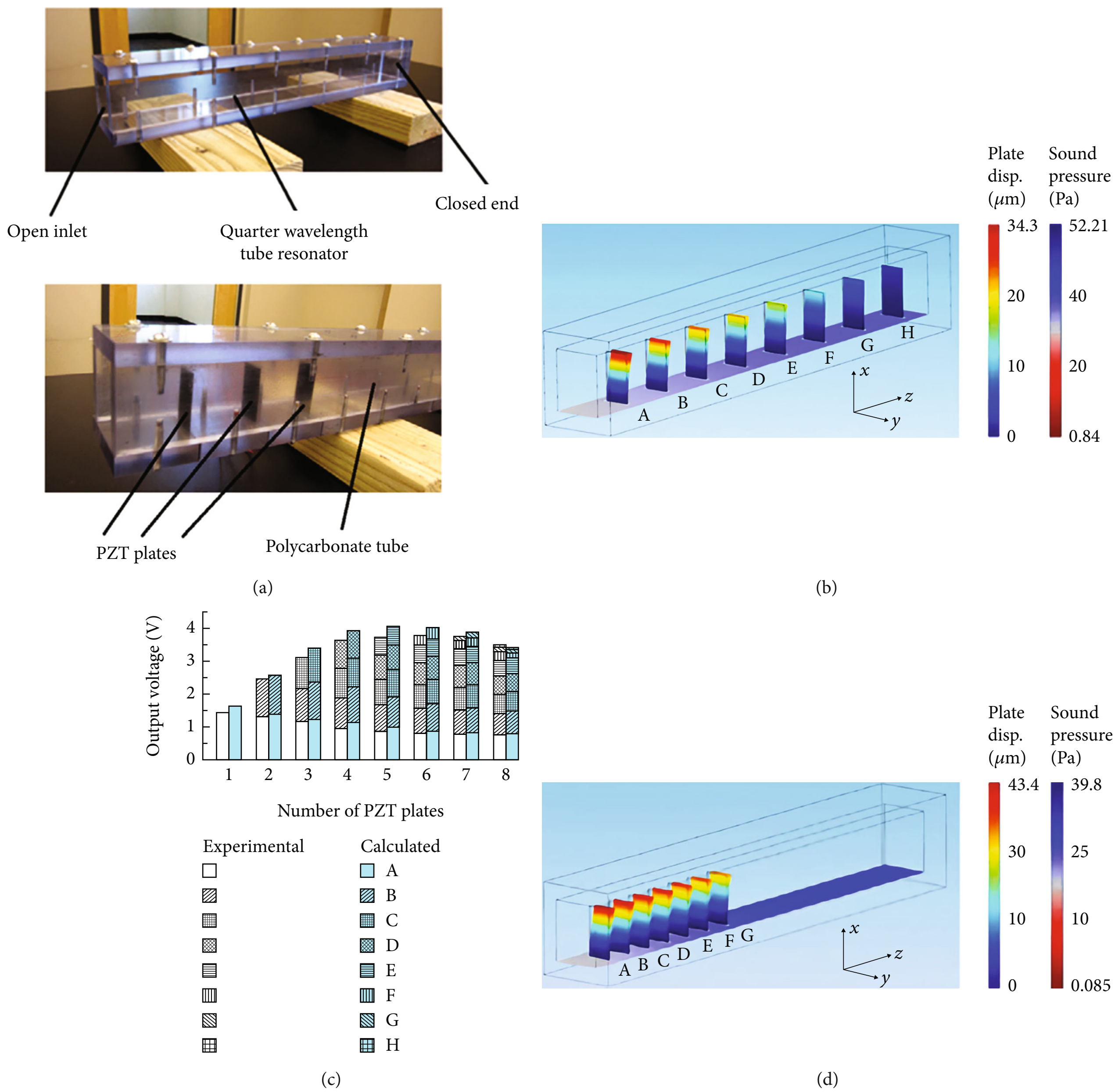


(h)

Figure 5: Acoustic crystals and enhanced materials acoustic harvesters. (a) Schematic of an acoustic metamaterial structure. (b) Variation curve of output power with external load resistance. (c) Variation curve of output voltage with external load resistance (copyright 2022, Elsevier). (d) Structure diagram and photo of the coupled resonance structure. (e) Under the excitation of acoustic wave, the output voltage of the structure with and without coupling resonance changes with frequency. (f) Output power and voltage of an acoustic energy harvester versus load resistance under acoustic excitation (copyright 2008, JSAP). (g) Architecture and application of acoustic energy harvesting using metamaterial and Helmholtz coupled resonator. (h) Output performance of the device when external resistance is connected (copyright 2020, Elsevier).

sound pressure. The power is 12.697 mW, and the output voltage is 15.689 V at an incidence sound pressure level of 110 dB. The related power densities for volume and surface are 15.115 W/cm3 and 0.635 mW/cm^2, respectively.

Considering the space and cost limitations posed by the tube length of the quarter-wavelength tube and the cavity length of the traditional Helmholtz resonant cavity, the development of acoustic-electric transducers is restricted. Yuan et al. [110] proposed a new structure for collecting low-frequency sound waves. Their work proposes a spiral structure acoustic-electric transducer inspired by cochlear bionics, enabling finite-volume collection of low-frequency sound energy, as shown in Figure 6(f). There are two components to the invention. A spiral tube with an open entrance makes up the first component. The tube wall is an acoustic hard wall, and there is a circular hole at the top as an air channel coupled with the second part. The first section's design was inspired by the sonic quarter-wavelength resonator tube, yet the adoption of a spiral linear structure ensures a more compact overall design. The second part primarily consists of a little hollow disk that is filled with air, positioned on the upper side of the first part. Under the acoustic resonance frequency of 175 Hz and SPL of 100 dB, the measured acquisition power of the device can reach 7.3 μW using the built experimental platform, as shown in Figure 6(g). The voltage signals that were observed are displayed in Figure 6(h), indicating an experimental sound pressure amplification ratio of 5.88. While the acoustic energy collection ability of the spiral



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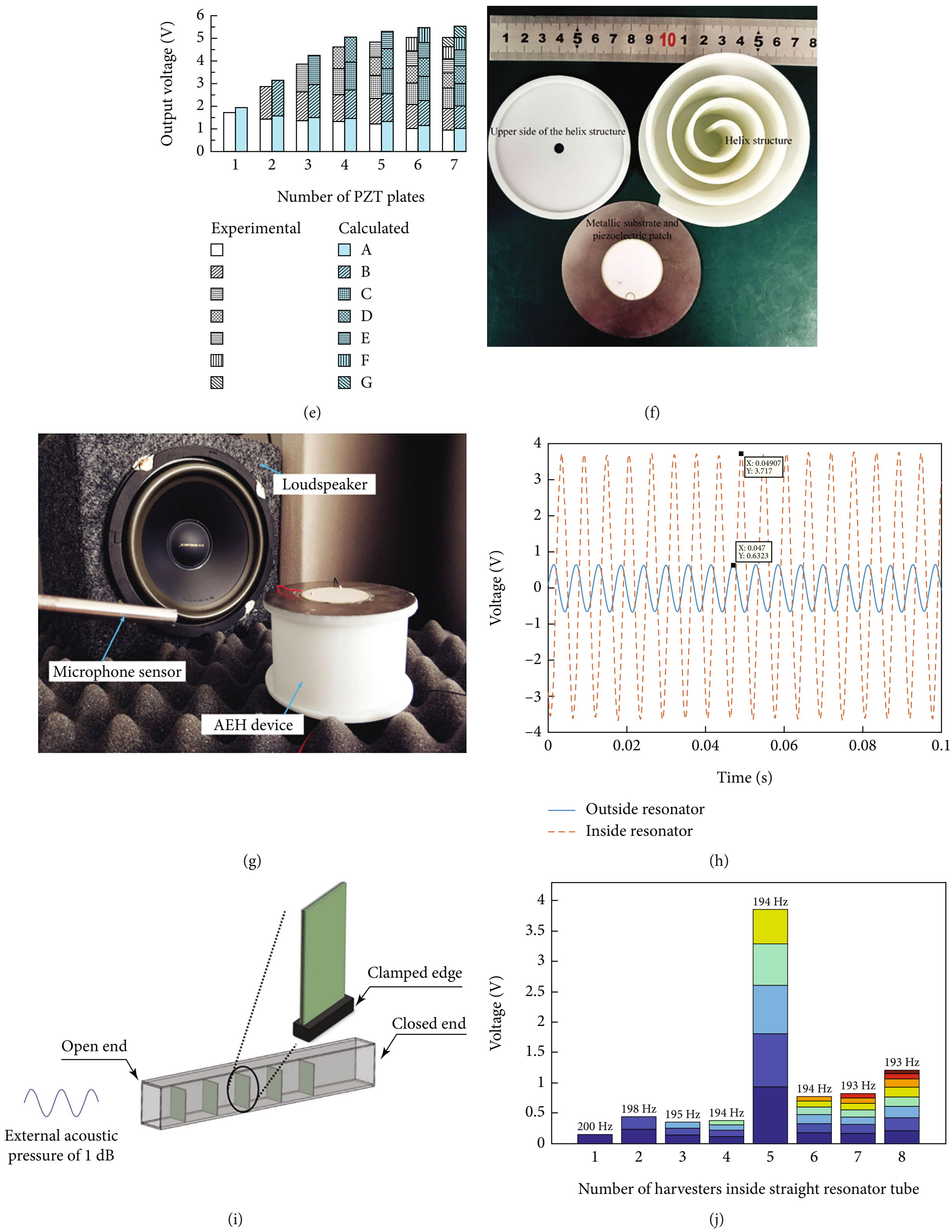

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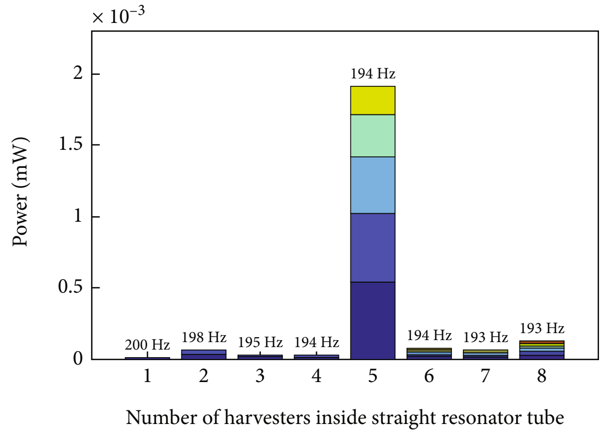


(k)

Figure 6: Quarter-wavelength tube acoustic harvester. (a) Schematic diagram of a quarter-wavelength tube resonance device. (b) The simulation calculation of displacement and sound pressure of 8 piezoelectric plates placed along the tube. (c) Voltage output with an incident SPL of 100 dB as 8 piezoelectric plates installed inside the tube. (d) The simulation calculation of displacement and sound pressure of 7 piezoelectric sheets placed in the first half of the tube. (e) Voltage output of 7 piezoelectric plates placed in the first half of the tube (copyright 2013, IOP). (f) Schematic diagram of a spiral-structured acoustic energy harvester. (g) Acoustic energy harvesting experimental study. (h) Comparison of microphone test signals before and after the metallic substrate is not mounted to the structure (copyright 2018, AIP). A quarter-wavelength tube with several piezoelectric bimorph cantilever plates. Cumulative (j) voltage and (k) power of the harvesters and the frequency corresponding to the maximum value (copyright 2016, Taylor and Francis).

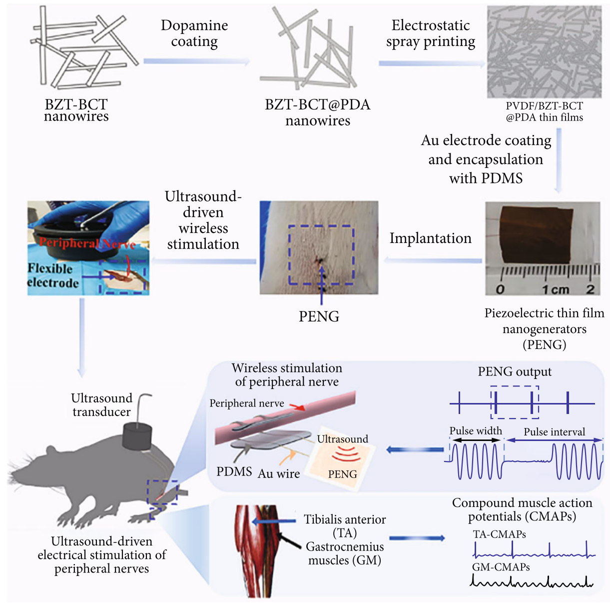
structure collector may not be as efficient as that of the quarter-wavelength tube or the traditional Helmholtz resonator combined with the PZT piezoelectric cantilever beam, it still demonstrates the ability of the generation within the low-frequency band and low-frequency acoustic resonance. Moreover, the proposed spiral structure presents a feasible solution for addressing the voluminous nature of traditional resonant cavities.

In Kumar et al.'s work [111], the numerical study of $K_{0.5}Na_{0.5}NbO_3$-$LiSbO_3$-$CaTiO_3$ ceramics for low-frequency sound harvesting is carried out. Figure 6(i) shows the quarter-wavelength tube with several bimorph cantilevers. As shown in Figures 6(j) and 6(k), both output voltage and power increase to the maximization when five piezoelectric energy harvesters are employed in the tube. A maximum output voltage of 3.8 V is recorded at a resonance frequency of 194 Hz when acoustic sound pressure of 1 dB is applied at the tube opening. The highest power is 2 mW. The numerical results demonstrate the promise of lead-free piezoelectric materials for acoustic energy harvesting applications.

