Extreme Mechanics Letters 42 (2021) 101100

Contents lists available at ScienceDirect

Extreme Mechanics Letters

journal homepage: www.elsevier.com/locate/eml

Triboelectric mechanical sensors—Progress and prospects

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ARTICLE INFO

Article history:
Received 15 October 2020
Received in revised form 9 November 2020
Accepted 9 November 2020
Available online 12 November 2020

Keywords:
Triboelectric nanogenerators
Triboelectric mechanical sensors
Triboelectric mechanical motion sensors
Triboelectric vibration sensors
Triboelectric pressure sensors
Triboelectric tactile sensors

ABSTRACT

The development of sensing technologies has increased the intelligence level of equipment. It is difficult for traditional sensing technologies to meet many current application requirements, such as complex trajectory monitoring, flexible manufacturing or other fields. Triboelectric nanogenerators were first invented in 2012 and have revolutionized energy generation and sensing. Triboelectric sensors have a variety of structures, which have promoted their applications in the field of internet of things, biomedicine, intelligent transportation and motion sensing or something. The development of triboelectric nanogenerators in machinery industry has attracted wide attention. This review covers recent progress in the development of triboelectric mechanical sensors for monitoring mechanical motion, mechanical vibration, mechanical pressure and mechanical tactile perception. The prospects of triboelectric mechanical sensors are then summarized.

Contents

1. Introduction

Sensing technologies are important in the development of industrial technology and progress of the internet of things [1,2].

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https://doi.org/10.1016/j.eml.2020.101100
2352-4316/

The machinery manufacturing industry is a major component of industrial development. Accurate real-time monitoring of machinery operation is important for improving the intelligence level of equipment [3]. Sensors based on different principles are widely used in industry. These include monitoring the motion of mechanical parts [4,5], sensing mechanical vibration [6,7] and pressure sensing [8,9], all of which can be used to optimize the running state of machinery. The characteristics of sensors affect potential applications. For example, optical fiber sensors are often used to monitor position [10,11]. Piezoelectric sensors are suitable for monitoring vibration and acceleration because of their fast response and high sensitivity [12,13]. Capacitance sensors have high precision and are used for monitoring surface roughness and micro-nano displacement [14]. There are many other motion monitoring sensors including piezoresistive sensors [15] and hall sensors [16,17].

Wang's group firstly invented the triboelectric nanogenerator (TENG) based on the coupling of triboelectrification and electrostatic induction in 2012, which can effectively convert mechanical energy into electric power/signal [18]. TENGs have attracted extensive attention resulting from the compatibility with a wide selection of materials, low assembly requirement and flexibility [19,20]. TENGs have played a significant role in energy generation and self-powered sensing [21]. The development of TENGs has promoted the development of sensing technology using a new approach.

Sensors based on TENGs that convert measured information into electrical signals through the relative motion of contact or non-contact between two electrode pairs with different electronegative properties can be described as triboelectric sensors. Triboelectric sensors can be classified into several types according to their output signals, monitoring objects and structures [22] include physical sensors [23,24], biomedical and healthcare technology sensors [25] and smart traffic sensors [26]. The application of TENGs in other fields will lead to more types and applications of triboelectric sensors. The rapid development of intelligent and integrated equipment is increasing the requirements for new sensing technologies. For example, triboelectric mechanical sensors (TMSs) have been developed for monitoring mechanical condition. TMSs transform mechanical signals such as position, acceleration, velocity, vibration, pressure and tactile sense into pulsed electrical signals, and then process, display and record information on the mechanical state. This review summarizes recent progress of TMSs, and is divided into sections covering mechanical motion, pressure, tactile and vibration sensors.

2. Triboelectric nanogenerators

TENGs have revolutionized sensor technology and are important for the rapid development of intelligent internet of things [27]. TENGs provide opportunities for developing sensors and realizing self-powered monitoring systems [28]. This section introduces the basic principle of TENGs and the physical basis of triboelectric sensors.

2.1. Principle of triboelectric nanogenerators

Maxwell's displacement current is regarded as the theoretical source of TENGs based on the coupling of triboelectrification and electrostatic induction [29,30], which is described as:

$$\boldsymbol{J_D} = \frac{\partial \boldsymbol{D}}{\partial t} = \varepsilon \frac{\partial \boldsymbol{E}}{\partial t} + \frac{\partial \boldsymbol{P}_s}{\partial t}. \quad (1)$$

The first term $\varepsilon \frac{\partial \boldsymbol{E}}{\partial t}$ is the induced current generated by the changing electrical field, which is the theoretical basis for the generation of the electromagnetic wave. The second term $\frac{\partial \boldsymbol{P}_s}{\partial t}$ represents the current arising from the polarization field generated by the electrostatic charges on the surface, which is the fundamental theoretical basis and source of the nanogenerator. TENGs have significant potential in energy harvesting and internet of things sensing applications, which is significant for the intelligent, integrated and miniaturized development of sensing technology [22], as shown in Fig. 1.

2.2. Physical basis of triboelectric sensors

TENGs can be categorized according to their electrodes and motion forms. Categories include vertical contact-separation mode [31,32], contact-sliding mode [33], single-electrode mode [34], and freestanding triboelectric-layer mode [35], as is depicted in Fig. 2. The vertical contact-separation mode involves movement along the direction normal to the two electrodes to achieve contact separation. Plate charge transfer occurs, which forms a current in an external circuit. Contact-sliding mode involves two electrodes sliding relative to each other along the *x*-axis. Charge transfer occurs between the two electrodes through an external circuit and the alternating current is generated. Single-electrode mode typically involves a friction material generating separation movement. The electrode and the ground form a circuit through which current can pass. In freestanding triboelectric-layer mode, the friction material slides horizontally across the two electrodes generating charge in each. Negative charge electrons flow between the two electrodes through an external circuit and the alternating current is generated. In addition, the researches of some hybrid modes have also been conducted to improve the performances of TENGs [36].

The electrodes of a TENG require interval arrangement to convert a mechanical trigger into a pulsed electrical signal, and this arrangement depends of the working mode [27]. Triboelectric sensors exploit electrodes arranged according to a certain pattern to generate regular pulsed electrical signals through mechanical movement. The information that is extracted and analyzed reflects the working state of the mechanical equipment, for example the amplitude, phase and frequency of the signals. Fig. 2(e) shows the physical basis of the triboelectric sensors.

3. Triboelectric mechanical sensors (TMSs)

TMSs can be categorized according to their detection objects and structures. The four categories include triboelectric mechanical motion sensors (TMMSs), triboelectric vibration sensors (TVSs), triboelectric pressure sensors (TPSs) and triboelectric tactile sensors (TTSs). TMMSs have a high degree of flexibility in detecting motion, and can be further categorized according to the motion form and motion dimensions of the object. These three further categories include triboelectric linear motion sensors, triboelectric rotary motion sensors and triboelectric multi-dimensional motion sensors. Fig. 3 shows the various categories of TMSs. The following sections detail the characteristics of each type of TMS and the various challenges associated with it.

3.1. Triboelectric mechanical motion sensors (TMMSs)

Mechanical equipment cannot function properly without a variety of mechanical motions, including linear motion, rotary motion, multi-dimensional motion and others [43]. These diverse mechanical motions have led to the development of many sensors for measuring motion parameters [44–46]. TMMSs have received huge interest because of their simple and flexible mechanical structure, and multiple optional materials compared with traditional sensors. The following section discusses progress on the research on TMMSs, which are shown in Fig. 4.

