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Full paper

Regulating random mechanical motion using the principle of auto-winding mechanical watch for driving TENG with constant AC output – An approach for efficient usage of high entropy energy

Gaofa He [a,*], Yingjin Luo [a], Yuan Zhai [b], Ying Wu [b,*], Jing You [a], Rui Lu [a], Shaokun Zeng [a], Zhong Lin Wang [c,d,**]

[a] School of Mechanical and Power Engineering, Chongqing University of Science & Technology, Chongqing 401331, China
[b] School of Intelligent Technology and Engineering, Chongqing University of Science & Technology, Chongqing 401331 China
[c] Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 101400, China
[d] School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0245, United States

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ABSTRACT

The world is fulfilled with low-quality, irregular, and widely distributed energy, but highly efficient harvesting of such high-entropy energy is hardly possible due to the limitation of currently existing technologies. Recently, triboelectric nanogenerators (TENGs) were invented to harvest random and ambient mechanical energy, and have shown wide applications because of their high efficiency and low-cost. However, the output of the TENG is dictated by the irregularity of the input mechanical agitation. This paper reports a mechanical regulator using the principle of auto-winding mechanical watch for driving the triboelectric nanogenerator with constant AC output (Constant Output TENG, CO-TENG). The device which comprised energy harvest and storage module, energy controllable release module, and energy conversion module can achieve energy harvesting-storage-release not only steadily but also continually under even low-frequency (0.5 Hz) and random working stimulation. The CO-TENG has been successfully applied to harvest the energy of random waves, wind, and water flows, through the adjustment of the input gear train and energy collection parts, such as water turbine, wind scoop, and oscillating buoy. The CO-TENG can steadily and continually produce an open-circuit voltage of 550 V, a short-circuit current of 6 μA, and transferred charges of 190 nC under low-frequency and random mechanical stimulation. With the rectifier filter, a commercial thermometer and 450 LEDs in serial connection were separately powered by the CO-TENG. It demonstrates that the CO-TENG is a potential solution for effective usage of high entropy energy that has a random amplitude and irregular low-frequency.

1. Introduction

With the development of Microelectromechanical systems (MEMS) and Internet of Things (IoT) technology, microelectronic monitoring equipment have shown broad application prospects in the fields of human health, environment and military monitoring [1–5]. However, power supply adapted to microelectronic monitoring equipment becomes a new challenge, especially for wireless usage in forests [6], oceans [7] and other similar uninhabited wild environments. Traditionally, these devices are powered by various chemical batteries, such as dry, lithium batteries or others, which will be replaced or charged frequently because of their limited capacity. This not only increases costs of long-term use, but also brings serious environmental pollution. To avoid these problems, a potential solution is to harvest ambient mechanical energy to supply power for monitoring devices [8–10]. Triboelectric nanogenerators (TENGs), invented by Wang's group in 2012, is a new nano-energy technology by coupling of tribo-electrification and electrostatic induction [11–15]. Compared with the electromagnetic induction and piezoelectric effect [16,17], TENGs are regarded as outstanding solutions for transformation from low-frequency mechanical energy into electric energy with advantages of microminiaturization, application scenario diversification and simple

* Corresponding authors.
** Corresponding author at: Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 101400, China.
E-mail addresses: hegaofa@cqust.edu.cn (G. He), wuying1992@cqust.edu.cn (Y. Wu), zhong.wang@mse.gatech.edu (Z.L. Wang).

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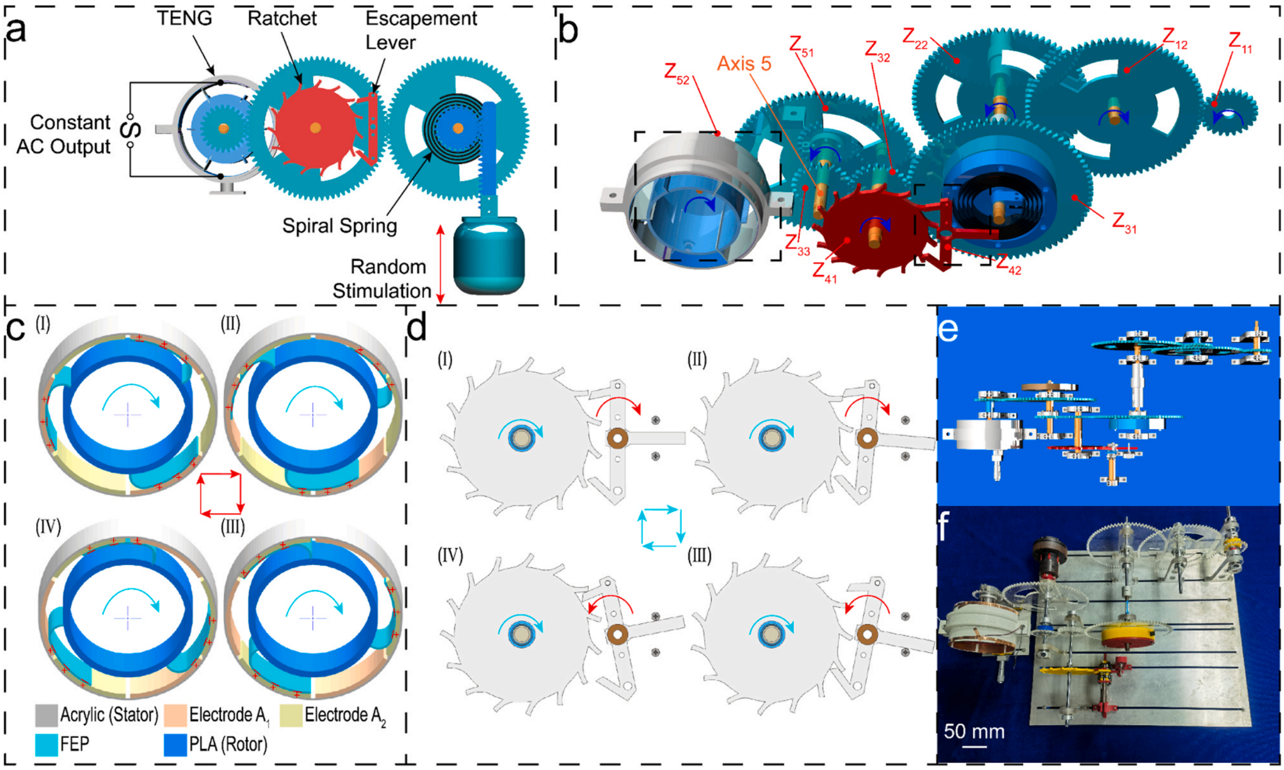