A basic acoustic amplifier known as a quarter-wavelength resonator has the advantages of a straightforward structure, a strong sound pressure amplification effect, and a wide resonance bandwidth. It has a great deal of promise for low-cost, mass manufacturing.

3.4. Implantable Piezoelectric Acoustic Energy Harvester. Ultrasonic wave is a kind of sound wave. Its frequency is much higher than that of sound wave, but its wavelength is short and has good anisotropy. Therefore, ultrasonic wave has many applications in medicine and industry. Implantable medical devices, such as cochlear implants and cardiac pacemakers [112, 113], can be employed as diagnostic aids and therapeutic techniques to enhance human life quality [114]. In biomedical applications, electrical stimulation therapy has demonstrated significant advantages, and the utilization of piezoelectric nanomaterials in constructing electrical end-effectors presents an innovative application. These minimally invasive devices, when implanted in the body, can generate local control and radio signals for stimulation therapy through external acoustic wave excitation. Additionally, they can be designed as a self-driven device eliminating the need for battery replacement and reducing the occurrence of additional surgeries, thus minimizing disease incidence and economic costs [115]. For an effective ultrasonic energy harvester, a multilayered piezoelectric with strain-improved piezoelectricity is laid out. When implanted into tissues at a distance of 5 to 10 mm under an ultrasound probe established at 25 mW/cm^2, this device delivers an impressive peak output power of about 13.13 mW and a short-circuit current of about 2.2 mA, which is higher than the necessary power level of bioelectronic devices and current level of nerve stimulation [116].

Ultrasound has the advantages of deep tissue penetration and high clinical safety in biomedicine. Wu et al. [117] studied an ultrasonically activated thin film nanogenerator based on nanowire and PVDF polymer piezoelectric composite film. Figure 7(a) demonstrates the conceptual schematics for ultrasound-responsive thin-film nanogenerators used in neurostimulation. These soft piezoelectric thin film nanogenerators, driven by programmable ultrasonic pulses, directly generate electricity to stimulate peripheral nerves. Direct electrical nerve stimulation was successfully achieved by subcutaneous implantation of a piezoelectric thin film nanogenerator with a thickness of roughly 30 μm using rat sciatic nerve as a model, and the stimulation controllability under different ultrasonic parameters (including sound pressure, pulse width, and pulse interval) was systematically



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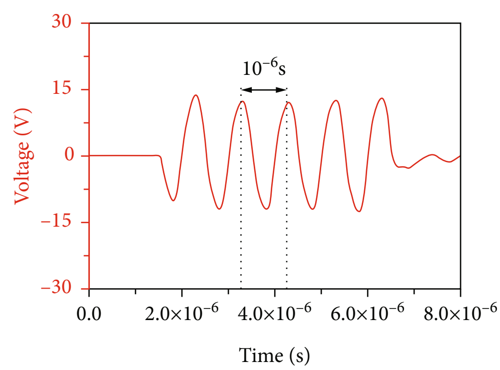

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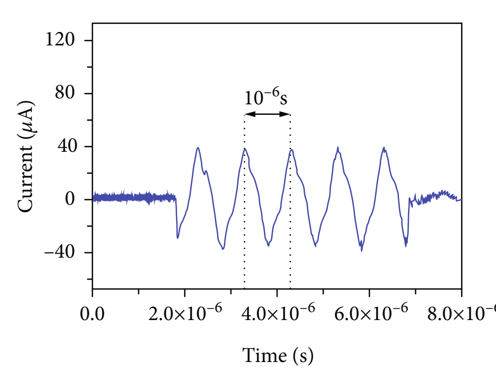

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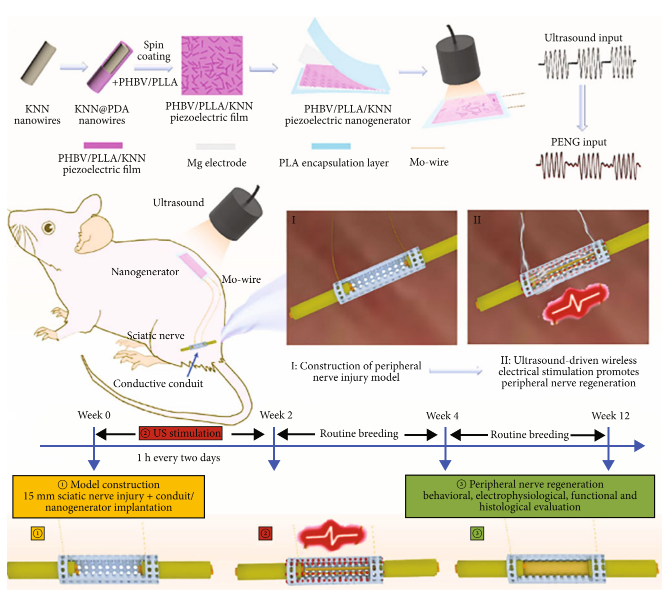

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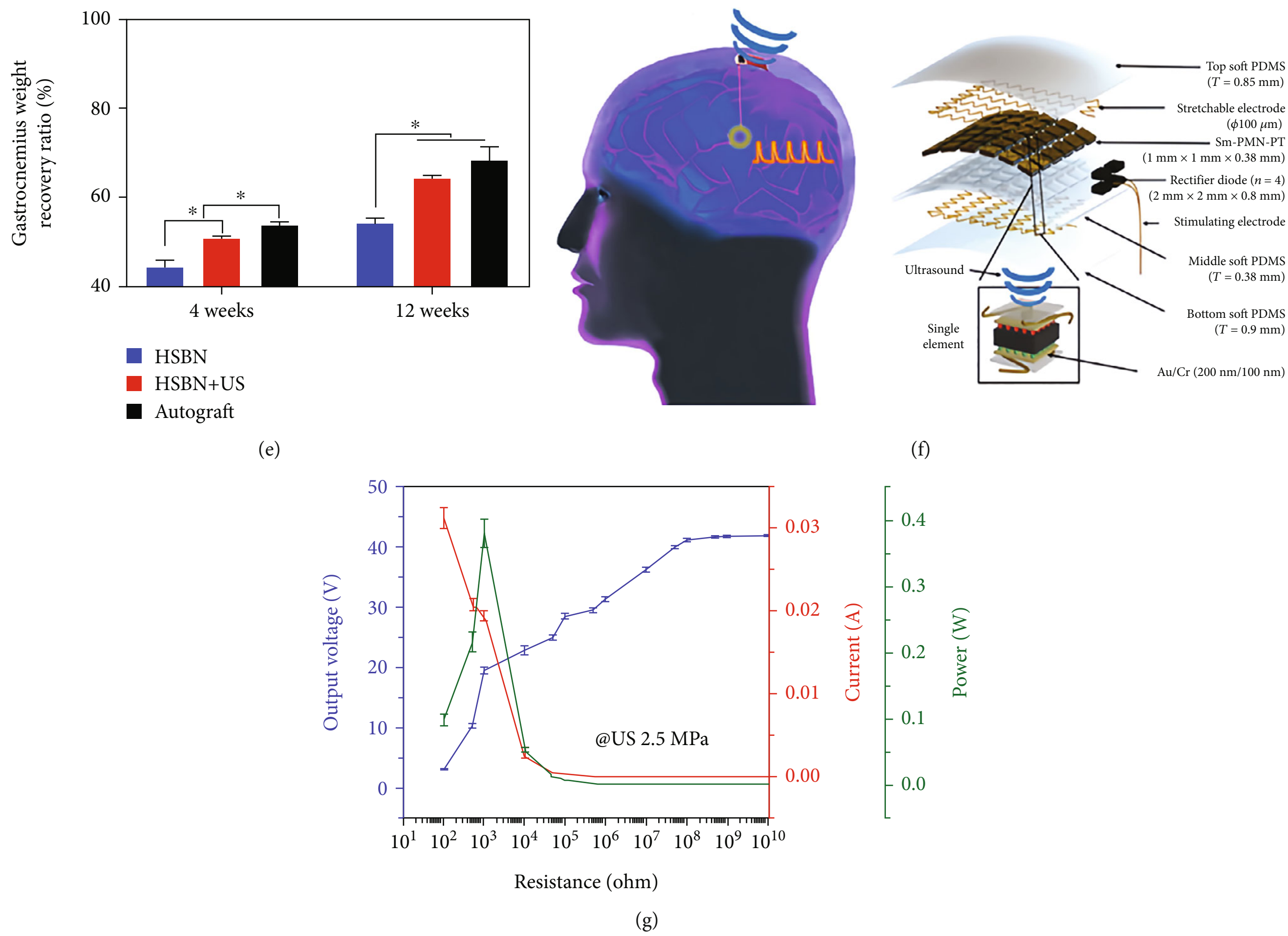


Figure 7: Implantable piezoelectric acoustic energy harvesters. (a) Electrical stimulation of peripheral nerves in rats with implantable piezoelectric thin film nanogenerators. (b) The open-circuit voltage and (c) short-circuit current generated under ultrasound excitation (copyright 2021, Elsevier). (d) The thin film piezoelectric nanogenerator of ultrasound-driven for peripheral nerve repair. (e) The gastrocnemius weight recovery ratio's statistical findings (copyright 2022, Elsevier). (f) The schematic diagram of the Sm-PUEH device designed for DBS and analgesia and the exploded view of the device. (g) The output voltage, current, and power of Sm-PUEH under different load conditions driven by a pulse ultrasound with 2.5 MPa.

studied. The thin film nanogenerator was subjected to a pressure of 1 kPa and a frequency of 10 Hz, and the resulting open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) were measured. The optimal output performance was achieved when the mass ratio of BZT-BCT@PDA nanowires in the PVDF polymer matrix was 50%. To ascertain how an ultrasonography reacts to PVDF/BZT-BCT@PDA (50%) thin film nanogenerators, the thin film nanogenerators were stimulated by 1 MHz ultrasound under the water. The output voltage and current from the piezoelectric thin film nanogenerator are both sinusoidal waves with signal intervals of around 10^{-6} s, as shown in Figures 7(b) and 7(c). A fresh method for using programmable battery-free brain stimulators with remote control in bioelectronic medicine is provided by the implantable thin film nanogenerator.

Chen et al. [118] performed an ultrasound-driven in vivo electrical stimulation (ES) method based on a biodegradable PENG for the regeneration of peripheral nerve injuries, significantly lowering the risk of postoperative infection. Figure 7(d) illustrates the schematic of a wireless ultrasound-driven ES that improves peripheral nerve healing. The PENG is composed of biodegradable piezoelectric materials. By remotely activating mechanical excitation through programmable ultrasonic pulses, the implanted PENG can transmit adjustable electrical stimulation to the biodegradable conductive conduit of the peripheral nerve at a time other than intraoperative. The following ultrasound stimulation settings were used for nerve repair: 100 kHz ultrasound frequency, 10 ms pulse width, 1 s pulse interval, and 0.3 W/cm^2 of ultrasound intensity. The autograft group (control group) was contrasted with two conduit groups: the HSB conduit/nanogenerator with ultrasound excitation (HSBN+US group) and the HSB conduit/nanogenerator without ultrasound excitation (HSBN group). Figure 7(e) displays the rates of muscle weight recovery for the three groups at week four. Experiments have shown that ultrasonic-driven wireless ES effectively upregulated muscle recovery. In addition, a real-time, dynamic feedback method may be provided via in situ ES of the repaired nerves through implanted nanogenerators. This work evaluates nerve repair without sacrificing animals and provides a new strategy for a biodegradable implantable piezoelectric nanogenerator with ultrasonic response for in vivo electrical stimulation for tissue engineering applications.

Deep brain stimulation (DBS) is a clinically established technique for treating various neurological disorders [119–122]. Recently, researchers have developed a miniature and flexible piezoelectric ultrasound energy-harvesting device using Sm-doped Pb $(Mg_{1/3}Nb_{2/3})$ O_3-$PbTiO_3$ (Sm-PMN-PT), (Sm-PUEH) [123]. Figure 7(f) depicts the schematic diagram of the Sm-PUEH device for DBS and analgesia in addition to an exploded image of the device. In vitro Sm-PUEH may provide an average charging power of 4270 ± 40 nW and an instantaneous output power of up to 1.1 W/cm^2. The variation in the device's output voltage, current, and power is shown in Figure 7(g) over an external load resistance range of 100 Ω to 10^4 MΩ. After implantation into the head of rats, electrophysiological and behavioral experiments confirmed the device's ability to achieve ultrasound-driven deep brain electrical stimulation, effectively modulate neural activity in the brain, and achieve significant pain inhibition. This study introduces a new strategy for deep brain stimulation and pain suppression technology, while providing a new idea for energy supply of biomedical implantable devices.