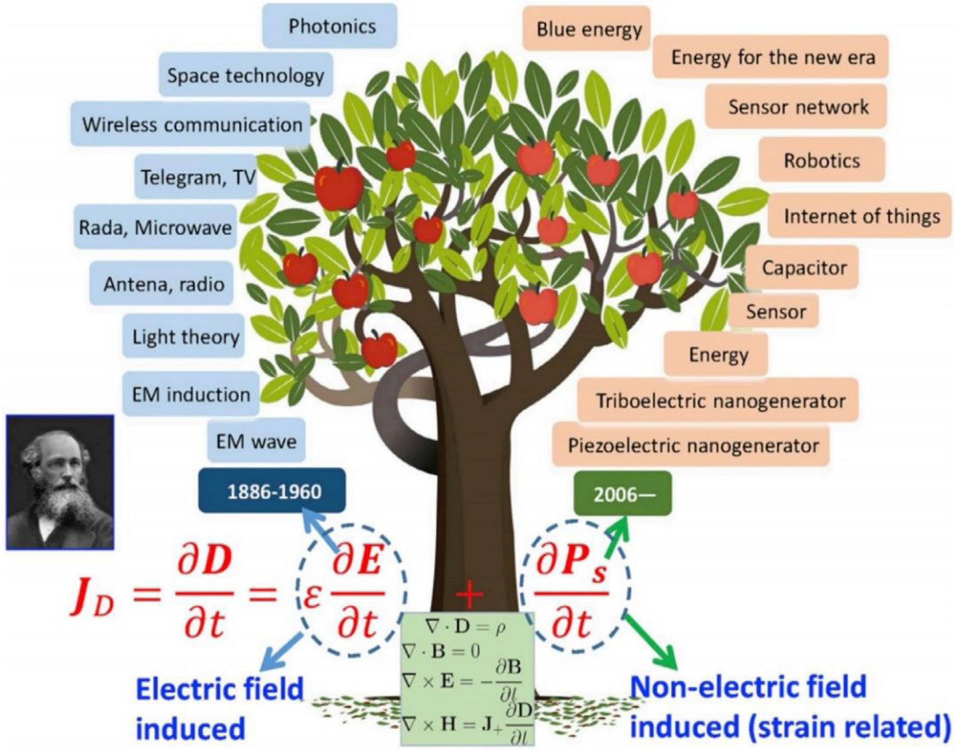

Fig. 1. The influence of Maxwell's displacement current on science and technology industry.
Source: Reproduced with permission [29].

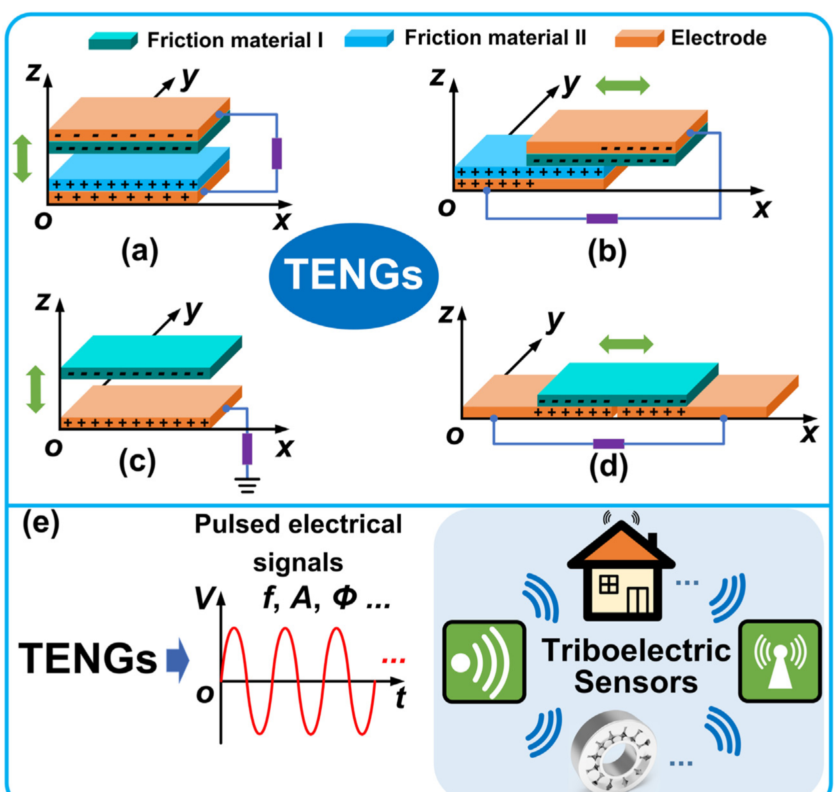

Fig. 2. The four working modes of TENGs and the physical basis of the triboelectric sensors. (a) The vertical contact-separation mode. (b) The contact-sliding mode. (c) The single-electrode mode. (d) The freestanding triboelectric-layer mode. (e) The physical basis of the triboelectric sensors.

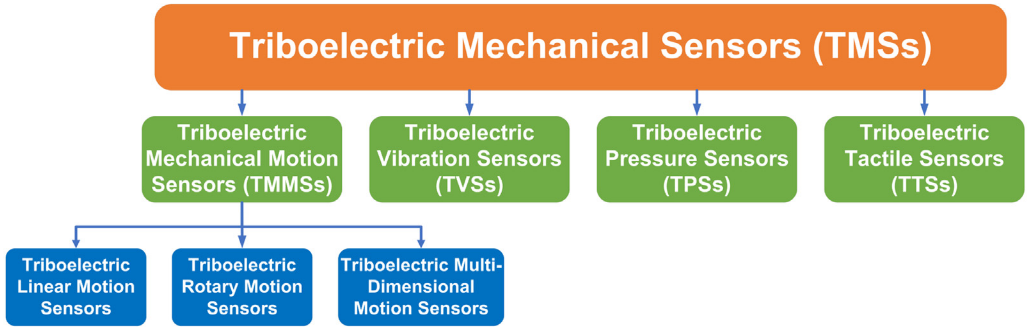

Fig. 3. The triboelectric mechanical sensors (TMSs) include four types of mechanical motion sensors, vibration sensors, pressure sensors and tactile sensors.

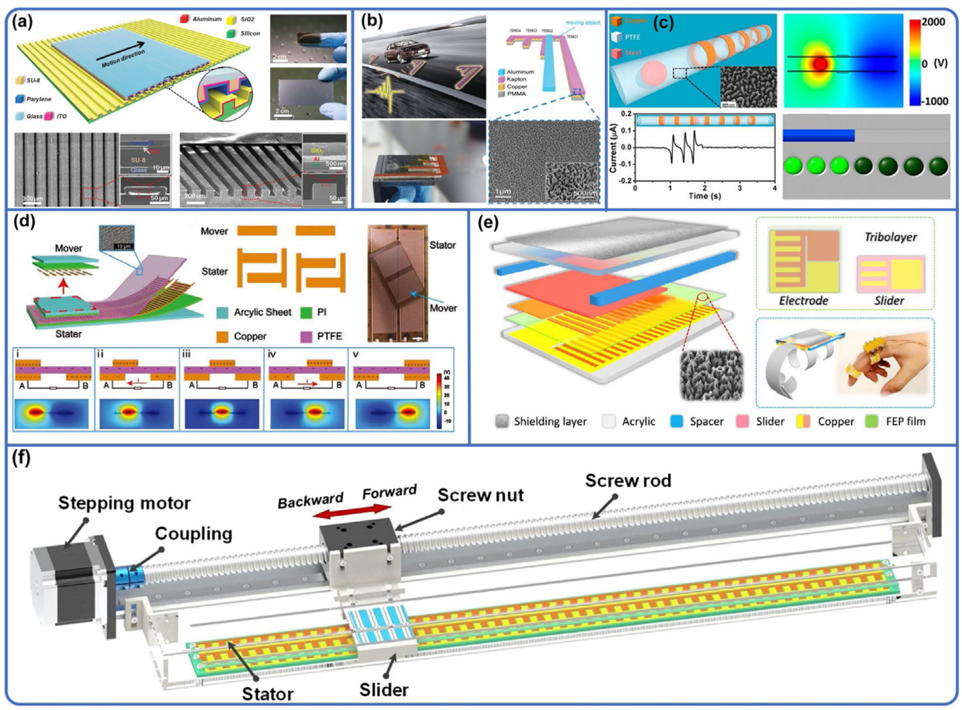

Fig. 4. Triboelectric linear motion sensors. (a) Microgrid linear sensor. Reproduced with permission. [37] Copyright 2014, Wiley Online Library. (b) Motion tracking linear sensor for traffic monitoring. Reproduced with permission. [38] Copyright 2014, Wiley Online Library. (c) Pipeline motion monitoring sensor. Reproduced with permission. [39] Copyright 2014, American Chemical Society. (d) Sliding linear displacement monitoring sensor. Reproduced with permission. [40] Copyright 2018, Wiley Online Library. (e) Motion tracking sensor of robot finger. Reproduced with permission. [41] Copyright 2018, Elsevier. (*f*) Sweep-type triboelectric linear motion sensor. Reproduced with permission. [42] Copyright 2020, Elsevier.

