

# Triboelectric nanogenerator with double rocker structure design for ultra-low-frequency wave full-stroke energy harvesting

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## ABSTRACT

The triboelectric nanogenerator (TENG) is a unique revolutionary technology for harvesting energy from the environment and transforming that energy into electricity. The present paper proposes a double rocker triboelectric nanogenerator (DR-TENG), which is used to harvest energy from intermittent reciprocating motions and ultimately obtain electric energy in a controllable manner. The DR-TENG comprises a mechanical transmission structure, generation unit, and shell. The mechanical energy harvested by the pendulum rod is stored in a spiral spring via the mechanical transmission structure, and the energy is then transformed into controllable electric energy through a switching structure and generation unit. The experimental results show that the open-circuit voltage of the DR-TENG is 450 V, the short-circuit current is 36  $\mu$ A, and the peak power is 11 mW. In a water-wave simulation experiment, the DR-TENG powered 400 LEDs in series and a commercial thermometer with a bridge rectifier. This paper provides an effective method for the harvesting of irregular full-stroke energy in an ultra-low-frequency environment.

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## 1. Introduction

Due to the large consumption of nonrenewable fossil fuels and the rapid development of industry in recent decades, environmental pollution, global warming, climate change, and other issues are becoming increasingly serious [1–4]. There is an urgent need to find sustainable, clean, and available sources of green energy [5–8]. In 2012, the triboelectric nanogenerator (TENG, also known as the Wang generator [9]) was first proposed by Wang group. The TENG can harvest energy from the environment and transform it into electric energy. As a unique revolutionary technology, the working mechanism of the TENG is based on the coupling effect of contact electrification and electrostatic induction [10–13]. The four basic working modes of the TENG, namely contact-separation [14], sliding-electrode [15], single-electrode [16], and freestanding triboelectric-layer modes [17], have been widely applied and studied in the fields of energy harvesting [18–21] and self-powered systems [22].

In recent years, the TENG has attracted much attention for its low cost, easy fabrication, diverse choice of materials, and other advantages [23–26]. TENGs having various structures are widely used in the harvesting of wind energy [27–30], ocean energy [31–34], and vibration energy [35–38]. In particular, great progress has been made using a series of TENGs with various mechanical structures in natural energy harvesting; e.g., mechanical frequency increment [29,30], random energy harvesting [35,36], and machinery regulation [39,40]. As a main form of vibration, reciprocating motion widely exists in natural environments; e.g., ocean energy, suspension systems, and human motion. Generally, these motions have the characteristics of ultra-low frequency [41], strong randomness, and irregularity [42–44]. That leads to output performance of TENG is usually irregular [45], which is also one of the critical problems of the limited application of TENG. Meanwhile, there are limited studies on how to harvest energy from these motions [46,47]. It is therefore highly desirable to explore approaches of harvesting energy from these motions.

This research proposed a double rocker triboelectric nanogenerator (DR-TENG) to harvest energy from intermittent reciprocating motions. The DR-TENG comprises a generation unit, shell, and mechanical transmission structure including double rocker mechanisms and a switch structure. The mechanical energy is stored in a spiral spring through the mechanical transmission

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structure. When the switching disc runs to the open position, the stored energy drives the flywheel to rotate. Fluorinated ethylene propylene (FEP) films are driven by the flywheel to slide on copper electrodes, and electric energy is ultimately obtained. The electrical output of the DR-TENG is an open-circuit voltage of 450 V, a short-circuit current of 36  $\mu\text{A}$ , and a peak power of 11 mW. In a water-wave simulation experiment, a commercial thermometer and 400 light-emitting diodes (LEDs) in series are driven by the DR-TENG with a bridge rectifier. The experimental results show that the DR-TENG supplies energy for low-power devices and has potential applications in wave energy harvesting.