4. AEH Based on TENG

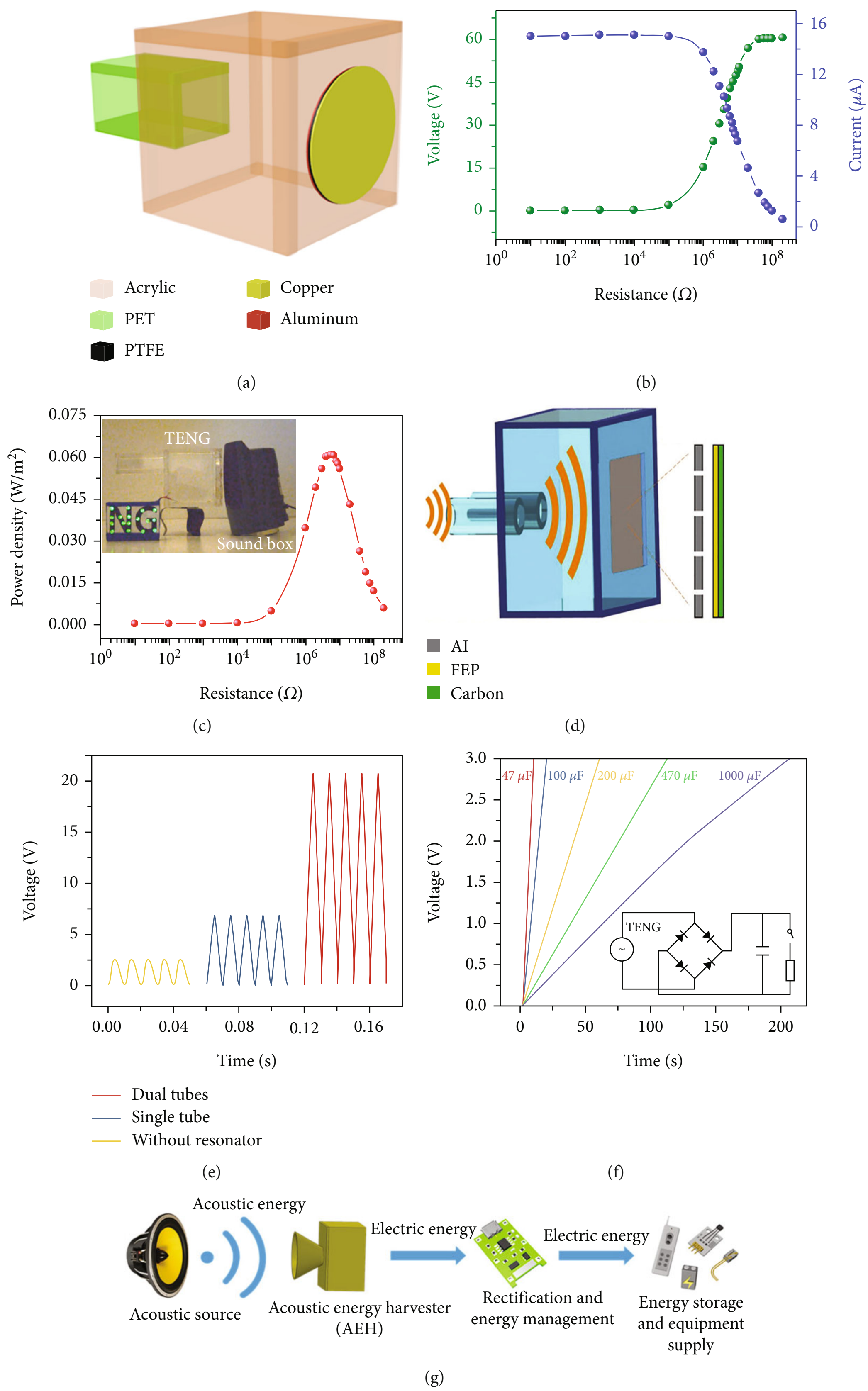
4.1. Helmholtz Acoustic Resonator-Assisted AHE Based on TENG. In 2014, Yang et al. [124] created the first organic film-based TENG that employs a Helmholtz cavity to gather surrounding acoustic energy as a reusable power source and function as a self-powered dynamic acoustic sensor in the low-frequency range of daily life. The design incorporates a circular nanogenerator embedded on the back plate of the Helmholtz resonator. Friction electrodes made of copper-coated polytetrafluoroethylene (PTFE) film and acoustic hole-covered aluminum film enable the conversion of acoustic energy into electrical energy, as shown in Figure 8(a). The acoustic sensitivity of the device reaches 9.54 V/Pa. Under incident acoustic wave conditions of 240 Hz and 110 dB, the energy harvesting device operates in a resonant working state, and its corresponding voltage, current, and peak power density are 60.5 V, 15.1 μA, and 60.2 mW/m^2, respectively. The generated power can simultaneously supply energy to 17 commercial light-emitting diodes (LEDs) conducted in series, and the energy conversion efficiency is as high as 60%. The above conclusion is proved in Figures 8(b) and 8(c). Further experiments confirm such triboelectric acoustoelectric conversion device is a self-powered acoustic sensor capable for sound recording and sound source localization. It has strong adaptability and high cost-effectiveness, offering valuable insights for the creation of TENGs for the capturing and sensing of acoustic energy.

By researching the coupling mechanisms between TENG theory and sound propagation theory, it is feasible to maximize the performance of acoustic energy harvesters and offer the best output in a certain frequency range. Zhao et al. [125] fabricated an efficient acoustic energy harvester by combining a dual-tube Helmholtz resonator with a triboelectric nanogenerator (HR-TENG), as shown in Figure 8(d). Experimental results demonstrate that the dual-tube resonator acoustic energy harvester outperforms the device based on a typical single-tube Helmholtz resonator, exhibiting an 83% increase in maximum output voltage. Comparison in Figure 8(e) reveals that the resonator-based triboelectric nanogenerator enhances the acoustic energy harvesting performance in the frequency range of 20~150 Hz. This efficient acoustic energy collection device achieves a maximum power density of 1.82 W/(Pa·m^2). Moreover, it can function as a self-powered acoustic sensor with a maximum acoustic sensitivity of 1.23 V/(Pa·cm^2). Figure 8(f) shows an illustration of the HR-TENG charging capacitors with various capacities. A rectifying bridge applies the TENG's AC output to a capacitor's two ends, allowing the capacitor to store electrical energy.

Modifying the resonant cavity structure to enhance the conversion efficiency of the triboelectric acoustic energy sensor is a crucial research area. Yuan et al. [126] presented a conical Helmholtz resonator-based triboelectric nanogenerator (CHR-TENG), as shown in Figures 8(g) and 8(h). The conical Helmholtz resonator in CHR-TENG serves to enhance sound energy collection. The FEP film in the CHR-TENG is alternatively detached from the aluminum electrode to provide continuous power output, which is driven by sonic waves. When collecting acoustic energy, the CHR-TENG's innovative design of tapered Helmholtz resonators may significantly enhance output performance and widen its response frequency spectrum. Through optimization, the CHR-TENG achieves a maximum acoustic sensitivity of 1.68 V/(Pa·m^2) and a unit sound pressure power density of 2.88 W/(Pa·m^2). Through comparison, the unit sound pressure power density is increased by 58.2%. Furthermore, the CHR-TENG successfully powers a temperature and humidity sensor continuously by charging a 1000 μF capacitor to 1.5 V, as demonstrated in Figure 8(i).

Subsequently, Zhang et al. [127] further established a triboelectric nanogenerator based on a multitube parallel Helmholtz resonator (MH-TENG), for obtaining acoustic energy in low-frequency noise situations. Relevant experiments show that the power generation capabilities and bandwidth of MH-TENG with a multitube Helmholtz resonator are significantly improved. The operating frequency and bandwidth of MH-TENG are improved by 130% and 77%, respectively, when compared to single-tube resonator TENG and double-tube resonator TENG. In the 230 Hz frequency range, the sound-driven MH-TENG can run 110 LEDs and an electronic thermometer constantly and maintain its normal working condition. Furthermore, the MH-TENG exhibits favorable capacitance charging performance, requiring only 52 seconds to charge a 220 μF capacitor to 3 V. The MH-TENG effectively improves the efficiency of acoustic energy collection and is anticipated to serve as an important supplement to low-power electrical devices in high-noise environments such as machinery factories, railways, and machine rooms.

How to combine high-efficiency low-frequency sound energy acquisition performance with high-quality sound



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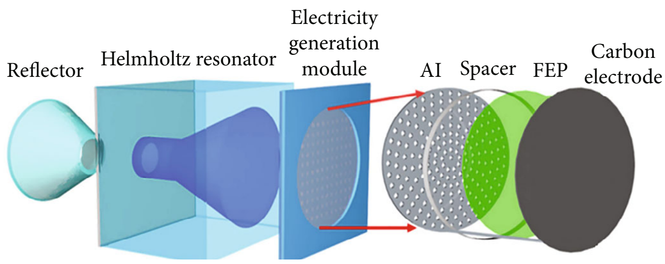

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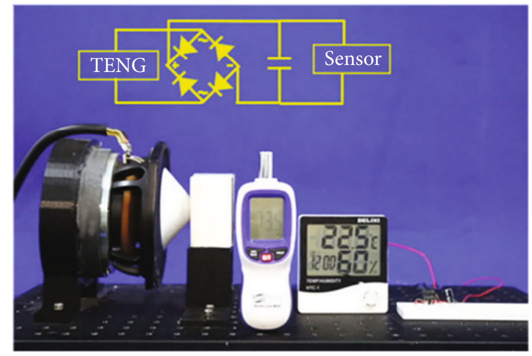


(i)

Figure 8: Helmholtz resonator acoustic harvesters. (a) Structural design of the organic film nanogenerators. (b) Relationship of the voltage and current output on the external load resistance. (c) Relationship of the power output on the external load resistance. 17 LEDs are being lighted up simultaneously (copyright 2014, ACS). (d) Structure scheme and working mechanism of the HR-TENG. (e) The HR-TENGs' open-circuit voltage under the identical sonic wave conditions. (f) The electrical output of the TENG is used to charge capacitors of various capacities (copyright 2019, WILEY-VCH). (g) The management system of the CHR-TENG. (h) A schematic illustration and the energy harvesting and (i) CHR-TENG powering the temperature and humidity sensors (copyright 202, MDPI).

sensing capabilities has always been a difficult challenge for TENG. To address this, Zhu et al. [128] proposed a triboelectric nanogenerator with a porous acoustic resonator (MHAR-TENG), which couples a porous acoustic resonator and a differential pressure acoustic receiver. The MHAR-TENG, which is depicted in Figure 9(a), comprise a perforated plate, an acoustic TENG, and an acoustic resonant cavity. It shows the acoustic TENG's intricate layer-by-layer structural layout. At the optimal frequency of 150 Hz and the sound pressure level of 104 dB, the MHAR-TENG displays a capacitance charging speed that can reach 31.9 C/s, which is faster than the previously announced acoustically powered TENG device. It also has an open-circuit voltage of 347 V, a short-circuit current of 95 A, a power density of 8.9 W/m^2, and a power density of 95 A. In order to evaluate the realistic power supply utility, the MHAR-TENG was linked to a full-wave rectifier bridge, allowing the output energy to power LEDs directly. All of the LEDs in the word "SICCAS" may be illuminated by an acoustic wave having a frequency of 150 Hz and an SPL of 104 dB, as illustrated in Figure 9(b). The MHAR-TENG's strong signal-to-noise ratio and precise high-frequency response make it possible to recover music and human voice in high quality. The MHAR-TENG's efficiency as a self-powered sound sensor is shown in Figure 9(c), where the original and restored speech's spectrograms and time-domain sound wave signals are similar. MHAR-TENG is able to recognize emotions and voiceprints autonomously with more than 90% accuracy thanks to machine learning. MHAR-TENG offers a lot of promise for effective auditory-electric conversion in fields including noise recovery, biological authentication, and human-computer interface since it is a sophisticated acoustic energy harvester. In the future, it offers a new way to use acoustic energy and acoustic sensing on a huge scale.

Utilizing new materials is a feasible approach to improve the efficiency of the transducer. Carbon nanotubes (CNTs) have desirable properties such as high conductivity, flexibility, and environmental stability, making them ideal conductive nanostructures with positive frictional charges. Moreover, CNTs enhance the contact surface area and stability of TENGs under any external stress. Javadi et al. [129] employed CNTs to increase the effective surface area of the contact electrode, resulting in a seven-fold increase in the output power of the sound-driven triboelectric nanogenerator. This enhancement was achieved through the implementation of an acoustic array structure. Figure 9(d) illustrates the structure, where the top electrode is connected to the bottom electrode using Kapton tape as a gasket, and multiwalled carbon nanotubes are dispersed on the top electrode. The TENG is embedded within a 1D phononic crystal (PnC) composed of five steel plates. At the incident acoustic frequency of 4.24 kHz, the measured output voltage enhancement coefficient is about 4, which is equivalent to 7 times the enhancement coefficient of the embedded TENG output power. For the resonance frequency (4.24 kHz), the observed output voltage signals for the free TENG (V_{Free}) and TENG imbedded inside the PnC (V_{PnC}) are displayed in Figure 9(e). The effect of adding CNTs on the open-circuit voltage of the investigated sonic nanogenerator is presented in Figure 9(f), respectively. Considering the loss and nonideality of other structures, the experimental results are in excellent alignment with the simulation results. The enhanced triboelectric acoustic energy harvesting device benefits from one-dimensional phononic crystal technology. It is completely compatible with TENG's structural features, with simple structure and good development prospects.