3.1.1. Triboelectric linear motion sensors

Linear motion is one of the most common forms of mechanical motion and plays an increasingly vital role in industrial manufacturing [47]. Linear motion sensors are widely employed in industrial production lines, processing and manufacturing, intelligent transportation and various other fields [48]. Various linear motion sensors have therefore been developed. Triboelectric linear motion sensors have promoted the development of linear sensing technologies.

Zhou et al. fabricated a self-powered nano-level static and dynamic sensor utilizing a micro-grid TENG, as shown in Fig. 4(a). The sensor has a large dynamic range and a long detection range with high resolution [37]. The sensor uses a grating pair to achieve a 173 nm resolution with a linear error of 0.02% within a working distance of several millimeters. The purpose of speed detection is realized by processing the amplitude of current. And the sensor has a linearity over a measurement range from 5 μm/s to 0.1 m/s. As is illustrated in Fig. 4(b), Chen et al. developed a self-powered motion tracking system with opposite triboelectric polarity composed of two friction layers (Kapton and Al) [38]. The sensor can monitor the motion velocity, direction, acceleration, starting and ending positions and motion trajectory of objects. As shown in Fig. 4(c), Su et al. fabricated a triboelectric sensor with a signal-to-noise ratio of 5.3 × 10^3 that can detect moving objects inside a plastic tube by generating electric output signals [39]. As is depicted in Fig. 4(d), Zhang et al. designed a linear sensor for security monitoring that can monitor the position, displacement, speed and direction of sliding contact objects [40]. The sensor can detect speeds as low as 0.001 m/s and detect the sliding direction, so has potential for detecting motion parameters and wind trajectory. As is depicted in Fig. 4 (e), Pu et al. developed a rotary sensor with a linear TENG that can control the gesture of a robot [41]. The sensor assigns the positive/negative directions of pulses to monitor forwards and backwards motion, which represents the flexion/extension of the robotic hands. 3.8° is the minimum resolution angle, and decreasing the grating width can further improve the resolution. As shown in Fig. 4 (f), Xie et al. designed a linear motion sensor with a flexible FEP film and a three-electrode with a differential phase [42]. These features reduce friction and wear and thus improve the service life. In

Table 1
The performance of triboelectric linear motion sensors.

Reference	Resolution (μm)	Velocity (mm/s)	Stroke (mm)
Zhou et al. [37]	0.173	0.005∼100	>10
Chen et al. [38]	N/A	−100 ∼ +100	N/A
Li et al. [40]	250	1∼500	N/A
Vo et al. [49]	N/A	26	23
Xie et al. [42]	2000	125	600
Jing et al. [50]	50	0.05∼0.30	N/A

addition, a linear sensor based on solid–liquid TENG is developed [49], which can monitor the change in motion and speed of liquids with a high degree of linearity ($R^2 = 0.99$). Triboelectric linear sensors have been widely used in transportation, pipeline monitoring, human–computer interaction and intelligent homes. The performance of various triboelectric linear motion sensors is summarized in Table 1. It shows that the researches of triboelectric linear motion sensors mainly focus on low speed and small stroke range. And their resolutions are mainly oriented to micron level due to the limitation of processing technic.

3.1.2. Triboelectric rotary motion sensors

Rotary motion is characterized by stable operation and low impact on mechanical equipment, so is therefore very important for smooth operation [51]. The input for most modern mechanical equipment is largely rotational motion, so monitoring this allow real-time control of the input parameters and ensure smooth running. There have been many studies on self-powered sensing using the pulse signal of TENGs to monitor rotary motion [52–54]. A summary of developments in triboelectric rotary motion sensors is given below.

As is depicted in Fig. 5(a), Wu et al. fabricated an angle sensor based on a TENG, which has a resolution of 22.5° [55]. The sensor can determine the location of the rotator, and can calculate the motion angle through output voltage signals combined from four channels. Increasing the number of channels can further improve the angle resolution. As is depicted in Fig. 5(b), Xi et al. developed a wind-speed sensor based on a TENG, which uses the short-circuit current to measure the wind speed [56]. Other reported sensors also use rotating structures to measure wind speed [57–59]. As is illustrated in Fig. 5(c), Xie et al. designed a triboelectric speed sensor integrated into a bearing [60]. This stability of the output electrical signals of the sensor can be improved by changing the structural characteristics of the bearing. It can monitor the speeds in range from 10 rpm to 1000 rpm with an error of <0.3%. This study integrated a TENG into a mechanical bearing to detect rotation speed, and this has furthered the development of TENGs in mechanical sensing.

Triboelectric rotary motion sensors can be used to monitor the condition of mechanical parts. As is illustrated in Fig. 5(d), Meng et al. developed a fully self-powered rotation sensor in enclosed bearing-structured for complex motion measurement [61]. The sensor can detect the rotation speed, acceleration and trip, and the average error in the measured speed is <0.09%. The sensor is connected to the axis of rotation and has high precision, a wide detection range, rapid response and good durability. As shown in Fig. 5(e), Han et al. designed a self-powered and self-sensing triboelectric sensor incorporated into a ball bearing [62]. The sensor can monitor the missing of rolling ball and electrode breakage. The sensor generates electrical signals through the interaction of the ball and the outer ring when the rotor rotates. This design is simple and the sensor exhibits high linearity between the current and speed in the speed range of 200∼1600 rpm. As is illustrated in Fig. 5(f), Wang et al. designed a ball-bearing rotating speed sensor for use in nondestructive testing and multifunction sensors to measure rotational speed. The standard deviation from

Table 2
The performance of triboelectric rotary motion sensors.

Reference	Resolution (°)	Velocity (rpm)	Stroke (°)
Wang et al. [24]	2.03 nrad	<53.33	0∼360
Pu et al. [41]	3.8	60°/s	20∼60
He et al. [54]	0.25	N/A	36
Wu et al. [55]	22.5	<1500	0∼360
Xie et al. [60]	6	10∼1000	N/A
Meng et al. [61]	22.5	<2200	0∼360
Han et al. [62]	N/A	1658	N/A
Li et al. [63]	9	300	N/A

repeated measurements is < 0.8 [63]. The sensor collects energy from the rotational kinetic energy and monitors nondestructive damage. Ra et al. designed a geared TENG and the output signal can monitor broken teeth in gears [64]. The materials used in these sensors currently limit the application of such bearings. Further research on monitoring the condition of mechanical parts is therefore required.

Triboelectric rotary motion sensors can be used to achieve alcohol monitoring [65], wireless traffic volume monitoring [66], remote meteorological monitoring [67], intelligent sensing [68], fluid monitoring [69] and multifunctional sensing [70]. Table 2 summarizes the performance of various triboelectric rotary motion sensors. The research results in Table 2 show that the resolution of triboelectric rotary motion sensors can reach nano-radian, but most of researches are still in the testing range of low speeds and low resolutions, and further researches are needed combined high speeds and high resolutions.

3.1.3. Triboelectric multi-dimensional motion sensors

Single-dimensional motion sensors are limited by their inherent monitoring characteristics. To improve the working efficiency of motion systems, motion in more than one dimension often needs to be monitored. Triboelectric multi-dimensional motion sensors have been developed with the multiple functions for various motion monitoring [71].

