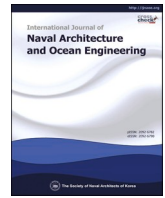




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Numerical and experimental investigation of an Inertial Tilting hybrid wave energy converter for powering small-scale marine systems

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ABSTRACT

The increasing global demand for marine resource exploration, maritime rights protection, and deep-sea engineering applications highlights the need for the diversification of marine engineering equipment and the expansion of its deep-sea capabilities, presenting significant technical and economic value. As the use of small-scale marine engineering equipment in deep-sea environments becomes more prevalent, optimizing energy supply methods for such equipment is critical to ensure their durability and efficiency in complex marine conditions. This paper proposes an Inertial Tilting Electromagnetic-Triboelectric Hybrid Energy Converter (ITHEC), which efficiently harvests energy from ocean waves to power small marine engineering devices. A comprehensive design and optimization framework was developed for this energy converter. This framework was based on theoretical analysis and simulations of structural dynamics and characteristics. Validation experiments were conducted using a custom-built structural characteristics testing platform. The results showed that under horizontal harmonic motion excitation with an amplitude of $d = 60$ mm and a frequency of $f = 1.5$ Hz, the open-circuit voltages of the triboelectric nanogenerator (TENG) and electromagnetic generator (EMG) reached 60V and 0.23V, respectively, with short-circuit currents of 1.3 μ A and 2.2 mA, and peak power densities of 1.18 mW/m² and 0.51 mW/m². When arrayed, the hybrid energy converter can meet the operating current requirements of small marine sensors. This study offers an innovative solution for energy supply challenges in small marine equipment and establishes the practical viability of hybrid power systems for marine energy harvesting.

1. Introduction

Exploring marine resources and safeguarding maritime rights are crucial measures for advancing maritime strategies. Small marine engineering equipment, such as sonar buoys, underwater robots and surface vehicles, is increasingly playing a key role in these areas (Motoki, 2018; Liu et al., 2019; Shen et al., 2021). Currently, major maritime powers such as Europe, the United States, and Japan are vigorously advancing marine exploration technologies, seeking to lead in marine engineering research (Kildow and Mcilgorm, 2010; Neill et al., 2017). However, the reliance on onboard batteries as the primary power source for small offshore marine engineering equipment significantly limits its operational duration, work intensity, and range, making it difficult to meet the growing demands of such equipment (Lu et al., 2018; Sun et al.,

2021). Therefore, there is an urgent need for a sustainable power supply technology with high energy density to support long-term, high-intensity operations in harsh marine environments. Harnessing wave energy as a power source for small marine engineering devices could fundamentally resolve their energy supply issues. Nevertheless, conventional wave energy harvesting devices suffer from several drawbacks, including complex mechanical structures, installation difficulties, susceptibility to corrosion, and high costs for both production and maintenance. Additionally, these devices are often bulky and inefficient in energy collection, making them unsuitable for powering marine sensors (Ahamed et al., 2020). In recent years, researchers have conducted extensive studies to optimize the structure of wave energy converters (WECs) and enhance their energy utilization efficiency. Poguluri et al. (2023) employed artificial neural networks (ANNs) to optimize

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asymmetric WEC designs and evaluated hydrodynamic parameters using computational fluid dynamics (CFD) and linear potential flow theory. Their optimization results demonstrated a significant improvement in energy extraction efficiency. Q. Zhang et al. (2025) proposed a floating WEC platform integrated with a decoupled power output system, where multi-dimensional vibration control optimization effectively enhanced energy harvesting efficiency. Furthermore, Kim & Koo (2024) investigated a wind-wave hybrid energy platform and found that the integration of a WEC significantly reduced the pitch and heave response of the floating offshore wind turbine (FOWT), thereby improving its overall stability. Notably, in the optimization and active control of WECs, the prediction of their dynamic response is also a critical technical challenge. To improve prediction accuracy and reduce computational complexity, Zhang et al. (2025a) introduced a multiple-input operator network (MIONet)-based method for nonlinear WEC response prediction. This approach integrates wave height and initial response conditions as inputs to the branch network while incorporating temporal information into the trunk network, thereby mitigating the sensitivity of nonlinear systems to initial conditions. The method significantly enhances predictive accuracy and generalization capability.

American scholar Arnold, D.P. (2007) discussed the practical significance and feasibility of small-scale EMGs, emphasizing the critical value of these devices in powering distributed microelectronic systems such as smart sensors, robots, and wireless communication networks. Building on this idea, Wang et al. (2023) proposed a ring-shaped EMG for wave energy harvesting. This generator featured a simple structure, low manufacturing cost, and good responsiveness to external wave energy excitation. It can continuously charge capacitors and power LED loads, demonstrating promising potential for powering marine sensors. In the same year, Pan et al. (2023) developed a drum-type EMG to enhance the performance of low-frequency wave energy harvesting. Under an excitation frequency of 2.6Hz, the device achieved a voltage output of up to 3V and, by incorporating an energy management unit, was able to effectively power wireless temperature and humidity sensors as well as LED lights. Furthermore, under optimal resistance conditions, the device's average output power reached 65 mW, showcasing considerable energy harvesting capability.

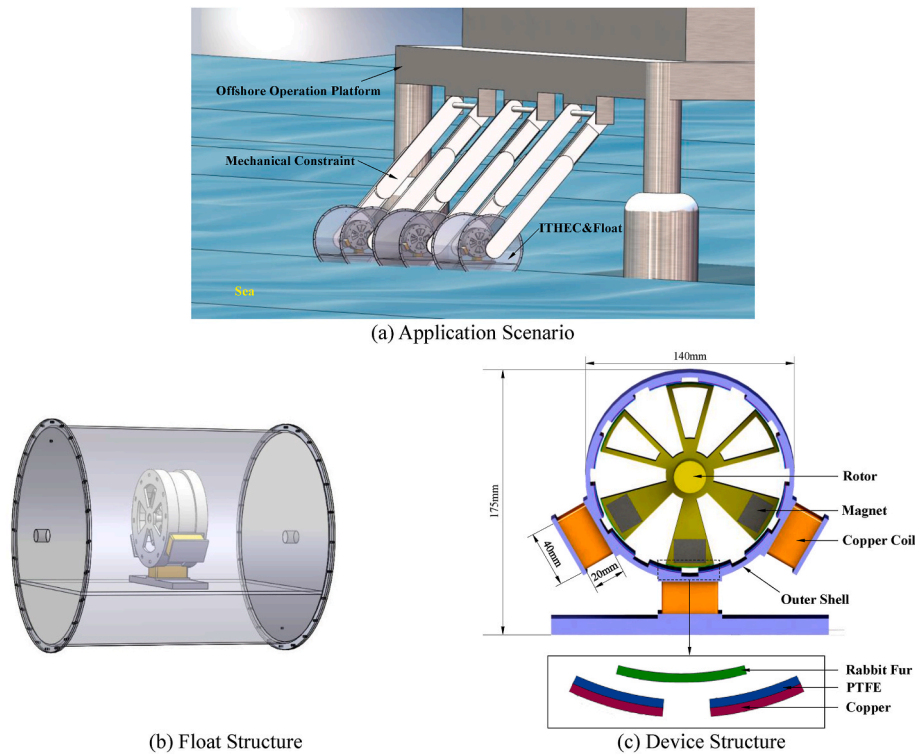
However, despite the well-established and reliable technical framework of traditional EMGs, they require relatively high startup frequencies to ensure stable and efficient operation. Natural wave conditions often fail to meet this frequency requirement, resulting in poor startup performance in wave energy systems that rely on EMGs as the primary energy conversion device (Brown et al., 2017; Mendoza et al., 2015; Li et al., 2018; Dalton et al., 2010). To address this issue, Wang et al. (2024) investigated an integrated system combining an unmanned surface vehicle (USV) and a wave energy converter (WEC). Their study optimized the hydraulic power output parameters and identified that piston area and accumulator pressure had the most significant impact on electrical power generation. Additionally, Kim et al. (2023) conducted wave flume experiments to analyze the energy conversion performance of a multi-hemisphere WEC array. Their results demonstrated that the wave channel resonance (WCR) mechanism effectively amplifies wave energy, thereby improving energy harvesting efficiency in low-energy wave regions. Meanwhile, Kim & Cho (2021), through both experimental studies and numerical simulations, confirmed that when a WEC is positioned at the anti-node of a WCR, its wave energy extraction capacity is significantly enhanced, leading to improved power generation efficiency in low-energy wave environments.

Wang et al. (2012) invented a flexible TENG with a sandwich structure. This device harnesses the triboelectric effect between a polyester (PET) substrate and a nanostructured Kapton film to accumulate charges, and through electrostatic induction between the triboelectric material and a backside metal electrode, it successfully harvests mechanical energy and converts it into electrical energy. The device provided an output voltage of 3.3V and a power density of 10.4 mW.

This breakthrough ushered in a new era of micro-mechanical energy harvesting and utilization, marking a significant advancement in the field of micro/nano-scale power generation and self-powered systems (Lee et al., 2023; Dziadak et al., 2023). Notably, the combination of a small EMG with a TENG presents the potential for more efficient energy conversion from environmental sources into electrical energy, offering superior energy conversion efficiency and enhanced adaptability to diverse environmental conditions (Askari et al., 2018; Quan et al., 2016; Zhang et al., 2020). Thanks to the persistent efforts of researchers (Zhao et al., 2017; Saadatnia et al., 2017; Olsen et al., 2019), substantial progress has been made in hybridizing EMG and TENG technologies. Chi Zhang et al. (2014) summarized the theoretical principles of EMG and TENG, demonstrating the feasibility and advantages of combining these two types of generators, and validated their findings through experiments.

There are various forms of electromagnetic-triboelectric hybrid energy converters, with many researchers proposing sliding or rolling-type hybrid devices. Ting et al. (2016) reported the first electromagnetic-triboelectric hybrid generator based on shared electrodes, which provided a high output current of approximately 3.8 mA and a high output voltage of about 245V. Additionally, it could function as an acceleration sensor, with detection sensitivities of $143.2\text{V}/(\text{m/s}^2)$ and $291.7\mu\text{A}/(\text{m/s}^2)$ for voltage and current, respectively. Hao et al. (2019) designed a box-type energy harvester, where the contact and separation between a PMMA cylinder wrapped in aluminum film and an Ag electrode wrapped in silicone film generated triboelectric charges. Simultaneously, the electromagnetic generation was achieved by a magnetic ball rolling over four copper coils. The results showed that under loads of 100 MW and 1 kW, the instantaneous peak power outputs for the TENG and EMG were 0.08 mW and 14.9 mW, respectively. This generator was able to power 60 LED lights simultaneously. Kim et al. (2020) introduced a spherical hybrid wave energy device that, under an acceleration of 1 m/s^2 , generated an output power of 85 nW from the TENG and 4 mW from the EMG. Compared to individual components, the hybrid energy device produced higher output voltages of 7V and output currents of 20 mA. Additionally, many electromagnetic-triboelectric hybrid generators have been developed to harvest energy from vibrations. Rodrigues et al. (2019) designed a triboelectric-electromagnetic-piezoelectric hybrid nanogenerator capable of harvesting energy from human walking and integrated it into shoe insoles, optimizing it for insole applications. Saadatnia et al. (2018) introduced a point-absorber-based triboelectric-electromagnetic hybrid energy harvester for wave energy collection, which can be utilized to design sustainable, environmentally friendly, cost-effective, and efficient wave energy harvesting systems. Khan et al. (2022) proposed a highly integrated uniaxial piezoelectric-triboelectric-electromagnetic hybrid generator that could generate an instantaneous power of 49 mW under low-frequency environmental vibrations (5Hz). Additionally, this device exhibited excellent charging characteristics, increasing the output voltage of a 22 μF capacitor to 2.7V within 12 s. This work offers a superior solution for harvesting low-frequency environmental energy by enhancing the performance of hybrid nanogenerators. Similarly, Kim et al. (2020) introduced a spherical hybrid wave energy device that, under an acceleration of 1 m/s^2 , produced higher output voltages of 7V and output currents of 20 mA compared to individual components.

From the research conducted by domestic and international scholars, it can be observed that current studies on the structural characteristics of triboelectric-electromagnetic hybrid devices predominantly rely on experimental methods. Although such methods provide direct insights, they are often costly and time-consuming. In terms of the motion characteristics and output performance, there is a noticeable lack of systematic simulation studies under various operating conditions, and few comparative validations between simulation results and experimental data have been conducted. In response to these gaps, this paper proposes a novel design for an Inertial Tilting Electromagnetic-Triboelectric Hybrid Energy Converter (ITHEC) and systematically



Figs. 2-1. Introduction to the ITHEC

investigates its structural characteristics, dynamic behavior under multiple working conditions, and output performance, along with experimental validation. First, simulation models of both the EMG and TENG are developed in COMSOL. By optimizing key parameters such as the axial width of the TENG, the device radius, and the magnet strength, the optimal structural dimensions for the hybrid energy converter were determined. Subsequently, based on the structural parameters, a kinematic model is constructed to simulate the actual motion under different excitations and evaluate the electrical performance of each component, thereby identifying the optimal operating conditions and performance outputs of the device. Finally, experimental validation confirms the accuracy of the simulation results, showing that, when deployed in an array, the device can meet the power supply requirements of small marine sensors. The ITHEC proposed in this paper offered a reference for research on efficient self-powered systems for small marine engineering equipment such as ocean sensors.