4.2. Quarter-Wavelength Tube-Assisted AHE Based on TENG. The abovementioned devices are based on the acoustic Helmholtz resonators, which are excellent for generating improved excitation. However, when the bottom parts of the Helmholtz resonators adopt flexible membranes, sound pressure amplification is typically decreased. In contrast to the Helmholtz resonator, the quarter-wavelength resonator is actually another significant structure that has distinct advantages including a straightforward design and straightforward construction. But in the area of acoustic TENG, this

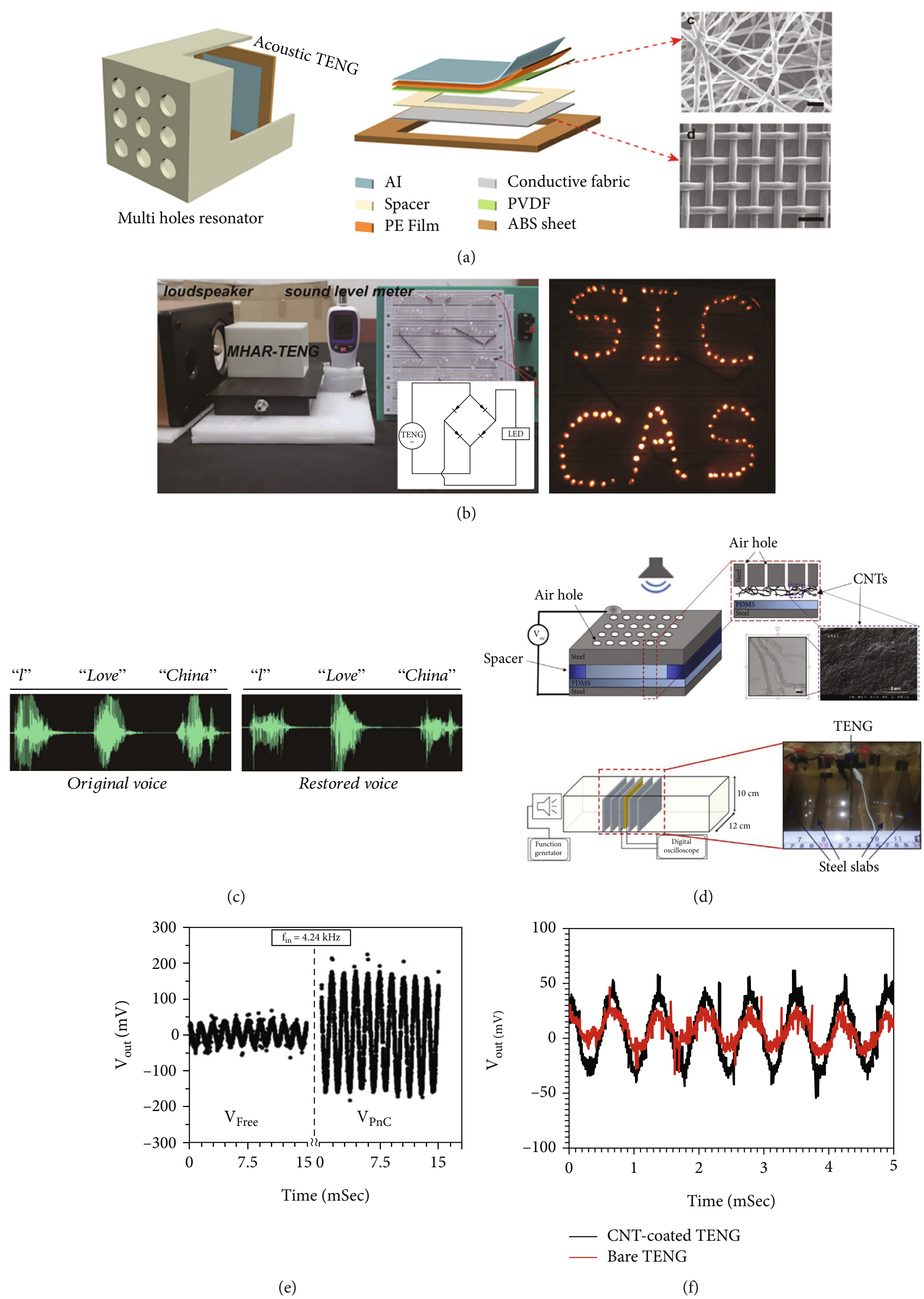


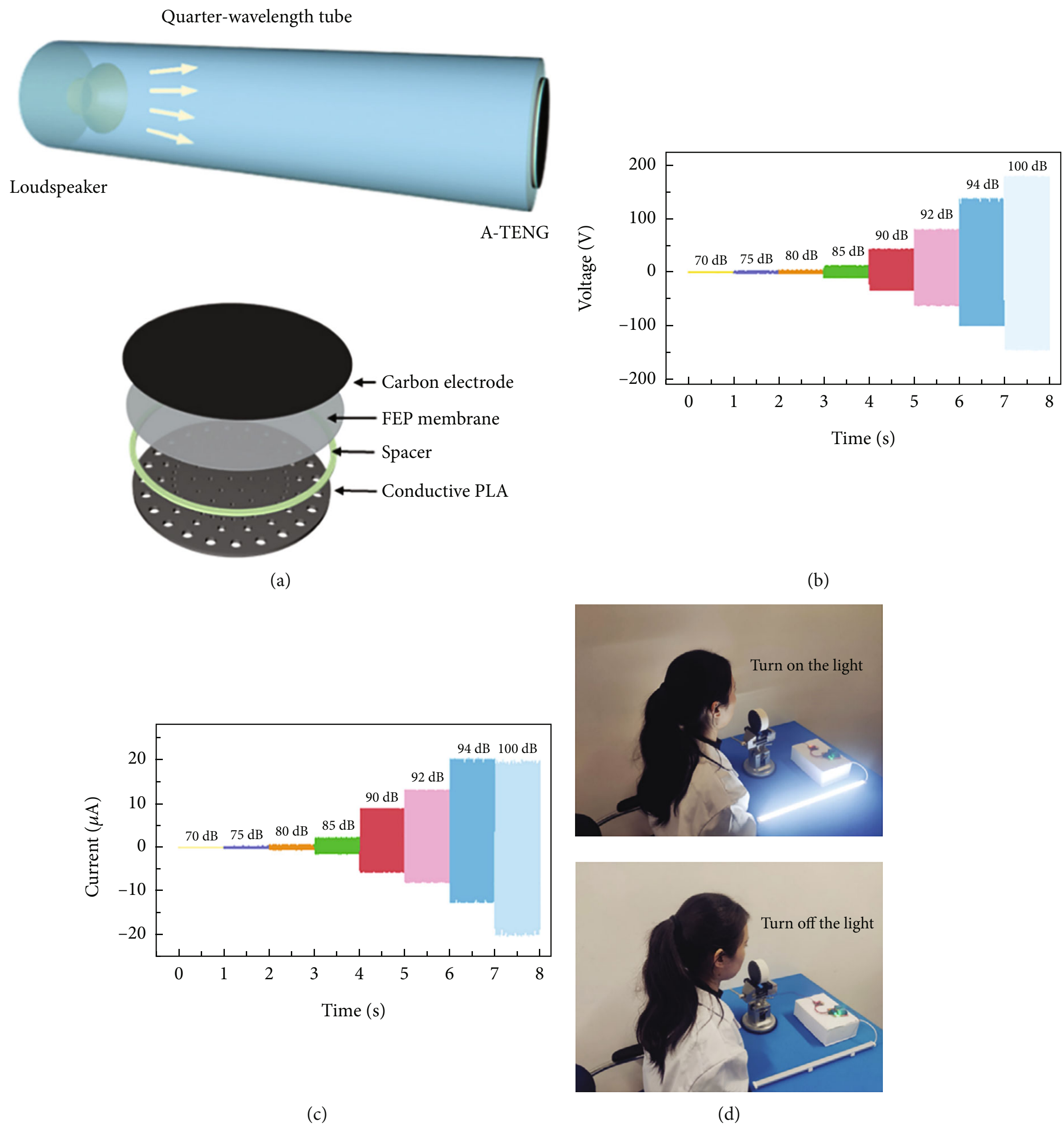
Figure 9: Acoustic energy harvesting devices with porous resonator structure. (a) The MHAR-TENG's structural layout. (a) The MHAR-TENG directly illuminates LED lights. (c) The MHAR-TENG can also directly record and clearly recover a spoken sentence that has been played aloud (copyright 2023, Elsevier). (d) Schematic of the fabricated sonic TENG. (e) Along with the signal from the embedded TENG, the free nanogenerator also outputs voltage signals at resonance frequency. (f) Output voltage values of the CNT-based TENG and the bare TENG (copyright 2018, Elsevier).

structure has not yet received enough attention. In 2021, Yuan et al. conducted a comprehensive investigation on an acoustic energy harvesting system (A-TENG) based on a quarter-wavelength resonator coupled with TENG [130]. Figure 10(a) shows the device structure of the A-TENG. The harvester uses an aluminum tube as a quarter-wavelength acoustic resonator structure. The upper and lower electrodes of TENG are 3D-printed conductive polylactic acid perforated plate (PLA) and printed deposited carbon electrodes on the back of FEP film, respectively. The FEP film is charged by corona charging technology to enhance the surface charge density, while an insulating gasket is in the middle to ensure sufficient contact separation between the upper and lower parts. In the experiment, the speaker is positioned at the closed end of the quarter resonator, and the triboelectric nanogenerator is placed at the open end. Figures 10(b) and 10(c) depict the A-TENG device's output voltage and current at various SPLs. The harvester can generate up to 4.33 mW of electrical energy under 100 dB sound pressure level, enabling direct power supply for electronic devices. It can simultaneously and continuously supply 72 LED lights and a calculator simultaneously and continuously. In addition, real-time voice recognition using a self-powered sensor system is demonstrated. The speech signal is converted into an electrical signal through the A-TENG, which is then processed and recognized by an AI chip through built-in networks to control the subsequent circuitry. By combining acoustic energy harvesting systems with artificial intelligence sensing technologies, these innovative approaches are deployable in the Internet of Things' periphery, with the advantages of multifunction, independent computing, low cost, and no maintenance. It is believed such comprehensive, intelligent, and self-powered intelligent system represents a promising direction for future advancements. Figure 10(d) shows the demonstration of the self-powered edge sensing technology for real-time speech identification.

As shown in Figure 10(e), Chen et al. [131] developed a novel triboelectric-acoustic energy harvester based on electropunk PVDF nanofibers. Specifically, the TENG was constructed by conductive fabric, Kapton, and PVDF, with PVDF nanofibers used as vibrating membranes. Experimental results in Figure 10(f) show that with a sound frequency of 170 Hz and a sound pressure of 115 dB, this sound-driven TENG aggregate with a polymer tube can produce an open-circuit voltage and short-circuit current of 400 V and 175 A. And a 7 W/m^2 instantaneous maximum peak power density is present. The unique structural design is conducive to the capture of sound energy and the enhancement of sound pressure. Figure 10(g) shows that the TENG can drive 55 LEDs and a temperature and humidity sensor. By testing the electrical impulses at various frequencies and sound pressure levels, it is found that the TENG can operate within a bandwidth of sound waves from 20 Hz to 1000 Hz for audio analysis and noise detection. Additionally, the developed TENG acts as a self-powered sensor to detect the sound source direction and motion speed of the acoustic object. Its structure and installation diagram are shown in Figure 10(h). The comparison between the tested speed and the real speed of the linear motor platform is shown in Figure 10(i). As seen in Figure 10(i), the recorded velocity is almost identical to the actual speed, and the highest inaccuracy is less than 1%. This work not only provides a simple, economical, and efficient method for manufacturing high-performance environmental acoustic energy harvesting TENG but also provides a self-powered sensing method, which has potential value in military monitoring, artificial intelligence, and the Internet of Things.

Xiao et al. [132] proposed a triboelectric nanogenerator QWR-TENG based on a quarter-wavelength resonator for low-frequency acoustic energy harvesting. As seen in Figure 10(j), the TENG is made up of a layer of conductive carbon nanotubes, a flexible FEP sheet, and an aluminum film that has been evenly perforated. Within the frequency range, the QWR-TENG resonator showed two sound pressure difference peaks and output voltage peaks that were related to the two natural resonance frequencies of 80 and 210 Hz, respectively, as shown in Figure 10(k). The sound pressure difference at the resonant frequency of 80 Hz is 15.6 dB, and the value is 11.5 dB at the resonance frequency of 210 Hz. As the frequency increased, the open-circuit voltage of the QWR-TENG showed two output peaks with respective values of 194 and 158 V, which were consistent with the sound pressure difference's variation pattern. QWR-TENG effectively expands the response bandwidth of acoustic-electric conversion in the low-frequency range. In order to improve the ability of acoustic-electric conversion of QWR-TENG, a conical energy concentrator was installed by researchers at the open end of the quarter-wave tube (CQWR-TENG). Figure 10(l) displays peak open-circuit voltages for QWR-TENG and CQWR-TENG under the identical acoustic excitation circumstances of 242 V and 348 V, respectively. Compared with QWE-TENG, the output voltage of TENG is increased by 40% due to the introduction of conical concentrator. Figure 10(m) shows the experiment of QWR-TENG lighting 196 LEDs at the same time under 90.1 dB and 100 Hz sound excitation. Future applications of the QWR-TENG design to real-world industrial contexts are depicted in Figure 10(n). Through this work, it is shown that QWR/CQWR-TENG has superior capacitive load behavior and may be used to power dispersed sensor nodes and other tiny electrical gadgets in the Internet of Things.