Array sensors can be arranged and coded by multiple electrodes in planar coordinates. Each position has corresponding coordinates in the plane, so the sensor can monitor the plane motion of moving objects. As is illustrated in Fig. 6(a), Yang et al. fabricated a displacement vector sensor using a sliding-mode with a single-electrode TENG [34]. The sensor can not only illuminate one hundred light-emitting diodes, but also monitor the position and direction of the object at the center by measuring the output electrical signals in real-time. As is depicted in Fig. 6(b), Han et al. proposed a triboelectric sensor using a simple cost-effective grid to monitor velocity and trajectory tracking [72]. A resolution of 250 μm with 41×41 pixels on the grid structure can be realized by the sensor. The plane position of an object is monitored through cross channels. Zhang et al. proposed a two-dimensional motion sensor based on the TENG with an electrode structure [73], which is shown in Fig. 6(c). The sensor can determine the trajectory, velocity, acceleration and other motion information of the target. It realizes the monitoring of different positions of planar objects through different output signals of the electrodes in different positions. Increasing The number of channels is increased to improve the resolution of array sensors, which results in complex sensor structures. However, the limited number of channels in equipment can make it difficult to improve the resolution of array sensors.

Multi-dimensional motion can also be monitored by clever design of the electrode structure or using cross guides. As is illustrated in Fig. 6(d), Jing et al. proposed a motion triboelectric vector sensor with highly pliable organic films. The films generate ±5 V electrical signals to attain a ≥65 mW/m^2 peak power

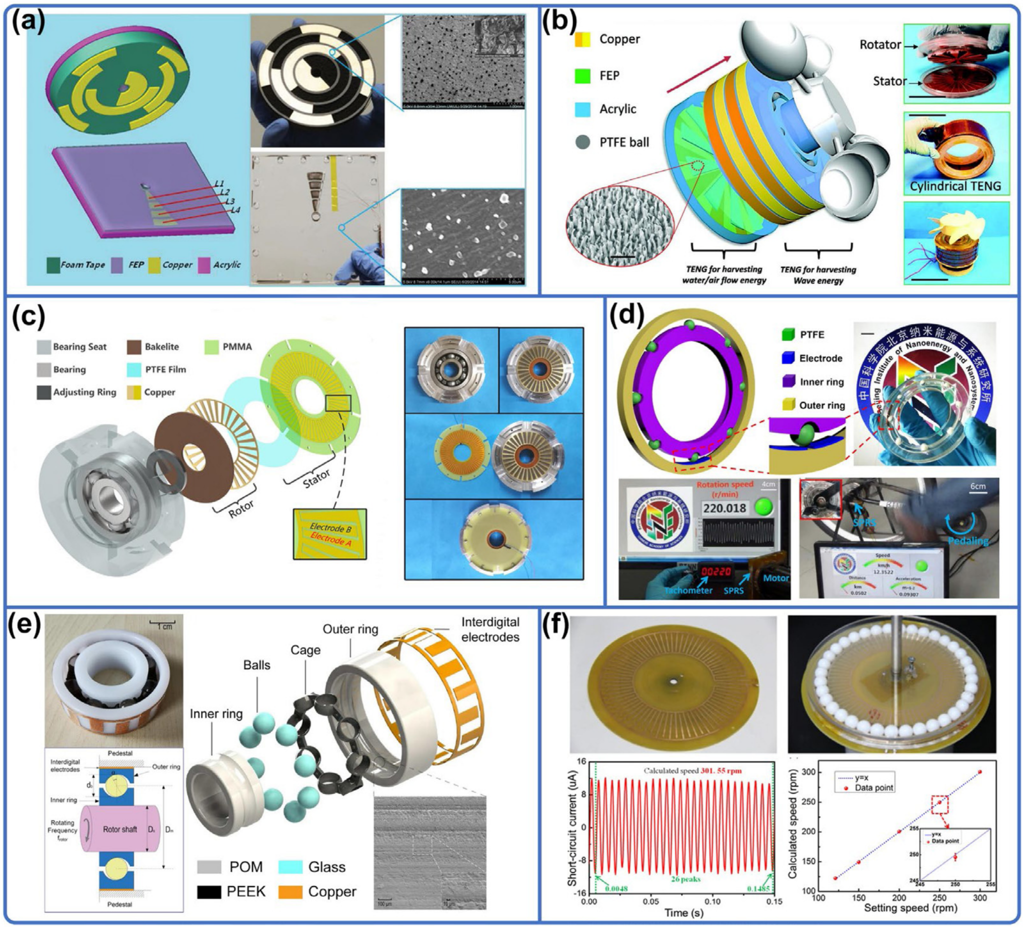

Fig. 5. Triboelectric rotary motion sensors. (a) Coded rotary motion sensor. Reproduced with permission. [55] Copyright 2015, Wiley Online Library. (b) Wind speed sensor. Reproduced with permission. [56] Copyright 2017, Wiley Online Library. (c) Bearing speed sensor of mechanical equipment. Reproduced with permission. [60] Copyright 2020, Elsevier. (d) Fully enclosed bearing rotating motion monitoring sensor. Reproduced with permission. [61] Copyright 2015, Elsevier. (e) Rolling ball bearing rotary motion sensor. Reproduced with permission. [62] Copyright 2020, Elsevier. (f) Ball bearing rotating motion monitoring sensor. Reproduced with permission. [63] Copyright 2016, IOP Science.

density at a speed of 0.3 m/s. The sensor shows good stability, repeatability and durability. The sensor uses two identical linear electrode structures to monitor the two-dimensional motion on a plane. A dual mode speed sensor integrating a TENG into a commercial digital circuit was also developed [74], which is shown in Fig. 6(e). The sensor realizes measurements of linear velocities ranging from 0.1 m/s to 0.6 m/s with the error of ±0.5% and rotational velocities ranging from 300 rpm to 700 rpm with the error of ±0.9%. Multi-functional motion sensors based on TENGs have emerged recently [75]. As is illustrated in Fig. 6(f), Wang et al. developed a multifunctional motion sensor consisting of a magnetic regulation and TENG [76]. The sensor can monitor eight directions and acceleration of movement and also determine the direction and rotary speed. Triboelectric multi-dimensional motion sensors can be used to monitor the acceleration [77–79] and orientation [80] of motion. Table 3 shows that most triboelectric multi-dimensional motion sensors are 2-DOF, and their resolutions and sensitivities need to be further improved within wide measuring ranges.

3.2. Triboelectric vibration sensors (TVSs)

Vibration is inevitable in mechanical systems, and high vibration amplitudes negatively affect the lifetime of mechanical systems [83]. The vibration monitoring of mechanical systems is important because it can uncover equipment faults and vibration sources before damage occurs [84]. TVSs can be used

Table 3
The performance of triboelectric multi-dimensional motion sensors.

Reference	Resolution (μm)	Sensitivity	DOF	Measuring range
Yang et al. [34]	200	N/A	2	N/A
Han et al. [72]	250	N/A	3	N/A
Jing et al. [74]	N/A	N/A	2	**Linear:** 0.1∼0.6 m/s **Rotation:** 300∼700 rpm
Zhang et al. [77]	N/A	15.56 V/g	3	2∼100 Hz
Yi et al. [73]	N/A	0.45 V/mm	2	<0.05 m/s
Pang et al. [78]	N/A	0.289 V s^2/m	3	3.0∼40.0 m/s^2

to monitor vibration because of their environmental adaptability and simple assembly requirements [85–87]. Chen et al. developed a multifunctional triboelectric vibration motion sensor [88], which provides a good basis for developing TENGs for mechanical vibration sensors.