Fig. 1. Structure and working principle of the CO-TENG. (a) Working principle of CO-TENG; (b) motion transfer process of CO-TENG; (c) electric energy conversion processes; (d) operating principle of the escapement-spring-leaf mechanism; (e) floor plan of CO-TENG; (f) picture of whole structure of CO-TENG.

manufacturing process [18–21].

In recent years, the reports of using TENGs to collect mechanical energy in the environment (such as wind [22–24], water flow [25–27], waves [28–31], various objects and organisms [32–34]) are very active. There are still some disadvantages in practical use, because the external excitation generated by the ambient mechanical energy is random or irregular in amplitudes, direction, and/or frequency [35–37]. To effectively harvest low-quality, irregular, and widely distributed energy such high entropy energy [38], many scholars have done a lot of research work. Xia et al. demonstrated a water balloon TENG that can harvest all-weather water wave energy [39]. Lu et al. developed a TENG, which can realize entire stroke energy harvesting by the bidirectional gear [40]. Feng et al. designed cylindrical TENG that can efficiently harvest ultra-low-frequency water wave energy by the swing structure [41]. Chen et al. proposed a chaotic pendulum TENG to harvest wave energy [42]. Cheng et al. developed a TENG based on a cam and a movable frame to realize ambient mechanical energy harvesting [43]. Although these cleverly designed TENGs generated electrical energy under low-frequency and random excitation, the output electrical energy is often random and disordered, or it disappears as soon as the external excitation stops. Bhatia et al. designed a random energy harvest device using a flat spiral spring that can achieve outstanding electrical output in the external excitation range of 0–50 Hz [44]. Yin et al. demonstrated a mechanical regulation TENG, which realized controllable and quantitative output of random energy [45]. Wang et al. proposed an impact energy harvesting system using a mechanical vibration frequency stabilizer that can maintain the output frequency stabilization with a variation of 33% when the input frequency changed by 436% [46]. All of these researches have worked on the storage of random vibration energy. However, the methods to control the energy releasing are not considered enough. For example, the speed of the rotor that is powered by the elastic potential energy of the spiral spring is unsteady due to the mismatch between the flywheel inertia and the frictional resistance, so that the energy output is intermittent and discontinuous. Therefore, to efficiently harvest energy from random external excitation in natural environment, an excellent mechanical energy-electricity transformation system that can independently realize steady power energy of harvest-storage-release is required.

In this paper, we present a mechanical regulator using the principle of auto-winding mechanical watch for driving the triboelectric nanogenerator with constant AC output (Constant Output TENG, CO-TENG) under low-frequency and random excitation. The auto-winding mechanical watch is a device that stores random arm swing energy into potential energy, which is regularly released to drive the watch at a designed operation pace. The device consists of three parts: Part I - energy harvest and storage module, composed of input shaft, input gear train, and flat spiral spring (spiral spring), for converting various random environment energy, such as waves, water flow, and wind, to elastic potential energy of the spiral spring, through the replacement of the input gear train and energy collection parts, respectively water turbine, wind scoop, and oscillating buoy. Part II - energy controllable release module, consisted of escapement-spring-leaf and transmission gear train, controls elastic potential energy of the spiral spring released with a constant velocity by the escapement-spring-leaf. The working principle of the escapement-spring-leaf is like the escapement mechanism of the auto-winding mechanical watch. Part III - energy conversion module, made up of output gear train, one-way shaft system, flywheel, and TENG transmission unit, translates the mechanical kinetic energy to electric energy, continuously and steadily.

2. Experimental section

2.1. Fabrication of the CO-TENG

The CO-TENG mainly comprises three parts: energy harvest and storage module, energy controllable release module, and energy conversion module. The gears and gear support involved in each component are made of acrylic materials and processed by laser engraving (X-7050, G.U. EAGLE, Beijing). The spring barrel, limit pile, ratchet, and escapement lever are made of polylactic acid (PLA) and fabricated by the 3D printer (RT-JD200, RUITE 3D, Xi'an). The base plate and each drive shaft are fabricated with aluminum alloy, which is made by CNC machining (M-V70En, Mitsubishi Heavy Industries, Japan). The TENG transmission unit comprises two parts: the stator and the rotor. Six copper electrodes with 50 mm (length) × 50 mm (width) × 50 μm (thickness) apply to the inner of the stator. Three flexible films are FEP films, which attached to a rotor, with 65 mm (length) × 50 mm (width) × 50 μm (thickness).

