Nano Energy 69 (2020) 104440

Contents lists available at ScienceDirect

Nano Energy

journal homepage: http://www.elsevier.com/locate/nanoen

A chaotic pendulum triboelectric-electromagnetic hybridized nanogenerator for wave energy scavenging and self-powered wireless sensing system

Xin Chen [a,b,1], Lingxiao Gao [a,b,1], Junfei Chen [a], Shan Lu [a], Hong Zhou [a,b], Tingting Wang [c], Aobo Wang [c], Zhifei Zhang [d], Shifeng Guo [e], Xiaojing Mu [a,**], Zhong Lin Wang [b,f,g,***], Ya Yang [b,g,h,*]

[a] *Key Laboratory of Optoelectronic Technology & Systems Ministry of Education, International R & D Center of Micro-nano Systems and New Materials Technology, Chongqing University, Chongqing, 400044, China*

[b] *CAS Center for Excellence in Nanoscience, Beijing Key Laboratory of Micro-nano Energy and Sensor, Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing, 100083, China*

[c] *China Academy of Aerospace Aerodynamics, Beijing, 100174, China*

[d] *School of Automotive Engineering, Chongqing University, Chongqing, 400044, China*

[e] *Guangdong Provincial Key Laboratory of Robotics and Intelligent System, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen, 518055, China*

[f] *School of Material Science and Engineering, Georgia Institute of Technology, Atlanta, GA, 30332-0245, USA*

[g] *School of Nanoscience and Technology, University of Chinese Academy of Sciences, Beijing, 100049, China*

[h] *Center on Nanoenergy Research, School of Physical Science and Technology, Guangxi University, Nanning, Guangxi, 530004, China*

A R T I C L E I N F O

Keywords:
Hybridized nanogenerator
Chaotic pendulum
Wave energy
Self-powered wireless sensor system

A B S T R A C T

The marine environment monitoring system is of considerable significance to the sea development. However, the power-supply issue of the sensor nodes in the system is a crucial consideration all the time. Here, a chaotic pendulum triboelectric-electromagnetic hybridized nanogenerator integrated with the power management circuit to power the wireless sensing nodes by scavenging wave energy has been proposed. The physical design of the harvester utilized the virtue of low working frequency and high electromechanical conversion efficiency characteristics of the chaotic pendulum. To verify the utility and applicability of the hybridized nanogenerators, several experimental scenarios were selected, the maximum output power of TENG can reach 15.21 μW and the EMG is up to 1.23 mW as triggered by the water wave. The hybridizied nanogenerator can light up about 100 LEDs. Moreover, the self-powered wireless sensing node distant transmission has been realized, and data transmission capability exceeds 300 m. This study provides a new direction of scavenging low-frequency vibrations from the environment of marine, also in the aerospace and industry.

1. Introduction

The lack of land resources and the acceleration of urbanization desperately need the exploitation and utilization of marine resources [1–3]. However, an increasing number of human activities have gradually deteriorate the marine environment, and the development of monitoring system is vital problem and has attracted a batch of researchers to study [4,5]. Small multi-parameter ocean environment monitoring buoys have the advantages of small size [6,7], low energy consumption, real-time data transmission and suitable for the complex

* Corresponding author. CAS Center for Excellence in Nanoscience, Beijing Key Laboratory of Micro-nano Energy and Sensor, Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing, 100083, China.

** Corresponding author. Key Laboratory of Optoelectronic Technology & Systems Ministry of Education, International R & D Center of Micro-nano Systems and New Materials Technology, Chongqing University, Chongqing, 400044, China.

*** Corresponding author. CAS Center for Excellence in Nanoscience, Beijing Key Laboratory of Micro-nano Energy and Sensor, Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing, 100083, China.

E-mail addresses: mxjacj@cqu.edu.cn (X. Mu), zhong.wang@mse.gatech.edu (Z.L. Wang), yayang@binn.cas.cn (Y. Yang).

[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.nanoen.2019.104440
Received 19 November 2019; Received in revised form 25 December 2019; Accepted 26 December 2019
Available online 30 December 2019

marine environment, thus widely used in the field of marine monitoring [8–11]. The monitoring system most consists of a sensor network, a communication network, and monitoring parameters such as sea temperature and humidity [12,13]. As the primary means of monitoring the dynamic marine environment, buoys realize the monitoring of long-term fixed-point real-time stereo and help to have a better understanding of the marine environment. Also the buoys avoid the damage caused by maritime operations under adverse sea conditions [14–16].