The vibration amplitude reflects the strength of mechanical vibrations. As is illustrated in Fig. 7(a), Hu et al. fabricated a vibration sensor for monitoring the vibration source position with an error of <6% [89]. Wang et al. fabricated a vibration sensor for monitoring the amplitudes of vibrations as low as 3.5 μm [90]. Zhang et al. proposed a magnetic levitation TVS that can detect vibrations with amplitudes of <7.5 mm [91]. Zhu et al. fabricated a vibration sensor based on a piezoelectric nanogenerator and

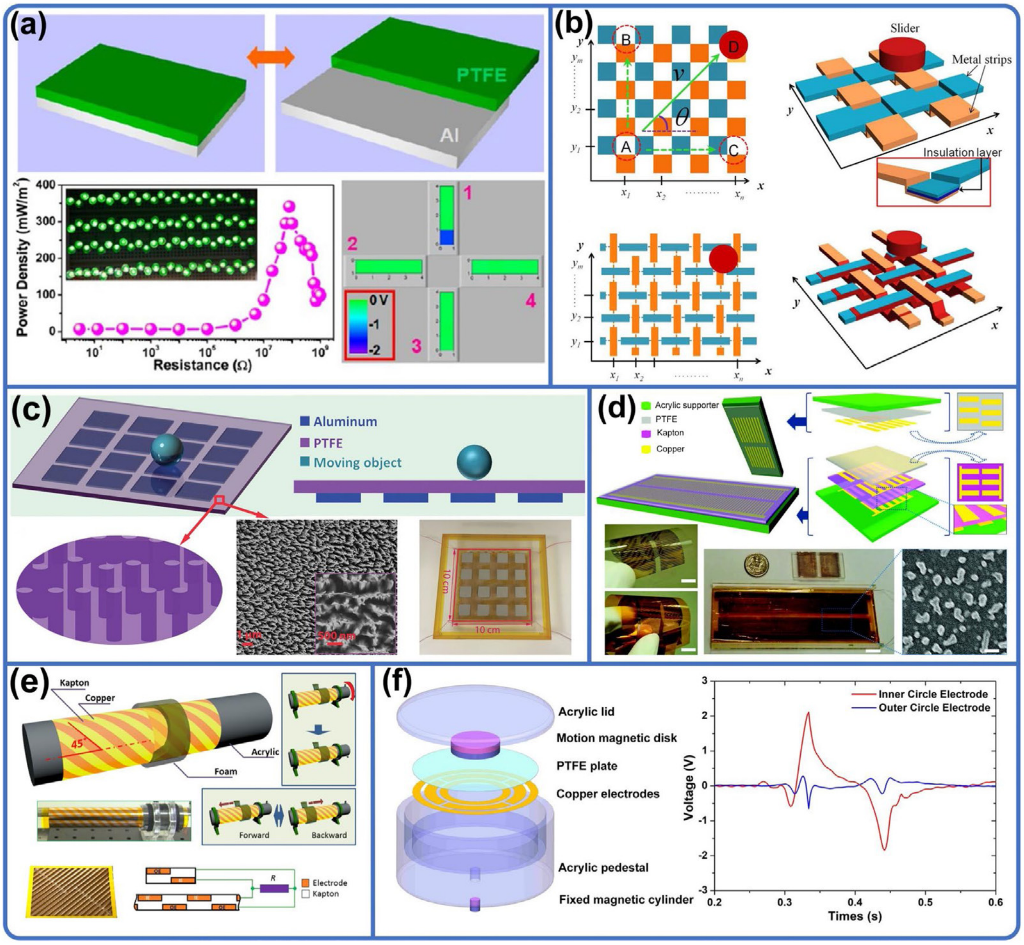

Fig. 6. Triboelectric multi-dimensional motion sensors. (a) Single electrode vector sensor. Reproduced with permission. [81] Copyright 2013, American Chemical Society. (b) Planar trajectory tracking sensor. Reproduced with permission. [38] Copyright 2014, Elsevier. (c) Track tracking motion sensor. Reproduced with permission. [73] Copyright 2014, Wiley Online Library. (d) Plane vector sensor. Reproduced with permission. [82] Copyright 2015, Nature. (e) Multi-mode sensor. Reproduced with permission. [74] Copyright 2014, Elsevier. (f) Multifunctional motion sensor. Reproduced with permission. [76] Copyright 2018, American Chemical Society.

TENG with sensitivities of 3.65 μW/g and 6.14 μW/g and linearity errors of 4.23% and 5.12% for vibration amplitudes of 3 mm and 6 mm, respectively [92]. As shown in Fig. 7(b), Chen et al. fabricated a real-time oscillation-monitoring triboelectric sensor with a sensitivity of 223 mV/mm [93]. Such sensors for amplitude monitoring are important for the development of vibration sensors based on TENGs [94,95].

Frequency is an important parameter of vibration. The periodic information of vibrating objects can be analyzed by their frequency [96]. Various vibration sensors have been reported for monitoring vibration amplitude and frequency. As is illustrated in Fig. 7(c), Yang et al. fabricated a sensor for throat-attached anti-interference voice recognition and cardiovascular characterization [97]. The sensor has a sensitivity of 51 mV Pa^{-1} and a dynamic range from 2.5 Pa to 1200 Pa with a wide bandwidth from 0.1 Hz to 3.2 kHz. The vibration amplitude and frequency measurement of the sensor can be used to determine the acceleration [98–100], such as in a reported multi-axis acceleration sensor [101]. As is illustrated in Fig. 7(d), Zhang et al. fabricated a sensor for vibration monitoring [102], which can detect vibration acceleration with a 0.26 V s/m^2 sensitivity in the acceleration range of 0∼60 m/s^2. Vibration position monitoring is also important. Heo et al. developed a sensor to detect the magnitude and direction of impact [103]. Chen et al. proposed a triboelectric vibration direction sensor [104].

Vibrations cause malfunctions in mechanical equipment, and TVSs have received much attention for diagnosing faults in mechanical systems. As is illustrated in Fig. 7 (e), Wang et al. fabricated a vibration sensor using flexure hinges [105]. The self-powered displacement sensor can monitor axis deviation. As is illustrated in Fig. 7 (f), Qu et al. fabricated a triboelectric sensor for structural health monitoring [106]. Xiao et al. proposed a self-powered sensor to monitor engine conditions [107]. Jung et al. developed a triboelectric resonator for crack monitoring [108]. These studies have greatly promoted the application of TENGs in mechanical equipment and provide guidance for associated engineering. Table 4 shows that the resonance frequencies of TVSs are mostly concentrated in the low frequency range. Moreover, most of them are limited to single degree of freedom, and their sensitivities need to be further improved to ensure that they can monitor weak vibration signals.

3.3. Triboelectric pressure sensors (TPSs)

Pressure affects the performance of mechanical equipment, and monitoring can assist in obtaining optimum pressure and thus improve the mechanical system [110]. The flexible structures of triboelectric mechanical pressure sensors are suitable for special pressure monitoring.

Bai et al. designed an air pressure sensor for security surveillance and healthcare monitoring, which is shown in Fig. 8(a). The