4.3. AHE Based on TENG without Resonator Assistance. In 2015, Fan et al. [133], based on the operating mode of vertical contact separation, created an ultra-thin, rollable paper-based TENG for acoustic energy harvesting and self-powered recording. The physical and material construction drawings are shown in Figures 11(a) and 11(b). The thickness of this acoustic energy converter is only 125 μm. Copper is plated on the surface of a paper as one friction layer, and PTFE film is used as another friction layer. The two films contact with each other to separate and transfer charges. A circular acoustic hole array is introduced to reduce air damping and enhance sound response. The maximum area power density can reach 121 mW/m^2, and the volume power density is 968 W/m^3 under the acoustic wave condition of 250 Hz and 117 dB sound pressure level.



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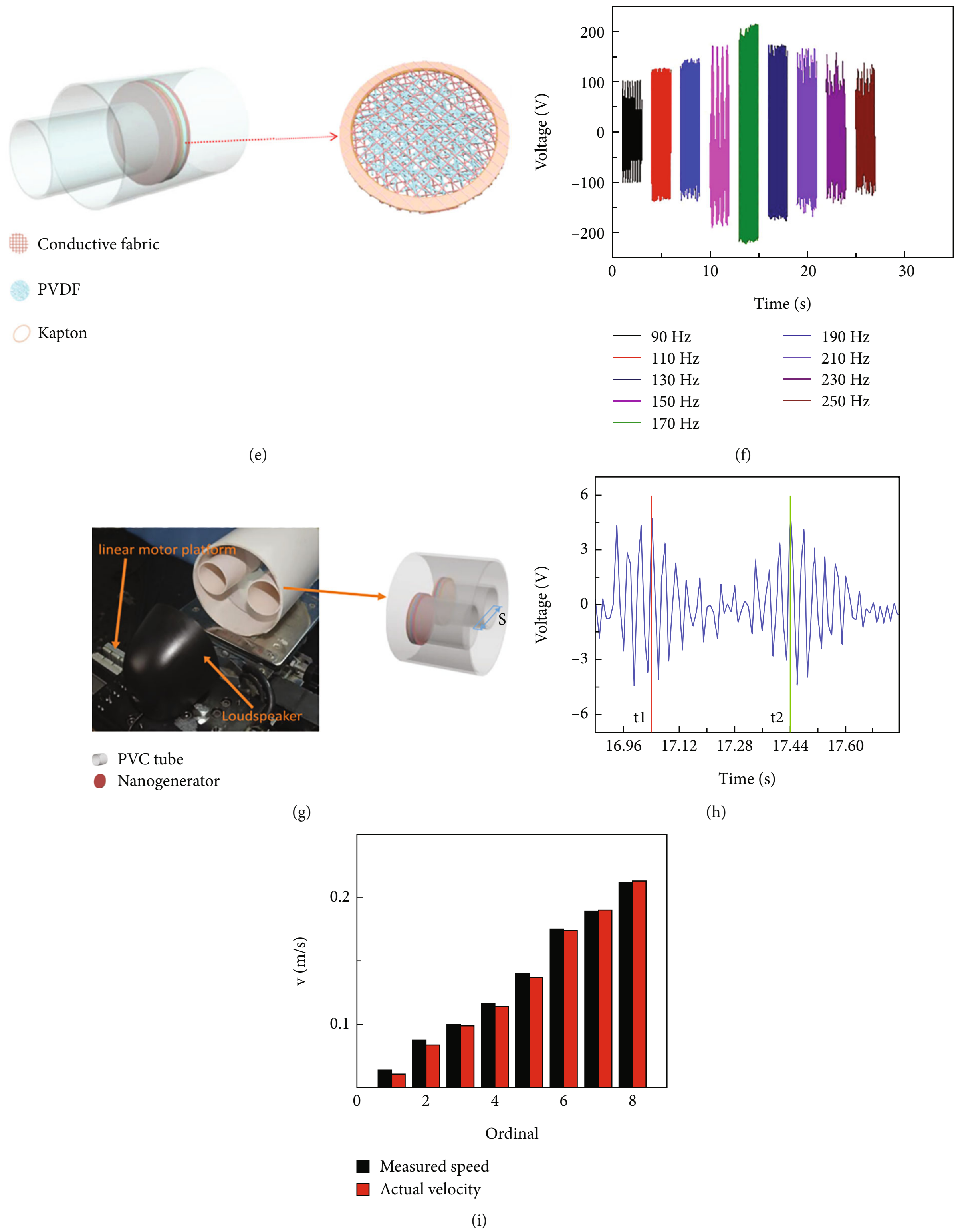

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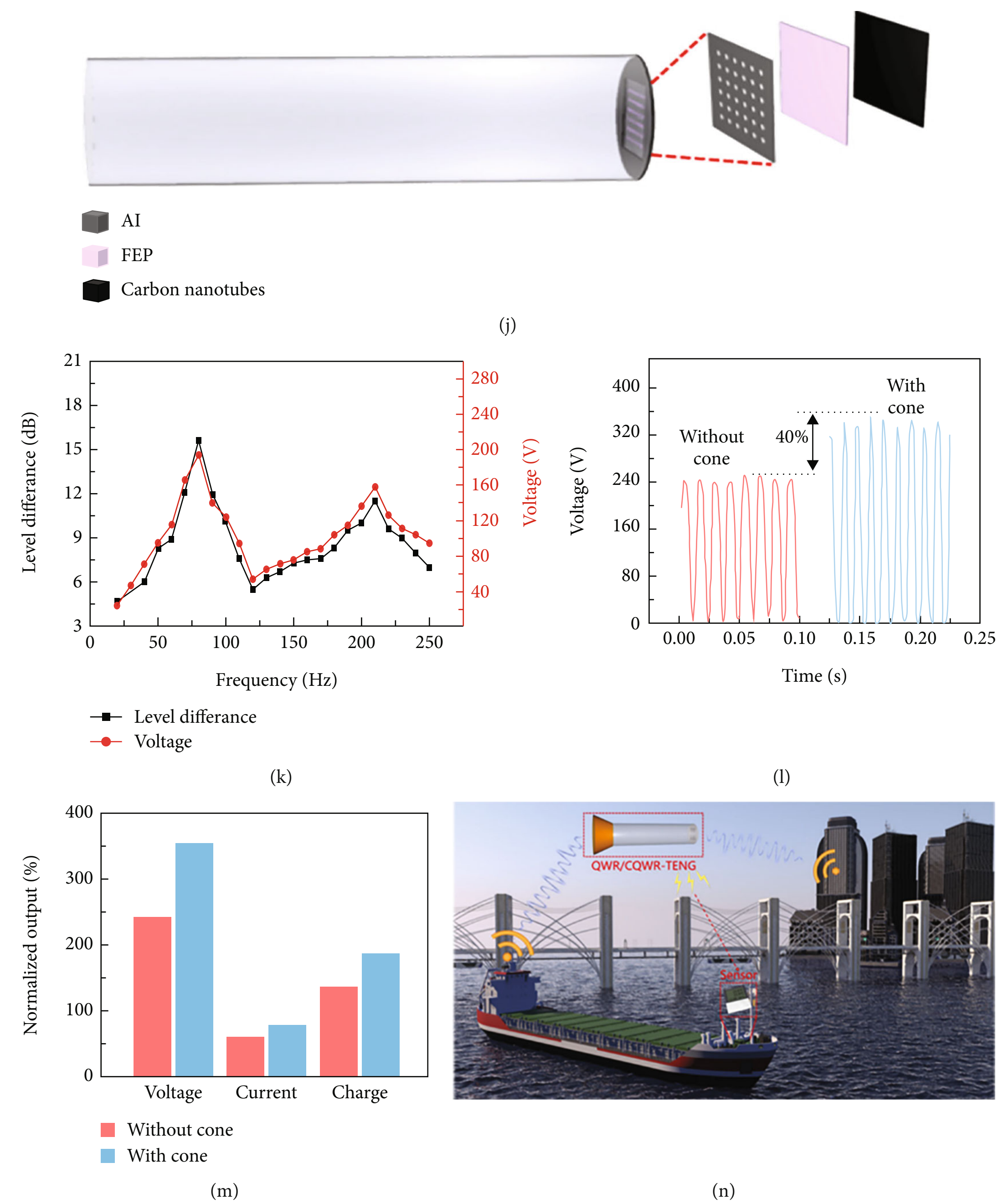
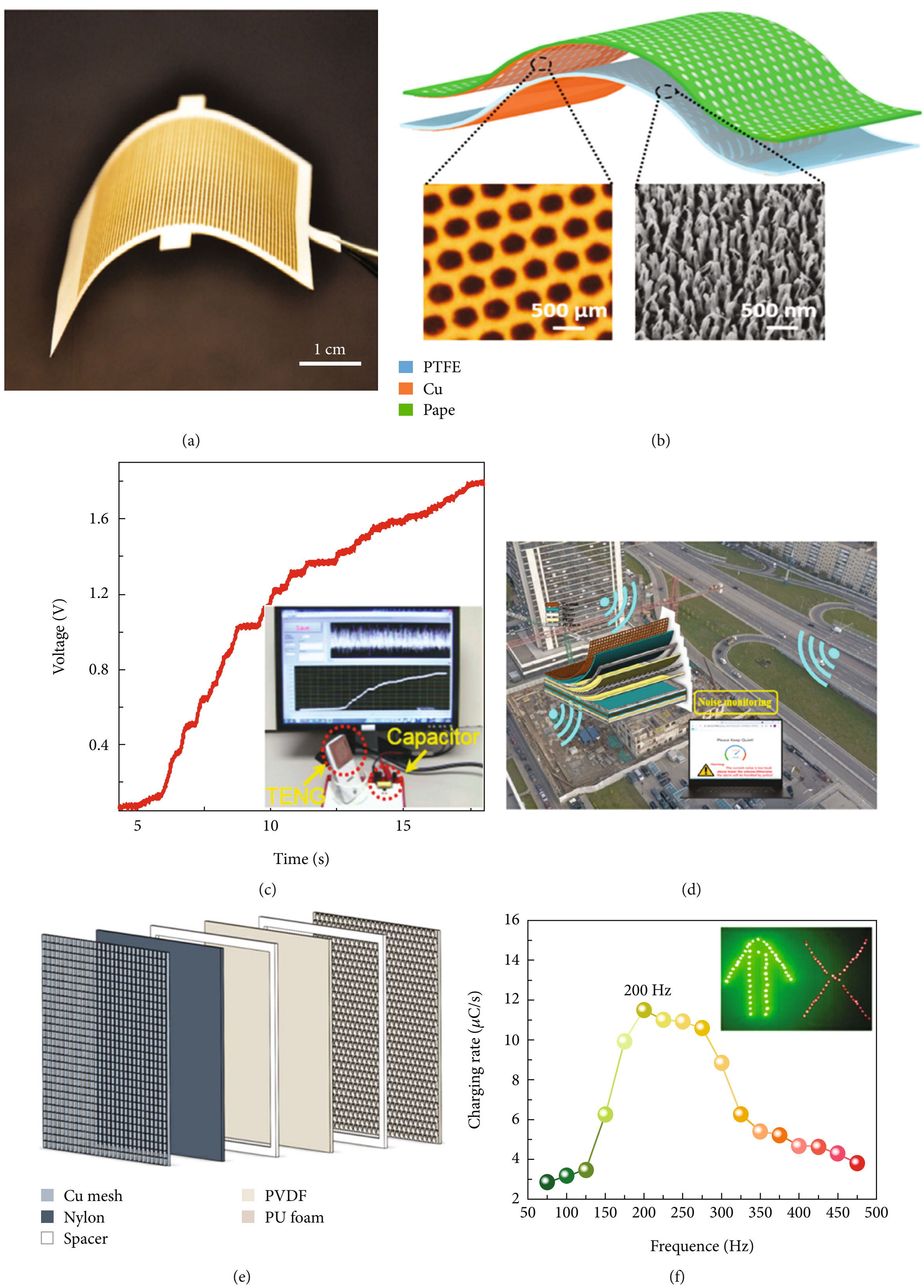


Figure 10: Acoustic harvesting and self-powered triboelectric nanogenerator based on quarter-wavelength resonator. (a) Presentation drawing of the A-TENG device. (b) Voltage outputs and (c) the acoustic harvester's short-circuit current outputs at various sound levels. (d) Speech recognition and perception demonstration experiment (copyright 2021, Elsevier). (e) Structure design of the sound-driven TENG. (f) The voltage output of TENG based on PVDF nanofibers under 115 dB, different frequency acoustic excitation. (g) The structure diagram of the proposed speed sensor. (h) The voltage signal recorded in the velocity measurement experiment. (i) The comparison between the measured speed and the actual speed of the linear motor platform (copyright 2018, Elsevier). (j) The structure design of QWR-TENG. (k) The functional relationship between the acoustic pressure difference and the open-circuit voltage of QWR-TENG and the acoustic frequency. (l) The influence of cone concentrator on the output voltage of QWR-TENG. (m) The effect of the front tapered cavity on the output performance of QWR-TENG. (n) Application of QWR/CQWR-TENG in a variety of low-frequency sound sources, including ships and industrial facilities (copyright 2023, MDPI).

