

Enhancing performance of the wave driven-triboelectric nanogenerator through the floating structure design for maximum wave energy harvesting

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 Cite this article: Nano Research, 2025, 18, 94907923. <https://doi.org/10.26599/NR.2025.94907923>

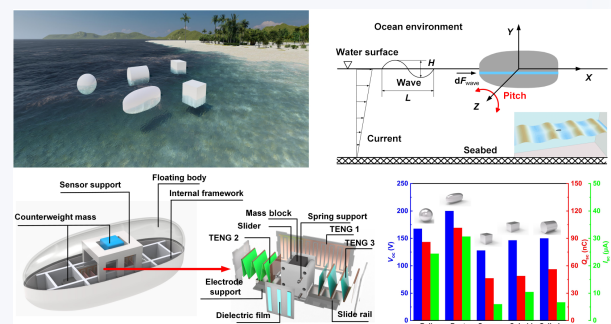
ABSTRACT: The structural design of wave energy harvesting devices play a crucial role in complex marine environments. To enhance output performance of triboelectric nanogenerator (TENG) in small-amplitude wave environments, this paper proposes a floating design method that utilizes wave energy converter (WEC) combined with elastic support coupled TENG based on boat design concepts. Using hydrodynamic model, the study investigates various types of WEC structures, resulting in maximum energy generation for the TENG. Additionally, the coupled TENG designed with elastic support demonstrates excellent performance in various experiments.

The results indicate that the power density of the coupled TENG can reach 13 W/m³. Wave testing confirms that various floating structures significant differences in TENG output performance, and the boat-type float notably enhances the performance of TENG. The boat-type TENG exhibits an increase of 155% in open-circuit voltage, 414% in short-circuit current, and 218% in transferred charge for the interpolated electrodes, compared to the lowest square-type TENG. This work presents a novel approach for WEC design and improving energy conversion efficiency in large-scale ocean wave energy collection and accelerates the industrialization process of TENG in the field of marine engineering.

KEYWORDS: triboelectric nanogenerator, wave energy converter design, hydrodynamic model, elastic support

1 Introduction

With the intensification of global climate and energy challenges, the promotion of renewable energy to replace traditional fossil fuels has



become a broad consensus of the international community [1–4]. As an ideal renewable resource, ocean wave energy has huge reserves and a wide coverage is one of the most sustainable energy sources [5, 6]. However, the inherent randomness and low frequency of waves significantly increases the difficulty of their development, necessitating an urgent pursuit of technical solutions.

In recent years, the triboelectric nanogenerator (TENG) technology proposed by Wang et al. has seen rapid development [7]. Compared with traditional electromagnetic power generation technology, TENG has significant advantages in the low-frequency field, such as light weight, low cost, and diverse structures [8–11].

Received: June 9, 2025; Revised: July 18, 2025

Accepted: August 15, 2025

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Based on the coupling principles of the triboelectric effect and electrostatic induction, driven by Maxwell's displacement current, TENG can convert low-frequency energy into electrical energy [12–14]. In the blue energy, researchers have developed various TENG devices for wave energy collection in marine scenarios [15–17], mostly using floating structures as carriers to capturing wave energy. Based on their structure and operating mechanisms, which can be broadly classified into three types: regular floating body [18–21], biomimetic structure [22–24] and traditional floating structure [25–27].

The regular floating body usually adopts sphere [28], cube [29] and cylinder [30] shapes as the floating body structure equipped with TENG, which has the characteristics of simple production and low cost, but the output performance of the TENG is relatively low. The biomimetic design of the floating body can further improve the adaptability of TENG in the Marine environment, but its high production difficulty increases the production cost. The traditional floating structure has higher adaptability in the Marine environment, but its energy capture performance in the low-frequency wave environment still needs further study. The above structures are typically combined with contact-separation and freestanding mode TENG for wave energy harvesting. Enhancements in performance have been achieved through more sophisticated structural forms that increase spatial utilization [31–33], surface charge density [34–36], contact area [37–39], the transistor-inspired design [40, 41], and other methods [42–44]. Meanwhile, some researchers have also focused on the relationship between floating body motion response and the output performance of TENG. Liu et al. [45] developed a cylindrical TENG based on buoys and validated its hydrodynamic compatibility with marine buoys. Wang et al. [46] proposed sandwich-structured TENG, calibrated numerical models experimentally, and analyzed the effects of mooring configurations, wave frequencies, and wave heights on performance under small-amplitude waves. Based on fluid dynamics theoretical models and hydrodynamic experiments, Zhang et al. [47] revealed the energy conversion and interaction mechanisms between the floating body and waves, and optimized the device structure and output. Xu et al. [48] employed infrared

optical tracking and AQWA software to explore wave-structure interactions, identifying universally applicable modes and parameters for floating TENG systems. Therefore, enhancing wave energy capture through buoy design could be another effective approach to improving the output performance of TENGs.

Hence, a floating design method based on inspiration from boat design to improve the output performance of TENG and a boat-type TENG (BT-TENG) using coupling electrode with elastic contact interfinger electrode is proposed in this work. The interaction process between the main design parameters of the floating and the small-amplitude wave conditions under is systematically analyzed. The prototype structure of the BT-TENG was designed, and the motion and force of BT-TENG in waves was analyzed. The output performances of the power generation unit under various movement conditions are tested. Finally, different types of floating bodies are made to transport the power generation unit, while ensuring the same parameters. Wave testing verifies the output performance of the BT-TENG and the performance enhancements of the floating body design. Temperature sensor and ocean indicator light application experiments are also conducted to verify the availability of electrical energy.