## 2. Results and discussion

### 2.1. Structure and working principle of the DR-TENG

#### Nomenclature

LDRM	The left double rocker mechanism
MTS I	The mechanical transmission structure I
$\alpha$	The energy storage angle of the switching disc
RDRM	The right double rocker mechanism
MTS II	The mechanical transmission structure II

The overall structure (Fig. 1a) of the DR-TENG comprises a mechanical transmission structure (Fig. 1b), a generation unit (Fig. 1c), and a shell. The mechanical transmission structure comprises a left double rocker mechanism (LDRM), a right double rocker mechanism (RDRM), three one-way clutches, a switch structure, and a shaft. The limit rod in the switch structure is used to control the movement of the flywheel, so that the switch structure can realize the control of energy storage and release. The LDRM and RDRM can be installed in two modes: mechanical transmission structure I (MTS I) (Fig. S1a, Supporting Information) and mechanical transmission structure II (MTS II) (Fig. S1b, Supporting Information). The complete prototype is shown in Fig. 1(d), and details of the generation unit are presented in Fig. 1(e). The switching disc for controlling the storage energy time is shown in Fig. 1(f).

The mechanism operation of the DR-TENG is presented in Fig. 2(a). In the initial state [Fig. 2a(i)], the pendulum rod is not driven by an external force, the switch structure is in the open state, and the return spring is not compressed. The pendulum rod to the right when the right excitation acts on the pendulum rod [Fig. 2a(ii)]. The RDRM rotates anticlockwise and drives the shaft and switching disc to rotate anticlockwise through one-way clutches II and III. Simultaneously, the limit rod is pushed by the switching disc to block the flywheel for energy storage. Although the LDRM and one-way clutch I rotate clockwise, no reverse torque is provided to the shaft. Therefore, the flywheel does not rotate and the generation unit does not output an electrical signal. When the pendulum rod swings to the left under the excitation [Fig. 2a(iii)], the LDRM rotates anticlockwise and drives the shaft to rotate anticlockwise via one-way clutch I. Although the RDRM and one-way clutches II and III rotate clockwise, no reverse torque is provided to the shaft and switching disc. The switching disc does not rotate, while the spiral spring is continuously compressed for energy storage, and the flywheel remains locked. After several excitation cycles, the switching disc rotates 360°. The limit rod moves left to the slot of the switching disc with the assistance of the return spring, the flywheel is unlocked and the energy stored in the spiral spring is released. The stored energy drives the flywheel to rotate, then the generation unit outputs an electrical signal [Fig. 2a(iv)].

Fig. 2(b) shows the charge transfer principle of the DR-TENG. In the initial state [Fig. 2b(i)], the Copper-2 is in complete contact with FEP films. Owing to the difference in electronegativity between the FEP films and copper electrodes, the FEP films and Copper-2 produce the same amounts of opposite charge. In the process of FEP films sliding from Copper-2 to Copper-1, the potential difference between Copper-1 and Copper-2 drives electron flow from Copper-1 to Copper-2, and external circuit thus generates current [Fig. 2b(ii)]. When the Copper-1 is in complete contact with FEP films [Fig. 2b(iii)], equal amounts of positive and negative charge accumulate on the surfaces of FEP films and Copper-1. As the FEP films slide continuously, the potential difference between Copper-1 and Copper-2 drives electron flow from Copper-2 to Copper-1, and the external circuit similarly generates current [Fig. 2b(iv)]. Repeating the whole process, a continuous alternating current is obtained in the external circuit. Meanwhile, COMSOL software is used to simulate the change in the potential difference (Fig. 2c).