Charging a 2 μF capacitor takes 15 s to reach a voltage of 27 V. It also has good directional independence and wide response frequency band. Figure 11(c) shows a typical cell phone that can charge capacitors with a paper-thin triboelectric nanogenerator. Due to the novelty of the structure without using the resonator and the superior output performance, the technology can obtain acoustic energy from portable electronic devices and generate electrical energy to charge the capacitor at a speed of 0.144 V/s. Moreover, the wide operating bandwidth, simple structure, and flexibility of this



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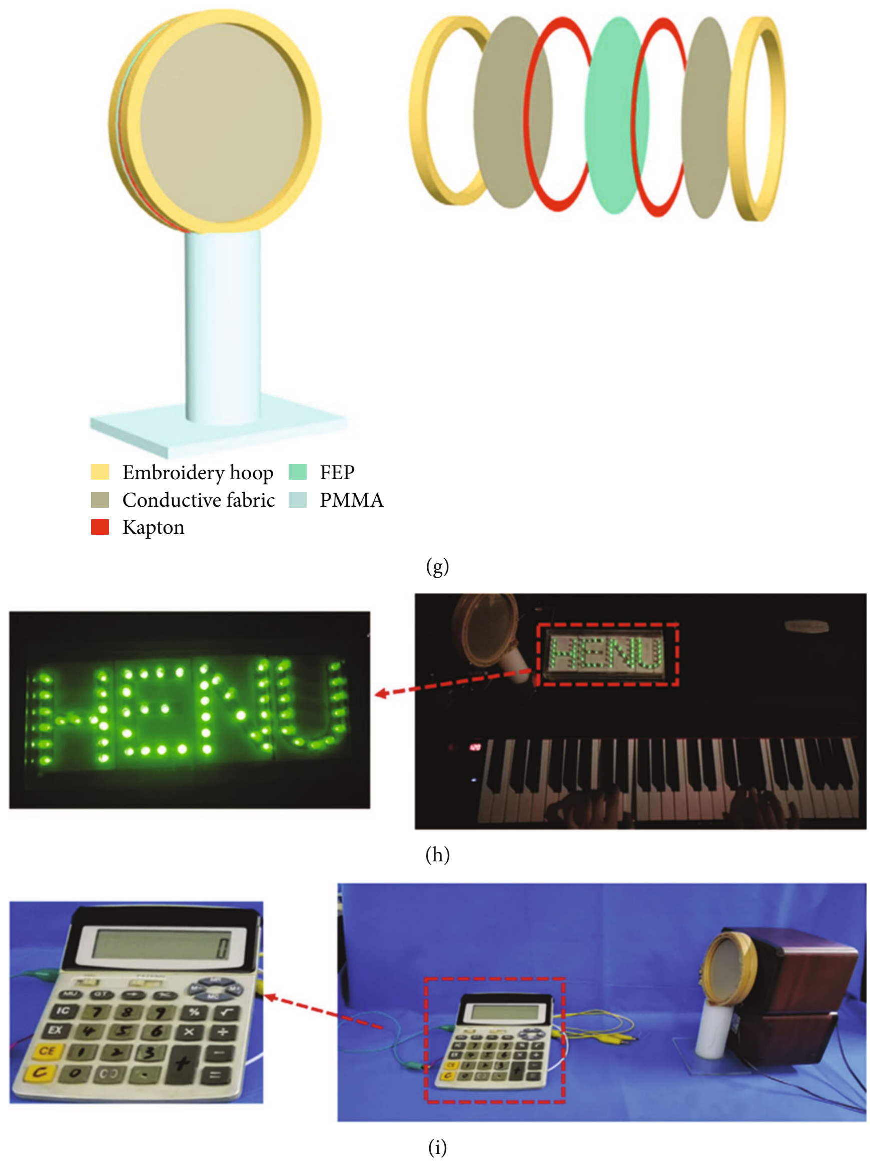


Figure 11: Tribo-electroacoustic energy harvester without acoustic resonator. (a) Photograph of the paper-based triboelectric nanogenerator. (b) Structure of the TENG. (c) The acoustic energy recovered from a cell phone charges the capacitor (copyright 2015, American Chemical Society). (d) Schematic diagram of LEN-TAEH. (e) The LEN-TAEH is used for urban real-time noise monitoring. (f) The LEN-TAEH's charging speed when recharging a 100 F capacitor (copyright 2022, Elsevier). (g) Structure schematic of the EH-TENG. (h) 55 green LEDs were turned on by the EH-TENG when the piano was played. (i) A commercial digital calculator is powered by the EH-TENG and a piano chord (copyright 2021, Wiley-VCH).

scroll structure make it suitable for angle-independent sound recording in self-powered microphones. The concepts and designs presented in this paper can be broadly applied to a wide range of different energy harvesting or sensing applications, including wearable and flexible electronics, military surveillance, noise reduction for jet engines, low-cost implanted human hearing, and wireless technology applications. From an economic point of view, the ultrathin TENG is made mostly from inexpensive, lightweight, and biodegradable paper components with a straightforward structure, considerably reducing the potential environmental expenses. As a result, the paper-based TENG is incredibly economical.

TENG built on polymer films has developed into a potent method for gathering energy [134]. They are used to transform multiple mechanical energies converted into electrical energies in a variety of devices, such as self-powered sensors [135] and environmental energy harvesting [136]. Kim et al. [137] constructed a powerful thin-film acoustic energy harvester (AO-TEG) using a flexible poly (3,4-ethylenedioxythiophene) (PEDOT) film as an electrode. This all-organic triboelectric generator prepared in this study has high flexibility and durability. Through testing, the device reaches an open-circuit voltage of 700 V, a short-circuit current density of 50 mA/m^2, and a maximum power density of 12.9 W/m^2, respectively. When the palm touches AO-TEG (120 N), AO-TEG can instantly light up 180 LED bulbs. Furthermore, AO-TEG serves as a thin film acoustic energy collector, capable of harnessing the energy from music to power 5 LEDs. This work presents an economical organic semiconductor that may be utilized as a TEG electrode to capture mechanical and acoustic energy without the need for sophisticated procedures, high vacuum, or adjustable temperature systems.

Xu et al. [138] designed a self-powered triboelectric conversion device using electropunk nanofiber materials for real-time (LEN-TAEH) decibel monitoring, as shown in Figure 11(d). A laminated acoustic energy collecting system was built using nylon nanofibers and electropunk PVDF. When the sound pressure is 104 dB and the resonance frequency is 200 Hz, the output electric energy can simultaneously light up about 100 LED bulbs. Figure 11(e) shows the laminated structure of LEN-TAEH. Moreover, the double-layer LEN-TAEH, consisting of two power generation units, achieved a maximum output voltage of 170 V, 1.28 W/m^2 of power density, and 53.6 V/Pa of sensitivity at the resonance frequency. Figure 11(f) displays the LEN-TAEH's charging rates for charging a 100 F capacitor at frequencies between 75 and 475 Hz, with the highest charging rate of 11.5 C/s being possible at 200 Hz. The output performance of LEN-TAEH remained above 90% even following 30 days of nonstop use in high humidity environment, demonstrating good working stability and durability. This study realizes the voice recognition and real-time noise monitoring utilizing LEN-TAEH at various frequencies and sound pressure level excitation, showing the broad application prospect of triboelectric conversion as a self-powered noise sensor in environmental noise monitoring.

Inspired by the embroidery hoop, as shown in Figure 11(g), Wang et al. [139] developed a novel type of TENG (EH-TENG) for collecting acoustic energy without the Helmholtz resonant cavity. The device is mainly composed of conductive fabric, vinyl fluoride propylene (FEP) film, and two Kapton separators. The conductive fabric has the advantages of being lightweight and easy to manufacture. FEP has excellent electronegativity, good flexibility, and low friction coefficient. It is prone to vibration under the action of acoustic waves of different frequencies and pressures. The open-circuit voltage and short-circuit current may both exceed 500 V and 124 A when the resonance frequency is 170 Hz and the sound pressure is 110 dB, respectively. Figures 11(h) and 11(i) depict 55 green LEDs that can be lit at the same time and continuously power the digital calculator driven by piano chords. Additionally, the study proposes a general power management strategy; to efficiently control the TENG's output mode and power different low-power appliances, especially business low-power wireless sensor nodes, a combination of low-cost electronic components with commercial integrated circuits (ICs) is used. This work not only leads the way for TENG to implement remote environmental information monitoring in conjunction with Internet of Things technology, but it also provides guidelines for the production of specific TENG-related energy management integrated circuits, which will support the engineering use of TENG in the Internet of Things space.

The majority of currently produced acoustic energy harvesters are built around an acoustic resonant cavity. The wide-ranging use of these methods is constrained by variables like the intricacy of the needed structures and the size of the required resonance cavities, which provide very low-volume specific energies. The abovementioned resonatorless acoustic energy harvester idea and design are applicable to a broad range of diverse contexts for energy harvesting or sensing reasons, including wearable and flexible electronics, military, airplane noise reduction, and wireless technology applications.

4.4. Implantable Triboelectric Acoustic Energy Harvester. The advancement of precision manufacturing, microelectronics, and biomedical technology has brought immense benefits to thousands of patients through implantable medical devices (IMD). However, the longtime power supply of IMD in the body is a huge challenge. Replacing the battery by surgery or using wired power transmission will bring additional pain and risk to patients. Currently, wireless energy transmission research primarily relies on electromagnetic induction and the piezoelectric effect. However, these approaches face limitations when applied underwater or for in vivo implantation.

The piezoelectric effect was primarily used in earlier transducer designs [140]. Design and size restrictions apply because the piezoelectric receiver can only effectively harvest acoustic waves at a specific frequency [141]. Over the past ten years, TENGs have been studied for energy harvesting and continue to excel in the realm of implantable and wearable technology [142]. They can be made of biocompatible, flexible [143], and nontoxic materials, and they can draw energy from the body's mechanical motions [144]. In addition, triboelectricity produces a surface charge that is proportional to area, relieving the need to design for resonance matching. Therefore, the research and development of wireless self-powered IMD based on triboelectric acoustic energy harvester have received extensive attention in recent years.

Hinchet et al. [145] show a thin implantable vibrating triboelectric generator capable of efficiently harvesting mechanical energy delivered by ultrasound through skin and liquids. Through contact electrification, ultrasound can cause a thin polymer membrane to move at a micrometer scale, generating electrical energy. A lithium-ion battery recharges in water at a rate of 166 μC/s. Under pig tissue, the generated voltage and current reached 2.4 V and 156 mA. The result is the first technology to use capacitive triboelectric electret instead of piezoelectric to generate ultrasound in vivo and power medical implants.

Kim et al. [146] demonstrated a wireless energy harvesting system based on triboelectric technology for ultrasonic energy transmission, shown in Figure 12(a). By using ferroelectric materials to adjust the surface potential, an effective wireless energy transmission of ultrasonic sound waves is achieved. Without the use of capacitance or a battery, the transferred energy can power 200 LED lights and an industrial IoT sensor unit at milliwatt levels, as shown in Figures 12(b) and 12(c). Compared with the piezoelectric acoustic energy harvester, this triboelectric harvester has more uniform transmission efficiency in a wide frequency range. This work successfully overcomes the problems of short distance, electromagnetic shielding, and rapid attenuation in liquid and solid in