2. Structural design and principle of the hybrid wave energy converter

2.1. Device structure

The ITHEC is designed based on the principles of EMG and TENG. It is integrated into a buoy and mechanically constrained to connect with an offshore operation platform, enabling it to capture wave energy and convert it into electrical power to support the operation of small-scale marine systems, as depicted in Figs. 2-1(a). The device primarily consists of a rotor and a base frame, both of which are 3D-printed using PLA material. Three rectangular magnets are embedded in the blades at the lower part of the rotor, while the base frame features three rectangular slots at the bottom. Electromagnetic induction coils are placed within these slots in the base frame. The outer surface of the rotor is covered with rabbit fur, and the inner wall of the base frame is lined with copper foil serving as the electrode plate, which is coated with fluorinated ethylene propylene (FEP) as the triboelectric material. The rotor is connected to the base frame via bearings, allowing the rotor to oscillate

freely within the frame. When ITHEC is excited by wave motion, the magnets inside the rotor undergo a sinusoidal oscillating motion, which induces periodic changes in the magnetic flux through the coils. Simultaneously, the two triboelectric materials with different electron affinity repeatedly come into contact and separate, converting wave energy into electrical energy.

As shown in Figs. 2-1(b), the float is constructed by assembling cylindrical acrylic panels with side covers, with sealing gaskets added at the joints to ensure waterproofing. The two sides of the assembly are secured with 24 bolts. A circular base plate is positioned at the bottom of the cylindrical float, and the energy harvesting device is fixed onto this base. The space between the base plate and the cylindrical float can be used to place mass blocks, allowing control over the float's submersion depth in the water. A wiring hole is reserved at the top of the side cover of the cylindrical float, enabling the connection of the device to external measurement instruments.

ITHEC is composed of two energy generation units: a TENG and an EMG. These units are optimally arranged within the base frame according to the working modes determined earlier. For compatibility with standard dimensions, the height of the base frame is preset to 175 mm, a diameter of 140 mm and an axial width of 60 mm. The thickness of the cylindrical area at the top of the frame is set at 3 mm, and to reduce friction between the materials, the thickness in the effective friction region is increased by 2 mm. The base thickness is set at 10 mm, as shown in Figs. 2-1(c). The detailed dimensions are listed in Tables 2-1 and 2-2.

2.2. Working principle

The ITHEC proposed in this paper is an innovative energy conversion device in which the TENG and EMG units operate independently yet synergistically to achieve efficient energy conversion. The EMG follows Faraday's law of electromagnetic induction, using the oscillation of magnets embedded in the rotor to induce changes in the magnetic flux within the coils, thereby generating an induced current. On the other hand, the TENG utilizes the principles of triboelectric generation and

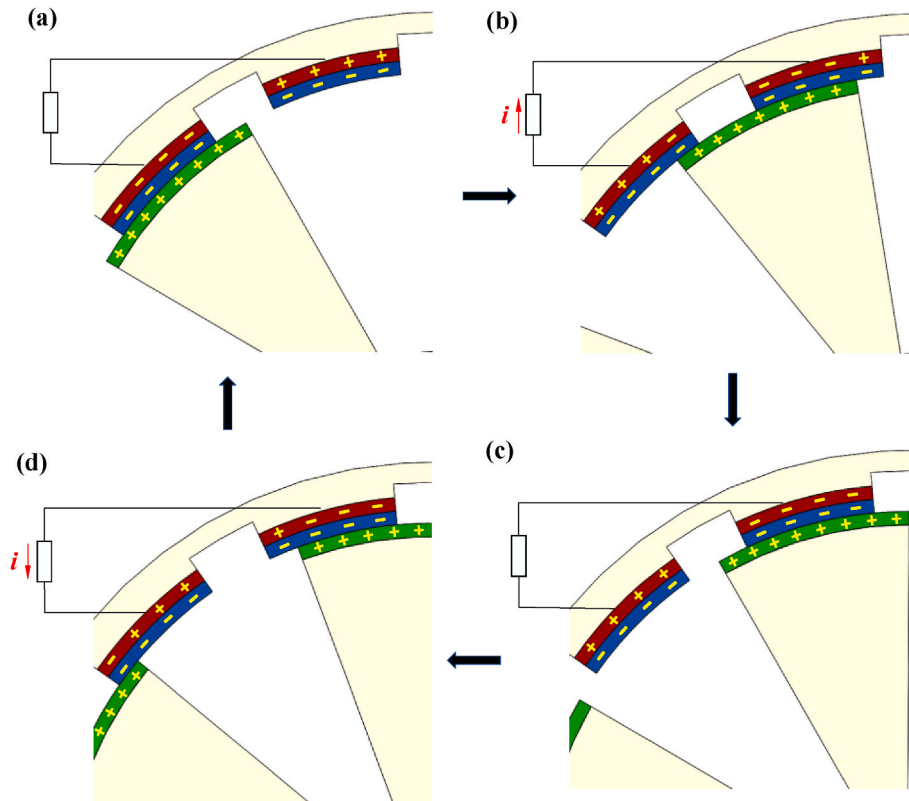
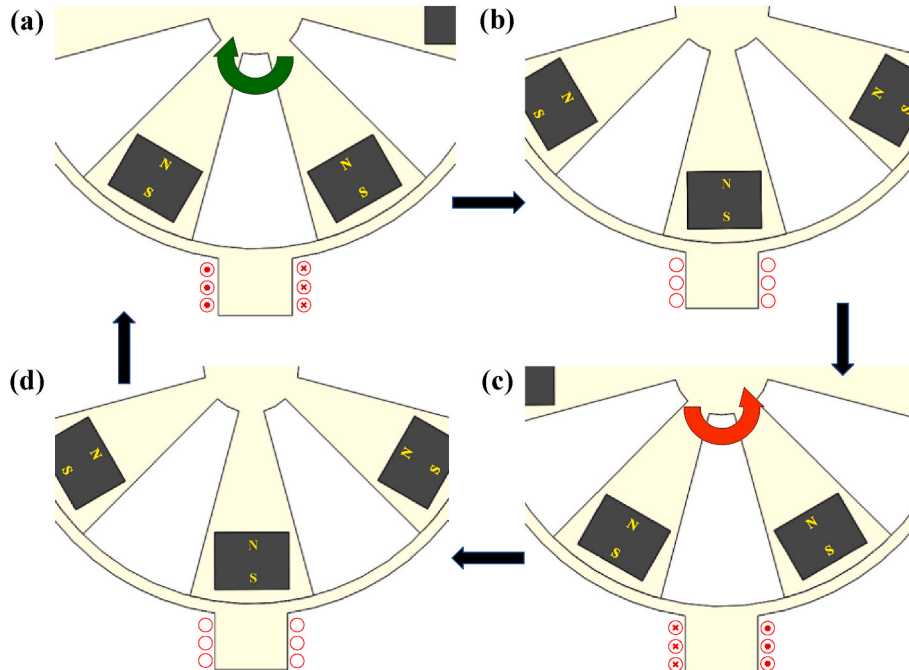


Fig. 2-. Working principle of the TENG

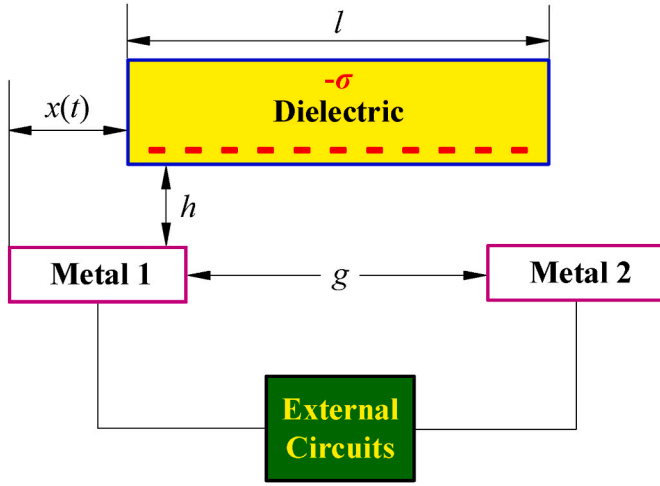


Figs. 2-3. Working principle of the EMG

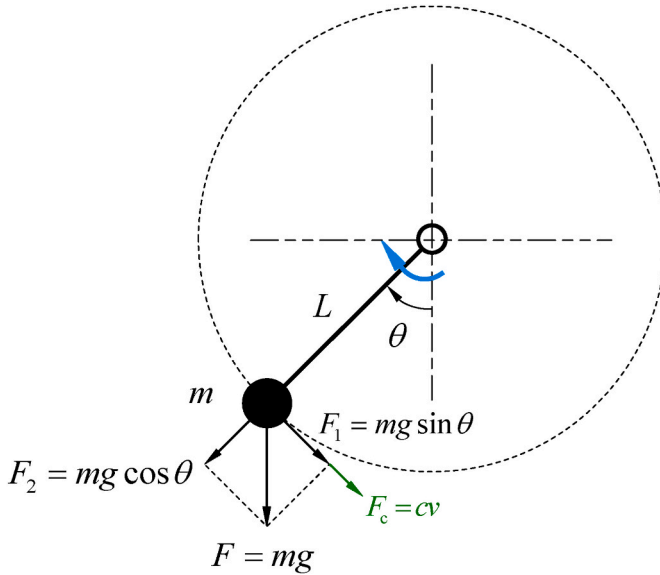
electrostatic induction. When different triboelectric materials come into contact, a charge transfer occurs due to the disparity in their ability to lose or gain electrons. As the materials separate, the resulting potential difference drives the flow of electrons between the electrodes, producing alternating current from the TENG. This system combines different energy conversion mechanisms to efficiently harvest and utilize energy,

offering an innovative solution for the continuous power supply of small marine engineering equipment.

The working principle of the TENG is illustrated in Figs. 2-. Under the influence of gravity and wave motion, the rotor undergoes reciprocating oscillations, causing relative sliding friction between the rabbit fur and the PTFE film. During the continuous friction between these two



Figs. 3–1. Basic principle of the Freestanding TENG



Figs. 3–2. Diagram of free vibration for a single degree of freedom system with viscous damping.

materials, charge transfer occurs on their surfaces. When the materials separate, a potential difference is created. Due to electrostatic induction, an induced electromotive force is generated between the electrodes on the backside of the materials. When the two electrodes are connected to an external load through wires, a continuous alternating current is generated in the circuit. After a period of friction, the charge density on

the surfaces of the triboelectric materials reaches saturation. The PTFE film becomes densely covered with negative charges, while the rabbit fur surface accumulates positive charges, generating induced charges, as shown in Figs. 2-(a). As the rotor oscillates, the contact area between the negatively charged material and the right-side electrode surface increases, causing electrons to flow from the right electrode to the left electrode, thus forming a current, as shown in Figs. 2-(b). When the rotor completely separates from one of the materials, no charge transfer occurs between the metal electrodes, as shown in Figs. 2-(c). As the amplitude of the rotor's motion increases, the contact area between the negatively charged material and the left-side electrode surface increases, causing electrons to flow from the left electrode to the right electrode, forming another current, as shown in Figs. 2-(d). Therefore, as the rotor continues to oscillate, the TENG generates alternating current. Additionally, the TENG employed an independent layer mode and is distributed between the outer wall of the rotor and the inner wall of the base frame. This design ensures that the rotor has no contact with external circuits, allowing it to move freely. It also helps save space within the structure, ensuring that the TENG operates efficiently while the EMG functions normally.

The operating principle of the EMG is illustrated in Figs. 2–3. ITHEC is mechanically excited by external wave motion, and this energy is converted into the oscillation of the magnets. The back-and-forth movement of the magnets inside the rotor causes periodic changes in the magnetic flux through the coils at the bottom. According to Lenz's law, the induced voltage in the coil is proportional to the rate of change of the magnetic flux. When the rotor rotates clockwise by a certain angle, as shown in Figs. 2–3(a)–(b), the magnetic flux inside the coil gradually increases, generating a counterclockwise current in the coil. Conversely, when the rotor rotates counterclockwise by a certain angle, as shown in Figs. 2–3(c)–(d), the magnetic flux inside the coil gradually decreases, generating a clockwise current in the coil. As the rotor oscillates back and forth, the EMG continuously generates alternating current.

3. Fundamental theories of the ITHEC

3.1. Theoretical analysis of the independent-layer TENG

The TENG within the ITHEC proposed in this paper adopts a sliding independent-layer structure. This design offers the advantage of preventing contact between the electrodes and external circuits, thereby reducing wear and minimizing the risk of malfunction. Additionally, it is well-suited to low-frequency, large-amplitude wave motion, improving energy harvesting efficiency, making it especially suitable for long-term use in harsh marine environments.

Since the potential on the dielectric surface is not constant, this interface cannot be considered as a single node. Thus, the principle of potential superposition is applied in the analysis, as shown in Figs. 3–1. First, assume that only a small portion, dk , of the dielectric surface on the bottom contains triboelectric charges. The charge quantities dQ_1 and



(a) Copper



(b) PTFE



(c) Rabbit Fur

Figs. 4–1. TENG materials.



(a) N33 Magnet



(b) 0.25mm Copper Wire

Figs. 4-2. EMG materials.



(a) Keithley 6514



(b) Keithley DMM 6500

Figs. 4-3. Measuring equipment.

Tables 2-1

Model parameters of the TENG unit.