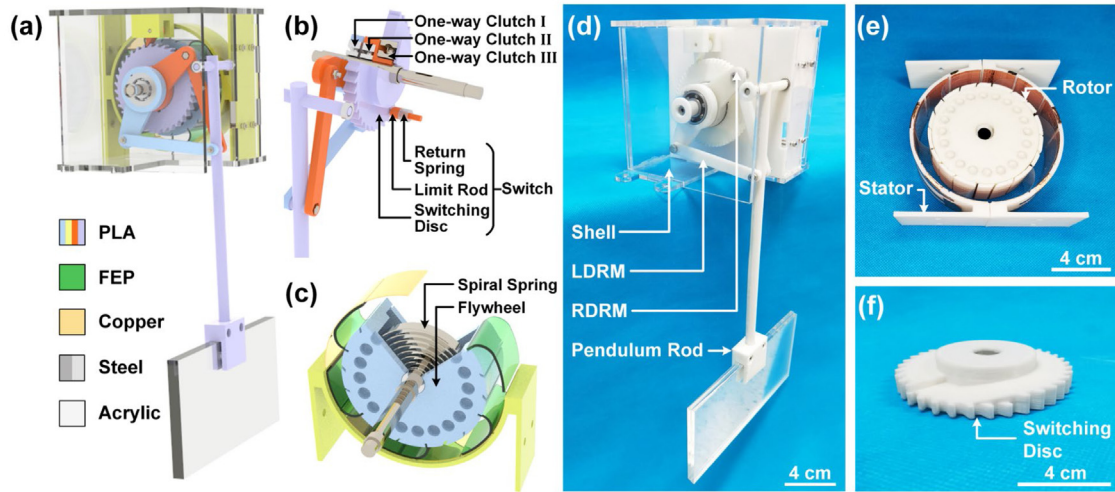
### 2.2. Output performance of the DR-TENG

A series of experiments were carried out adopting the two installation methods to study the effects of the different installation methods of the mechanical transmission structure on the output performance of the DR-TENG.

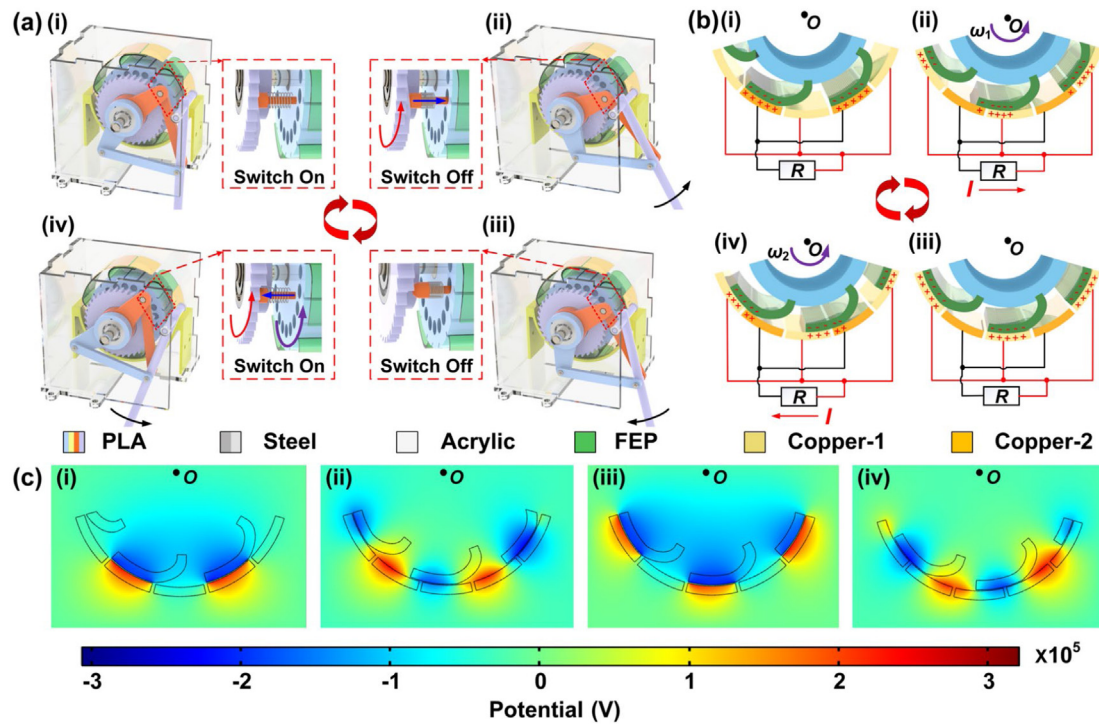
Experiments involving different spiral spring stiffnesses and flywheel masses were first carried out. The blades of the DR-TENG were made from FEP film and had a length of 45 mm and width of 35 mm (Figs. S2 and S3, Supporting Information). Under conditions of uniform excitation and the same spiral spring stiffness, with an increase in the flywheel mass, the short-circuit current decreases [Fig. 3a(ii)], the open-circuit voltage [Fig. 3a(i)] and the transferred charge [Fig. S4a, Supporting Information] remain unchanged, and the flywheel running time gradually increases (Fig. 3e, g). Under conditions of uniform excitation and the same flywheel mass, with an increase in spiral spring stiffness, the short-circuit increases (Fig. 3a–c), open-circuit voltage (Fig. 3a–c) and transferred charge (Fig. S4, Supporting Information) remain unchanged, and the output energy increases gradually (Fig. 3d, f). As a result of contrastive analysis, a spiral spring stiffness of 5.32 N mm rad<sup>-1</sup> and a flywheel mass of 602 g are chosen in the following experiments.