2 Results and discussion

2.1 Structure and working mechanism

Converting ocean wave energy into usable electrical energy involves three distinct energy allocation stages, as shown in Fig. 1(a). Firstly, wave energy is initially stored in the moving ocean waves, as shown in Fig. 1(a)(i). Subsequently, the kinetic energy and potential energy of water are converted into the kinetic energy of the float through different shapes wave energy converters (WECs), as depicted in Fig. 1(a)(ii). However, this energy cannot be fully used in the energy conversion of power generation devices. Traditional electromagnetic ocean power generation devices usually convert this part of energy into other forms of energy through power take-off system (PTO) devices [49, 50], resulting in significant energy loss. Different from it, TENG can directly utilize the motion

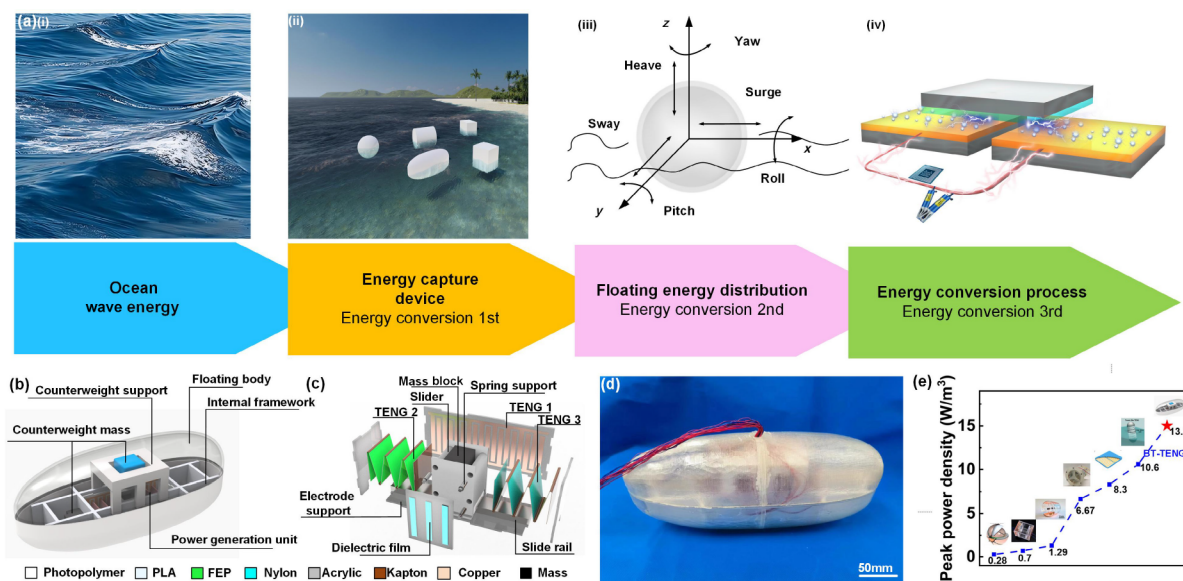


Figure 1 Energy capture principle and BT-TENG structure. (a) Process of ocean wave energy conversion. (b) Structure of the BT-TENG. (c) Structure of the coupled TENG unit. (d) BT-TENG physical prototype. (e) Comparison of the power density of this work with that of other reported works [51, 52].

response of floats distributed on six degrees of freedom, as shown in Fig. 1(a)(iii), including roll, sway, pitch, heave, surge, and yaw. Finally, the conversion from float kinetic energy to electrical energy was achieved through different TENGs structures, as shown in Fig. 1(a)(iv).

To study the motion of different floats in waves, BT-TENG and different type TENGs are designed as shown in Fig. 1(b) and Fig. S1 in the Electronic Supplementary Material (ESM). All floating shells of different TENGs composed upper and lower parts. Inside the shell, a supporting framework is being designed, serving as a fixed frame for the internal power generation unit and providing support for adjusting the float's mass, center of gravity, and inertia moment parameters with a mass block. The power generation unit, comprising three independent TENGs, is positioned at the center of the float, as illustrated in Fig. 1(c). The frame and guide rail are being fixedly connected, and the middle part is being designed with a guide rail slider with a counterweight mass. On both sides of the slider, two independent layer electrodes are supported by springs, forming TENG 1 with interfinger electrodes on both sides of the frame. To increase the overall output and ensure the stability of both structures under large amplitude conditions, mirror-image foldable electrodes TENG 2 and 3 are being set on both sides of the power generation unit.

Figure 1(d) depicts the physical prototypes of BT-TENG, and Fig. S2 in the ESM shows different types of TENG include ball, square, cuboid, and cylindrical types. To ensure a fair comparison of different floating body designs, the actual parameters of each prototype during the manufacturing process are shown in the Tables S1 and S2 in the ESM, which can be seen that the volumes, weights, and center of gravity positions of different floats are approximately equal, while differences in float dimensions lead to variations in the overall moment of inertia. Mounting identical power generation units on different floats, as shown in Fig. S3 in the ESM, allows for experiments that more intuitively verify the effectiveness of the float-based design in enhancing the overall output performance of the system. Figure 1(e) illustrates a power density comparison between the prototype in this work and previously reported works, demonstrating superior output performance in the prototype of this study. All compared devices operate within a confined volume range (0.01–0.03 m³) to ensure equivalent hydrodynamic conditions.

2.2 Theoretical analysis of BT-TENG

Floating carriers integrated with TENG generally have typically characterized by compact volumes, making them particularly advantageous for deployment in small-amplitude wave environmental conditions. To achieve efficient energy conversion of TENG in complex environments, this study analyzes the BT-TENG based on its energy conversion process, including float motion response analysis, energy capture mechanism analysis, and forced motion analysis of the power generation unit.

2.2.1 Float motion response analysis

In small-amplitude wave conditions, the size characteristics of the TENG will mainly be affected by wave and current loads, as shown in Fig. 2(a). Due to the aspect ratio of the floating carrier of the TENG being mostly less than 0.2, it can be classified as a small-scale float. Therefore, its environmental load can be calculated using the Morison formula [47]

$$F_{\text{wave}} = \frac{1}{2} C_D \rho D u_x |u_x| + C_M \rho A \frac{du_x}{dt} \quad (1)$$

where ρ represents the density of seawater, u_x represents the fluid velocity relative to the buoy along the x -axis direction, C_D and C_M represent the drag coefficient and the inertia coefficient. D and A represent the cross-sectional width and the lateral cross-sectional area, respectively. C_D is influenced by factors such as the cross-sectional shape of the object, surface roughness, Reynolds number, and the degree of adhesion to the object. C_M can be represented by added mass and the Froude–Kriloff force. Considering the floating TENG and the ocean, based on the coordinate system established in the ESM, the dynamic motion equation of the float can be obtained as follows

$$M \ddot{X}(t) + \int_{-\infty}^t [K(t-\tau)] \dot{X}(\tau) d\tau + CX(t) = F_{\text{wave}}(t) \quad (2)$$

where M and C represent the inertia matrix and static water stiffness matrix of the floating TENG. $X(t)$ represents the displacement matrix and $K(t-\tau)$ represents the delay function. $F_{\text{wave}}(t)$ represents the wave force.