Parameter		Value	Unit
Outer Electrode	Radius	69.7	mm
	Thickness	0.2	
Stator Friction Layer	Radius	69.9	
	Thickness	0.1	
Air Gap		0.25	
Rotor Friction Layer	Radius	69.25	
	Thickness	0.2	
Axial Length of Triboelectric Nano-Generator Unit		30	
Rotor Blade Inclination		20	Rad
Relative Permittivity of Material	PTFE	2	–
	Rabbit Fur	1.6	–
Physical Field	Surface Charge Density	10^{-5}	C/m ²
Circuit	External Circuit Resistance	10	MΩ

Tables 2-2

Model parameters of the EMG unit.

Parameter		Value	Unit
Magnet	Strength	N33	T
	Dimensions	$15 \times 20 \times 20$	mm
Coil	Turns	1000	–
	Radius	0.25	mm
Distance from Magnet to Rotor Center		55	mm
Distance between Coil and Magnet		30	mm
Coil Dimensions		$20 \times$	mm
Circuit	External Circuit Resistance	90	Ω

dQ_2 on the two electrodes during a short-circuit condition can be expressed by the following equations:

$$dQ_1 = \frac{\sigma \omega dk}{1 + \frac{C_2(k)}{C_1(k)}} \quad (1)$$

$$dQ_2 = \frac{\sigma \omega dk}{1 + \frac{C_1(k)}{C_2(k)}} \quad (2)$$

In the equations, σ represents the surface charge density, $\sigma \omega dk$ is the total charge on the two electrodes, and $C_i(k)$ is the capacitance between the small interface and metal electrode i .

Based on the principle of electrostatic field superposition, the total charge quantities Q_1 and Q_2 on the two electrodes during a short-circuit condition can be expressed by the following formulas:

$$Q_1 = \sigma \omega \int_0^l \frac{dk}{1 + \frac{C_2(k)}{C_1(k)}} \quad (3)$$

$$Q_2 = \sigma \omega \int_0^l \frac{dk}{1 + \frac{C_1(k)}{C_2(k)}} \quad (4)$$

Therefore, the amount of transferred charge Q in the sliding independent-layer TENG can be expressed by the following formula:

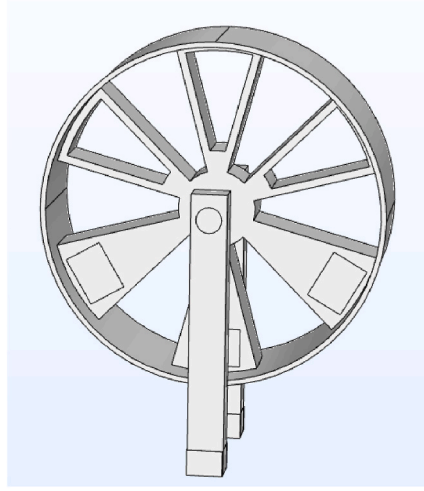
$$Q = \int_0^l \frac{\sigma \omega dk}{1 + \left(\frac{C_2(k)}{C_1(k)} \right)_{x=g+1}} - \int_0^l \frac{\sigma \omega dk}{1 + \left(\frac{C_2(k)}{C_1(k)} \right)_{x=0}} \quad (5)$$

The power generation principle of TENG is generally derived from a capacitor model. Therefore, the current in the external circuit can be expressed by the following formula:

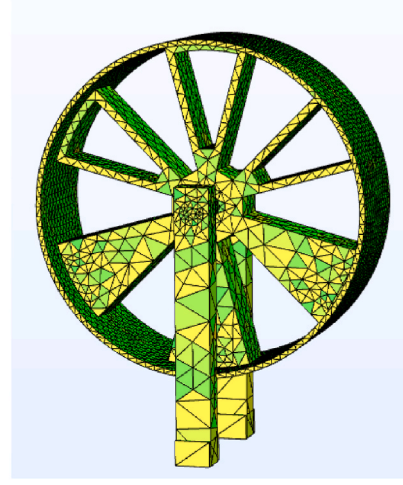
$$I_{\text{TENG}} = \frac{Q}{t} = \frac{\sigma A}{t} \quad (6)$$

In the equation, A represents the area of the dielectric, and t is the time.

The potential difference between the two electrodes of the TENG consists of two main components. One part comes from the polarized triboelectric charges, contributing a voltage V_{TENG} , and the other part comes from the already transferred charge Q . The contribution of the transferred charge to the potential difference is $-Q/C$, where C is the

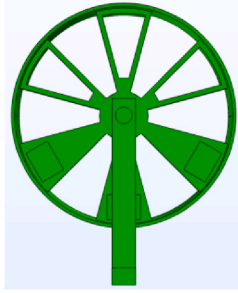


(a) Simulation Model Diagram

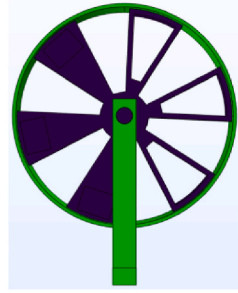


(b) Mesh Diagram

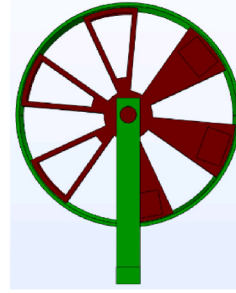
Figs. 5–1. Structural dynamics simulation model.



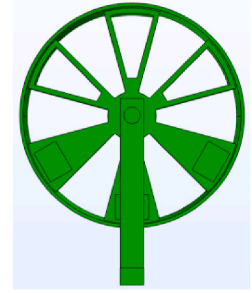
(a) Initial Position



(b) Movement to the Right

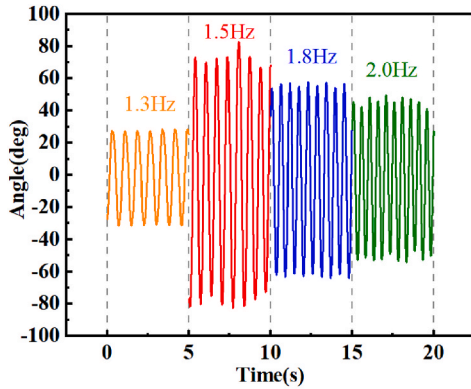


(c) Movement to the Left

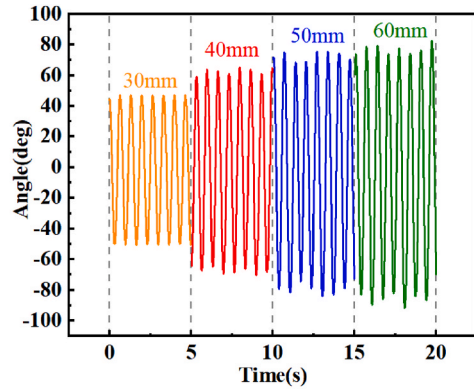


(d) Final Position

Figs. 5–2. Simulation of motion cycle.



(a) Motion Curves for Different Frequencies



(b) Motion Curves for Different Amplitudes

Figs. 5–3. Rotor motion curves.

capacitance between the two electrodes. Based on the principle of potential superposition, the total potential difference between the two electrodes can be expressed by the following formula:

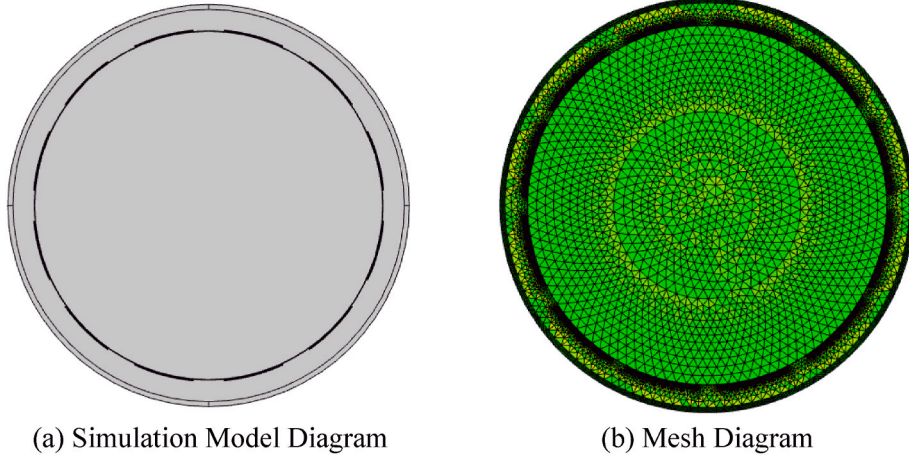
$$V = -\frac{Q}{C} + V_{\text{TENG}} \quad (7)$$

Under the short-circuit conditions, the transferred charge Q will completely neutralize the potential difference generated by the

polarized triboelectric charges. Therefore, the voltage can be expressed by the following formula:

$$V_{\text{TENG}} = \frac{Q}{C} = \frac{\sigma A}{C} \quad (8)$$

Based on the aforementioned theory, in the subsequent triboelectric generation simulation analysis, the output current and voltage of the TENG will be derived according to Eqs. (6) and (8). These two equations



Figs. 5-4. TENG simulation model.

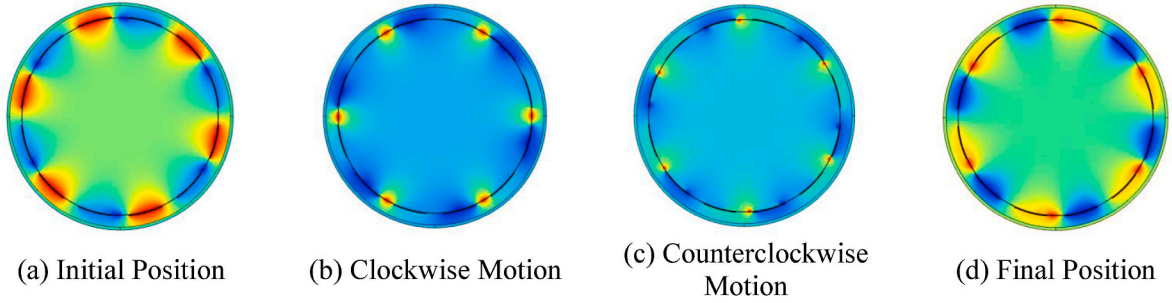


Fig. 5-. TENG motion cycle simulation diagram.

respectively describe the current generated by charge transfer and the effect of the potential difference on the output voltage.

3.2. Theoretical analysis of the oscillation in a viscously damped single-degree-of-freedom system

The forces acting on the oscillation of the single-degree-of-freedom system during motion, as shown in Figs. 3-2, can be analyzed as follows:

$$\sum F_x = -mg \sin \theta - cL\dot{\theta} = mL\ddot{\theta} \quad (9)$$

Thus,

$$m\ddot{\theta} + c\dot{\theta} + \frac{mg}{L} \sin \theta = 0 \quad (10)$$

When θ is relatively small, $\sin \theta$ can be approximated as θ , so the equation simplifies to:

$$m\ddot{\theta} + c\dot{\theta} + k\theta = 0 \quad (11)$$

Where,

$$k = \frac{mg}{L} \quad (12)$$

Here, c is the damping coefficient. Eq. (11) is the damped free oscillation differential equation for a single-degree-of-freedom system. By solving it numerically, the characteristic roots can be obtained as:

$$\lambda_{1,2} = -\frac{c}{2m} \pm \sqrt{\frac{c^2}{4m^2} - \frac{g}{L}} \quad (13)$$