Experiments were then conducted using different excitation frequencies and different energy storage angles  $\alpha$  of the switching disc. When  $\alpha$  of the switching disc is uniform and the excitation frequency increases, the short-circuit current (Fig. 4a, d), the open-circuit voltage, and the transferred charge (Fig. S5, Supporting Information) of the DR-TENG remain unchanged. The energy release time, that is, the running time length of the flywheel after the limit rod releases the flywheel, is unchanged, but the storage energy time, that is, the length of time the flywheel is locked, appreciably shortens. Meanwhile, when the excitation frequency is uniform and  $\alpha$  of the switching disc increases gradually, the short-circuit current increases (Fig. 4b, e) and the storage energy time increases gradually (Fig. 4c, f). Because the greater  $\alpha$  is, the greater the compression of the spiral spring is, which increases the corresponding storage energy time and storage energy. The experimental results show that the DR-TENG has good output performance at ultra-low frequency (<1 Hz). Compared with the DR-TENG using MTS I, the DR-TENG using MTS II has a longer storage energy time and better output performance.

Furthermore, because the external environment excitation is generally changing, to verify the DR-TENG has controllable output characteristics under random excitation, the linear motor was used to simulate the random input, and relevant experiments of the DR-TENG were conducted. When  $\alpha$  of the switching disc



**Fig. 1.** Basic structure of the DR-TENG: (a) overall structure, (b) mechanical transmission structure, and (c) generation unit, photographs of (d) the DR-TENG, (e) the structure of the generation unit, and (f) the switching disc.