Using Eq. (2), the position of the BT-TENG in waves with a significant wave height of 0.15 m and a frequency of 1.0 Hz can be determined. It can be observed that the motion response of the float in the waves mainly focuses on movement along the X and Y axes, as well as rotation around the Z axis. Figures 2(c)–2(e) shows the motion responses of floats with different shapes in the three main directions under wave conditions. It can be observed that the different floats have a significant impact on their motion. The displacement in the X -direction shown in Fig. 2(c) indicates that using a boat-type curved surface structure can significantly reduce the displacement of the float in the X -direction. Similarly, as seen in Figs. 2(d) and 2(e), using a boat-type float can significantly reduce its oscillation amplitude in the Y -axis direction, while increasing the float's rotation angle and frequency in the Z -axis. The maximum rotation angle of the boat-type float can reach +42.57° and −36.9°, achieving 17 rotations in opposite directions within 10 s. In contrast, the Ball float which follows closely, can only achieve 12 rotations within the same period. The oscillation cycles of the remaining floats are all less than 10 times, and their amplitudes are also smaller than those of the boat-shaped float.

The above results indicate that using a boat-shaped float can effectively reduce the positional displacement caused by waves, increase its swing amplitude, and frequency. In other words, the superior performance of the BT-TENG arises primarily from the hydrodynamic amplification and optimized structural design of the floating unit.

2.2.2 Energy capture mechanism analysis

To study the energy collection of the float in waves, combined with the motion response of the float on its six degrees of freedom in waves, based on Eq. (2) analyzed motion and wave force responses as shown in Figs. S4 and S5 in the ESM, the power components of the float in waves for each degree of freedom can be determined according to Eq. (3).

$$W_{\text{component}} = \begin{cases} \mathbf{F}_{x,y,z} \cdot \mathbf{S}_{x,y,z} & \text{Displacement component} \\ \mathbf{M}_{x,y,z} \cdot \boldsymbol{\theta}_{x,y,z} & \text{Rotation component} \end{cases} \quad (3)$$

where $\mathbf{F}$ and $\mathbf{M}$ respectively represent the force and torque exerted on the float. $\mathbf{S}$ and $\boldsymbol{\theta}$ represent the displacement and angle of

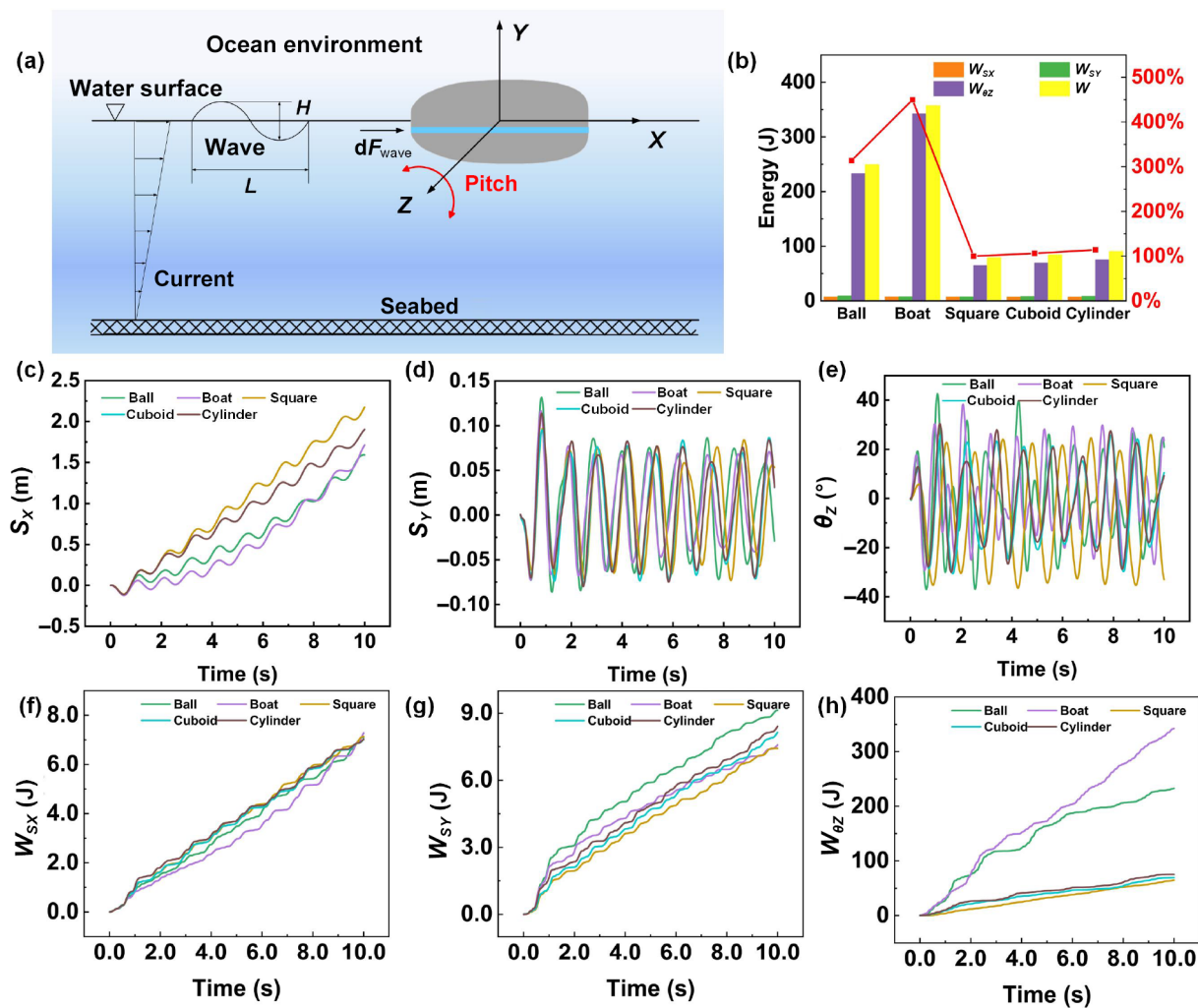


Figure 2 Capturing energy model construction and calculations. (a) Motion coordinate system of the floating body. (b) Energy distribution in various directions of the floating body. (c) and (d) Displacement of the floating body in the X and Y direction. (e) Rotation angle of the floating body in the Z direction. (f) and (g) Translation kinetic energy captured by the floating body in the X and Y direction. (h) Rotational kinetic energy captured by the floating body in the Z direction.