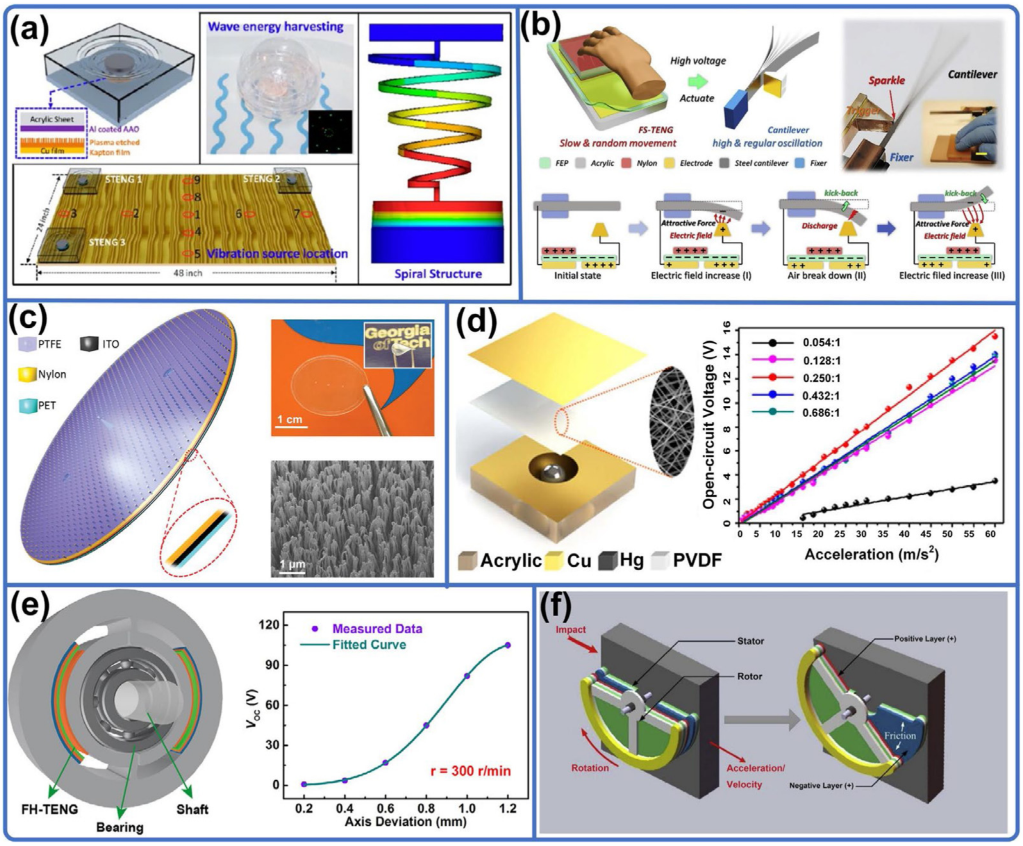

Fig. 7. Triboelectric vibration sensors (TVSs). (a) Vibration sensor with 3d spiral structure. Reproduced with permission. [89] Copyright 2013, American Chemical Society. (b) Cantilever vibration sensor. Reproduced with permission. [93] Copyright 2019, Elsevier. (c) Eardrum-inspired active sensors. Reproduced with permission. [97] Copyright 2015, Wiley Online Library. (d) Vibration acceleration transducer. Reproduced with permission. [102] Copyright 2017, American Chemical Society. (e) Vibration sensor using flexure hinges. Reproduced with permission. [105] Copyright 2018, Elsevier. (b) Triboelectric sensor for monitoring mechanical movements. Reproduced with permission. [106] Copyright 2019, Elsevier.

Table 4
The performance of triboelectric vibration sensors (TVSs).

Reference	Resonant frequency (Hz)	Sensitivity	Measuring range
Wu et al. [83]	N/A	N/A	0∼8 Hz
He et al. [86]	700	0.97 V/N	50∼3000 Hz
Chen et al. [88]	N/A	6 N/mm	N/A
Hu et al. [89]	30	N/A	0∼30 Hz
Wang et al. [90]	15	N/A	5∼80 Hz
Zhang et al. [91]	N/A	N/A	**Acceleration:** 0∼30 m/s^2 **Amplitude:** 0∼7.5 mm
Zhu et al. [92]	N/A	3.65 μW/g	N/A
Chen et al. [93]	N/A	223 V/m	5∼200 mm/s
Guo et al. [94]	N/A	315 V/m	0.01∼0.11 m
Chen et al. [95]	12	N/A	2∼200 Hz
Liang et al. [96]	N/A	N/A	0∼500 Hz
Yang et al. [97]	N/A	N/A	10∼1500 Hz
Xu et al. [98]	**Vertical:** 16 **Horizontal:** 8.5	N/A	**Vertical:** 0∼23 m/s^2 **Horizontal:** 0∼15 m/s^2
Liu et al. [99]	N/A	20.4 $V/(m/s^2)$	1∼11 m/s^2
Yu et al. [100]	N/A	0.391 $V/(m/s^2)$	N/A
Shi et al. [101]	N/A	**X:** 6.08 V/g, **Y:** 5.87 V/g, **Z:** 3.62 V/g, **Rotation:** 3.5 $mVs^{\circ -1}$	X: 4.87 g Y: 5.06 g
Zhang et al. [102]	N/A	0.26 V s/m^2	0∼60 m/s^2
Qu et al. [106]	N/A	N/A	**Acceleration:** > 0.1968 g **Velocity:** 0.2∼0.498 m/s
Wang et al. [109]	N/A	N/A	±20°

sensor achieves resolutions of 0.34 Pa and 0.16 Pa for increasing and decreasing air pressure, respectively [111]. Li et al. developed a TENG-piezoelectric nanogenerator hybrid pressure sensor based on three-dimensional fibers [112]. The sensor structure is shown in Fig. 8(b), and it can monitor strain from human motion. Fig. 8(c) shows a reported paper-based origami TPS [113].

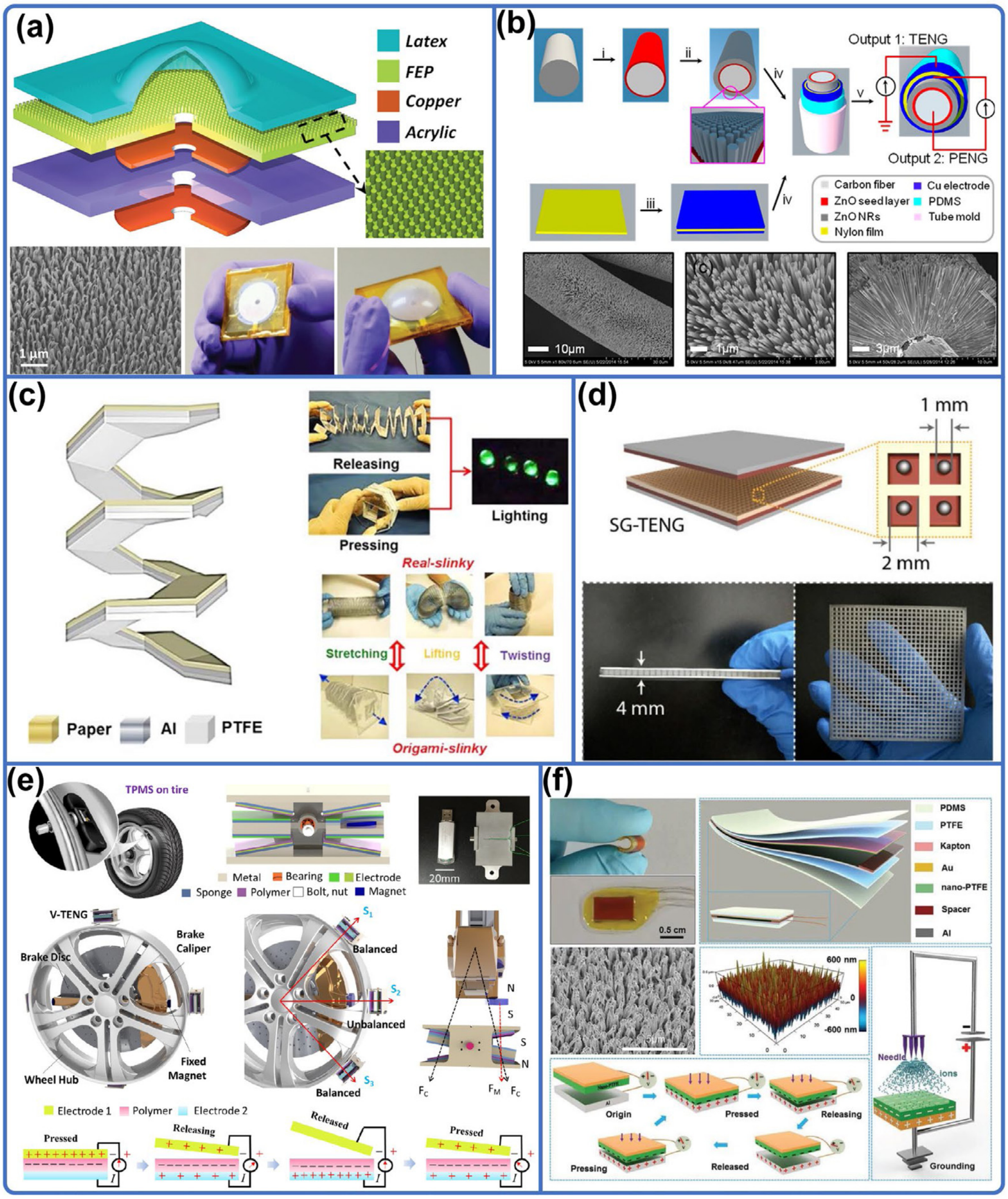

Fig. 8. Triboelectric pressure sensors (TPSs). (a) Thin-film pressure sensor. Reproduced with permission. [111] Copyright 2014, Wiley Online Library. (b) 3D fiber pressure sensor. Reproduced with permission. [112] Copyright 2014, American Chemical Society. (c) Paper-based pressure sensor. Reproduced with permission. [113] Copyright 2015, American Chemical Society. (d) Impulse force sensor. Reproduced with permission. [114] Copyright 2018, Springer. (e) Tire pressure Sensor. Reproduced with permission. [115] Copyright 2018, Elsevier. (f) Endocardial pressure sensor. Reproduced with permission. [116] Copyright 2019, Wiley Online Library.