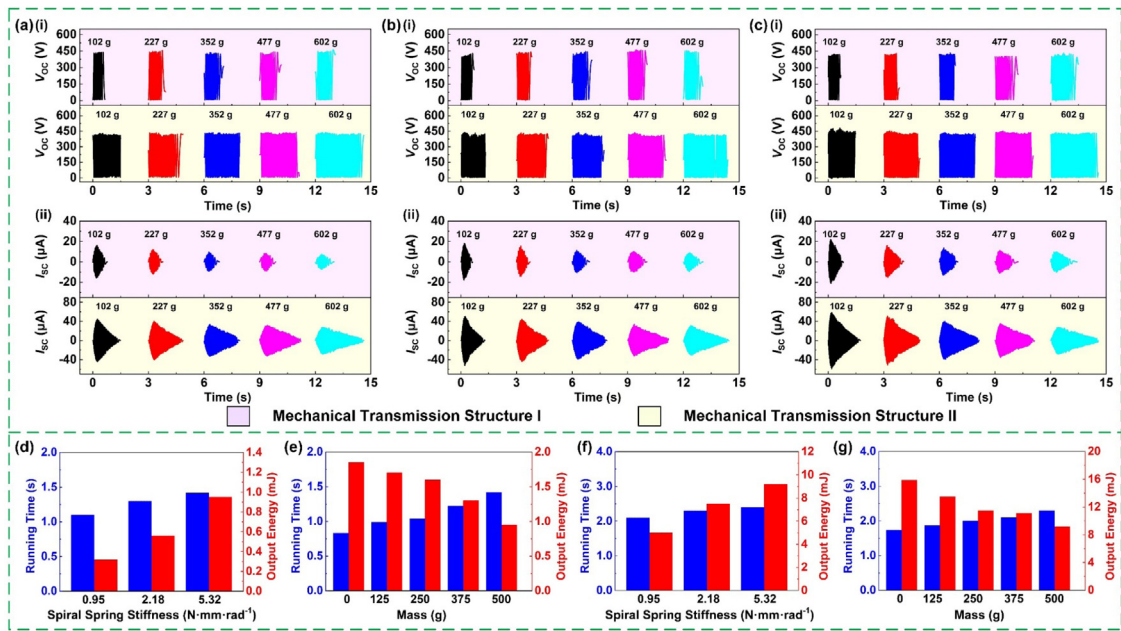


**Fig. 2.** Working principle of the DR-TENG: (a) mechanism operation, (b) electron transfer schematic, and (c) simulation of electrical potential distributions.

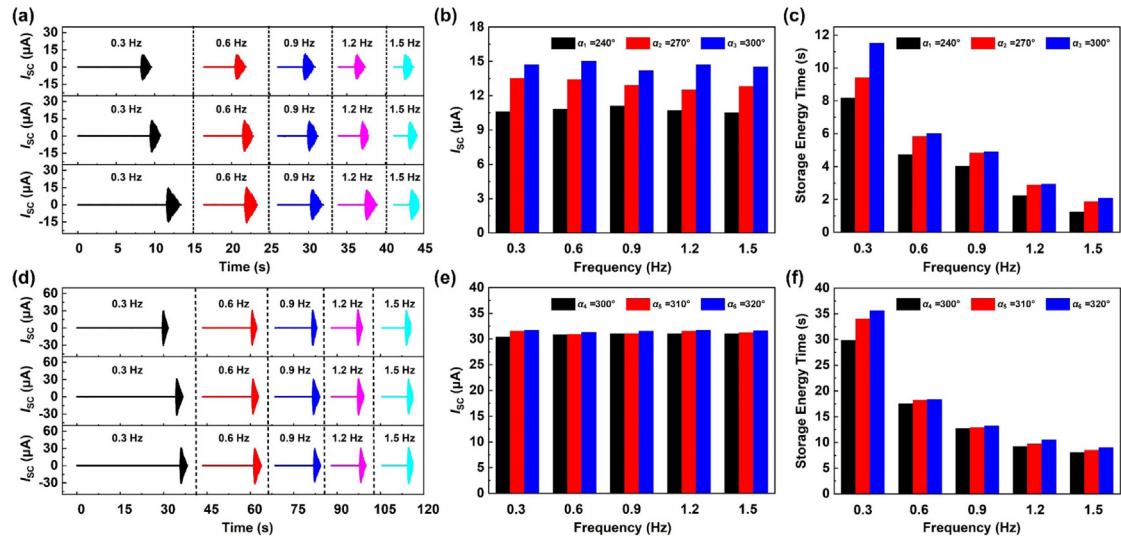
is  $320^\circ$ , the output characteristic of the DR-TENG under MTS II in four continuous working cycles under different excitation frequencies and amplitudes is shown in Fig. 5. It is seen that the DR-TENG with MTS II provides controllable electrical output under a condition of excitation with variable frequency and amplitude (Fig. 5 and S7a, Supporting Information). Similarly, the DR-TENG with MTS I has controllable performance output under the random condition (Figs. S6 and S7b, Supporting Information).