rotation. The energy capture efficiency of the floating can be determined as follows

$$\eta = \frac{\sum W_{\text{component}}}{W_{\text{wave}}} \quad (4)$$

where W_{wave} represents the work done by the waves on the entire plane A during one cycle.

Figures 2(f)–2(h) show the energy variations in three main motion directions of different floats. The kinetic energy in the X direction continues to increase for different floats, and by the time 10 s has elapsed, the absorbed energy by each float is nearly equal. Due to its curved surface structure, the spherical float can obtain more energy in the Y direction compared to other floats. The boat-type float possesses an unmatched advantage in rotation around the Z-axis. Figure 2(b) better describes the differences in energy capture among different floats in a wave environment with a wave of 1 Hz and 15 mm, with boat-type and spherical-type floats having a relative advantage in total energy compared to other floats. In terms of energy distribution in each direction, the rotational energy in the Z direction is greater for all floats, accounting for 87.7%, 95.8%, 81.67%, 82.05%, and 82.97% respectively. Therefore, for floating wave energy conversion systems, harnessing swing energy proves to

be significantly more efficient than capturing energy from other motion directions. When benchmarked against the least efficient type of energy capture as revealed by hydrodynamic simulations, the boat-shaped floating device demonstrates a remarkable enhancement in energy collection, achieving an impressive 449.8% increase.

2.2.3 Theoretical analysis of power generation units

The motion of the floating TENG primarily comes from the wave forces acting on the floating body. Figure 3(a) illustrates the characteristics of the BT-TENG in the ocean environment, the floating body exhibits four motion states with the direction of wave motion: the floating body (i) before the wave, (ii) at the peak of the wave, (iii) after the wave, and (iv) in the valley of wave. State (ii) and (iv) belong to intermediate states, but their directions of motion are opposite. The phase diagram calculated from the simulation model reveals typical states of the BT-TENG with a wave height of 0.15 m, as illustrated in Fig. 3(b) and Fig. S6 in the ESM.

Figure 3(b)(i) shows the state of the float body before the wave, where the center of buoyant and gravity positions of the BT-TENG are depicted in enlarged figure. After reaching the maximum inclination angle, restoring torque M is generated under the effects

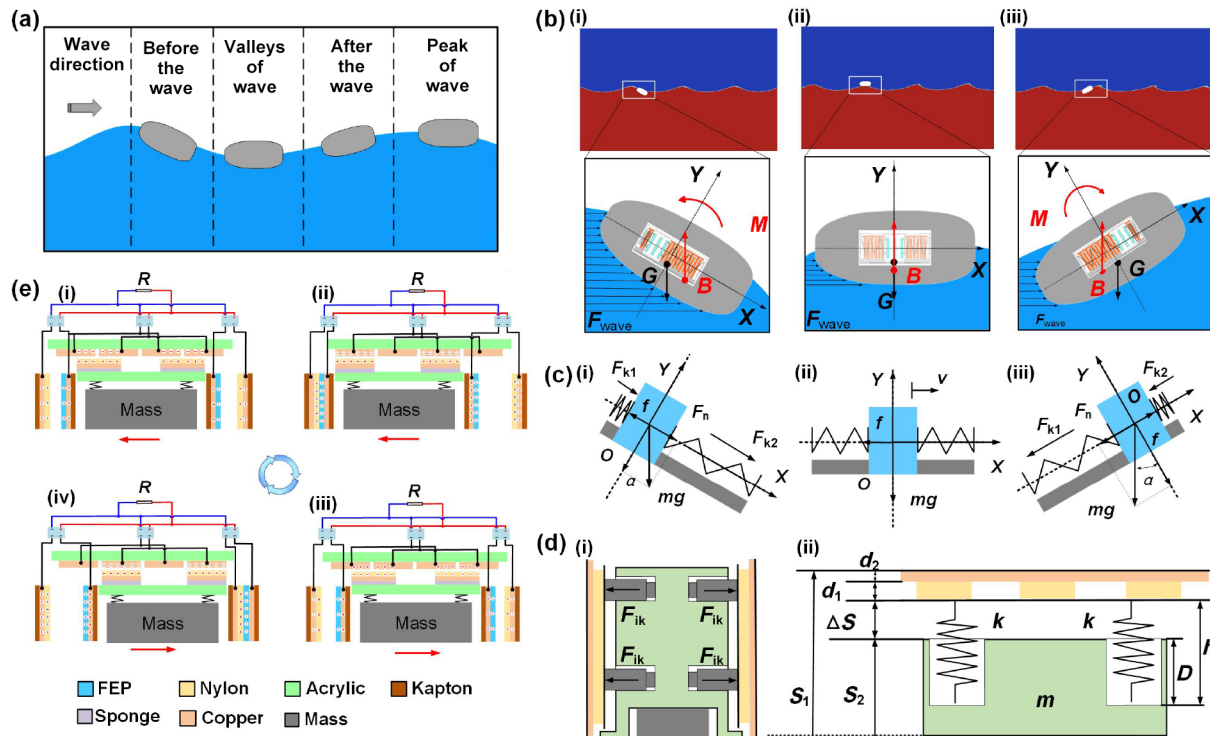


Figure 3 The theoretical analysis of the BT-TENG. (a) The state of BT-TENG in wave environments. (b) Phase diagram and force analysis of the float in different wave positions. (c) Force analysis of TENG. (d) Theory analysis of elastic support structure. (e) Charge transfer analysis.

of buoyancy, gravity, and wave forces, forcing BT-TENG to rotate. Similarly, Fig. 3(b)(iii) shows the state of the float body after the wave, though the direction of the applied force remains unchanged, the recovery torque M generated by the change in the position of the buoyancy center is opposite to the former. Figure 3(b)(ii) depicts the state of the float at the peak of wave, where both the center of buoyant and gravity are aligned on its axis. At this moment, the forward motion of the wave and the inertia of the float continue to rotate backward along its center of gravity axis.