At present, most ocean buoys are powered by batteries, and the sensor network consumes most of the battery's energy. The ocean buoy is far from land, and changing the battery of buoys is rather challenging, which limits its cost and stability for service. These cause the pollution of the marine environment and the cost of remanufacturing it. Thus the study of powering the sensor network of the marine environment monitoring system is still a hot research topic [17–19]. Many research groups have equipped the buoys with solar energy storage equipment, greatly reducing the number of battery changes. But the collection of solar energy is greatly affected by weather conditions, and the production of solar panels is characterized by high pollution and high energy consumption. Hence, an effective and nondestructive means supplying power to the sensor nodes of the marine environment monitoring system is highly desired [20–23].

Wave energy is considered as one of the most important sources of ocean energy, which is characterized by high energy density and weather resistance [24–26]. And its development and utilization have far-reaching significance for alleviating energy crisis and reducing environmental pollution. Although considerable efforts have been made for exploiting the wave energy to supply power sensor nodes for some time, rare advancements have been achieved. Current experimental machines usually need complex mechanical structures to catch and convert waves to highly regular motions for driving the generator. However, they are often bulky, costly and vulnerable in the harsh ocean environment. The triboelectric nanogenerator (TENG) provides a different way towards the goal [27–31]. Different from the electromagnetic generator [32–34], the TENG based on triboelectrification and electrostatic induction [35–37] has the superior advantages of lightweight and low cost, which is suitable and effective for low grade and low-frequency wave energy [38–41]. A batch of works hybridized the TENG with EMG utilizing many structures to harvest the wave energy and convert that into electrical energy to power sensor nodes [42–44]. Previously, Zhang et al. has reported a self-powered intelligent buoy system (SIBS), in which a high-output multilayered TENG is used for water wave energy harvesting [45]. In other hands, Lin et al. presented a pendulum structurehugely improving the harvesting efficiency through a transformation of impact kinetic energy into potential energy, but the designed harvester was justly a triboelectric nanogenerator [46]. This work has provided a universal platform for self-powered wireless sensor network nodes, but the consumed energy for wireless sensing and data transmission is a little bit high and close-range data transfer. Thus, a new design of hybridized nanogenerator to power the low-cost self-powered wireless sensor nodes is strongly desired.

Here, a chaotic pendulum triboelectric-electromagnetic hybridized nanogenerator for harvesting wave energy to power the wireless sensor nodes of the marine environment monitoring system is proposed. The structure is designed and calculated in line with the reciprocating motion of waves to effectively transfer wave energy into electricity. Results illustrate that the maximum output power of the TENG and EMG are 15.21 μW and 1.23 mW, respectively. And the hybridized nanogenerator can light up about 100 LEDs. Furthermore, the nanogenerators can effectively scavenge wave energy to power the wireless sensing nodes of the monitoring system and realize the remote transmission of marine environmental information to monitor the environment of ocean. In addition, the hybridized nanogenerator is widely applicable for the construction of other marine platforms.

2. Results and discussion

To solve power supply issues in buoys (Fig. 1a), a hybridized nanogenerator is presented. The motion of wave was analyzed to highly active harvest the ocean energy, as displayed in Fig. 1b, the waves travel because gravity pulls the water in the crests downward. Forced out from beneath the falling crests, the falling water pushes the former troughs upward, and the wave moves to a new position. Notice that the actual motion of the water itself beneath these waves is circular or orbital, which confirms our experience that we are carried up and forward as the wave approaches, and down and back as it passes. Owing to the reciprocating motion and low frequency of the wave, the nanogenerator is designed as a chaotic pendulum to harvest the wave energy effectively powering the sensing nodes within the buoy. The chaotic pendulum consists of the major pendulum and the inner pendulum, as exhibited in (Fig. 1c), the main pendulum is the model of mathematical pendulum and the inner pendulum consists of three magnetic balls equally spaced on the rotating shaft. The motion state of the chaotic pendulum is affected by the factors of initial position and starting speed. The major pendulum follows a simple rule that the pendulum swings back and forth at the time of the water wave oscillating. The inner pendulum starts to motion while the major pendulum swings, and the motion track is chaotic and unpredictable.