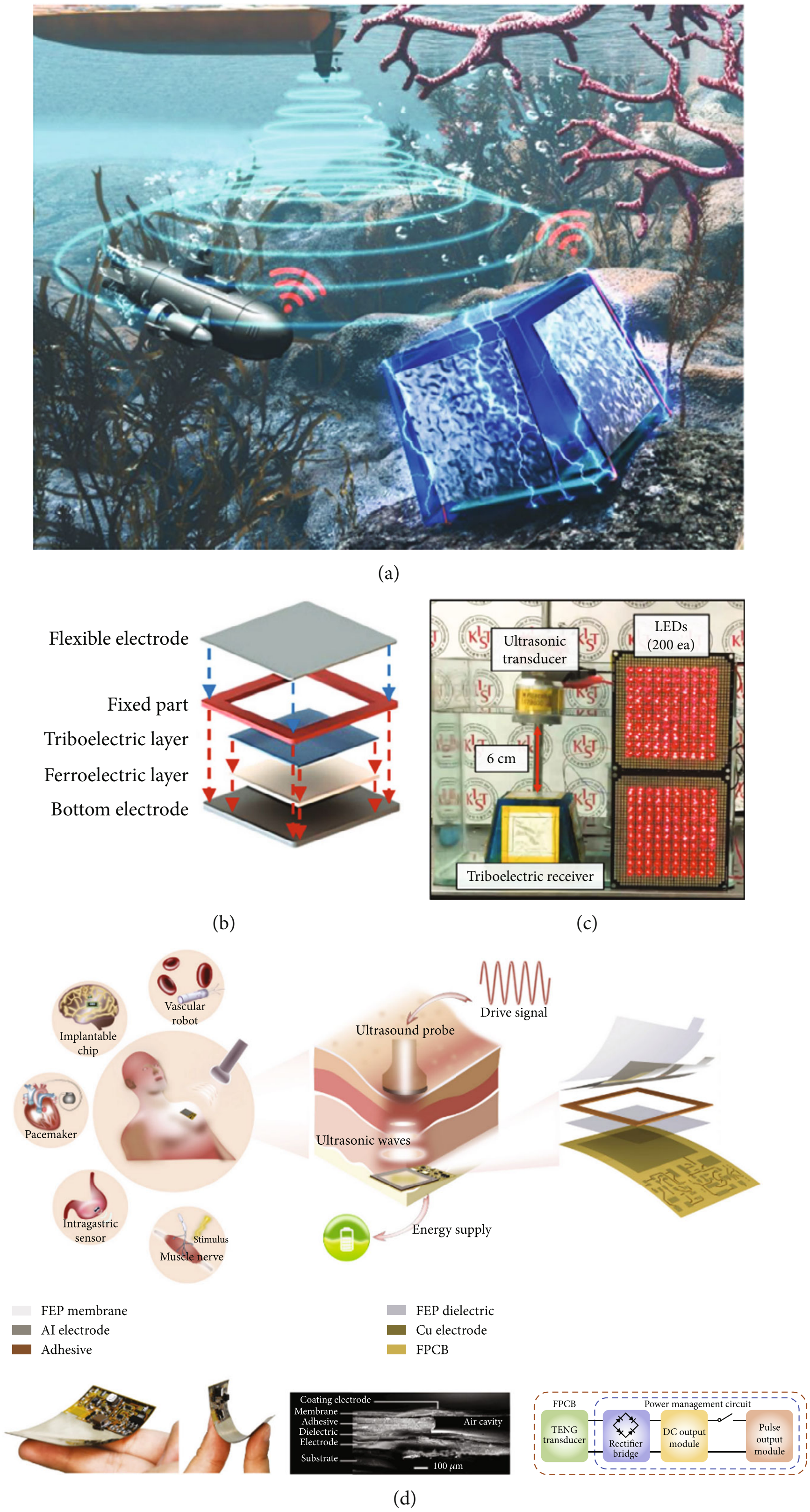


FIGURE 12: Ultrasonic-driven triboelectric acoustic energy harvester. (a) Concept map of underwater acoustic energy transfer (AET) system. (b) Schematic diagram of ferroelectric enhanced triboelectric acoustic energy harvester. (c) Underwater wireless AET system can illuminate 200 LEDs (copyright 2022, RSC). (d) The USD-TENG system in general. The USD-TENG system may be inserted beneath the skin and powers the implanted IMDs wirelessly via ultrasound (copyright 2022, Elsevier).

traditional electromagnetic induction sound energy transmission. This research establishes the necessary groundwork for the efficient and useful deployment of triboelectric-based acoustic energy harvesting and transmission technology and has good development prospects in human implantable sensor communication, submarine cable monitoring, through-wall power transmission, and data communication.

Scientists have created a range of TENGs with various structures to harvest and perceive ultrasonic energy based on the developing technology of TENGs. These ultrasonic devices, however, often rely on wired electrical signal connection, which is constrained by electromagnetic interference and communication distance. Complex manufacturing procedures and high maintenance expenses also place restrictions on the application space [147]. Therefore, there is still a need to actively promote research into self-powered underwater ultrasonic sensing and communication equipment with extremely quick response times and extremely high sensitivity, free from electromagnetic interference, simple to manufacture, good stability, safety, and environmental protection.

Liu et al. have developed a subcutaneous implantable flexible ultrasonic energy harvesting system (USD-TENG) [148], integrating a power management circuit and a triboelectric nanogenerator (TENG) onto a single flexible manufactured circuit board. The whole USD-TENG system is shown in Figure 12(d). By enhancing the attached electrode TENG's structural parameters, the system achieves a 66% increase in output power compared to previous works, along with reduced impedance. This flexible system can produce a steady DC voltage of 1.8 V, a serial DC output power of more than 1 mW, and an instantaneous power of more than 10 mW, all of which are adequate to constantly operate different sensor systems for nerve stimulation. The over of the USD-TENG system is shown in Figure 12(d).

Implantable TENG has made continuous breakthroughs in daily life and clinical monitoring as a portable electronic device. However, at present, researchers have only studied the biosafety and biocompatibility of implantable TENGs in a short period of time (no more than one month) at the cellular and tissue levels. Therefore, the long-term biosafety of implantable TENG needs to be further evaluated [149].

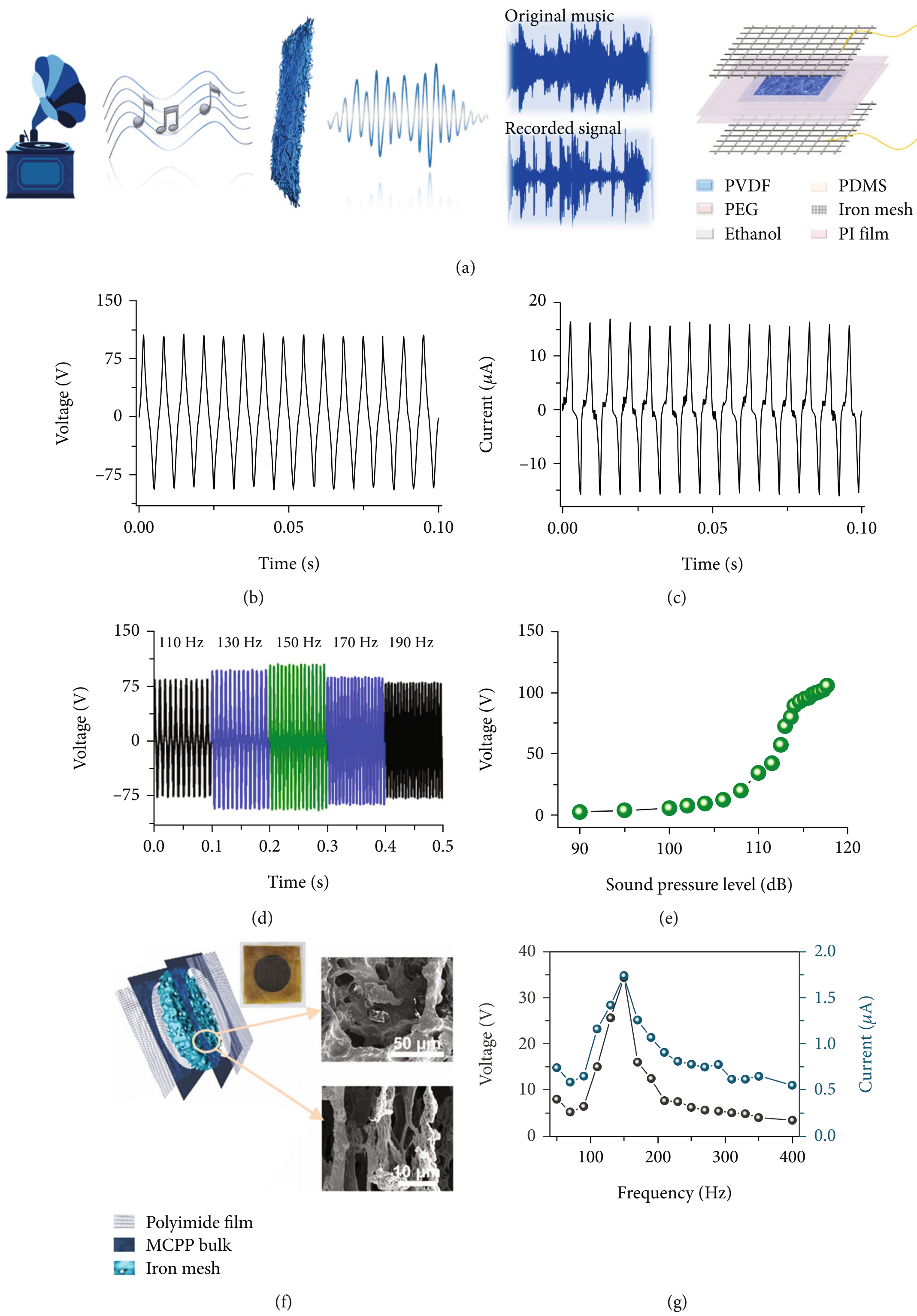
5. Hybrid Acoustic Energy Harvesters

As shown above, acoustic energy harvesting technology based on only piezoelectric or triboelectric nanogenerators has been applied to many fields, such as biomedical and scientific detection [150]. However, a single energy harvesting principle often faces challenges in effectively converting environmental acoustic energy due to low power density and limited frequency range [151]. To address this, combining piezoelectric and triboelectric nanogenerators seems to be a good way to enhance the acoustic-electric conversion efficiency. Compared with the traditional energy conversion technology that relies on a single principle for power generation, hybrid generators offer improved collection and conversion of environmental acoustic energy into electrical energy [152, 153]. These approaches surpass traditional single-principal energy conversion techniques and better compensate for the limitations of devices based on a single principle.

TENG has attracted extensive attention because of its excellent performance, simple design and construction, tiny weight, and high degree of adaptability. However, in some cases, using the original triboelectric material for TENG operation may not be sufficient to effectively drive/sense small- and medium-sized electronic systems. Therefore, the PENG and TENG effects are combined in a suggested hybrid method [154, 155]. In the above three principles of energy conversion technology, there is no complicated modification of the device construction necessary for the combination of the piezoelectric and triboelectric effects. The primary need is that the triboelectric nanogenerator's electrode material be made of piezoelectric material [156].. PVDF is a kind of piezoelectric polymer. Because of its unique electrical activity, high flexibility, good machinability, and long-term stability, it has become a commonly used piezoelectric nanogenerator material and is widely used in the collection and conversion of acoustic energy, acoustic wave detection, and recognition applications [157].

Yu et al. [158], innovatively using nanoporous PVDF hollow nanofibers and PDMS valve architectures, have developed a novel piezoelectric and triboelectric hybrid nanogenerator (PHVAH) for effective acoustic energy conversion, as shown in Figure 13(a). Figures 13(b) and 13(c) show that at a sound stimulation level of 117.6 dB and 150 Hz, a perfect output is 105.5 V and 16.7 A, and the power density is 0.92 Wm^{-2}. Figure 13(d) shows the voltage response of PHVAH in the frequency range of 110~190 Hz, and the output voltage exceeds 80 V. It can be proved that the proposed PHVAH has a wide operating frequency band, which provides considerable feasibility for its acoustic energy harvesting applications in more occasions. It has the ability to recognize audio signals as well as transform acoustic into electrical energy and light up 7 LED lamps in a row. We reproduced the actual application conditions of acoustic harvesting by adjusting the decibel of sound independently and further evaluating the electrical performance in order to further examine the sensitivity of PHVAH to the response of sound. According to Figure 13(e), the output voltage of PHVAH increases from 2.4 to 105.5 V as the loudness increases from 90 to 117.6 dB. The device's performance is further enhanced by the PDMS valve, which amplifies the film's vibration in response to sound waves and creates more chafe with the PVDF fiber. The piezoelectric-friction composite sound power generation device proposed in this paper has excellent durability and stability. It is an effective method to fully utilize the sound energy that is present everywhere, and it offers significant potential and power for employing acoustic-electric conversion for running different kinds of low-power sensors.

In order to better overcome the inherent shortcomings of sound energy, researchers used freeze-drying and liquid nitrogen quenching to prepare a beam-like multivacancy and tympanic membrane structure piezoelectric and triboelectric double-effect nanogenerator (MCPP ANG), which exhibits satisfactory acoustic energy harvesting ability and broadband response characteristics [159]. Figure 13(f) displays the structure of the MCPP ANG and SEM images of



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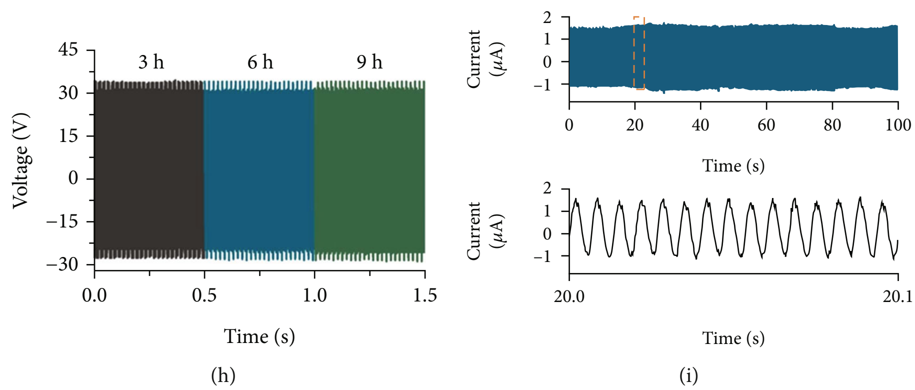

Figure 13: Hybrid acoustic energy harvesters. (a) Schematic and structure diagram showing the conversion of sound to electricity using a made-up PHVAH. (b) voltage and (c) current of PHVAH when exposed to 150 Hz and 117.6 dB sound stimuli. (d) Voltage response of PHVAH in the frequency range of 110~190 Hz. (e) Voltage response of PHVAH under various sound pressure levels at a frequency of 150 Hz (copyright 2021, ACS). (f) Structure diagram of the MCPP ANG. (g) Voltage and current responses of the MCPP ANG under different frequencies. (h) Output voltage of the MCPP ANG with extended use. (i) The MCPP ANG's output current stability within 100 s (copyright 2022, Elsevier).

the aerogel bulk. The external resonant cavity or contact separation structure is not included in this design, substantially simplifying the construction and enhancing the device's flexibility and robustness. The particular shape encourages acoustic wave diffraction and dispersion inside the hole wall to increase vibration and friction, which improves piezoelectric and triboelectric output. MCPP ANG performs admirably across a wide frequency range of 110-400 Hz, as shown in Figure 13(g). Under the acoustic excitation of 115 dB and 150 Hz, the device's open-circuit voltage and short-circuit current are 1.74 A and 34.4 V, respectively, and its output power density is 11.62 mW/m^2. Seven LEDs may be immediately lit in sequence with it. In long-term tests, the equipment further displays strong stability and acoustic signal-detecting capabilities. Figures 13(h) and 13(i) show that within nine hours, the MCPP ANG's output voltage barely decreased. The ANG proposed in this paper adopts a novel, simple, and effective structural design to achieve flexible and stable acoustic acquisition, which provides a promising way for the application of the acoustic spectrum, noise detection, and powering several low-power sensors.