He et al. designed an impulse force sensor [114] in which the value of the current reflects the amplitude of the impulse force. The impulsive force sensor provides a new performance form of TENG and a guidance in pressure sensing field. As shown in Fig. 8(e), Qian et al. fabricated a self-powered tire pressure sensor [115]. Fig. 8(f) shows an endocardial pressure sensor for implanting in animals developed by Liu et al. [116]. The sensor has a linearity (R^2=0.997) with a 1.195 mV $mmHg^{-1}$ sensitivity. This study demonstrates the application of TENGs in biomedicine and more generally the flexibility of triboelectric sensors. Frictional power sensors have been developed with flexible structures from various materials, such as a strain gauge for monitoring static and dynamic force [117] and multifunctional pressure sensors [118,119]. Chen et al. proposed a virtual reality three-dimensional control sensor based on a TENG [120]. The sensor can detect the vector force of six-axis directions in three dimensions and the shear force direction with a step resolution of at least 15°. Pressure sensors based on TENGs are becoming flexible, multi-functional and multi-dimensional. Table 5 shows that TPSs have high sensitivities and wide measuring ranges of pressures. Further researches on monitoring low pressures with high frequencies will be conducted to improve the sensitivities of TPSs.

3.4. Triboelectric tactile sensors (TTSs)

As the tactile sensing element of the end-effector, tactile sensors promote the development of artificial intelligence. Tactile sensors based on TENGs are suitable for intelligent sensors resulting from their low cost, simple structure and flexible structures [121].

As is illustrated in Fig. 9(a), Yang et al. proposed a tactile sensor with a sensitivity of 0.29 V/kPa and a minimum pixel unit of 3 mm × 3 mm [122]. They also proposed a TTS for self-powered

Table 5
The performance of triboelectric pressure sensors (TPSs).

Reference	Resolution	Sensitivity	Power density (mW/m^2)	Measuring range
Bai et al. [111]	0.16 Pa	6.9 V/kPa	N/A	N/A
Yang et al. [113]	N/A	N/A	0.9	0.0625∼0.2815 kPa
Liu et al. [116]	N/A	8.98 × 10^{-3} V/kPa	N/A	9.31∼46.55 kPa
Dong et al. [118]	8 × 8 pixels	N/A	230	N/A
Chen et al. [120]	15°	3.6 V/N	N/A	0∼18 N

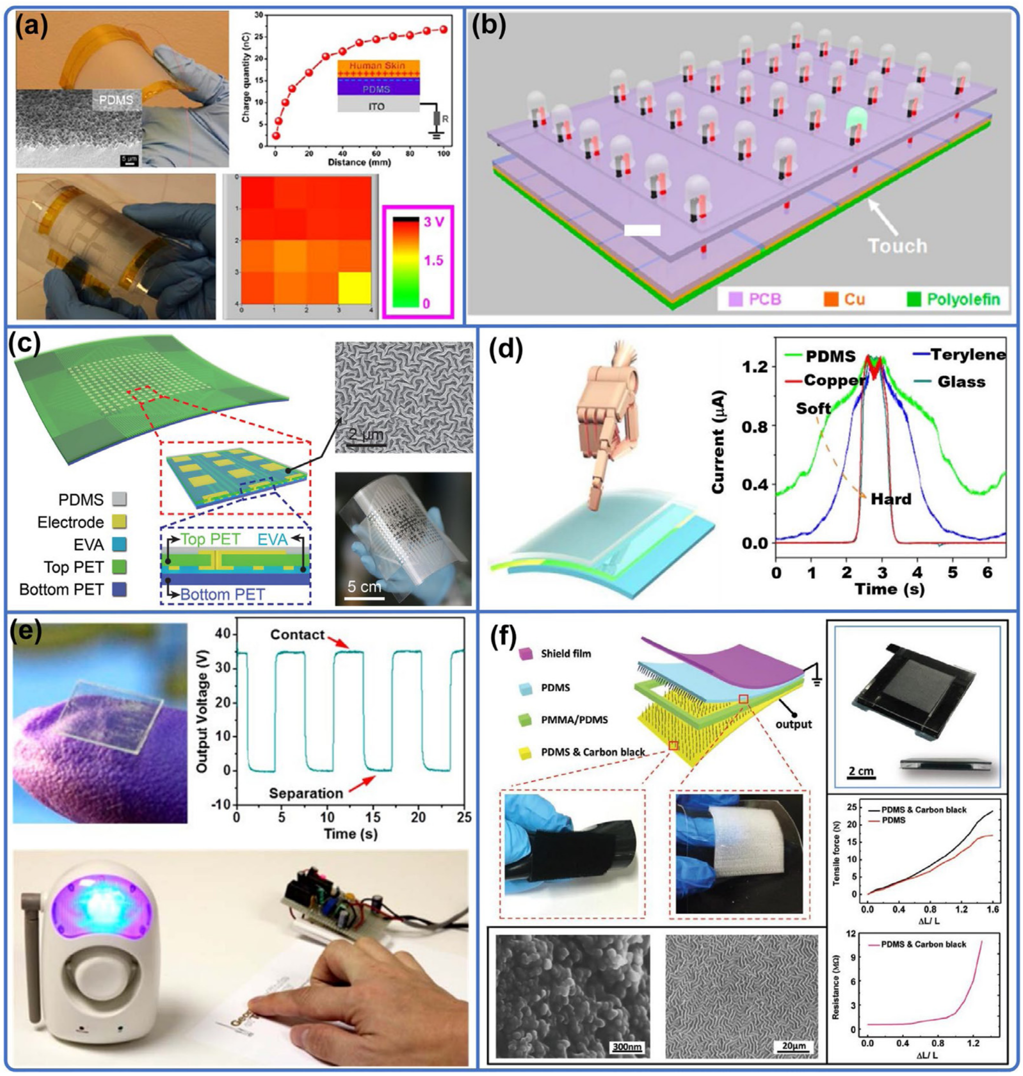

Fig. 9. Triboelectric tactile sensors (TTSs). (a) Human skin tactile sensor. Reproduced with permission. [122] Copyright 2013, American Chemical Society. (b) Instantaneous tactile imaging matrix. Reproduced with permission. [123] Copyright 2014, American Chemical Society (c) Real-time tactile monitoring sensor. Reproduced with permission. [124] Copyright 2016, Wiley Online Library. (d) Smart tactile sensor. Reproduced with permission. [125] Copyright 2014, American Chemical Society. (e) Flexible tactile sensor. Reproduced with permission. [126] Copyright 2017, American Chemical Society. (f) Tactile sensors for detecting both normal and tangential forces. Reproduced with permission. [127] Copyright 2018, Wiley Online Library.

instantaneous tactile imaging [123], which is shown in Fig. 9(b). Flexible tactile sensors using planar matrix arrangements are promoting the application of TENGs in tactile sensing. There are some studies about the sensor array for tactile imaging [128], tactile sensor array systems [129], a thin-film tactile matrix [130] and a self-powered tactile sensing panel [131]. As shown in Fig. 9(c), Wang et al. fabricated a sensor matrix with a 5 dpi resolution and a 0.06 kPa^{-1} sensitivity for real-time tactile mapping [124]. Tactile pressure is important in tactile sensing, and TENG tactile pressure sensors have been developed to measure the contact pressure. Li et al. proposed a smart TPS with a plane resolution of 2 mm and sensitivity of 28 mV N^{-1} in the range of 40∼140 N [125], which is shown in Fig. 9(d). As is illustrated in Fig. 9(e), Zhu et al. fabricated a flexible TPS utilizing flexible thin-film materials. Its sensitivity can reach 44 mV/Pa (0.09% Pa^{-1}) and a maximum touch sensitivity can obtain 1.1 V/Pa (2.3% Pa^{-1}) at pressures of <0.15 kPa [126]. Fig. 9 (f) shows a TTS proposed by Ren et al. based on a TENG for detecting normal pressure and tangential pressure [127]. Normal pressure detection can reach 1.5 MPa with an approximately 51.43 kPa V^{-1} sensitivity, and tangential forces can be detected in range of 0.5∼40 N with sensitivities of approximately 0.83 N V^{-1} (for 0.5∼3 N) and 2.50 N V^{-1} (for 3∼40 N). Tactile sensors based on TENGs are mainly