The natural frequency of the system is:

$$\omega_n = \sqrt{\frac{g}{L}} \quad (14)$$

When the term under the square root in Eq. (13) equals zero, the damping coefficient c is defined as the critical damping coefficient c_c , which is:

$$c_c = 2\sqrt{\frac{m^2g}{L}} = 2m\omega_n \quad (15)$$

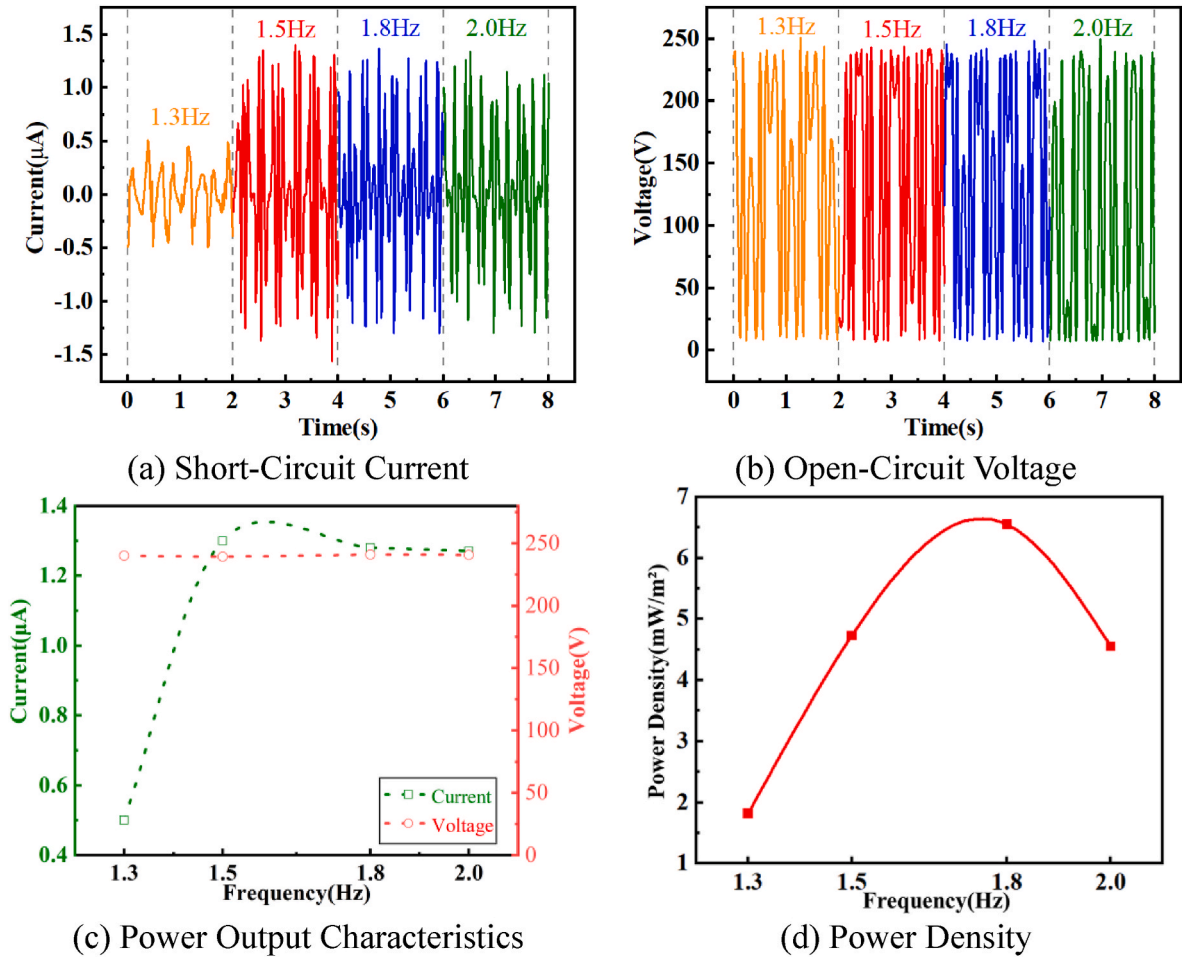
The damping ratio ζ is:

$$\zeta = \frac{c}{c_c} = \frac{c}{2\sqrt{\frac{m^2g}{L}}} \quad (16)$$

Substituting the dimensionless damping ratio ζ into Eq. (13), the characteristic roots are expressed as:

$$\lambda_{1,2} = -\zeta\omega_n \pm \omega_n\sqrt{\zeta^2 - 1} \quad (17)$$

When the damping ratio ζ varies, the system exhibits different types of motion. Specifically, when $\zeta > 1$, the system is in an overdamped state, characterized by a slow, non-oscillatory decay. This state ensures that ITHEC quickly stabilizes under extreme conditions. When $\zeta = 1$, the system is critically damped, allowing it to return to equilibrium as quickly as possible without oscillating, a feature useful for enhancing ITHEC's stability and response speed. In the underdamped state, where $\zeta < 1$, the system displays oscillatory motion with exponentially decaying amplitude. This underdamped condition will be used in subsequent simulation analyses to evaluate ITHEC's stability during sustained oscillations in actual marine environments.



Figs. 5–6. Simulation output of TENG at different frequencies.

4. Manufacturing of the ITHEC

4.1. Manufacturing of the TENG

As mentioned earlier, the TENG adopts a sliding independent-layer triboelectric generation mode. This configuration allows the electrodes to be distributed evenly on the inner wall of the base frame, ensuring that the rotor's movement is not affected by wiring. The TENG unit is composed of three main parts: copper electrodes on the inner wall of the base frame, PTFE film on the electrode surfaces, and rabbit fur on the rotor's outer wall. The PTFE film has a thickness of 0.1 mm, while the copper electrodes have a thickness of 0.065 mm, and both are uniformly distributed on the convex arc of the inner wall of the base frame, as shown in Figs. 4-1(a). Wires are used to connect the positive and negative electrodes to the measuring instruments. The PTFE film serves as a negative triboelectric material, while the rabbit fur acts as a positive triboelectric material, as shown in Figs. 4-1(b)–(c). Due to the softness of the rabbit fur, the frictional force generated when the two materials come into contact is relatively small, which helps to ensure smooth startup of the rotor.

4.2. Manufacturing of the EMG

The electromagnetic generation unit consists of magnets embedded in the rotor and coils positioned beneath the base frame. The magnets are embedded in three blades at the bottom of the rotor, ensuring that the rotor oscillates when subjected to external excitation. Each magnet is rectangular in shape and made of N33 neodymium iron boron (NdFeB)

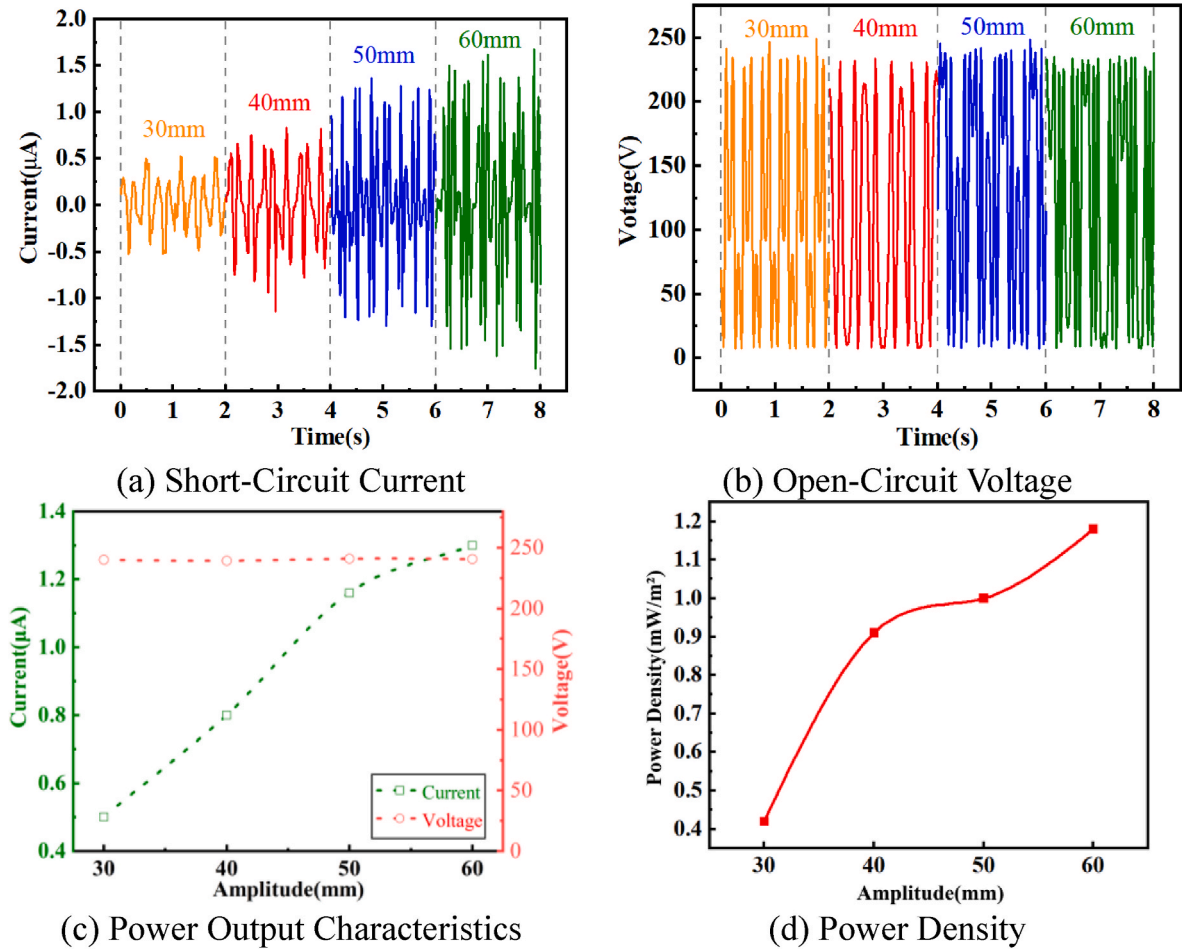
material, with dimensions of 15mm × 20mm × 20 mm, as shown in Figs. 4-2(a). The coils are wound into three grooves at the bottom of the base frame, using copper wire with a diameter of 0.25 mm, as shown in Figs. 4-2(b). These coils are connected to measuring instruments via wires.

4.3. Assembly of the ITHEC

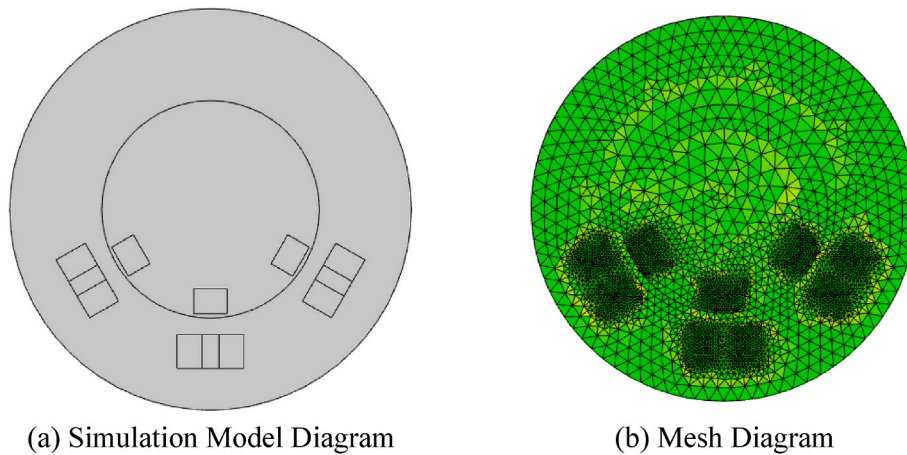
The ITHEC primarily consists of two main components: the stator frame and the rotor, both of which are manufactured using 3D printing technology. The chosen material for printing is PLA with a diameter of 1.75 mm, as it is well-suited for printing cylindrical models, maintaining the original shape with minimal distortion, and being fully biodegradable. During the printing process, slicing software is used to set the layer height at 0.2 mm to ensure smoothness of the printed parts. The stator frame and rotor are connected via bearings. The stator frame serves to support and accommodate external movements, while the rotor, influenced by these external motions, oscillates. The triboelectric materials are distributed on the inner wall of the stator frame and the outer wall of the rotor, with magnets embedded in the rotor's lower blades and coils positioned in the grooves at the base of the stator frame. When external forces act on the system and the rotor begins to oscillate, both the TENG and EMG units are activated simultaneously.

4.4. Measurement equipment

Based on relevant literature in the field, this study selected the Keithley 6514 Electrometer as the testing platform to validate the TENG



Figs. 5–7. Simulation output of TENG at different amplitudes.



Figs. 5–8. EMG simulation model.

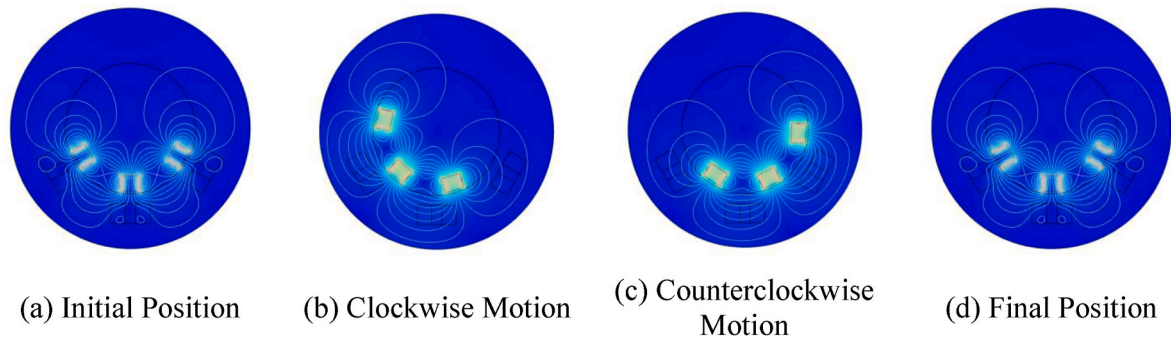
component. Given the low current and high internal impedance characteristics of the TENG, the Keithley 6514 Electrometer was used to measure its electrical properties, such as open-circuit voltage and short-circuit current. The experimental setup was configured as shown in Figs. 4-3(a).

Additionally, due to the relatively higher current generated by the EMG, the Keithley DMM 6500 Digital Multimeter and associated control software were used for data measurement during the experiments, as illustrated in Figs. 4-3(b).