Unlike the motion of the floating body, the internal TENG experiences a certain delay in its response. When the floating body moves to the starting angle in the state of Fig. 3(b)(i), the force state of TENG is shown in Fig. 3(c)(i), can be expressed as

$$F_n + F_{k1} + F_{k2} - f = ma \quad (5)$$

where f represents the resistance of TENG and the sliding rail. F_{k1} and F_{k2} represent the forces provided by TENG 2 and TENG 3, respectively. F_n represent the driving force which is the component of gravity in its direction of motion, expressed as

$$F_n = mgsin\alpha \quad (6)$$

The component force F_n of the counterweight mass in the X direction will overcome the resistance f of TENG and the slide rail, then driving the TENG on both sides to produce output. Installing contact-separation TENG on both sides can reduce the starting angle of the slide, due to their different tensile and compressive states.

As TENG moves to the position shown in Fig. 3(c)(ii), the driving force F_n becomes zero at this moment. Nevertheless, inertia causes the center of gravity mass block to keep moving at a speed v , which is influenced by the previous rotation angle. When the TENG moves to the state shown in Fig. 3(c)(iii), the force on the

TENG is completely opposite to the direction of the state shown in Fig. 3(c)(i), thereby achieving the reciprocating motion of the power generation unit with the oscillation of the floating body.

The elastic support structure is proposed to solve the contact problem of the interfinger electrode as shown in Fig. 3(d). The structure ensures that the independent layer can contact the copper electrode within pressure range during movement. Figure 3(d)(i) shows the detailed design of the structure, four spring pins are installed on the acrylic plate where the independent layer electrodes are located, and corresponding holes are provided on the designed slider. The pressure control principle is shown in Fig. 3(d)(ii). The internal spacing of the acrylic shell is S_1 , the width spacing of the slider is S_2 , the length of the positioning spring pin is h , the depth of the sinking hole is D , the independent layer electrode d_1 , and the thickness of the copper electrode d_2 . It can be inferred that the relation boat between the dimensions is as follows:

$$S_1 = S_2 + 2 \times (d_1 + d_2 + \Delta S) \quad (7)$$

Then the value of ΔS can be obtained, and the compression amount of the spring pin can be obtained as Eq. (8)

$$\Delta x = h - D - \Delta S \quad (8)$$

Therefore, by controlling the dimensions of S_1 , S_2 , and D in the size chain, the pressure between the electrodes can be determined.

Furthermore, the working mechanism of the power generation unit is illustrated in Fig. 3(e), relies on triboelectrification and electrostatic induction. The coordinated movement of the central mass block and the elastic support mechanism ensures that each oscillation cycle results in a complete contact-separation event, thereby generating alternating current. The contact-separation TENG on both sides will reach a state of contact and separation on one side under certain angle conditions and then charge transfer

will occur between the copper electrodes. When BT-TENG reaches its position limit, it begins to move in the opposite direction and finally reaches the reverse limit state. Because the charge transfer mechanisms differ between the freestanding mode and the contact-separation mode, it is not possible to simply parallelize them. The electrical energy generated by the entire structure must be rectified through a bridge rectifier and adapted to the external load circuit for effective utilization.

2.3 Output performance of power generation unit

The influence of various factors on the output performance of the power generation unit is examined to achieve higher energy conversion efficiency. Figures 4(a)–4(c) indicate that the interfinger electrode in power generation unit decreases as the designed depth D of the sinking hole increases. This can be attributed to the spring compression gradually decreasing as the depth of the sinking hole increases, leading to reduced pressure between the electrodes and a corresponding decline in output. Therefore, the experimental prototype selected a counterbore depth of 12.25 mm.

The driving force of the power unit is determined by the center counterweight mass. As the center mass increases, CS-TENG is subjected to greater impact force, resulting in higher output performance of CS-TENG, as shown in Figs. 4(d)–4(f). To enhance the performance of CS-TENG in power generation units, the

output performance of CS-TENG with different numbers of groups was studied under the condition of 250 g center mass. Figures 4(g)–4(i) show that as the number of groups increases; various performance indicators also increase. When $n = 6$, the V_{oc} , Q_{sc} and I_{sc} of CS-TENG can reach 106.09 V, 180.73 nC, and 15.99 μ A, respectively at 1.0 Hz and 30°.

Figure 5(a) shows the testing experimental system of the power generation unit, including the test platform, fixed bracket, support frame, and stepper motor. The output performance of different modes of TENG in the designed power generation unit was verified, as shown in Fig. 5(b) and Fig. S7 in the ESM. It can be observed in Fig. 5(b) that the open-circuit voltage of the interfinger electrodes is significantly higher than the contact-separation TENG on both sides. The reason is that elastic support structure enables better contact of the interfinger electrode and enhances the frequency response. In contrast, the contact-separation TENG on both sides only triggers when contact occurs, due to considerations of balancing the weight, operates under conditions where the driving mass is not significant, resulting in a less satisfactory actual contact area for the contact-separation mode TENG on both sides. However, as shown in Fig. 5(b)(ii), it can be observed that the contact-separation mode trigger larger transferred charge during brief contact, thereby providing more electrical energy output for the designed TENG. As seen in Fig. 5(b)(iii), the output currents of the three independent TENGs are relatively close. However, the