As shown in Fig. 6, a series of experiments were carried out to verify the applicability of the DR-TENG with MTS II. Fig. 6(a) shows the time required for the DR-TENG to charge different commercial capacitors. Fig. 6(b) shows the output performance of the DR-TENG with different load resistors. According to the formula  $P = I^2R$ , the peak power curve is plotted, and maximal

power is 11 mW. The DR-TENG can power 400 LEDs in series (Fig. 6c). As a comparison, we fabricated an ordinary TENG with no switch structure. The ordinary TENG cannot store energy and easy affected by the change of input excitation. A contrast experiment of brightness between ordinary TENG and DR-TENG (Supporting Movie S1) has been carried out. The result shows that the output performance of the DR-TENG is not affected by the change of input excitation. Furthermore, the performance differences between the DR-TENG and other TENGs are shown (Tab. S1, Supporting Information). The DR-TENG can power a thermometer (Fig. 6d and Supporting Movie S2) by harvesting energy from water waves. Experiments show that the DR-TENG can effectively harvest energy from low-frequency reciprocating motion and supply power to the low-consuming appliance.



**Fig. 3.** Output performances of mechanical transmission structure I (MTS I) and mechanical transmission structure II (MTS II) of the DR-TENG for different spiral spring stiffnesses and flywheel masses: the response of open-circuit voltage and short-circuit current to spiral spring stiffnesses of (a–c) 0.95, 2.18, and 5.32  $\text{N mm rad}^{-1}$ , the relation between the running time and output energy under MTS I in terms of the (d) spiral spring stiffnesses and (e) flywheel mass and under MTS II in terms of the (f) spiral spring stiffnesses and (g) flywheel mass.