The hybridized nanogenerator consists of two parts, triboelectric nanogenerator (TENG) and electromagnetic nanogenerator (EMG), and the structure diagram of the designed nanogenerators is displayed in Fig. 1d. The TENG with polytetrafluoroethylene (PTFE) films and Au electrodes utilizing the freestanding triboelectric-layer mode is fixed onto the sector of the central pendulum. And PTFE film is chosen because of its high negativity. The three magnetic balls of the inner pendulum and three coils pasted on the inside acrylic installed on the sector of the central swing made up the EMG. The weighted ball of the major pendulum, a magnetic ball, were set to increase the oscillation frequency of the inner pendulum and enhance the output electric of the EMG. When the triboelectric-electromagnetic hybridized nanogenerator is motivated from water oscillation, the PTFE film is fixed on the inner pendulum slide on the interdigitated electrode to converting oscillating mechanical energy into electrical energy. Meanwhile, the three magnetic balls inside the chaotic pendulum start to move under their own gravity and external magnetic incentive condition. That brings about the change of the magnetic flux of copper coils attached to the inner side of the chaotic pendulum. Thus, the triboelectric-electromagnetic hybridized nanogenerator could harvest the wave energy and transfer the low-frequency mechanical vibration into electric energy.

The motion trail of the nanogenerator is simplified and presented the working process of the TENG and EMG (Fig. 2a–b). And the working principle of the TENG is based on the triboelectric effect and electrostatic induction. Initially, chaotic pendulum is at rest, and the PTFE film and the Au electrode are in an entirely coincident position, the negative charges can be accumulated on the surface of the PTFE and the positive charges are aggregated on the surface of the Au electrode, it can be attributed to the electrical polarity of PTFE and Au at both ends of the electrical sequence of the triboelectric material. Amounts of positive charge and negative charge are equivalent electrostatic equilibrium in this state, so that there is no electron transfer from the respective electrodes. While the main pendulum gets a push as the excitation starts, and the PTFE is pasted on to the main pendulum rub with the Au electrode from the position of electron 1 to electron 2, the electric potential difference is produced during this procedure. The positive charges flow from the electrode 1 to the electrode 2 towards the sliding direction, and form an instantaneous current on the external load. When the main pendulum swings in the opposite direction, PTFE film and Au electron are contacted and rubbed from the direction electron 2 to electron 1, and the direction of current flowing is consistent with the main pendulum movement. Thus, the process of electricity generation is continuous, as displayed in Fig. 2c. For the TENG, the open circuit voltage (V_{OC}) and