2.2. Characterization and measurements

A stepping motor (ECMA-CM1306PS, DELTA, Shanghai) provides external excitation for the wave pool. An air compressor (OLF-3540, FENGBAO, Shanghai) was used to make breeze and the wind speed was obtained by an anemometer (ST8816, SMART SENSOR, Hong Kong). A submersible pump (HLW-400, SUNSUN, Zhejiang) was used to generate water flow and the flow rate was obtained by a kinemometer (LJ20B, XIANGRUIDE, Nanjing). Moreover, a programmable electrometer (6514, Keithley, USA) and a Data Acquisition Card (USB-6251, National Instruments, USA) was used to test open-circuit voltage, short-circuit current, and transferred charges, and the rotor speed was captured by a non-contact tachometer (VC6236P, Victor, Shenzhen). Finally, the measured data can be saved and analyzed on LabVIEW.

3. Results and discussion

3.1. Structure and working principle of the CO-TENG

Fig. 1 show the working principle, overall and partial detailed design and display of the CO-TENG. Fig. 1a depicts the working principle of the CO-TENG. The vertical movement of the wave after transmission, compresses the spiral spring to collect mechanical energy, and then the spiral spring will drive the rotor of TENG with controlled by the escapement-spring-leaf mechanism like the principle of auto-winding mechanical watch.

The motion transfer process of the CO-TENG is illustrated in Fig. 1b. The power of the energy-harvest unit drives the spiral spring shaft to rotate by the gear pairs Z_{11}-Z_{12} and Z_{21}-Z_{22} (The spiral spring shaft bearing is one-way bearing, which ensures that the spiral spring shaft can only rotate in clockwise. Gear Z_{21} is behind the gear Z_{12}, and not be shown in the Fig. 1b.) and compress the spiral spring and convert random environmental energy into elastic potential energy storage of the spiral spring. The gear Z_{31}, which is rigidly connected with the spring barrel and driven by the spiral spring, rotates clockwise and engages with the gear Z_{32}, thus driving the ratchet Z_{41} and gear Z_{33}. The escapement lever Z_{42} can open and close intermittently under the drive of the gear Z_{41}, then the energy of the spiral spring is controlled and released by the frequency of the escapement lever Z_{42}. The spiral spring energy which was controlled by gear Z_{32} drive gear Z_{33} intermittent rotation, through a one-way bearing (installation between gear Z_{33} and flywheel shaft) and then drive flywheel and gear Z_{51}. Under the joint action of the flywheel and one-way bearing, the rotating speed of the axis 5 can ensure very stable. Finally, the stable relative rotation of the rotor and stator is implemented by the gear pairs Z_{51}-Z_{52}. The rotating speed of the rotor of TENG is controlled by the vibration frequency of the spring leaf and the number of the ratchet teeth. In other words, the output speed is controllable, stable, and continuous, which has nothing to do with the external excitation frequency, direction, and amplitude.

The electric energy conversion processes are shown in Fig. 1c, which is based on the triboelectrification effect and electrostatic induction. Three flexible films are made by fluorinated ethylene propylene (FEP), in which one end of the film is attached to the outer wall of the rotor, and the other end slides between adjacent copper electrodes A_1 and A_2. In the initial state, the FEP film completely covers the electrode A_1, as shown in Fig. 1c(I). Because of the triboelectrification effect, the FEP film obtains negative induced charges, and electrode A_1 receives positive charges. When the FEP film slides from A_1 to A_2, the electrons flow from A_2 to A_1 by electrostatic induction, as shown in Fig. 1c(II). When the FEP film arrives at the position that completely overlaps with electrode A_2, the electrons completely change to A_1, ensuing in the positive charges on electrode A_2, as shown in Fig. 1c(III). When the rotor continues rotating, the electrons flow back to A_2 from A_1, as shown in Fig. 1c (IV).

The escapement-spring-leaf mechanism, just like the hairspring system and escapement of the mechanical watch, is sketched in Fig. 1d. The hairspring system and escapement are innovatively integrated into an escapement-spring-leaf mechanism, that not only guarantees the kinetic characteristics but also shortens the transmission chain and reduces the loss of energy in the transmission process. Detailed operation process of the escapement-spring-leaf mechanism is sketched to show in Fig. 1d. The initial status of the escapement-spring-leaf is shown Fig. 1d (I), there is no external excitation input to the spring leaf system. The ratchet Z_{41} rotates clockwise under the drive of the gear Z_{32}. Meanwhile, the ratchet Z_{41} transmits the external force to the escapement lever Z_{42}. Finally, the balance of the spring leaf vibration subsystem is broken, so that the escapement lever and mass block swing clockwise, as shown in Fig. 1d(I-II). At the same time, the restoring moment of the spring leaf is triggered by its deformation. The direction of the moment is opposite to the motion direction of the escapement lever and mass block, so the moment will hinder the movement of the escapement lever and mass block, and makes their angular velocity decrease gradually. When the escapement lever rotates to the right limit, the restoring moment of the spring leaf achieves the maximum, as shown in Fig. 1d(II-III). The escapement lever and mass block gradually move to the equilibrium position, because the restoring moment is transformed into the angular velocity of the escapement lever and mass block in this process. When the escapement lever and mass block reach the equilibrium position again, the spring leaf is completely relaxed. Therefore, the restoring moment achieves zero and the angular velocity accomplishes the maximum. They will go beyond the equilibrium position and rotate the left limit under inertia, as shown in Fig. 1d(III-IV). In this way, the control of the ratchet Z_{41} is realized, that is, the controlled release of the elastic potential energy of the spiral spring is demonstrated. The floor plan and whole structure of the CO-TENG are shown in Fig. 1e and f, respectively.