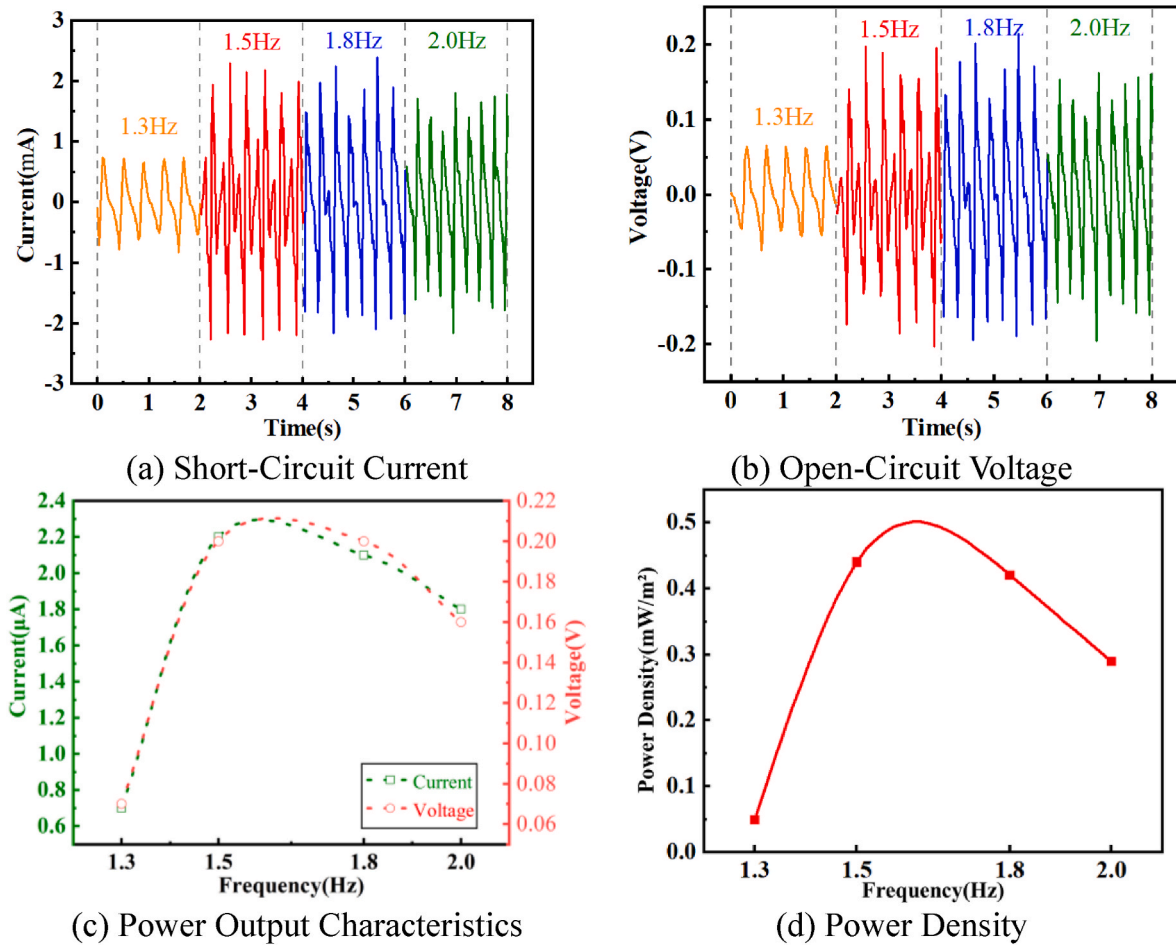
5. Results and discussion

5.1. Finite element simulation

COMSOL is a Multiphysics finite element simulation software capable of coupling multiple physical fields for computation. Based on the finite element method (FEM), it solves partial differential equations or systems of partial differential equations to simulate real-world physical phenomena, meeting the simulation requirements of this



Figs. 5–9. EMG motion cycle simulation diagram.



Figs. 5–10. Simulation output of EMG at different frequencies.

model. Therefore, COMSOL was used to perform structural dynamic analysis, TENG output characteristic analysis, and EMG output characteristic analysis for this device.

5.1.1. Structural dynamic simulation

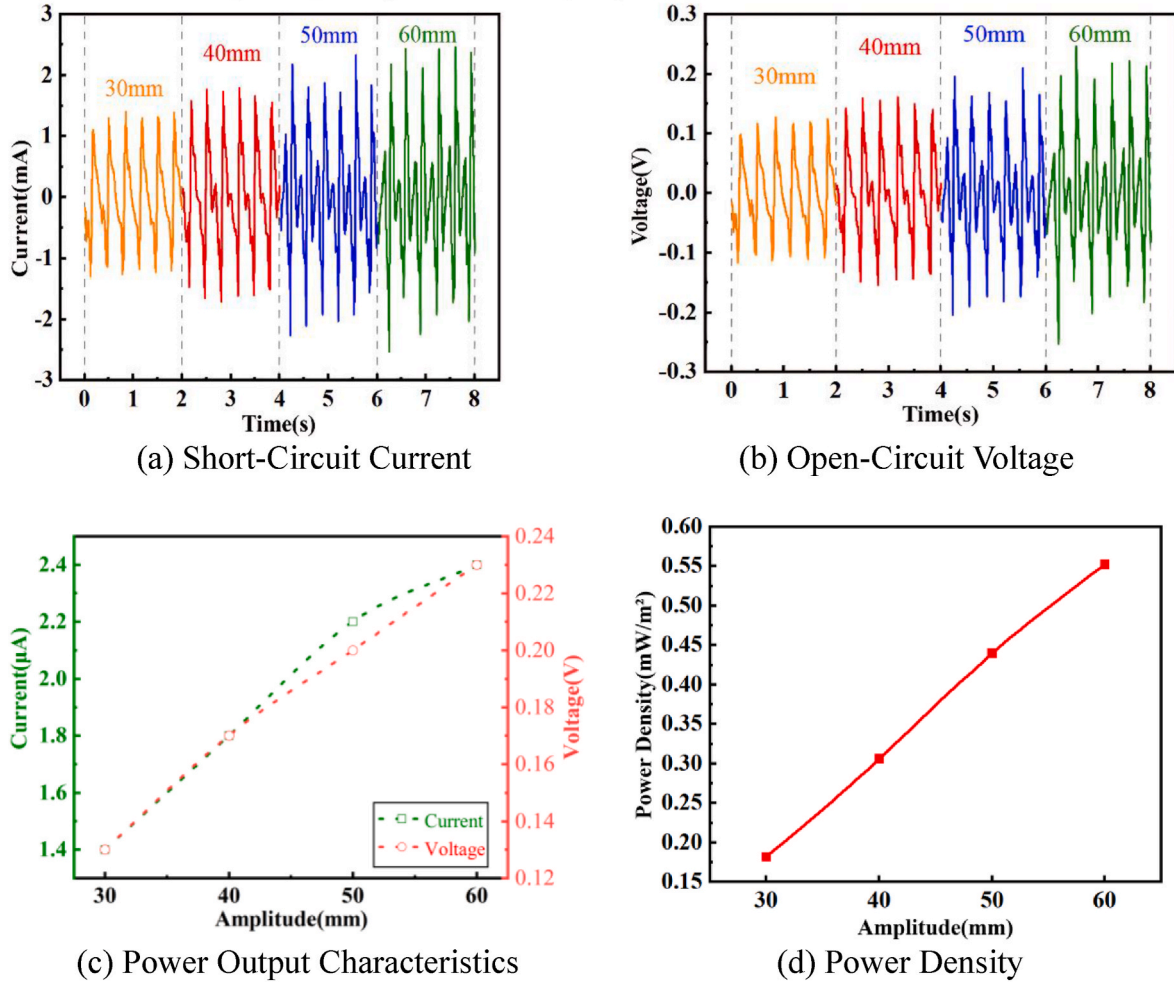
The structural parameters of ITHEC were selected based on the data presented in Tables 2.1 and 2.2. First, the rotor and the magnets embedded in the rotor were modeled. Then, the base frame was simplified into a rectangular support, with the rotor and frame connected via a hinged joint. Finally, a structural dynamics simulation model was created. The 3D simulation model and mesh distribution are shown in Figs. 5–1.

The motion process of ITHEC is illustrated in Figs. 5–2. When the

device moves to the right, due to the conservation of momentum, the rotor swings to the left. Similarly, when the device moves to the left, the rotor swings to the right. Therefore, when the device is subjected to external forces, the rotor continuously oscillates back and forth, thereby driving the device to collect energy.

By applying horizontal harmonic vibrations to ITHEC, the absolute motion curve of the rotor was calculated. The simulation process considered the effects of gravity and friction on the rotor, with friction mainly including resistance between the triboelectric materials, air resistance acting on the rotor, and resistance from the bearing components. Experimental measurements indicated that the sliding friction force is approximately 0.1N.

When the horizontal harmonic vibration has an amplitude of $d = 50$



Figs. 5–11. Simulation output of EMG at different amplitudes.

mm, Figs. 5-3(a) shows the rotor's motion at different frequencies. As the frequency gradually increases, the rotor's oscillation amplitude also increases correspondingly. However, when the frequency reaches a certain critical value, the amplitude shows a slight downward trend, indicating that the rotor's motion stability is limited at higher frequencies.

When the frequency of the horizontal harmonic vibration is $f = 1.5$ Hz, the rotor's motion at different amplitudes is shown in Figs. 5-3(b). At motion amplitudes of 30 mm, 40 mm, 50 mm and 60 mm, the rotor's swing amplitude stabilizes at 90° , 140° , 161° and 169° respectively. This indicates that as the amplitude of the vibration increases, the rotor's oscillation amplitude also increases, but the rate of increase diminishes progressively.

5.1.2. TENG simulation

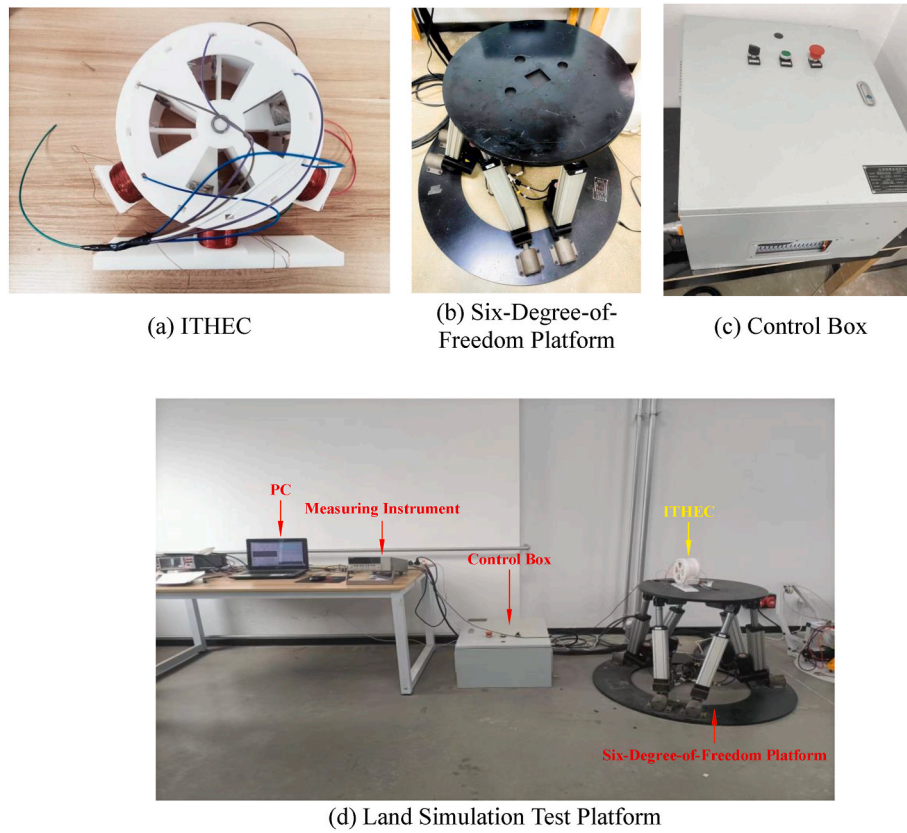
Since the TENG has a cylindrical structure, a 2D spatial model was established in COMSOL to reduce computational complexity. The simulation model and mesh distribution are shown in Figs. 5-4. Under different operating conditions, the current and voltage output were simulated to explore the power generation performance of the TENG component in the hybrid wave energy device under varying conditions.

The entire motion cycle of the TENG is illustrated in Figs. 5-. As the rotor rotates clockwise from its initial position, the contact area between the rabbit fur material on the rotor surface and the left electrode (covered with PTFE material) gradually increases, creating a potential difference that drives electrons to flow toward the left electrode. When the rotor rotates counterclockwise, the contact area between the rabbit

fur and the left electrode gradually decreases, while the contact area with the right electrode increases, generating a potential difference that drives electrons to flow toward the right electrode. As the rotor rotates clockwise again and returns to its initial position, the potential difference drives electrons toward the left electrode once more, completing the entire motion cycle.

By applying the rotor's motion at different frequencies, with an amplitude of $d = 50$ mm as shown in Figs. 5-3(a), into the TENG simulation model, and connecting an ammeter and voltmeter to the circuit, the short-circuit current and open-circuit voltage at various frequencies were obtained, as shown in Figs. 5-6. It can be observed that as the motion frequency f increases from 1.3Hz to 2.0Hz, the peak short-circuit current of the TENG initially rises from $0.5 \mu\text{A}$ to $1.3 \mu\text{A}$, then slightly decreases, remaining largely unchanged. The peak open-circuit voltage remains steady at 240V. The power density rose initially from 1.82 mW/m^2 to a peak of 6.55 mW/m^2 , then declined to 4.55 mW/m^2 . This indicates that, as described by Eq. (6), the motion dynamics significantly influence the current output of the TENG—the greater the oscillation amplitude, the higher the current output. In comparison, the voltage output is largely unaffected by the motion dynamics and is primarily determined by the structural design, which explains the stable voltage output, thus validating the correctness of Eq. (8).