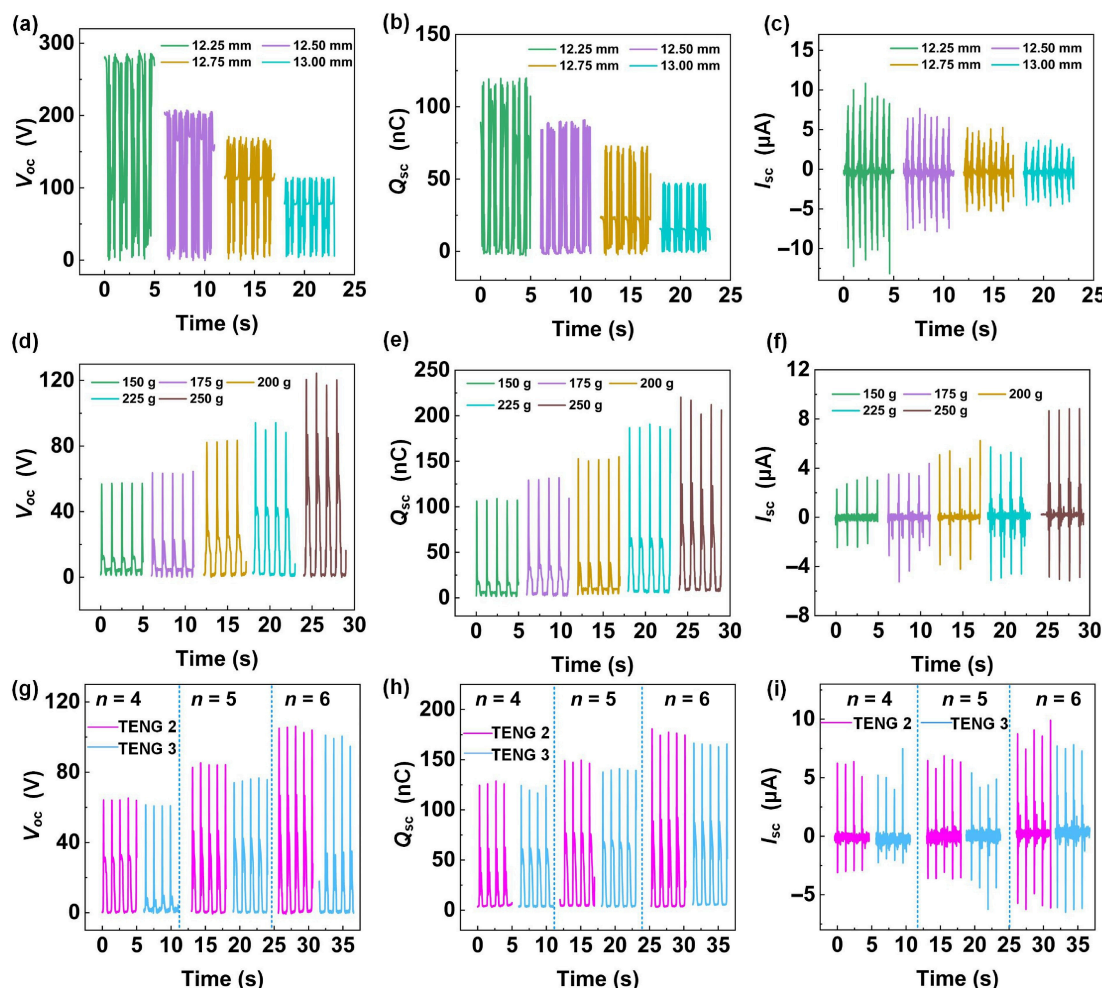


Figure 4 Performance test of different BT-TENG factors. (a)–(c) Different sinking hole depths D . (d)–(f) Different counterweight mass. (g)–(i) Different number of CS-TENG.

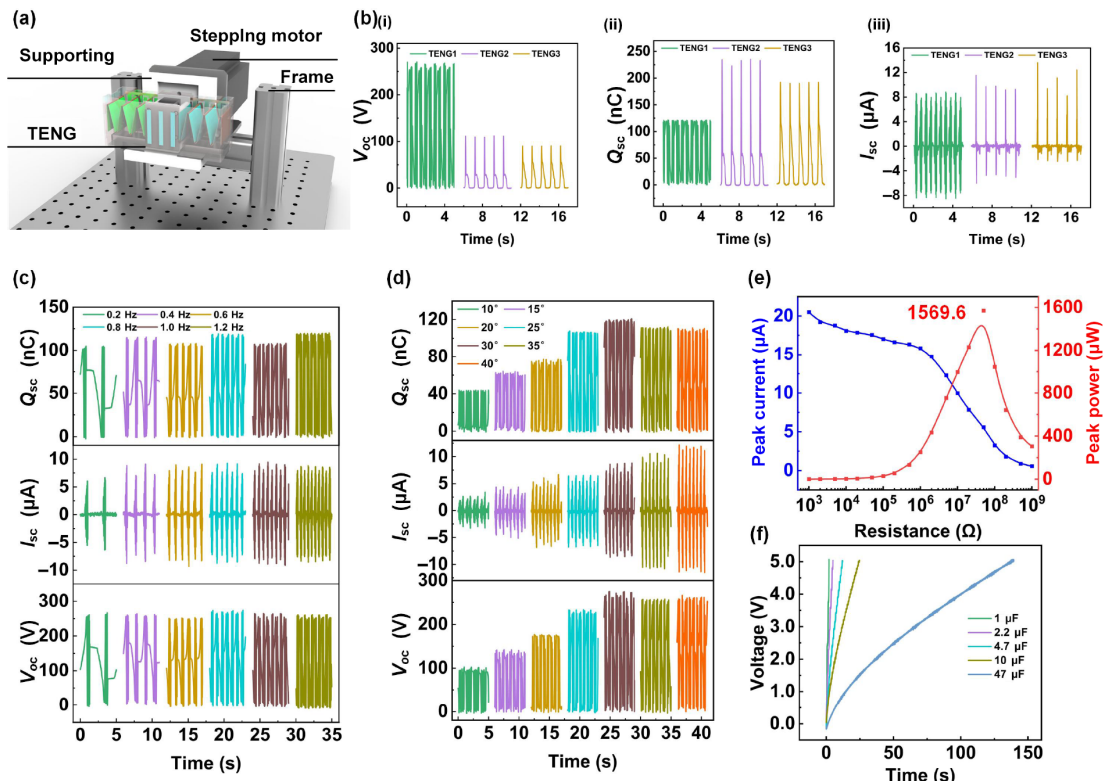


Figure 5 Output performance of power generation unit. (a) Prototype test equipment. (b) Comparison of outputs from different TENG units. (c) Trigger frequency. (d) Rotation angle. (e) Load power. (f) Charging capacity curve.

performance of the interfinger electrode surpasses the other two TENG units because of the frequency-enhancing characteristics. Therefore, in the subsequent testing process, the output performance of TENG 1 will be used to verify the overall performance of the device.