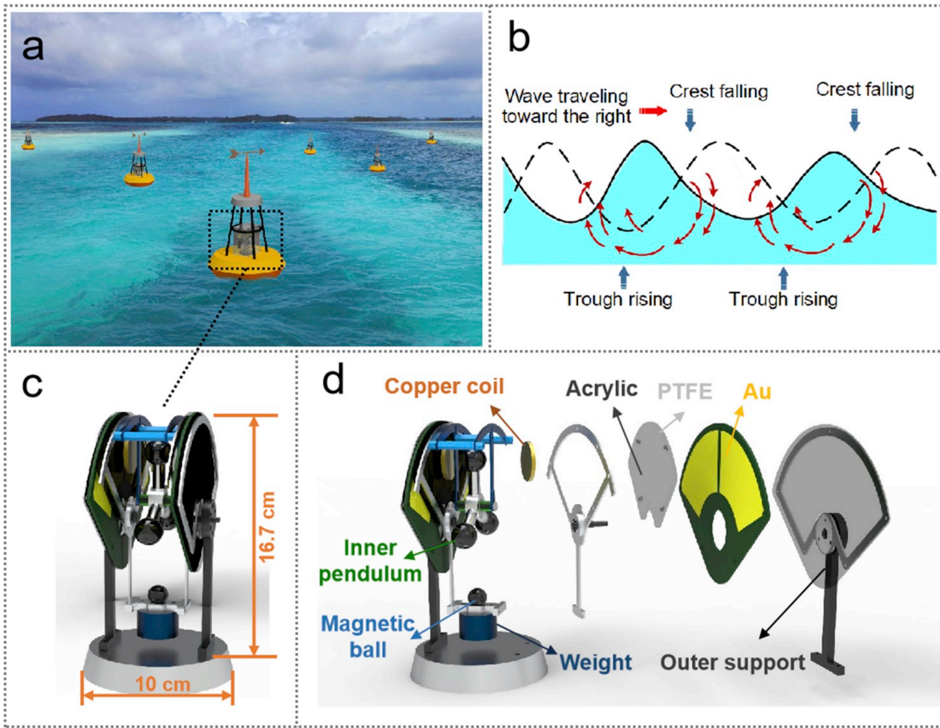

Fig. 1. Schematic diagram of the designed triboelectric-electromagnetic hybridized nanogenerator. a) Schematic diagram of hybridized nanogenerator used to monitor waves around a marine buoy. b) Diagram of wave motion model. c-d) Structural schematic diagram of the hybridized nanogenerator.

the transfer charge (Q_{SC}) under short-circuit conditions can be represented as [47–50].

$$V_{oc} = \frac{\sigma S}{C} \tag{1}$$

$$Q_{SC} = \int I_{SC} dt \tag{2}$$

where σ is the transfer charge density, S is the contact area between the PTFE and Au electrode, and C is the capacitance.

While the COMSOL Multiphysics software based on finite element simulation is used to calculate the potential distribution of two electrodes and PTFE film under different conditions, as presented in Fig. 2d. The results of the simulation intuitionistic describe the electric field of the triboelectric nanogenerator in motion. The underlying profile clearly illustrates the potential difference between the two electrodes, driving the current flowing in the external circuit.

The EMG is based on the principle of electromagnetic induction, producing an alternating current by a periodic change of magnetic flux. Fig. 2e illustrates the working principle of the EMG component. When the magnetic ball moves close to the coil, the magnetic flux in the coil increases at the time of the separation distance decreasing between the magnetic ball and coil, and the induced current is generated in the process. As the magnetic ball moves far from the coil, the magnetic flux in the coil reduces, and a reverse induced current is generated inside the loop. According to Faraday's law of electromagnetic induction, the induced electromotive force can be expressed as

$$E = -n\frac{d\Phi}{dt} \tag{3}$$

where E is induced voltage, n is the induction coil turns, Φ is the magnetic flux, and t is the time.

Then, the magnetic ball is kept moving to the position where has no magnetic flux change in the coil and the induced current is zero. With the reciprocating motion of the magnetic for a period, a full cycle of the electricity generation process finishes. The three-dimension model is also built by COMSOL software, and the simulation result of the working process of electromagnetic energy harvesting is presented in the Supporting Information Video S1. When the pendulum was subjected to the water wave, the three magnetic balls can rotate inner the chaotic pendulum, and the induced electromotive force in coils varies with the rotational position of the magnetic ball. Thus, the chaotic pendulum triboelectric-electromagnetic hybridized nanogenerator could generate the alternating current by combining the TENG part with EMG part.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.nanoen.2019.104440.

We simplified the model of the chaotic pendulum as the double pendulum, a classic model, to investigate the movement modal of the nanogenerators efficiently harvesting low-frequency environmental vibration, as presented in Fig. 3a. The position of a double pendulum is characterized by two angles ϕ_1 and ϕ_2 between the rods and the vertical. The length of the rods l_1 and l_2 and the bobs masses m_1 and m_2 are the control parameters. The positions of the bobs are

$$\begin{aligned} x_1 &= l_1 sin\phi_1; \\ y_1 &= -l_1 cos\phi_1; \\ x_2 &= l_1 sin\phi_1 + l_2 sin\phi_2; \\ y_2 &= -l_1 cos\phi_1 - l_2 cos\phi_2 \end{aligned} \tag{4}$$

The Lagrangian of a double pendulum is

$$\begin{aligned} L = &\frac{1}{2}(m_1+m_2)l_1^2\left(\frac{d\varphi_1}{dt}\right)^2 + \frac{1}{2}m_2 l_2^2\left(\frac{d\varphi_2}{dt}\right)^2 + m_2 l_1 l_2\left(\frac{d\varphi_1}{dt}\right)\left(\frac{d\varphi_2}{dt}\right)\cos(\varphi_1-\varphi_2) \\ &+ (m_1+m_2)gl_1\cos\varphi_1 + m_2 g l_2 \cos\varphi_2 \end{aligned} \tag{5}$$

leading to the following equations of motion [51].