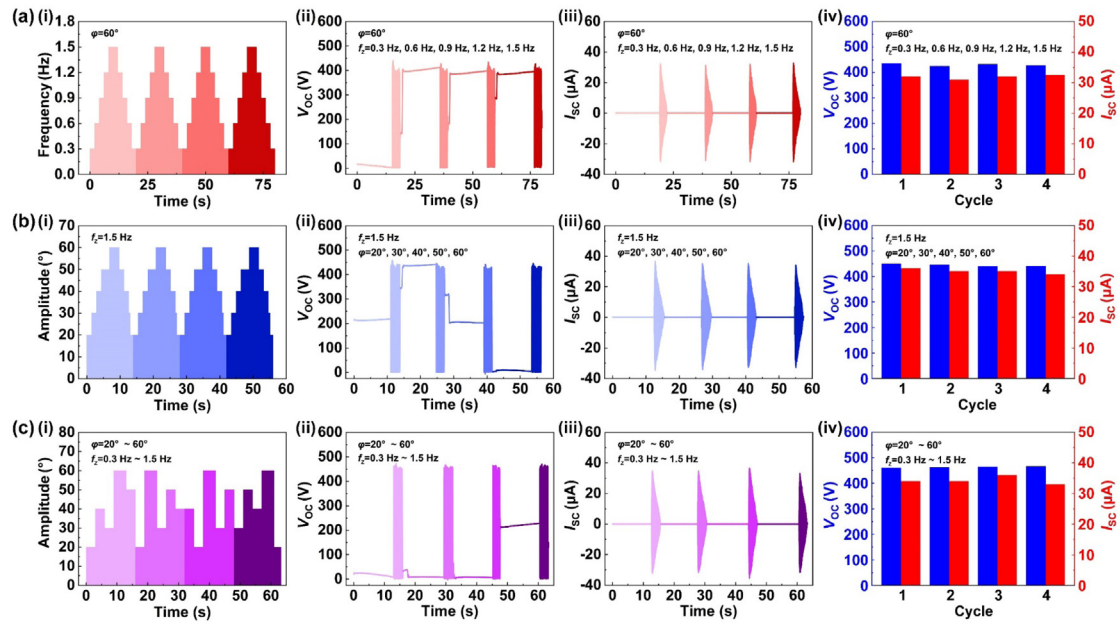


**Fig. 4.** The output performance of the DR-TENG with MTS I and MTS II: (a) short-circuit current response to different frequencies under MTS I when  $\alpha$  of the switching disc is  $240^\circ$  (upper),  $270^\circ$  (medium), and  $300^\circ$  (lower), (b) short-circuit current versus frequency and (c) storage energy time versus frequency under MTS I, (d) short-circuit current response to the frequencies under MTS II when  $\alpha$  is  $300^\circ$  (upper),  $310^\circ$  (medium), and  $320^\circ$  (lower), and (e) short-circuit current versus frequency and (f) storage energy time versus frequency under MTS II.

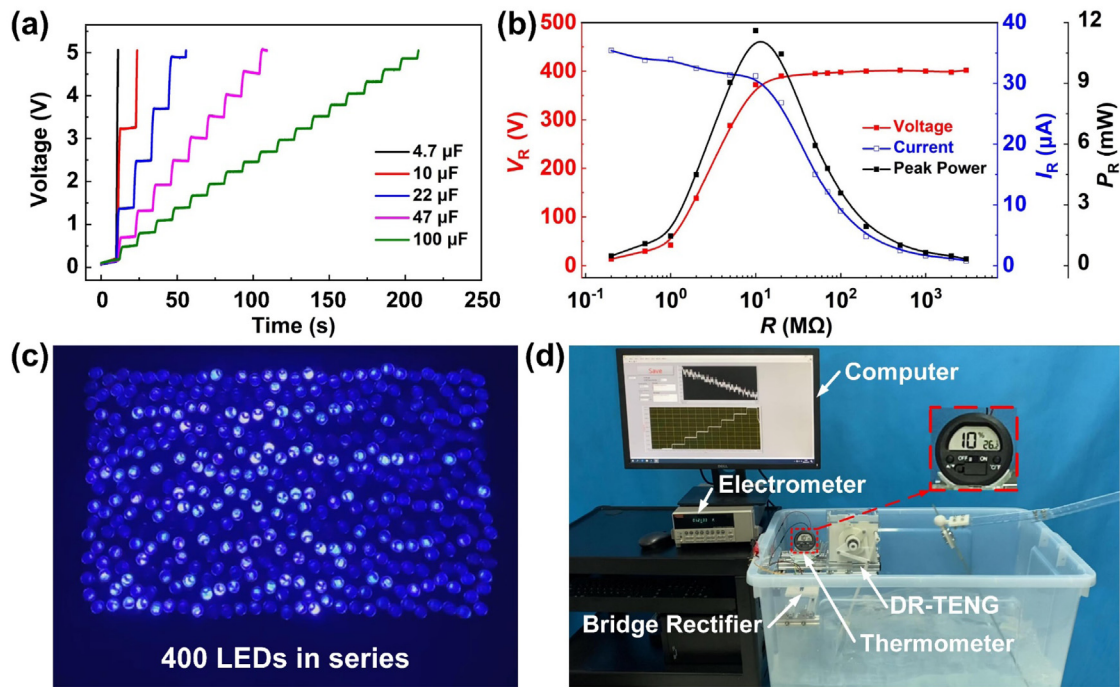
### 3. Conclusions

The DR-TENG harvested energy from intermittent reciprocating motions and converted it into controllable electric energy. The DR-TENG comprises a mechanical transmission structure, generation unit, and shell. Experimental results show that the DR-TENG has reasonable output performance when the flywheel mass is 602 g and the spiral spring stiffness is  $5.32 \text{ N mm rad}^{-1}$ . Meanwhile, the DR-TENG can harvest random and irregular mechanical energy effectively and output controllable electric energy at ultra-low frequency. The DR-TENG can generate an open-circuit voltage of 450 V, a short-circuit current of  $36 \mu\text{A}$ , and a peak power of