By applying the rotor's motion at different amplitudes, with a frequency of $f = 1.5$ Hz, as shown in Figs. 5-3(b), into the TENG simulation model, and connecting an ammeter and voltmeter to the circuit, the short-circuit current and open-circuit voltage at various amplitudes were obtained, as shown in Figs. 5-7. Clearly, as the oscillation



Figs. 5–12. Test device.

amplitude d increases from 30 mm to 60 mm, the TENG's peak short-circuit current rises from $0.5 \mu\text{A}$ to $1.3 \mu\text{A}$. The peak open-circuit voltage remains constant at 240V, and the power density increases from 1.82 mW/m^2 to 4.73 mW/m^2 .

These results also indicate that the oscillation amplitude of the TENG is positively correlated with current output, while the voltage output is largely unaffected by the motion dynamics.

5.1.3. EMG simulation

Similar to the cylindrical symmetric structure of the TENG, the EMG's coils and magnets are also symmetrically distributed. Therefore, a 2D model was chosen to reduce computational complexity. The model includes three magnets and three coils, with the simulation model and mesh distribution is shown in Figs. 5–8. Under various operating conditions, the current and voltage outputs were simulated to explore the power generation performance of the EMG component in the hybrid wave energy device.

The variation of magnetic flux lines throughout the entire motion cycle is illustrated in Figs. 5–9. When the magnets rotate clockwise from their initial position, following the rotor's movement, a changing magnetic field is generated. The coils at the bottom produce an induced current as they cut through the magnetic flux lines. Similarly, when the magnets rotate counterclockwise, following the rotor's motion, a changing magnetic field is again generated, and the coils produce induced current due to the cutting of the magnetic flux lines. Finally, the magnets return to their initial position, completing the motion cycle.

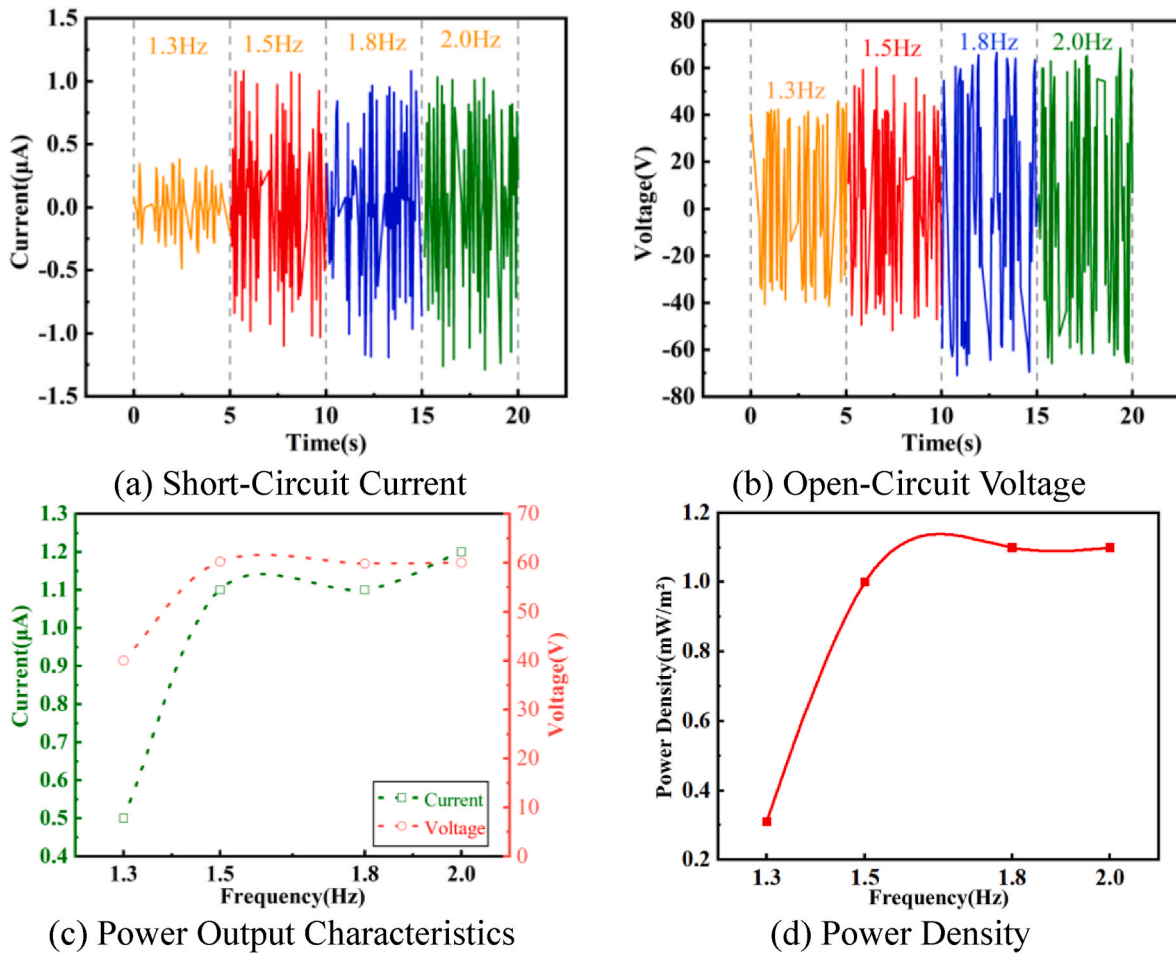
By applying the rotor's motion at different frequencies, with an amplitude of $d = 50 \text{ mm}$, as shown in Figs. 5-3(a), into the EMG simulation model, and connecting an ammeter and voltmeter to the circuit, the short-circuit current and open-circuit voltage at various frequencies were obtained, as shown in Figs. 5–10. It is clear that as the motion frequency increases from 1.3Hz to 2.0Hz, the peak short-circuit current of the EMG rises from 0.7 mA to 2.2 mA, and then decreases to 1.8 mA.

The peak open-circuit voltage increases from 0.07V to 0.2V, then decreases to 0.16V. The power density increases from 0.049 mW to 0.44 mW, and then decreases to 0.29 mW. These results indicate that, for the EMG, the short-circuit current, open-circuit voltage, and power density are frequency-dependent. The initial rise in values with frequency suggests that increased oscillations enhance energy conversion efficiency. However, the eventual decline indicates a threshold beyond which the system's performance stabilizes or diminishes, possibly due to mechanical limitations.

By applying the rotor's motion at different amplitudes, with a frequency of $f = 1.5 \text{ Hz}$, as shown in Figs. 5-3(b), into the EMG simulation model, and connecting an ammeter and voltmeter to the circuit, the short-circuit current and open-circuit voltage at various amplitudes were obtained, as shown in Figs. 5–11. Compared to the performance output at different frequencies, the performance output trend at different amplitudes is more straightforward. As the motion frequency increases from 1.3Hz to 2.0Hz, the EMG's short-circuit current rises from 1.4 mA to 2.4 mA, and the open-circuit voltage increases from 0.13V to 0.23V. The peak power density increases from 0.182 mW to 0.552 mW, showing an overall increasing trend. This indicates that increasing the frequency within a certain range helps improve the output performance of the EMG.

5.2. Land-based tests

The previous sections introduced the ITHEC device, conducted theoretical analysis, dynamic simulation analysis, and simulated the output characteristics of both the TENG and EMG. In this section, a prototype of the ITHEC was manufactured based on the aforementioned research, as shown in Figs. 5-12(a). The device model was mounted on a six-degree-of-freedom platform and connected to measurement instruments via wires. First, horizontal harmonic motion was input through the control box, causing the six-degree-of-freedom platform to



Figs. 5–13. Experimental output of TENG at different frequencies.

Tables 5–1

Comparison of experimental and simulation results of TENG at different motion frequencies.

	Experimental Results	Simulation Results	Error Rate
Peak Voltage of TENG/V	60	240	/
Peak Current of TENG/ μA	1.2	1.3	8.3 %

perform reciprocating motions at different frequencies and amplitudes, as shown in Figs. 5–12(b)–(c). Due to the different output characteristics of the TENG and EMG—where the former produces high voltage but low current, and the latter produces low voltage and low current—the output voltage and short-circuit current of the TENG and EMG were measured separately. The TENG's output was measured using a Keithley 6514 electrometer, while the EMG's output was measured using a Keithley DMM 6500 digital multimeter, both connected to a PC for data collection. Finally, the measurement data were collected and saved on the PC for analysis of the output patterns. The test platform setup is shown in Fig. 5-12(d).

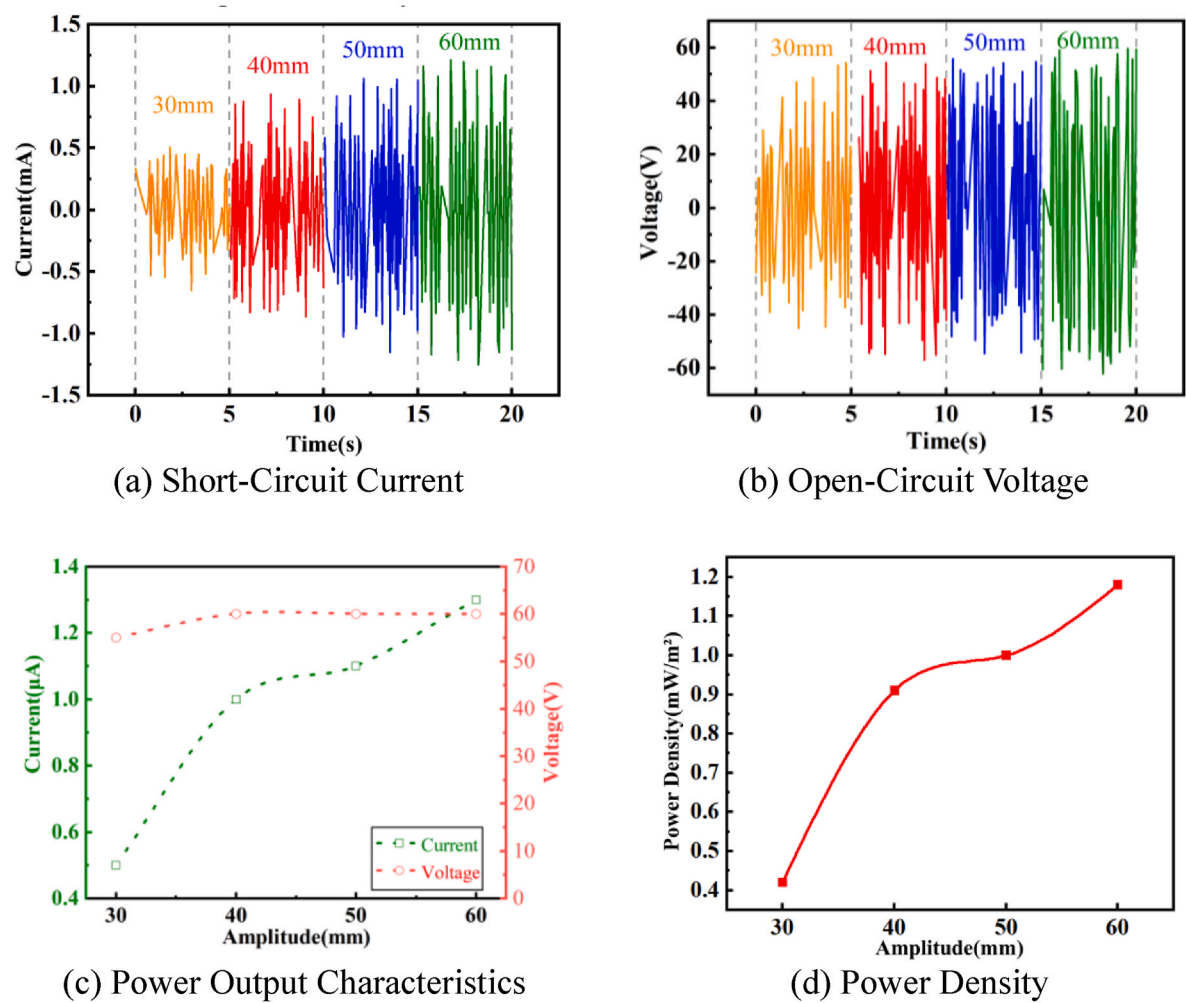
5.2.1. Land tests of TENG

First, the effect of motion frequency on the TENG unit was investigated by varying the frequency of the six-degree-of-freedom platform. Based on the previous simulation results of the TENG, this experiment selected a representative amplitude of 50 mm and motion frequencies of 1.3Hz, 1.5Hz, 1.8Hz, and 2.0Hz for comparative testing. As the rotor oscillated back and forth on the six-degree-of-freedom platform, the

TENG completed its periodic friction cycles.

To visually illustrate the relationship between the TENG's performance output and motion frequency, the different output parameters were summarized in Figs. 5–13. As the frequency increased from 1.3Hz to 2.0Hz, the peak short-circuit current of the TENG rose from 0.5 μA to 1.2 μA, indicating an enhanced charge transfer under increased oscillation frequency. The peak open-circuit voltage increased from 40V to 60V and stabilized. The power density increased from 0.31 mW/m² to 1.1 mW/m². As shown in Tables 5–1, the error rate between the experimental and simulation results for current was less than 10 %, indicating close agreement between the two. However, there was a larger discrepancy between the experimental and simulation results for voltage. According to Wang's research in *Triboelectric Nanogenerators* (2017), this discrepancy is due to the fact that the internal resistance of the voltmeter is not infinite. The leakage of internal voltage prevents the accurate recording of the actual voltage, leading to differences between the simulation and experimental results. In future research, high-impedance measurement instruments will be further explored to enhance measurement accuracy and minimize the impact of internal voltage leakage on the recorded results. Although there is a difference in numerical values, the voltage still tends to stabilize, consistent with the trend observed in the simulation. At $f = 1.3$ Hz, the voltage is relatively low, which may be due to insufficient friction during the motion, resulting in a lower voltage output.