In response, motion triggered by wave energy, the frequency and oscillation angle are important factors affecting the output performance. To investigate the influence of frequency variation on BT-TENG, output performance testing was conducted. **Figure 5(c)** shows that the V_{oc} and Q_{sc} remain unchanged with the increase in frequency, while the I_{sc} shows a significant increase under conditions below 0.6 Hz and no further change beyond 0.6 Hz. This differs slightly from the results of most ocean wave energy TENGs, where the increase of frequency leads to generating greater current. The reason is that the designed power generation unit in this study is primarily driven by gravity and shows a hysteresis characteristic relative to the rotation angle. As the frequency increases, its response speed can't match the change, resulting in no further increase in output. The variations in angle depicted in **Figure 5(d)** have led to substantial changes in various parameters. This occurs because alterations in the rotation angle cause corresponding changes in the component force of the driving mass and accelerating its motion speed. At low angles, the smaller driving force from gravity leads to a decrease in friction between TENGs, and lower voltage, charge and current output. The driving force increases with the increase of angle, and the open circuit voltage and transfer charge of TENG reach their maximum value when the swing angle reaches 30°. Due to the designed elastic support structure, as the electrode movement speed increases with the rotation angle, incomplete contact between electrodes has occurred and resulting in a slight decrease of output.

Figure 5(e) displays the peak power and peak current of the BT-TENG at 1.0 Hz and 30°. Power generation unit can achieve a maximum peak power of 1.57 mW when matched with an external resistance of 50 MΩ. To assess its practical application capability, charging performance was tested using different capacitors. The charging curve with a 47 μF capacitor can reach 5 V within 140 s, as shown in **Fig. 5(f)**. To verify the reliability of the TENG, durability tests were conducted on its core friction units (see Fig. S8 in the ESM). After continuous operation for 45 h at a frequency of 1 Hz and an angle of 30°, the device exhibited only a 15% decrease in output performance, demonstrating good performance stability. These experimental data provide strong evidence for the mechanical robustness and reliability of the device under prolonged operation and physical stress.

2.4 Wave energy test and application

To determine the correctness of the above theoretical analysis, a wave simulation system is designed, as shown in **Fig. 6(a)**. Different floating bodies shown in **Fig. 6(b)** and Video S1 in the ESM were placed in a simulated pool, including (i) ball-type, (ii) boat-type, (iii) square-type, (iv) cylinder-type, and (v) cuboid-type. The output performance of different types WEC equipped with TENG was measured, as shown in **Fig. 6(c)**. The results show that under 150 mm and 1.0 Hz wave conditions the output performance results are similarly to the simulation results (**Fig. 2(e)**). The best output performance of 101.48 nC, 210.27 V, and 30.673 μA can be achieved by the interfinger electrode in the boat-type floating body. Compared to square floating bodies the V_{oc} , Q_{sc} and I_{sc} have been improved on 155%, 414%, and 218%. Under the same wave conditions, the design of the floating body has a significant impact on the output performance of TENG. The larger motion response