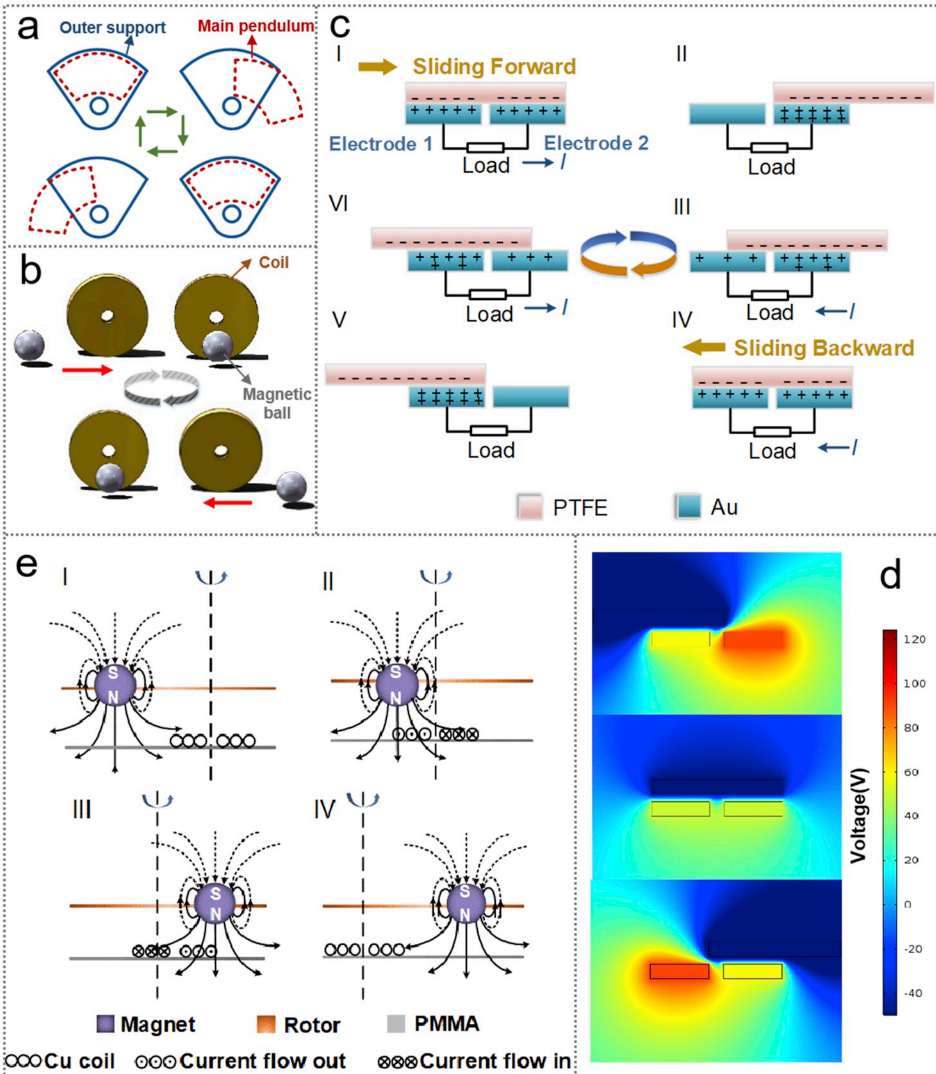

Fig. 2. Operating principle of the hybridized nanogenerator. a-b) The schematic of two direction of motion: a) the motion trail of Au electrodes and the PTFE film, and b) the motion trail of the magnetic ball and coil. c) The working principle of the TENG unit and the charge distributed in different stages. d) Simulated voltage profile of the two Au electrodes and the PTFE film with various positions. e) The working principle of the EMG unit.