Next, the relationship between the TENG and motion amplitude was experimentally studied. For this experiment, a representative frequency of 1.5Hz was selected, with motion amplitudes of 30 mm, 40 mm, 50 mm, and 60 mm for comparison. As the rotor oscillated back and forth on the six-degree-of-freedom platform, the TENG completed its periodic



Figs. 5–14. Experimental output of TENG at different amplitudes.

Tables 5–2
Comparison of experimental and simulation results of TENG at different motion amplitudes.

	Experimental Results	Simulation Results	Error Rate
Peak Voltage of TENG/V	60	240	/
Peak Current of TENG/ μA	1.25	1.3	4.1 %

friction cycles. Similarly, to visually illustrate the relationship between TENG performance and motion amplitude, the various output performance curves were summarized in Figs. 5–14. As the motion amplitude increased from 30 mm to 60 mm, the peak short-circuit current of the TENG rose from 0.5 μA to 1.25 μA. As shown in Tables 5–2, the error rate between the experimental and simulation results was within 5 %, indicating close agreement with the simulation results. The peak voltage remained constant at 60V, consistent with the conclusions drawn earlier. The power density increased from 0.42 mW/m² to 1.18 mW/m².

5.2.2. Land tests of EMG

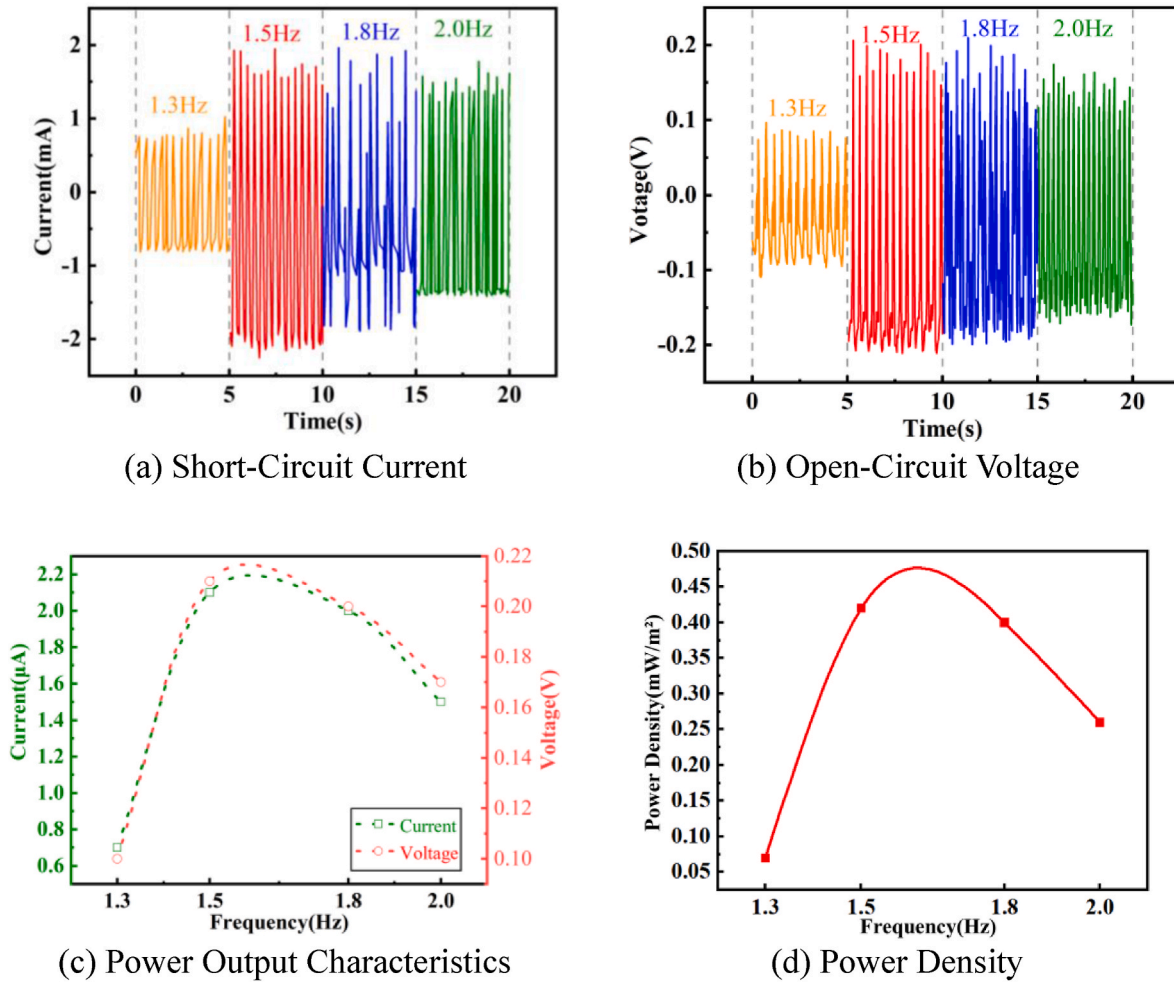
Next, the power generation performance of the EMG was explored. First, the effect of motion frequency on the EMG’s power generation performance was investigated by varying the frequency of the six-degree-of-freedom platform, to further verify the impact of frequency on the device’s output performance. Based on the EMG simulation calculations in Chapter 4, this experiment selected a representative

amplitude of 50 mm and motion frequencies of 1.3Hz, 1.5Hz, 1.8Hz and 2.0Hz for comparative testing. As the rotor oscillated back and forth on the six-degree-of-freedom platform, alternating current was induced in the copper coils.

To visually represent the relationship between EMG performance and motion frequency, the output performance data were summarized, as shown in Figs. 5–15. As the frequency increased from 1.3Hz to 2.0Hz, the peak short-circuit current of the EMG increased from 0.7 mA to 2.1 mA, then decreased to 1.5 mA. The peak open-circuit voltage increased from 0.1V to 0.21V, then decreased to 0.17V. The power density increased from 0.07 mW to 0.42 mW, then decreased to 0.26 mW. The experimental results had an error rate of less than 5 % compared to the simulation results, as shown in Tables 5–3, indicating similar trends.

Next, the relationship between the EMG and motion amplitude was experimentally studied. Based on the EMG simulation calculations in Chapter 4, this experiment selected a representative frequency of 1.5Hz, with motion amplitudes of 30 mm, 40 mm, 50 mm and 60 mm for comparison. As the rotor oscillated back and forth on the six-degree-of-freedom platform, alternating current was induced in the copper coils.

To visually illustrate the relationship between the performance of the electromagnetic generation unit and motion amplitude, the output performance data were summarized, as shown in Figs. 5–16. As the amplitude increased from 30 mm to 60 mm, the peak short-circuit current of the electromagnetic generation unit increased from 1.7 mA to 2.2 mA, and the peak open-circuit voltage increased from 0.2V to 0.23V. The power density rose from 0.34 mW to 0.51 mW. As shown in Tables 5–4, the experimental results closely matched the simulation



Figs. 5–15. Experimental output of EMG at different frequencies.

Tables 5–3

Comparison of experimental and simulation results of EMG at different motion frequencies.

	Experimental Results	Simulation Results	Error Rate
Peak Voltage of EMG/V	0.21	0.2	4.8 %
Peak Current of EMG/ μA	2.1	2.2	4.8 %

results, with an error rate of less than 10 %, likely due to limited measurement precision.

By analyzing the land-based experimental results, it was determined that the device exhibited optimal output performance at a frequency of 1.5Hz and an amplitude of 60 mm. Under these conditions, the TENG achieved a maximum short-circuit current of 1.25 μA and a maximum open-circuit voltage of 60V, while the EMG achieved a maximum short-circuit current of 2.2 mA and a maximum open-circuit voltage of 0.23V. A comparative analysis between the experimental and simulation results indicates that they are consistent, validating the accuracy of the simulation model.

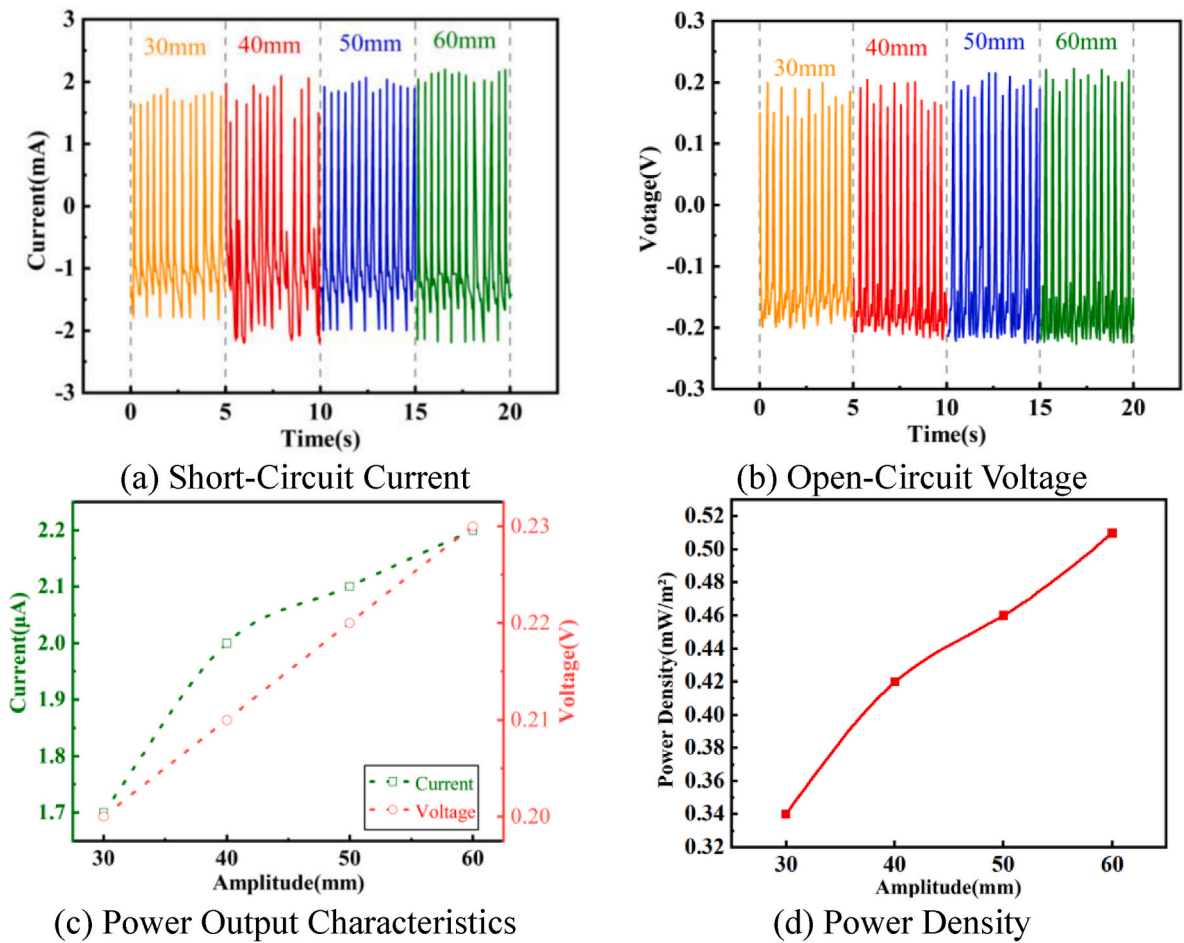
Therefore, under these conditions, further investigation was conducted to explore the power output of the TENG and EMG with different external loads. As shown in Figs. 5–17, the TENG reached a maximum power output of 0.4 mW with a 10,000M Ω load, while the EMG reached a maximum power output of 0.42 mW with a 50 Ω load.

5.3. Water Tank Experiment

The water tank test for the proposed ITHEC was conducted at the test pool of the Yantai Research Institute of Harbin Engineering University, as shown in Figs. 5–18. The test pool is 10 m long, 0.8 m wide and 0.8 m deep. One end of the pool is equipped with a mechanical wave generator, while the other end has a damping wave absorption device, allowing for the creation of different types of waves as needed. The tank is capable of generating regular waves with a wave period ranging from 0.5 to 2.0 s and a maximum wave height of 0.2 m, depending on the experimental requirements.

In addition, the device relies on the buoyancy of a float during the water tank test. Given that a spherical float could not be stably and effectively assembled with the test tank, a commonly used cylindrical float was designed based on the mass and dimensions of the ITHEC, as shown in Figs. 5–18. The float is made entirely of acrylic material to reduce weight, and it is fixed in the test tank using bearings and connecting rods to verify the operational feasibility of ITHEC when constrained, such as when fixed to target marine equipment.