On the basis of the traditional electrical conversion principles, a number of methods to harvest acoustic energy from the environment have been examined thereinbefore. Due to the limitations of each generator in real-world applications, hybrid generators that combine PENG and TENG have been encouraged to increase the output performance of acoustic energy harvesters as a whole. Increasing the charge density in the acoustic power generation system is one of the important means to improve the overall output performance of the device. The combination of PENG and TENG can effectively generate current due to the increase of its induced charge. At the same time, the composite sound energy collector can also avoid the adverse effects of the environment, such as humidity and dust, to a certain extent [160].

6. Conclusion and Prospects

According to a large number of existing research results, it has become one of the most promising technologies to realize the energy supply of WSN nodes in IoT by harvesting acoustic energy. In view of the important role of resonator in AEH, this paper reviews and discusses the research results of NG-based AEH from the perspective of resonator for the first time. Table 2 summarizes different types of AEHs, including different AEC principles based on PENG, TENG, and hybrid ones. Meanwhile, different acoustic energy conversion materials are given, including PVDF, PZT, FEP, PDMS, PEDOT, and other different materials, and the energy output under different resonator enhancement is given. It can be seen from these typical works that the working principle, material, and resonant structure will have an important impact on the output of AEH. Researchers can select the appropriate combination according to the actual use to meet the needs of energy supply. The research results of this paper can further promote the development of AEH based on NGs and can provide useful reference for the design and practical application of resonator in AEH based on NGs.

Currently, applications for wireless networks, sensors, low-power electronics, and biological fields are expanding quickly in everyday life. One of the main areas of research is how to effectively solve the problem of energy supply for the Internet of Things. There is a good application prospect to power the nodes of a wireless sensor network by converting the widely distributed sound energy into electricity. Relevant experiments have confirmed its viability, demonstrated stable operation, and met the energy requirements of small sensor devices. However, the history of acoustic energy power generation technology is relatively short. Most energy capture devices have only been studied in laboratory environments, and no power generation test is carried out in the actual application scenario. The lifespan and power generation efficiency of current devices remain unclear, necessitating further research. Therefore, continuous development, improvement, and optimization of environmental acoustic energy capture technology are still needed to realize the full potential of urban sensor network energy supply.

Table 2: Parameter list of typical sound energy power generation device.

The type of device	Power generation forms	Main constituent materials	The type of resonant cavity	Electricity output	Reference
Railway noise collection barrier	PENG	PVDF	Helmholtz resonator	The output voltage and output power can reach 74.6 mV and 1.24 μW at 110 dB incident sound pressure.	[102]
Piezoelectric acoustic power generation device based on acoustic crystal	PENG	PVDF	Acoustic crystal	The maximum output power is 37 nW.	[105]
Piezoelectric acoustoelectric energy conversion device based on acoustic metamaterials	PENG	PZT	Acoustic metamaterials	The peak power is 195.52 μW.	[106]
Coupled resonance structure for acoustic energy harvesting	PENG	PZT	Helmholtz resonator and acoustic metamaterials	At the resonance frequency of 5.545 kHz and the ideal load resistance of 4.4 k for an incoming acoustic pressure of 110 dB, the output power is 429 W.	[107]
Harvesting low-frequency acoustic energy in a straight tube resonance	PENG	PZT	Quarter-wavelength tube	The optimum output voltage is 15.689 V, and the power is 12.697 mW.	[109]
Harvesting low-frequency acoustic energy using a helix structure	PENG	—	—	The acquisition power is 7.3 μW at 175 Hz and 100 dB.	[110]
Implantable piezoelectric thin film nanogenerators	PENG	PVDF	—	Direct nerve electrical stimulation was successfully achieved.	[118]
HR-TENG [125]	TENG	FEP thin film	Helmholtz resonator	The maximum power density is 1.82 W/(Pa·m^2)	[125]
MHAR-TENG [128]	TENG	PVDF and PE thin film	Helmholtz resonator	The capacitor charging speed is 31.9 μC/s	[128]
Triboelectric acoustic energy generation device with acoustic array structure	TENG	Carbon nanotube (CNTs) and PDMS	Acoustic crystal	When the incident acoustic frequency is 4.24 kHz, the output voltage enhancement coefficient is 4 ($P_{out} = 4\ \mu W/m^2$).	[129]
A-TENG	TENG	FEP thin film	Quarter-wavelength tube	The TENG has a power output of 4.33 mW at an excitation level of 100 dB SPL.	[130]
AO-TENG	TENG	PEDOT thin film	—	The maximum power density can reach 12.9 W/m^2.	[137]
EH-TENG	TENG	FEP thin film and Kapton thin film	—	The open-circuit voltage and short-circuit current are 500 V and 124 μA, respectively.	[139]
USD-TENG	TENG	FEP thin film	—	Compared to the present work, there is a 66% increase in output power and a decrease in impedance.	[148]
New hybrid sound energy harvesting device	PENG and TENG	PVDF and PDMS	—	The optimum power density is 0.92W·m^{-2}.	[158]

With the sound of a car buzzing on the road, the background music in the commercial supermarket, and the keyboard hitting in the office, the city has created a never-ending sound of the city in the name of development, traffic noise, work production noise, and life noise [161]. According to the existing literature, various energy-capture technologies for environmental sound are still in their infancy and face many challenges. Therefore, we put forward the following prospects for the future evolution of acoustic energy harvesting technology, as shown in Figure 14.

6.1. Vigorously Develop the Hybrid Acoustic Energy Harvesters. Although the acoustic power generation devices mentioned above theoretically possess the capability to meet the power requirements of most energy-consuming devices in sensor networks, they still exhibit significant limitations. For example, electromagnetic generators have low efficiency in capturing low-frequency energy output, the power output of piezoelectric generators heavily relies on material properties, and friction nanogenerators have high impedance. With the future rapid development of IoT sensor networks, enhancing

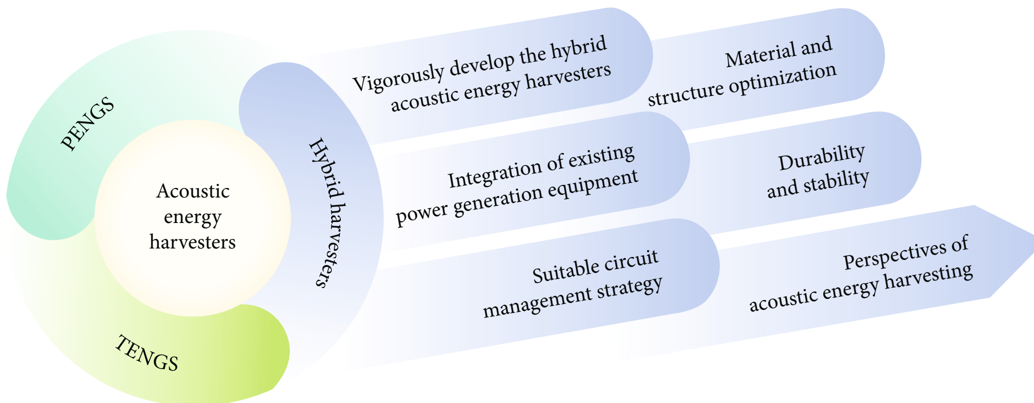

Figure 14: Perspectives of acoustic energy harvesting [27, 99, 168].

the efficiency of collecting and converting environmental low-frequency energy becomes increasingly crucial. To improve the performance of energy capture devices, developing hybrid acoustic energy capture devices has emerged as a consensus, aiming to enhance the energy capture efficiency of equipment.

In a broader context, the concept of hybrid energy harvesting devices encompasses not only the collection of multiple energy sources for self-powering energy-consuming equipment but also the conversion of environmental energy into electrical energy through various transduction mechanisms [162]. Different energy conversion mechanisms can be combined together to compensate each other, thereby increasing the output power [163]. Taking the EMG-TENG hybrid generator as an example, the energy capture device after mixing can effectively make up for the low efficiency of the electromagnetic generator for low-frequency input power generation, the bulky device, and the low output current of the triboelectric nanogenerator and maximize the conversion efficiency of acoustic energy [164]. PENG has good moisture and dust resistances, and TENG benefits from a wide range of easily accessible materials, lightweight, cheap cost, great efficiency, and ease of fabrication. However, the two complement each other in some aspects [30]. For example, TENG integrated manufacturing process is immature and vulnerable to environmental stability and humidity, while PENG can make up for this deficiency. If PENG and TENG are combined, it is possible to boost the system's total charge density, and under mechanical stress, the two effects complement one another nicely [165]. The advantages of the PENG and TENG hybrid acoustic harvesting systems are minimal weight, a simple construction, adaptability, and biocompatibility [166]. It exhibits excellent promise for effective energy harvesting and self-powered sensing in a variety of sophisticated applications.

At present, there are some achievements in the hybrid device for sound energy capture, mainly focusing on the combination of PENG-TENG, and there are still few other composite power generation devices. It has become a feasible way for the development of low-frequency energy capture devices in the future environment to develop a new structure of power generation devices with different principles and combine three types of energy capture devices with different principles as much as possible to capture sound energy more efficiently.

6.2. Material and Structure Optimization. The effectiveness and output efficiency of sound power generation devices can be enhanced by utilizing suitable materials in various sound environments. In terms of material selection, it is important to prioritize excellent power generation performance while also considering environmental friendliness and corrosion resistance to minimize environmental pollution. Additionally, the chosen materials should provide protection to the device itself. Researchers should also focus on strategies to mitigate corrosion caused by environmental factors and extend the device's service life.

In addition, the optimization and improvement of the construction of the resonant cavity used to capture acoustic energy cannot only improve the power generation performance. Compared with the traditional resonant cavity structure, the new structure can greatly reduce the volume of the acoustic energy generation device and better integrate with the miniaturization and convenience of the current electronic equipment.

6.3. Integration of Existing Power Generation Equipment. Given the speed of development of the city and the influx of population, the sound of car horns, building construction collisions, and aircraft landing roars are increasing. If they are not prevented, noise pollution will seriously affect people's physical and mental health. At present, the output performance of a single acoustic power generation unit has been verified in experiments. If the power generation unit can be mass-produced and integrated, supplemented by a specific energy management strategy to form a noise collection barrier, it cannot only reduce urban noise pollution but also use the power generated to power urban sensor networks to create a smart city. Such acoustic energy harvesting barriers may be tailored to various contexts, such as urban traffic tunnels, industrial parks, and airports, and have a wide range of potential applications. However, there are still many obstacles to truly realize this vision. In the future, the power output efficiency and durability of energy capture devices need to be continuously improved.

Acoustic power generation technology enables the collection and conversion of environmental sound into electrical energy. Using this technology, it is possible to continually turn the sound that is created by things like road traffic, industry machinery, and airplane engines into electrical energy. It can serve as a battery replacement or charger, giving energy to small, portable devices like microsensors and other micromechanical systems. The potential for this technology is vast. Acoustic power generation has a recent development history and is now in the research stage. The effectiveness of the acoustic-electric transducer, the low degree of integration of the power generation device that prevents system efficiency development, and the effect of current processing technologies on power production efficiency are the key elements affecting the system's performance. The research of acoustic energy harvester based on nanogenerator is finally oriented to practical application. Therefore, the present development trend is toward processing technology advancement, system parameter optimization for both the individual system and the entire system, system bandwidth expansion, high power, low voltage drive, downsizing, integration, and large-scale production at the same time. It is anticipated that acoustic power generating technology, as a unique method to power generation, will offer a theoretical basis and technological developments for innovation and breakthroughs in the creation of renewable energy.

6.4. Durability and Stability. A trustworthy AEH should continue to perform consistently for the duration of the service time [167]. Therefore, it is sought after that nanogenerator-based acoustic energy harvesters have exceptional endurance or perhaps require minimal maintenance. As mentioned above, the AEH based on NGs does provide a good solution for the wireless sensor power supply of the IoTs, but in particular, attention should be paid to the output performance of the harvester in practical application scenarios, such as the impact of dust, humidity, and other indicators on NGs. Therefore, packaging, material selection, and other aspects still need further study to further improve the durability of the equipment.

6.5. Suitable Circuit Management Strategy. Harvesting low-frequency mechanical energy in the environment through NGs is a promising strategy to solve the energy supply problem of WSNs in the IoTs. Therefore, it is necessary to develop an effective and safe energy management circuit to meet the normal operation of PENG and TENG and ensure that the output power is not wasted [168]. In the past few years, the research on the power management of NGs has mainly focused on rectification, electromagnetic conversion, capacitance conversion, and DC conversion [169]. However, with the booming application scenario of PENG and TENG, power management strategies are now facing biocompatibility and multidisciplinary issues [170].

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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