$$(m_1+m_2)l_1\frac{d^2\varphi_1}{dt^2}+m_2l_2\frac{d^2\varphi_2}{dt^2}\cos(\varphi_1-\varphi_2)+m_2l_2\left(\frac{d\varphi_2}{dt}\right)^2\sin(\varphi_1-\varphi_2)+(m_1+m_2)g\sin\varphi_1=0 \tag{6}$$

$$m_2l_2\frac{d^2\varphi_2}{dt^2}+l_1\frac{d^2\varphi_1}{dt^2}\cos(\varphi_1-\varphi_2)-l_1\left(\frac{d\varphi_1}{dt}\right)^2\sin(\varphi_1-\varphi_2)+g\sin\varphi_2=0 \tag{7}$$

As the equations of motion depict, the motion of the pendulum is non-linear and unpredictable. While the pendulum swings back and forth, there is the energy exchange between the main pendulum and the inner pendulum, increasing the energy storage of the device compared to the simple pendulum. The initial conditions of the pendulum are different, and the motion state of the pendulum is changed [52]. Actually, the external random force added to the chaotic system is normal. The following equations explain the motion of the pendulum on that condition.

$$\frac{d^2\varphi}{dt^2}+\alpha\frac{d\varphi}{dt}+\sin\varphi=\xi(t) \tag{8}$$

This formula describes a damped Brownian particle moving in a periodic potential.

According to the fluctuation-dissipation theorem for a stationary state, a gain of energy entering the system is exactly compensated by the energy loss to the reservoir, which gives

$$\langle\xi(t)\xi(0)\rangle=2\alpha k_BT\delta(t) \tag{9}$$

where k_B is the Boltzmann constant. The velocity-velocity autocorrelation function gives the frequency-dependent mobility μ (w, T),

$$\mu(w,T)=\frac{1}{k_BT}\int_0^\infty dt\langle\frac{d\varphi}{dt}(t)\frac{d\varphi}{dt}(0)\rangle\exp(iwt) \tag{10}$$

There may be one more advantages of the chaotic system. Linear system inevitably has resonant frequency range with limited bandwidth. For these systems, it performs efficiently at the optimum frequency and amplitude, but loses responsivity in out-range inputs. Besides, the chaotic system has wider responsivity to react randomness of input energy, which makes the device more versatile. To prove the feasibility of this structure in collecting wave energy, simulate the motion trajectory of the chaotic pendulum through the Adams software under a persistent excitation of sinusoidal excitation (sin30°) conformed to the actual wave motion trail. The motion state of the device is shown in