3.2. Performance of the CO-TENG

In CO-TENG, the rotor speed plays an important role in electrical output characteristic, especially the short-circuit current. Furthermore, from the previous analysis of the CO-TENG, it can be seen that the controlled release of the elastic potential energy of the spiral spring is achieved by the intermittent opening and closing of the escapement lever Z_{42} to control the rotation of the ratchet Z_{41}. Therefore, the frequency T_0 of the escapement lever Z_{42} is the key factor to control the rotor. According to the kinetic law and the rational mechanics, angle frequency ω of the escapement lever Z_{42} is denoted by

$$\omega = \sqrt{\frac{M_0}{J_0}} \quad (1)$$

Where J_0 is the rotational inertia of the mass block (the mass of the escapement lever is much smaller than the mass of the mass block, it is ignored); M_0 is the stiffness of the spring leaf, M_0 is expressed as

$$M_0 = \frac{Ebh^3}{12L} \quad (2)$$

Where *E, b, h, L* is elastic modulus, width, thickness, and working length of the spring leaf, respectively.

Therefore, the frequency of the escapement lever Z_{42} T_0 is

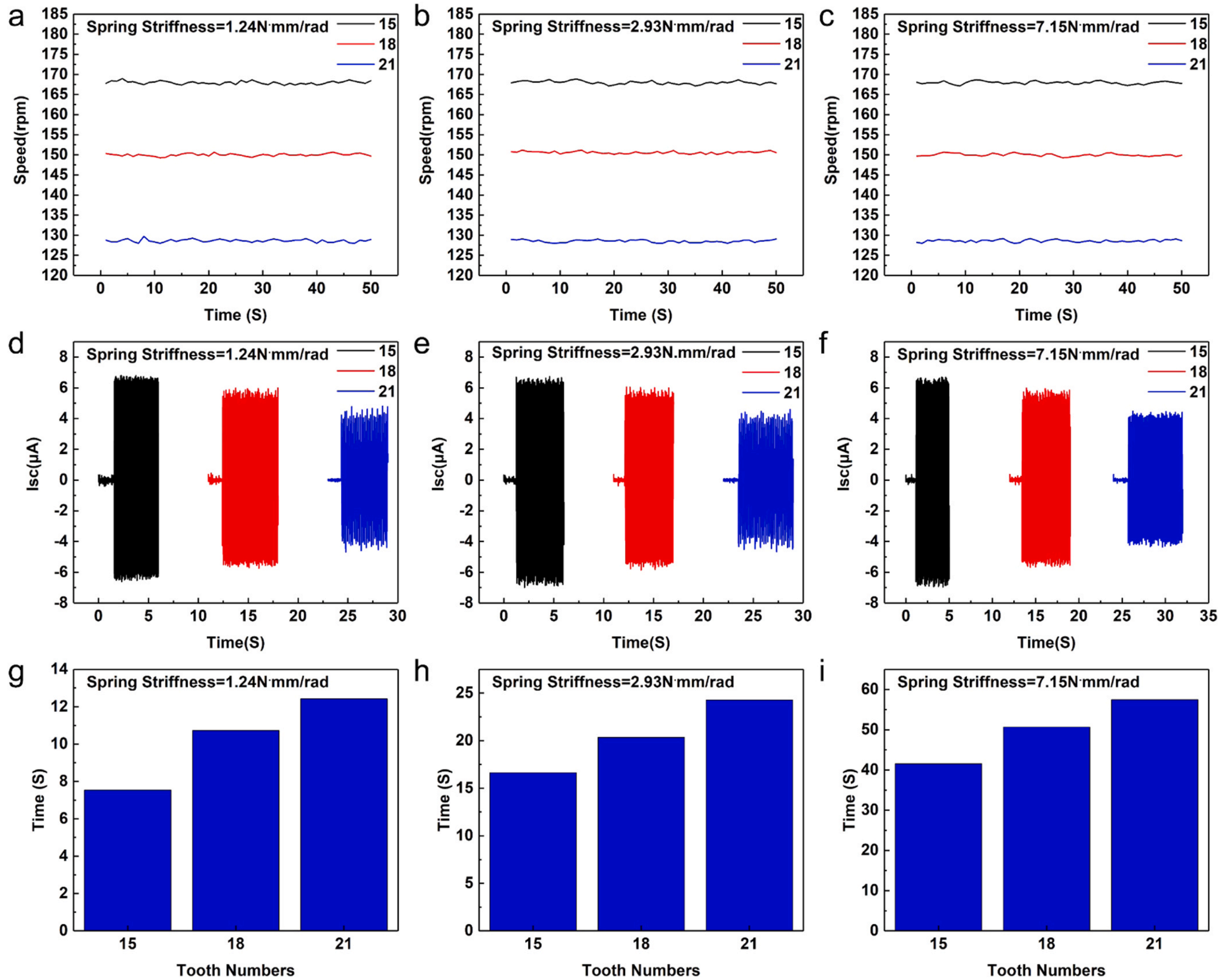

Fig. 2. Rotor speed, running time, and short-circuit current of the CO-TENG under fixed excitation conditions. Top row: Rotor speed under different numbers of ratchet teeth and same spiral spring stiffness; Middle row: Short-circuit current response to different numbers of ratchet teeth and same spiral spring stiffness; Bottom row: Running time on different numbers of ratchet teeth and same spiral spring stiffness.

$$T_0 = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{12J_0L}{Ebh^3}} \tag{3}$$