11 mW. As shown in Fig. S8 (Supporting Information), a durability experiment shows that the output performance of the DR-TENG remains almost stable after operating about 100,000 cycles. Simultaneously, to simulate the water-wave experiment, the linear motor is used to drive the push plate to push the water to produce low-frequency irregular water waves. In a simulated water-wave experiment, the DR-TENG provided power for a commercial thermometer and 400 LEDs in series by harvesting wave energy, which shows the potential application in the field of energy harvesting. This research is conducive to the collection of water-wave energy and provides important guidelines for the research



**Fig. 5.** Output performance of the DR-TENG with MTS II for four continuous working cycles at different excitation frequencies and amplitudes: excitation condition [a(i), b(i), c(i)], open-circuit voltage [a(ii), b(ii), c(ii)], short-circuit current [a(iii), b(iii), c(iii)], and comparisons of different cycles [a(iv), b(iv), c(iv)]. The excitation conditions are (a) different frequencies, (b) different amplitudes, (c) different amplitudes and frequencies.



**Fig. 6.** Performance demonstration and application diagram of the DR-TENG with MTS II: (a) charging experiments for different capacitors, (b) peak power curve, (c) LEDs powered by the DR-TENG, and (d) the DR-TENG harvesting energy from water waves.

and application of harvesting random mechanical energy in an ultra-low-frequency environment.

#### 4. Experimental section

##### 4.1. Fabrication of the DR-TENG

The dimension of the DR-TENG is 140 mm (length) × 130 mm (width) × 140 mm (height). In addition, the double rocker mechanism, switching disc, limit rod, and flywheel were all manufactured using a three-dimensional printer, and the material was

polylactic acid. The shell material was acrylic acid, which was processed using laser cutting technology. The raw materials of the return spring and spiral spring commonly adopted spring steel. The transmission shaft was made from stainless steel using a lathe. The mass of the flywheel was 102 g, and the steel plates inside the flywheel is used to adjust the mass of the flywheel. The mass of each steel plate was 62.5 g. The dimension of the six FEP films is 45 mm (length) × 35 mm (width) × 100 μm (thickness). The dimension of the twelve copper electrodes is 28 mm (length) × 35 mm (width) × 65 μm (thickness).

## 4.2. Electrical measurements of the DR-TENG

Excitation is generated by linear motor (LinMot PL01-19 × 600 /520). At the same time, a programmable electrometer (6514, Keithley, USA) and a data acquisition system (USB-6218, National Instruments, USA) are used to collect the signal of the DR-TENG. Then, LabVIEW transmits the signal and stores it in the computer.

## CRediT authorship contribution statement

**Yanfei Yang:** Conceptualization, Validation, Investigation, Writing - original draft. **Xin Yu:** Conceptualization, Validation, Investigation, Writing - original draft. **Lixia Meng:** Investigation, Writing - original draft. **Xiang Li:** Investigation, Data curation. **Yuhong Xu:** Investigation, Data curation. **Tinghai Cheng:** Writing - review & editing, Supervision, Funding acquisition, Resources. **Shiming Liu:** Writing - review & editing, Supervision. **Zhong Lin Wang:** Writing - review & editing, Supervision, Funding acquisition.

## 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.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.eml.2021.101338>.

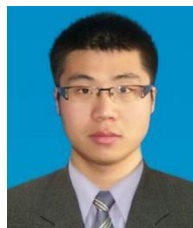
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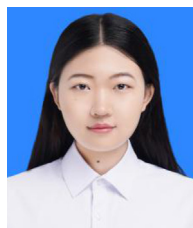
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