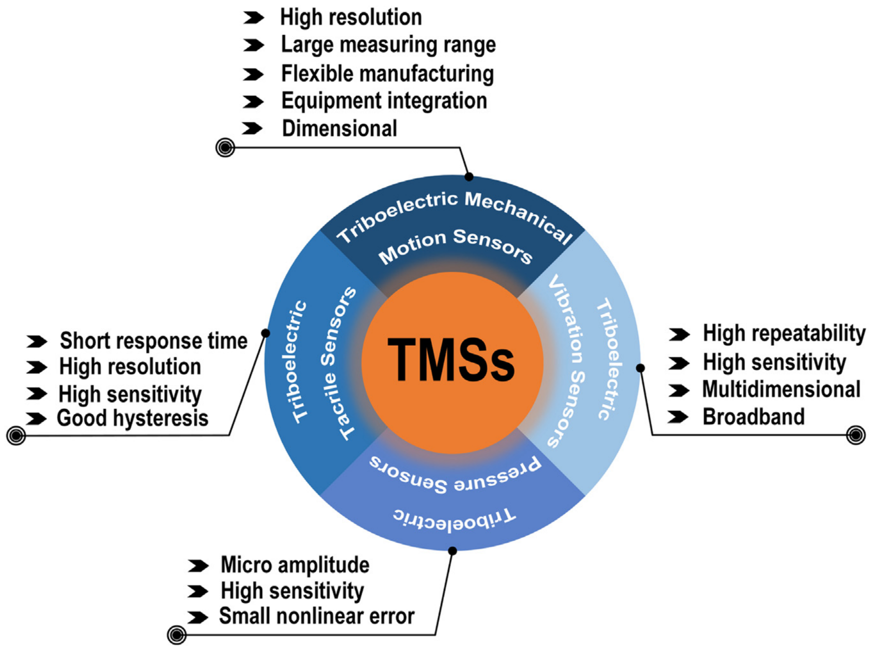

Fig. 10. The future prospects of the TMSs.

used to monitor tactile position with plane matrix structures and tactile stress by structural deformation.

Tactile sensors based on TENGs are useful in skin tactile sensing [132,133], biomedical engineering [134], wearable electronics [135,136] and sliding motion sensation [137]. Tactile sensors based on TENGs combine position and pressure sensing, which demonstrates their high flexibility. It has been shown in Table 6 that TTSs have wide measuring ranges and small sizes. They have monitoring functions of TPSs and TTSs, so they can be involved in the tactile sensing of end-effectors.

4. Summary and perspectives

The triboelectric mechanical sensors (TMSs) were first comprehensively reviewed here, including common triboelectric mechanical motion sensors (TMMSs) such as linear, rotation and multi-dimensional motion sensors, triboelectric vibration sensors (TVSs), triboelectric pressure sensors (TPSs) and triboelectric tactile sensors (TVSs). The current state of each TMS is discussed and its prospects are summarized. TMSs are involved in various engineering sensors including mechanical motion monitoring, end-effector feedback and vibration monitoring. Fig. 10 summarizes future prospects of TMSs in industry. TMSs are a rapidly developing technology that have the potential to greatly further industrial sensing. The following issues remain to be elaborated for TMSs to be widely applied in engineering and industry.

4.1. Stability and durability

The effects of friction and wear great affect the lifetime of a sensor. Reducing friction in TMMSs will improve their durability and increase their lifetime. Recent study by Shi et al. shows that adding an oil of low permittivity not only can effectively reduce searing of TENG, but also improve its performance [138]. Besides that, to improve the durability, a high performance TENG with a rod rolling friction structure on the basis of charge replenishment is proposed by Guo et al. [139].

4.2. Precision and measuring range

Precision and measuring range are the important parameters for sensors. Base on the requirements, a triboelectric linear motion sensor with a large measuring range and a triboelectric rotary motion sensor utilizing bearing structure with the error of 0.09% are proposed by Xie et al. and Meng et al. respectively [42, 61]. Hence, it is of significance to develop TMMSs with a high precision over a large range.

4.3. Hysteresis

Good hysteresis, a small nonlinear error and high repeatability of TMSs will promote their application and popularity in intelligent equipment.

4.4. Resolution

The resolution of TMSs needs to be improved and their structures require better miniaturization, which will promote the intelligent integration of mechanical equipment. Therefore, tang et al. fabricated a triboelectric rotary motion sensor which can reach a nanoradian resolution, which promoted the application of TMSs in industrial field [24].

In addition, the resolutions of the TMSs can also be improved by increasing the output charge density, and Hu et al. improved the output performances of TENGs in this way [140,141].

4.5. Sensitivity

The sensitivity of tactile, pressure, vibration and other sensors to amplitude needs to be improved. This will require developing flexible materials and structures. So far, there are many researches based on those. For example, the PDMS structure is employed by Wang et al. to enhance the sensitivity of triboelectric tactile sensor [124]. And it has certain reference value to improve the sensitivities of the TMSs by improving the output voltages of the TENGs [142,143].

Table 6
The performance of triboelectric tactile sensors (TTSs).

Reference	Sensitivity	Response time (ms)	Measuring range	Size (mm × mm)
Yang et al. [122]	0.29 V/kPa	100	N/A	3 × 3
Yang et al. [123]	N/A	N/A	N/A	10 × 10
Lin et al. [128]	0.31 kPa^{-1}	<5	>2.1 Pa, <40 kPa	N/A
Zhu et al. [130]	50 dpi	N/A	N/A	0.5 × 0.5
Jiang et al. [131]	2.82 mV/kPa	40	N/A	4 × 4
Wang et al. [124]	0.06 kPa^{-1}	70	1∼80 kPa	2.5 × 2.5
Li et al. [125]	**Position:** 2 mm **Pressure:** 0.28 mV/N	N/A	40∼140 N	N/A
Zhu et al. [126]	0.5∼44 mV/kPa	N/A	N/A	50 × 5
Ren et al. [127]	**Normals:** 51.43 kPa V^{-1} **Tangential:** 0.83 ∼2.50 N/V	N/A	**Normals**: 1500 kPa **Tangential:** 0.5∼40 N	N/A
Bu et al. [132]	0.13∼34 mV/Pa	90	26.3 kPa	N/A
Pu et al. [133]	0.013 kPa^{-1}	N/A	1.3∼70 kPa	N/A
Zhao et al. [136]	1.76 V/N	N/A	0.1∼1 N	N/A

4.6. Flexible electrode materials

TENGs can be developed using a wide range of materials. Developing TMSs with flexible electrode materials will promote their applications in sensing. Recently, Chen et al. reported soft robots based on TENG, which not only can grab object, but also make the corresponding information feedback at the same time [144].

4.7. Service characteristics under special working conditions

Improving the service characteristics of triboelectric sensors under special conditions will promote the applications of TMSs in intelligent sensing equipment. The stability of the TMSs under such conditions needs improving, such as at high temperatures and pressures and in electromagnetic environments. There are few researches on TMSs under special working conditions. However, studies based on TENG are conducted, which maintain good output performance in vacuum environments [145], high temperature environments [146], electromagnetic environment [71], and on Mars analogue environment [147]. These corresponding studies have important guiding significance for the research of TMSs under special working conditions.

CRediT authorship contribution statement

Qiang Gao: Investigation, Writing - original draft, Read and agreed to the published version of the manuscript. **Tinghai Cheng:** Writing - review & editing, Supervision, Read and agreed to the published version of the manuscript. **Zhong Lin Wang:** Writing - review & editing, Supervision, Read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Thanks to many group members in Professor Wang's group for their contributions in developing the technologies of triboelectric nanogenerators and self-powered sensors.

Funding

This research received no external funding.

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