In our experimental device, the frequency of the escapement lever Z_{42} was designed as 2 Hz. In order to further discuss the influence of other factors on the speed, different spiral spring stiffnesses, tooth numbers of the ratchet Z_{41} were studied when external excitation and frequency of the escapement-spring-leaf is constant. The rotor speed, running time and short-circuit current of the CO-TENG under constant excitation as shown in Fig. 2. The excitation amplitude is 20 mm and the frequency is 0.5 Hz. Fig. 2a, b, c shows the effect of the different tooth numbers on the rotor speed under the same spiral spring stiffness. The tooth numbers are 15, 18 and 21, and spiral spring stiffnesses are 1.24, 2.93 and 7.15$N{\cdot}mm/rad$, respectively. Significantly, it can be found that the rotor speed is almost constant under different spiral spring stiffnesses with the same tooth numbers (relative error of the speed $<1\%$), while the rotor speed has slumped from 169 to 129 rpm as the tooth numbers increase from 15 to 21. This demonstrates that the rotor speed has nothing to do with the spiral spring stiffnesses, and is determined by the tooth numbers of the ratchet Z_{41}. On the other hand, we tested the short-circuit current (Isc) of the CO-TENG under the same experimental conditions, as demonstrated in Fig. 2d, e, f. The Isc has a considerable decrease from 6 μA to 4 μA as the tooth numbers increase from 15 to 21 and there is a comparatively small variation at different spiral spring stiffnesses with the same tooth numbers. In order to obtain a reasonable spiral spring stiffness parameter, the influence on the CO-TENG is further discussed, as shown in Fig. 2g, h, i. Notably, the rotor running time of the CO-TENG is affected by it, which as the stiffness increases, the running time raises. Hence, under the comprehensive consideration of rotor speed and running time, in our experimental device, the spiral spring stiffness is set to 7.15$N{\cdot}mm/rad$, and tooth numbers of the ratchet Z_{41} is 15.

In order to demonstrate the feasibility of the CO-TENG's working under random external excitation, the electrical output characteristic of the CO-TENG, such as open-circuit voltage (Voc), short-circuit current (Isc) and transfer charge (Qsc), under random frequency and amplitudes was studied, as shown in Fig. 3. Fig. 3a, b, c shows the output performance at different frequencies with a fixed amplitude of 20 mm. Fig. 3d, e, f display the output performance at different frequencies with a fixed amplitude of 35 mm. Fig. 3g, h, i demonstrate the output performance at different frequencies with a fixed amplitude of 50 mm. Noticeably, the CO-TENG still has a stable output when external excitation conditions are random and disordered.