Furthermore, this study presents a 1:1 prototype tank test of ITHEC, with its dimensional parameters provided in Tables 2–1 and 2–2. The ITHEC was placed inside the float and waterproofed using rubber gaskets and waterproof adhesive. The device was then connected to measurement equipment through wires passed through a pre-reserved wire hole at the top of the float. During the test, different types of waves were generated in the test pool, similar to the land-based experiment. The output voltage and short-circuit current of the TENG and EMG were



Figs. 5–16. Experimental output of EMG at different amplitudes.

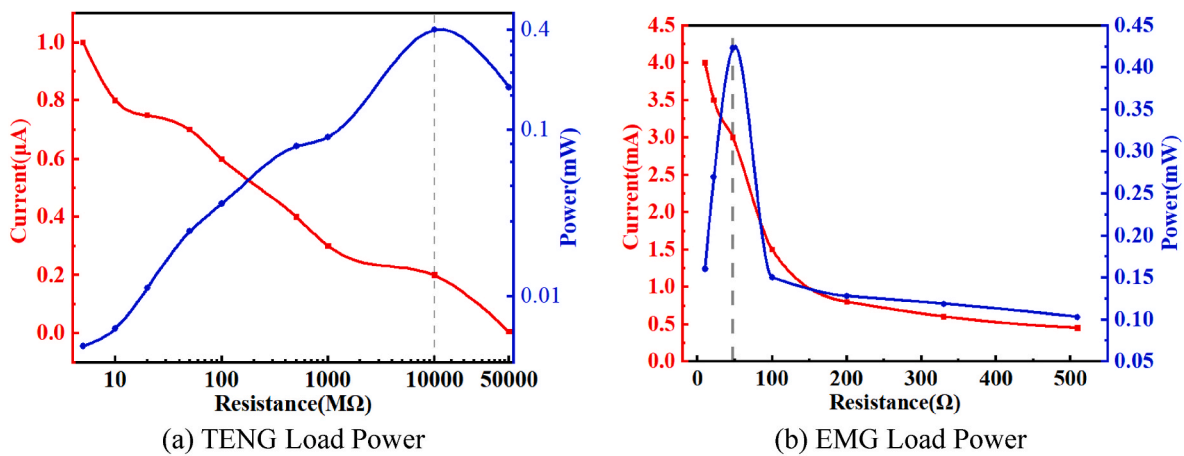
Tables 5–4
Comparison of experimental and simulation results of EMG at different motion amplitudes.

	Experimental Results	Simulation Results	Error Rate
Peak Voltage of EMG/V	0.230	0.231	0.4 %
Peak Current of EMG/ μA	2.2	2.4	9.1 %

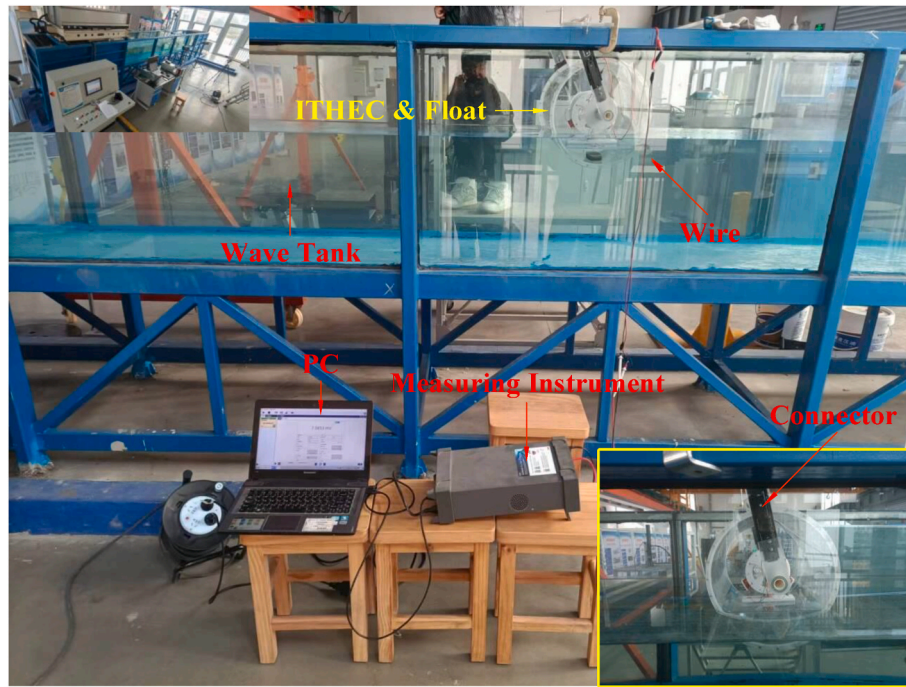
measured using a Keithley 6514 electrometer and a Keithley DMM 6500 multimeter, respectively, both connected to a PC. Finally, the measurement data were collected and saved on the PC, and the output patterns were analyzed.

According to the wave classification standards published by the China National Oceanographic Administration, sea conditions of levels 1 to 3 are shown in Tables 5–5.

Due to the limitations of the water tank equipment, this experiment only selected wave conditions within the range of Level 2 sea state, as specified in the wave standards published by the China National



Figs. 5–17. Load power.



Figs. 5–18. Water tank simulation test platform.

Tables 5–5

Sea state classification Table.

Sea State Level	Wave Height Range(m)	Average Period(s)
1	0–0.1	1.4
2	0.1–0.5	2.2
3	0.5–1.25	3.9

Oceanographic Administration. Regular waves with a height of 0.12m and a period of 2.2 s were generated using the control console. The device was connected to the measurement instruments via wires, and the output performance of the TENG and EMG under these wave conditions was measured. The wave tank experiment was conducted five times, and the relative error of each set of experimental data was less than 10 %, falling within a reasonable range of data fluctuation. Therefore, the mean value of the five trials was calculated for the final analysis.

As shown in Figs. 5–19(a)–(b), the TENG's peak short-circuit current output was 2.0 μA , and the peak open-circuit voltage output was 30V. As shown in Figs. 5–19(c)–(d), under the same sea state, the EMG's peak short-circuit current output was 1.5 mA, and the peak open-circuit voltage output was 0.25V. Based on the experimental data, the maximum output power of the device was as follows: the TENG unit reached a maximum power of 1.18 mW, and the electromagnetic generation unit reached a maximum power of 0.51 mW.

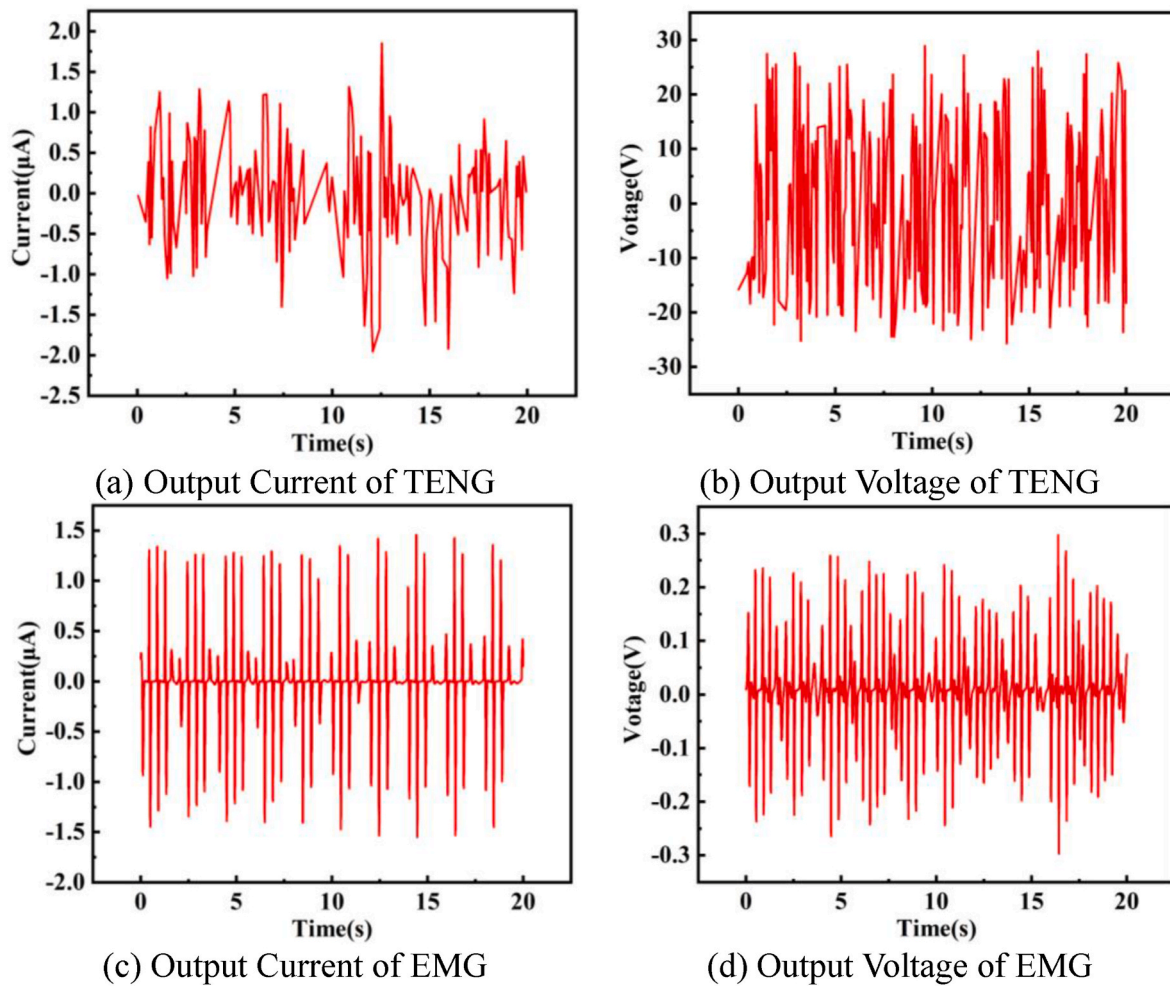
6. Conclusion

The triboelectric-electromagnetic hybrid energy harvesting device integrates TENG and EMG, effectively complementing each other's output characteristics, making it suitable for a wide range of operating frequencies. Based on the self-powering needs of marine sensors, this paper proposes an ITHEC, offering a new approach to solving this problem. The main conclusions of this study are as follows.

- (1) A structural dynamics simulation model was established using COMSOL Multiphysics software to analyze ITHEC's specific

motion under various operating conditions. With an amplitude of 50 mm and frequencies ranging from 1.3 Hz to 2.0 Hz, the rotor's swing angle increased from 62° to 158° before gradually decreasing to 96°. For a frequency of 1.5 Hz and amplitude variation from 30 mm to 60 mm, the swing angle increased from 90° to 169°.

- (2) Using optimized parameters in the finite element simulation model, the device's output performance under different conditions was calculated. The ITHEC demonstrated peak output at a frequency of 1.5 Hz and amplitude of 60 mm, with the TENG achieving a maximum short-circuit current of 1.3 μA and open-circuit voltage of 240 V, while the EMG attained a maximum short-circuit current of 2.4 mA and open-circuit voltage of 0.23 V.
- (3) A prototype of ITHEC was fabricated based on the optimal structure derived from simulations. Land-based tests were conducted with rabbit fur as the positive triboelectric material, PTFE as the negative, and copper as the electrode. Under 60 mm amplitude and 1.5 Hz frequency, the TENG achieved a maximum short-circuit current of 1.25 μA and open-circuit voltage of 60 V. The EMG, featuring NdFeB magnets (N33) and 1500 turns of copper wire, achieved a maximum short-circuit current of 2.2 mA and open-circuit voltage of 0.23 V. The strong agreement between theoretical, simulation, and experimental results validates the proposed methodology.
- (4) In a wave tank test conducted at the Yantai Research Institute of Harbin Engineering University, under wave conditions of 0.12 m height and 2.2 s period, the TENG reached peak short-circuit current and open-circuit voltage outputs of 2.0 μA and 30 V, respectively. The EMG produced peak short-circuit current and open-circuit voltage outputs of 1.5 mA and 0.25 V, with maximum power outputs of 1.18 mW and 0.51 mW, respectively. Through array deployment, ITHEC meets the operational current demands of small marine sensors, indicating its effectiveness in marine energy harvesting and potential for self-powered sensor applications.
- (5) In the actual marine environment, the long-term operation of ITHEC still faces several challenges, including corrosion, structural reliability, and long-term performance degradation. The



Figs. 5–19. Performance output of ITHEC water tank experiment.

high salinity and humidity of seawater may lead to aging of the TENG surface materials, reducing charge transfer efficiency. Similarly, the coils and magnets in the EMG unit may suffer from seawater corrosion, affecting output performance. Additionally, prolonged mechanical impact and fatigue could result in structural damage or wear of friction materials, thereby reducing the energy conversion efficiency of the device. Therefore, future research should focus on improvements in corrosion-resistant design, sealing and structural optimization, and the development of a well-planned maintenance strategy.

CRediT authorship contribution statement

Chongfei Sun: Writing – original draft, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Huaiyu Teng:** Writing – review & editing, Visualization, Validation, Software, Investigation, Data curation, Conceptualization. **Xiaoyan Ma:** Visualization, Validation, Project administration, Investigation, Data curation. **Hailong Chen:** Visualization, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation. **Liming Sun:** Visualization, Validation, Software. **Cun Shao:** Validation, Software, Investigation. **Fei Cao:** Validation, Project administration, Formal analysis. **Hengxu Liu:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest statement

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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