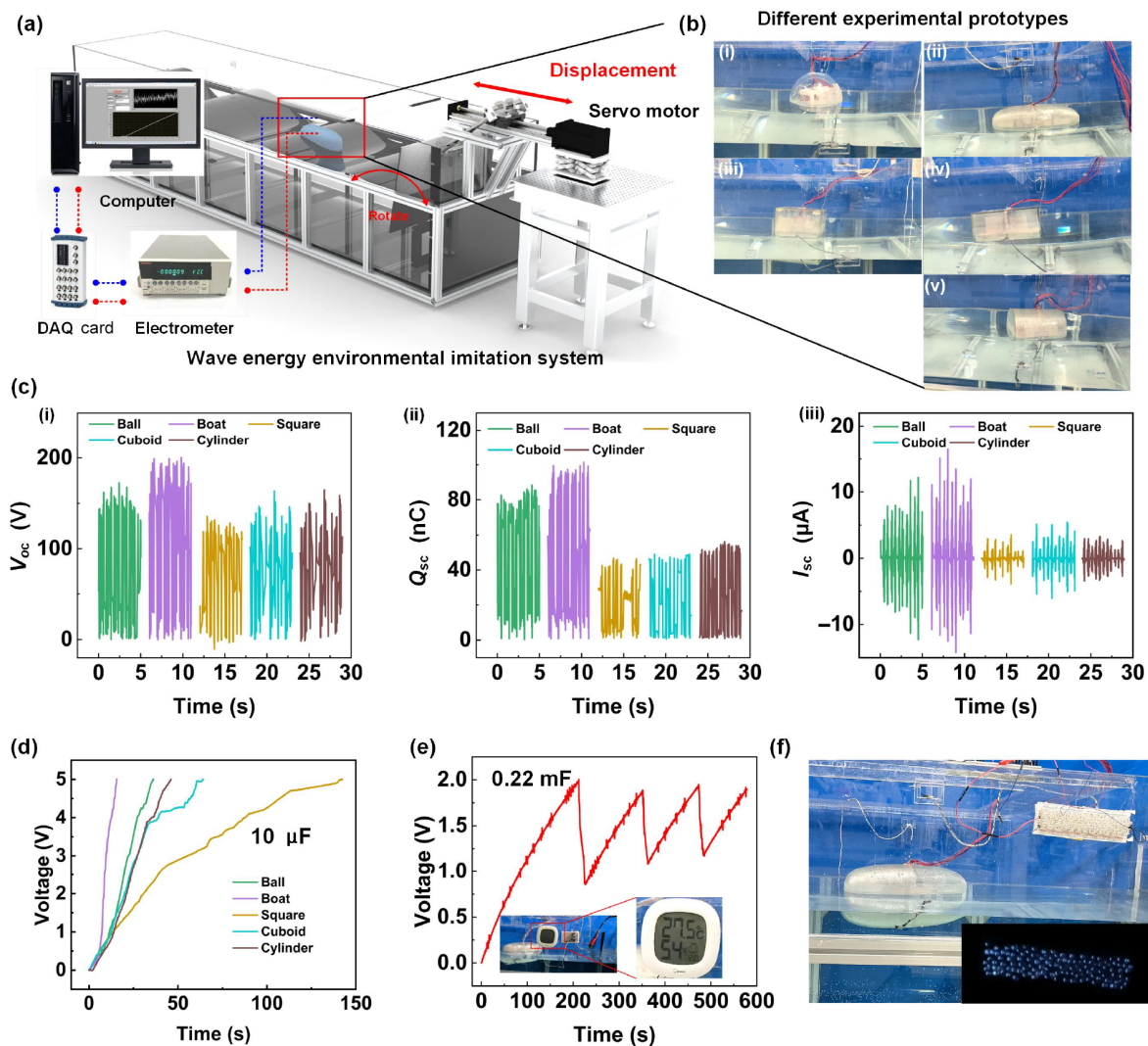


Figure 6 Wave Simulation Experiment Measurements. (a) Wave energy environmental imitation system. (b) Different experimental prototypes. (c) Output performance of each TENG under the same wave conditions. (d) Charging capacity curve. (e) BT-TENG powers temperature and humidity sensor. (f) BT-TENG supplies power for the LEDs.

amplitude of the boat-type floating body in wave simulation tests results in better output performance for the designed power generation unit.

In addition, the charging time of a 10 μF capacitor is measured for different TENG floats, as illustrated in Fig. 6(d). The best boat-type TENG can charge the capacitor to 5 V in 16.62 s, while the square-type TENG needs nearly 142 s, an 8.5-fold reduction in charging time. Compared to the charging curve in Fig. 5(f), the curve in wave simulation tests will experience varying degrees of fluctuation, which is caused by the designed wave making system's inability to simulate waves in an ideal stable state. The speed of capacitor charging can reflect the different performance of TENG carried by different floating bodies, indicating that the design of floating bodies can improve the output performance of TENG.

Figure 6(e) and Video S2 in the ESM demonstrate that a commercial temperature and humidity sensor was successfully powered using the 220 μF capacitor for energy storage in a simulated wave environment. Figure 6(f) and Video S3 show that the BT-TENG can light up 128 light-emitting devices (LEDs) in the wave environment, which can provide practical application functions.

3 Conclusions

In summary, this work introduces a floating design method to enhance TENG output performance and proposes a BT-TENG with an elastically supported interfinger electrode for efficient wave energy harvesting. The dynamic performance and energy conversion mechanism of the floating TENG in wave conditions are analyzed. The use of an elastic support electrode addresses the excessive resistance in the interfinger electrode, while the WEC design enhances TENG output performance. The BT-TENG was tested in various experiments, the results show that the power density of the BT-TENG can reach 13 W/m^2 . The results of wave simulation experiments indicate that under the same wave driving conditions, the output of the BT-TENG is significantly higher than other types, the V_{oc} , I_{sc} , and Q_{sc} have improved on 155%, 414%, and 218%. Furthermore, the BT-TENG was tested in various application scenarios, including capacitive charging, powering sensors, and indicator tests. These results demonstrate that the floating design method can improve the output performance of the TENG, and the conversion efficiency of wave energy into electric energy. The research on the BT-TENG could provide efficiency

improvement and optimization methods for the design of floating wave energy TENGs and accelerate the industrialization process of TENG in ocean engineering.

4 Experimental section

4.1 Fabrication of BT-TENG

The BT-TENG has overall dimensions of 345 mm × 118 mm × 159 mm (length × width × height), and the shell is made by a photocuring three-dimensional (3D) printer (Model: MONOX2, China), whose main component was photopolymer. Internal support framework was manufactured using 3D printing (Model: JG MAKER, A6, China), whose main component was polylactic acid (PLA). The prototype of power generator unit was manufactured using laser cutting, and the dimensions are 70 mm × 60 mm × 50 mm (length × width × height). The power generation unit consists of interfinger TENG and two CS-TENGs, the dimensions of interfinger TENG are 65 mm × 45 mm × 0.06 mm (length × width × thickness).

4.2 Experimental process and measuring

Material selection and performance testing of the BT-TENG electrodes were conducted using a stepper motor drive, and a PLC experimental system was independently designed to establish a self-built experimental system. To assess the basic performance and rectification current of a single power generation unit, an electrometer (Keithley Model 6514, USA) was used, and data was collected using a data acquisition card (Model: DA-ARM1651, China). Measurement data was displayed using LabVIEW software.

Electronic Supplementary Material: Supplementary material (additional figures, sections, and Videos, including the physical model of BT-TENG, the performance test and experimental test system, the additional simulation and theoretical analysis of BT-TENG, demonstration movies of powering the electronic devices by the BT-TENG, and the motion of different floating bodies in experimental waves) is available in the online version of this article at <https://doi.org/10.26599/NR.2025.94907923>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

Acknowledgements

This work was supported by the China Postdoctoral Science Fund (No. 2023M734086).

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.

Author contribution statement

M. J.: Conceptualization, investigation, validation, writing – original

draft. Q. G.: Conceptualization, investigation, validation. X. X.: Conceptualization, investigation, validation. J. L. W.: Investigation, writing – original Draft. J. Y. Z.: Investigation. M. L.: Investigation, validation. H. Y. L.: Writing – review & editing. Y. Y.: Writing – review & editing. J. M. W.: Validation, resources. T. W. H.: Validation, resources, supervision, writing – review & editing. T. H. C.: Conceptualization, resources, writing – review & editing, supervision.

Use of AI statement

None.

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