Based on the above experiment, the CO-TENG confirms that a stable

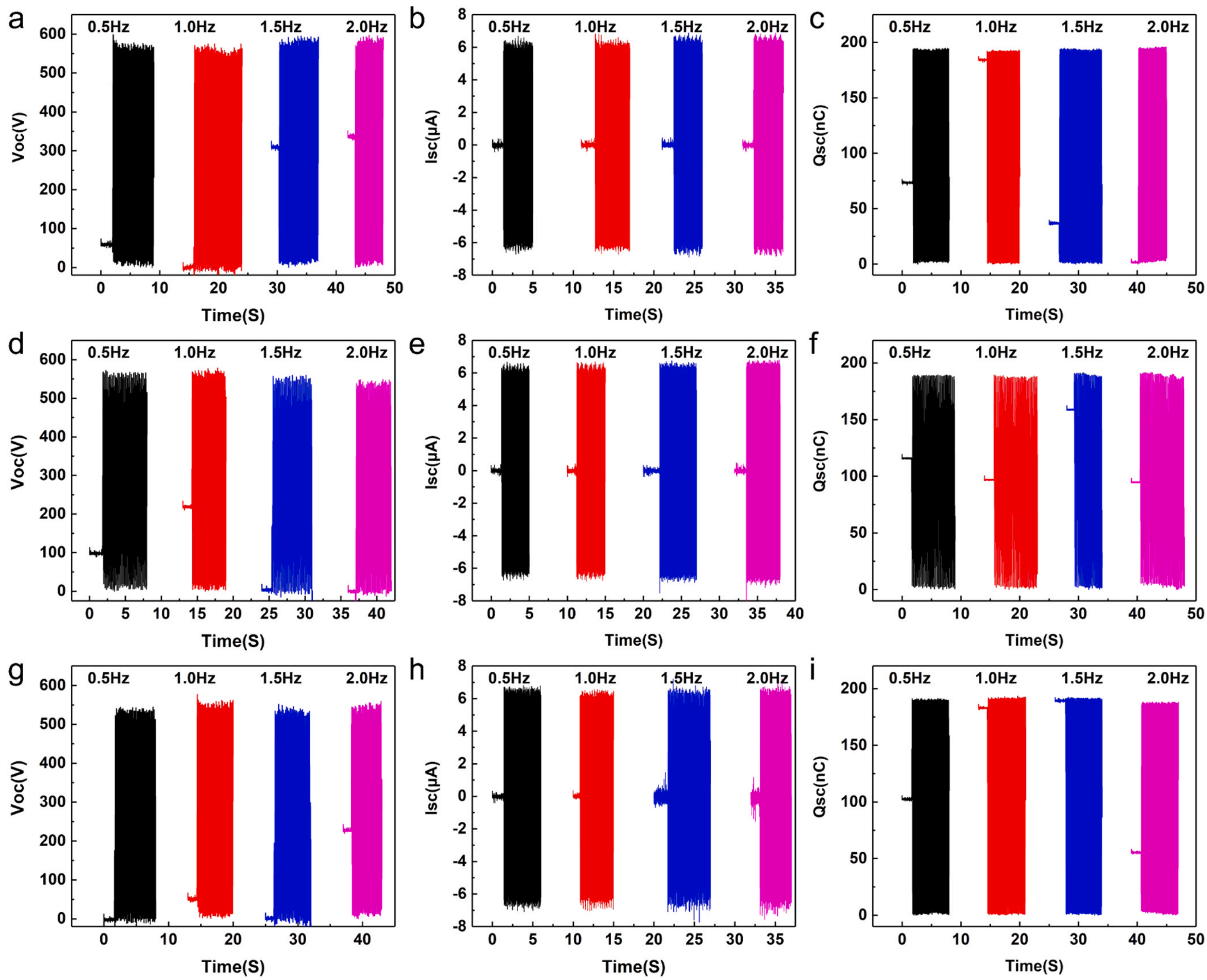

Fig. 3. Performance of the CO-TENG for harvesting random mechanical energy. (a-c) Electric output characteristic at different frequencies with a fixed amplitude of 20 mm; (d-f) electric output characteristic at different frequencies with a fixed amplitude of 35 mm; (g-i) electric output characteristic at different frequencies with a fixed amplitude of 50 mm; (a), (d), (g) open-circuit voltage; (b), (e), (h) short-circuit current; (c), (f), (i) transfer charge.

electrical output characteristic is conceivable even with random inputs. Therefore, we further explored the application prospects of the CO-TENG in ambient natural environments. First, energy harvesting from wave energy was demonstrated, the output performance and the experimental device are shown in Fig. 4a, b, c and Fig. 5a (harvesting wave energy to power a thermometer as shown in Video S1, Supporting Information). A simulated wave with an amplitude of 20–50 mm and a frequency of 0.5–2.0 Hz was generated by the wave pool. At this time, the wave energy collected by the oscillating buoy (inset in Fig. 5a) is transmitted to the CO-TENG through the rack-and-gear. Obviously, the electrical output characteristic of the CO-TENG is stable and continual under random and irregular waves, indicating the effectiveness of the CO-TENG in addressing random and low-frequency waves. Second, the CO-TENG harvesting wind energy was confirmed, while the output characteristic is shown in Fig. 4d, e, f, and the experimental device is shown in Fig. 5b (collecting wind energy to power a thermometer as shown in Video S2, Supporting Information). The breeze which wind speed is 3.5–9.8 m/s is simulated by an air compressor. The wind energy collected by the wind scoop (bottom inset in Fig. 5b) is transmitted to the CO-TENG through the transmission shaft. As will be readily seen, the CO-TENG still has steady and sustaining output when it works under a random breeze, demonstrating the feasibility of the CO-TENG in harvesting random wind energy. At last, it is demonstrated that the CO-TENG collects random water flow energy, the output performance is shown in Fig. 4g, h, i, and the experimental device is shown in Fig. 5c (harvesting water flow energy to power a thermometer as shown in Video S3, Supporting Information). The water flow of the experiment is 2.7–10.5 m/s is generated by the submersible pump. The input shaft of the CO-TENG is rigidly connected to a water turbine (bottom inset in Fig. 5c), which can harvest random water flow. Consequently, it is proved that the CO-TENG can still realize stable output under random water flow, which is feasible. Synthesize the above experiment, the CO-TENG, which applying simulated natural environments, can continuously and steadily translate the mechanical kinetic energy to electric energy, and provides potential solutions for the industrial application of TENGs.

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Fig. 5d shows the duration for CO-TENG to charge different commercial capacitors with capacitances of 2.2, 4.7, 10, and 22 μF to 5 V, which apply random wind energy. To prove the CO-TENG use as a stable power at random external excitation, which was connected to LEDs and a 22 μF capacitor. The alternating current generated by CO-TENG is converted into direct current by the rectifier filter. Fig. 5e displays that

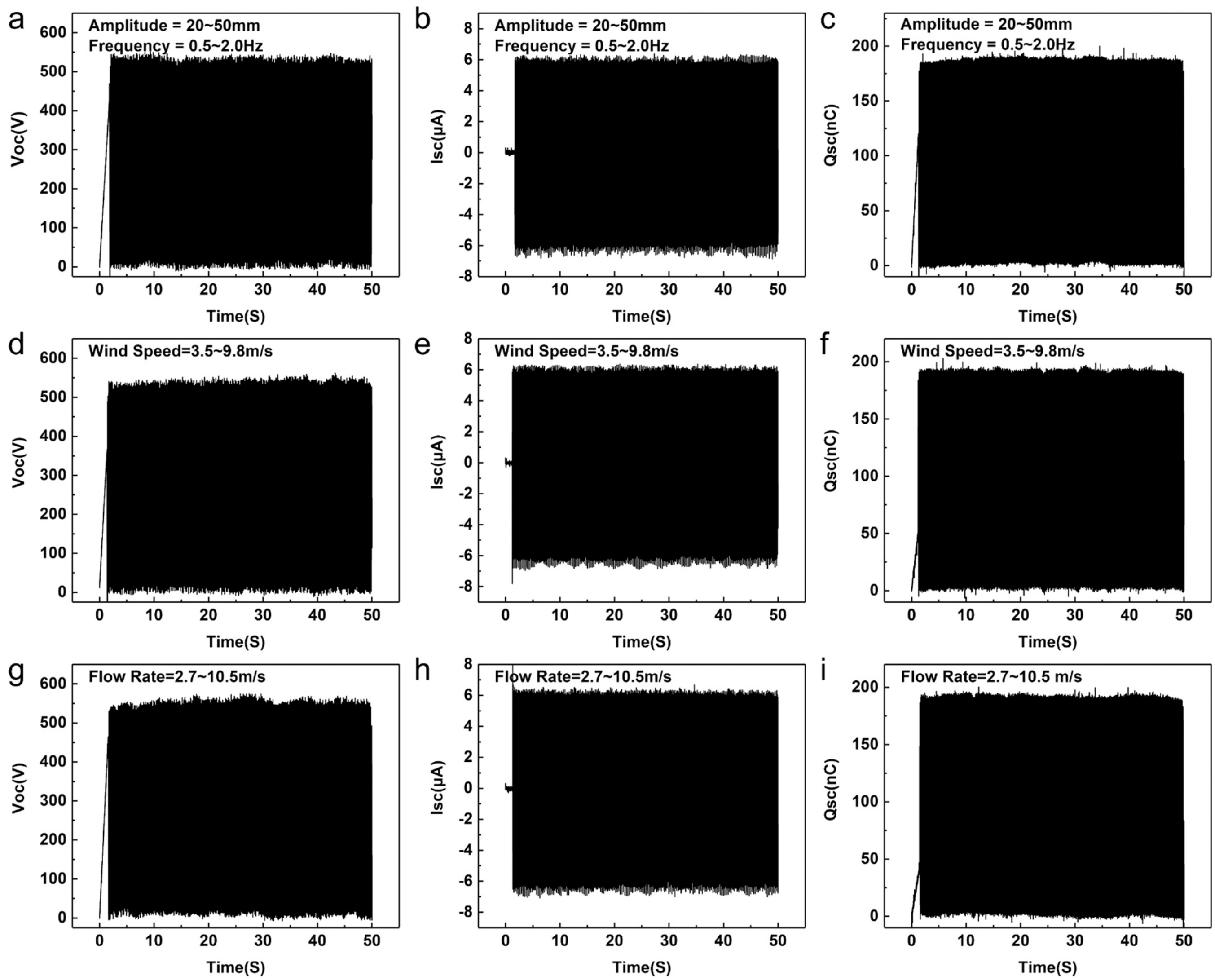

Fig. 4. Demonstration the electrical output characteristic of the CO-TENG for harvesting ambient natural environments. (a-c) Electrical output characteristic under random wave energy; (d-f) electrical output characteristic under random wind energy; (g-i) electrical output characteristic under random water energy.

the 22 μF commercial capacitor was charged via the CO-TENG to operate a commercial thermometer. Moreover, 450 LEDs in serial connection were lit up continuously and steadily by the CO-TENG, as shown in Fig. 5f (Video S4, Supporting Information). This demonstration shows that the CO-TENG can be regarded as a stable power supply for MEMS, regardless of changes in the external environment.

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4. Conclusion

In summary, we have successfully demonstrated the feasibility of the CO-TENG, which can steadily and continually release electric energy through a process of harvesting-storage-release without manual intervention although the original energy is random and low-frequency. The process is based on a flat spiral spring, escapement-spring-leaf, and one-way shafting. At the same time, the CO-TENG has been successfully applied to harvest the power from random waves, wind, and water flows through the adjustment of the input gear train and energy collection parts, such as water turbine, wind scoop, and oscillating buoy. In addition, under random and low-frequency experimental conditions, the CO-TENG has been steadily and continuously generated an open-circuit voltage of 550 V, a short-circuit current of 6 μA and transferred charges of 190 nC. After using the rectifier filter, a commercial thermometer and 450 LEDs in serial connection were separately powered by the CO-TENG. Therefore, this study illustrates that the CO-TENG can be regarded as a potential solution regulated usage of the random and low-frequency mechanical kinetic energy, providing an innovative approach for utilization of high entropy energy.

CRediT authorship contribution statement

Gaofa He: Conceptualization, Methodology, Writing - review & editing, Project administration, Funding acquisition. **Yingjin Luo:** Software, Validation, Investigation, Data Curation, Writing - original draft. **Yuan Zhai:** Data acquisition and processing, software. **Ying Wu:** Conceptualization, Resources, Writing - review & editing, data acquisition. **Jing You:** Investigation. **Rui Lu:** Investigation. **Shaokun Zeng:** Resources. **Zhong Lin Wang:** Writing - review & editing.

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.

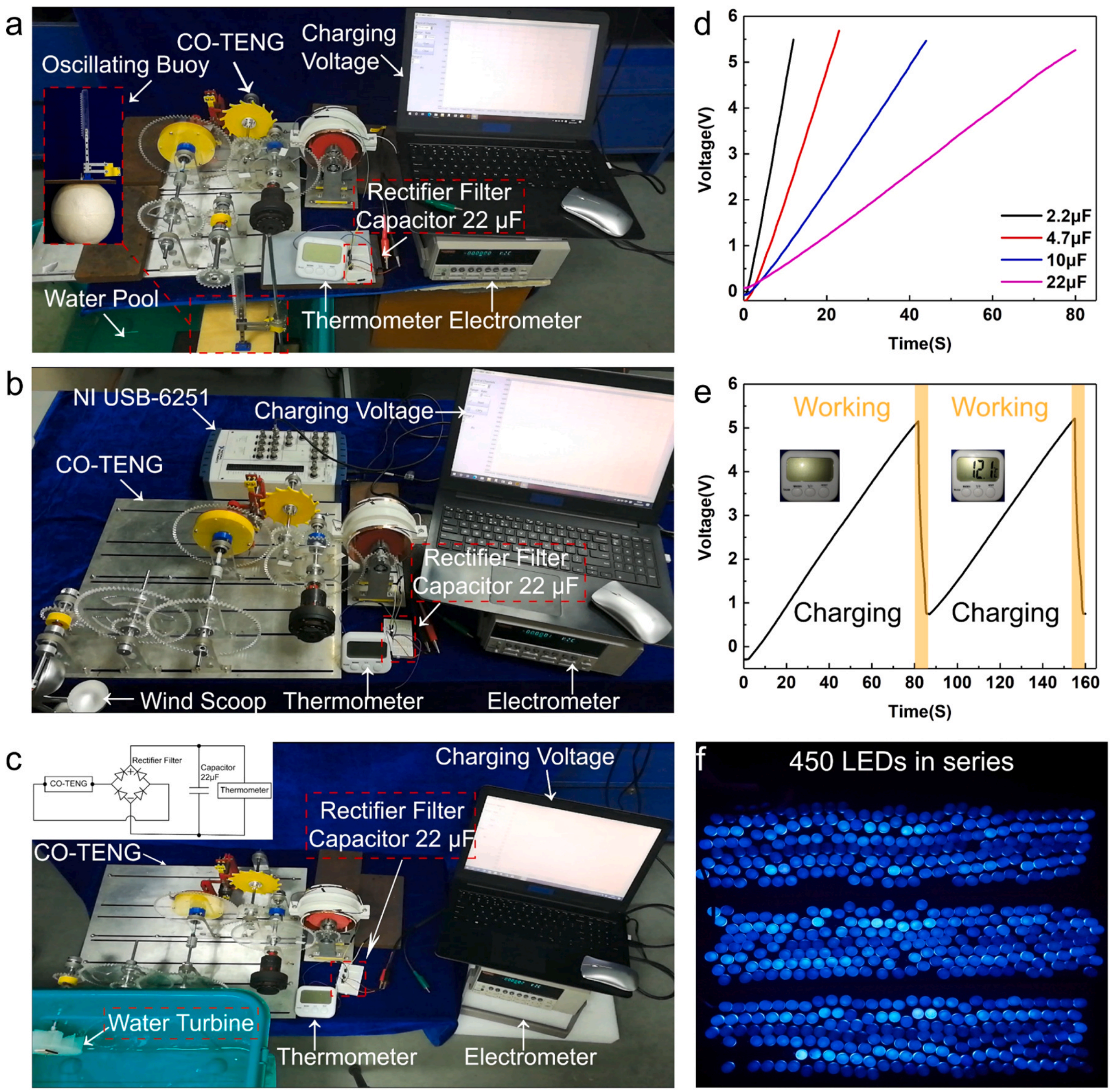

Fig. 5. Application of the CO-TENG harvesting environmental energy. (a) Photograph of the CO-TENG harvesting random wave energy; (b) photograph of the CO-TENG harvesting random wind energy; (c) photograph of the CO-TENG harvesting random water energy; (d) CO-TENG charging curves of various commercial capacitors (2.2, 4.7, 10, 22 μF); (e) voltage curves of 22 μF commercial capacitor with the thermometer powered by the CO-TENG; (f) photograph of 450 LEDs in serial connection powered by the CO-TENG.

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Prof. Gaofa He received the B. S., M.S. and Ph. D. degrees from Chongqing University in 1995, 2005 and 2010 respectively. He was a visiting scholar in the Department of Nanomechanics at Tohoku University in Japan from 2006 to 2007 and from 2012 to 2013, respectively. Currently, he is a professor at School of Mechanical and Power Engineering, Chongqing University of Science & Technology. His research interests are precise measurement, triboelectric nanogenerator, and sensing technology.

Yingjin Luo received his B.E. degree from Chongqing University of Science & Technology in 2019. Now, he is a postgraduate student at Chongqing University of Science & Technology. Currently, his research interests are mainly focused on energy harvesting for self-powered systems.

Dr. Yuan Zhai received the B.S. and Ph.D. degrees from Chongqing University in 2007 and 2013, respectively. Now, he is a lecturer at Chongqing University of Science & Technology. Currently, his research interests are TENG energy harvester, triboelectric nanogenerators, energy efficiency optimization.

Prof. Ying Wu is currently a professor at Chongqing University of Science and Technology. She achieved her Ph.D. degree in the College of Optoelectronic Engineering at Chongqing University. Her research interests include micro/nano devices, IOT technology, smart sensors and image processing.

Jing You received her B.E. degree from Yangtze Normal University. Now, she is a postgraduate student at Chongqing University of Science & Technology. Currently, her research interests are mainly focused on triboelectric nanogenerators.

Rui Lu received her B.E. degree from Chongqing University of Science & Technology in 2017. Now, she is a postgraduate student at Chongqing University of Science & Technology. Currently, her research interests are mainly focused on energy harvesting for self-powered systems.

Shaokun Zeng received his B.S. degree from Chongqing University of Science & Technology in 2016. Now he is an assistant experimenter at Chongqing University of Science & Technology. Currently, his research interests are mainly focused on mechanical design and manufacturing.

Prof. Zhong Lin Wang received his Ph.D. from Arizona State University in physics. He now is the Hightower Chair in Materials Science and Engineering, Regents' Professor, Engineering Distinguished Professor and Director, Center for Nanostructure Characterization, at Georgia Tech. Dr. Wang has made original and innovative contributions to the synthesis, discovery, characterization and understanding of fundamental physical properties of oxide nanobelts and nanowires, as well as applications of nanowires in energy sciences, electronics, optoelectronics and biological science. His discovery and breakthroughs in developing nanogenerators established the principle and technological road map for harvesting mechanical energy from environment and biological systems for powering personal electronics. His research on self-powered nanosystems has inspired the worldwide effort in academia and industry for studying energy for micro-nano-systems, which is now a distinct disciplinary in energy research and future sensor networks. He coined and pioneered the field of piezotronics and piezophototronics by introducing piezoelectric potential gated charge transport process in fabri cating new electronic and optoelectronic devices. Details can be found at: http://www.nanoscience.gatech.edu.