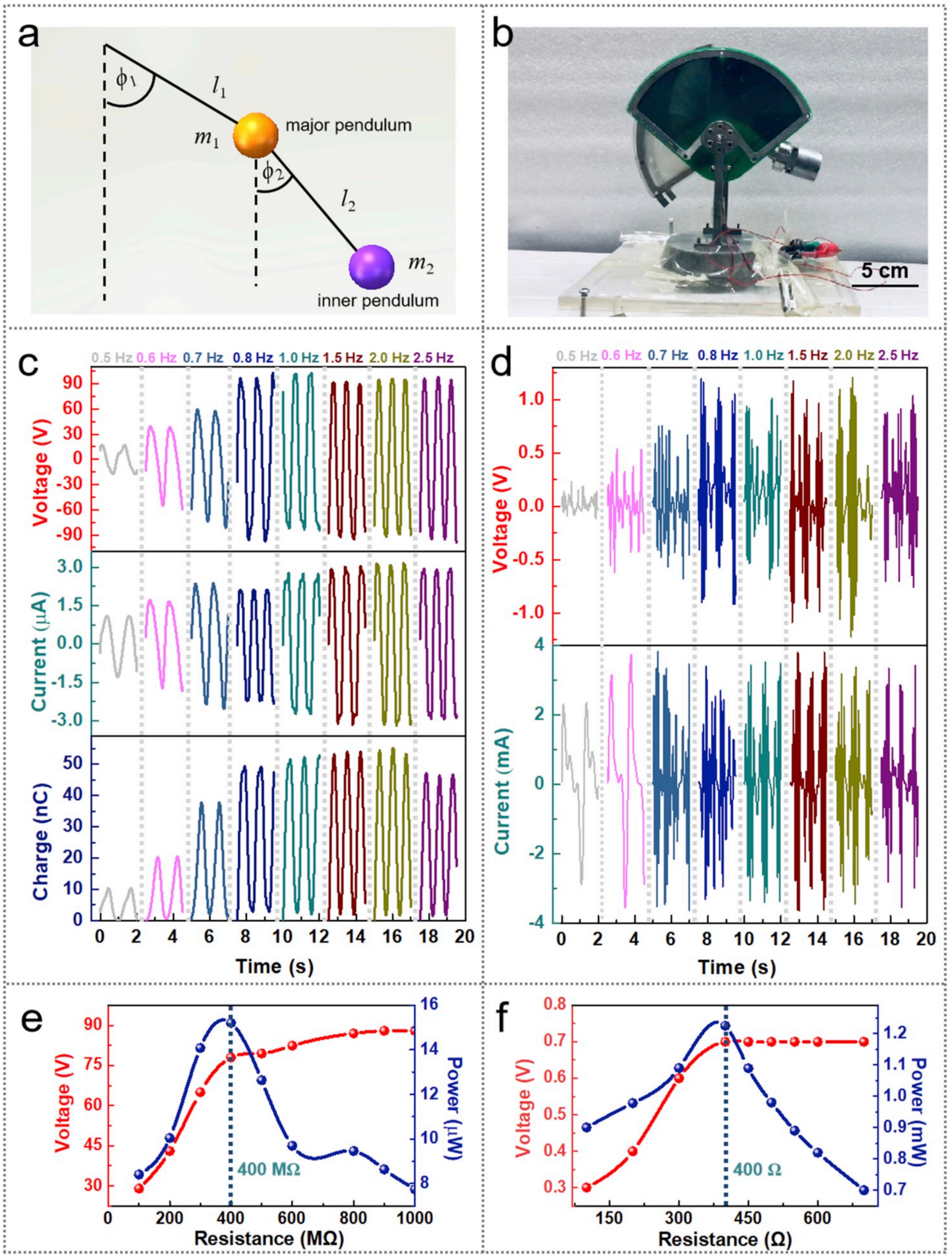

Fig. 3. Electrical measurement results of TENG and EMG, and a line motor is used to control the movement of the device. a) The simplified model of the chaotic pendulum. b) The nanogenerators are motivated by the linear motor. c) The output voltage, the short-circuit current and the transfer charge of the TENG under different frequencies. d) The output voltage and the short-circuit current of the EMG under different frequencies. e) Dependences of the output voltage and output power of the TENG and f) the EMG with impedance resistance.

Video S2 (Supporting Information). A linear motor producing uniform variable rectilinear motion was utilized in vertical direction to verify the above theory in Fig. 3b and Video S3 (Supporting Information). Usually, the halcyon condition of wave in the ocean is a common situation. To investigate the wave energy harvesting under the common circumstance, the frequency of the motor ranging from 0.5 Hz to 2.5 Hz was set to simulate that situation. The device was stuck on an acrylic platform fixed on the motor, and a programmable electrometer was used to measure the open circuit voltage and short circuit current of the nanogenerators. On account of the pendulum being a centrosymmetric device, and the output electric of symmetrical TENGs and EMGs being similar, we set the one side TENG and EMG as the sample demonstrating the output characteristic curve of the hybridized nanogenerator. With the variation of the excitation force frequency from 0.5 Hz to 2.5 Hz, the peak values of the output open voltage, the output short current, and the transferred charges all first rise and then level out. The maximum instantaneous peak-to-peak output voltage of the TENG is 197.03 V, the open circuit current is about 3 μA, and charges is 54 nC (Fig. 3c). The trend of EMG's electrical output characteristics change tendency is dissimilar to the TENG, the output electric of EMG is maximum as the excitation reaches the natural frequency, the open circuit voltage of EMG is 1.08 V, and the short circuit current is approached to 4 mA (Fig. 3d). With the increase of the frequency, the output power of TENG is leveling out, but the power of EMG is improving, which proves the theory of chaotic pendulum. The instantaneous peak output power of the hybridized nanogenerator was measured under the external excitation with frequency of 2.5 Hz, as presented in Fig. 3e–f. Once a variable external load is connected to the EMG and TENG, the output voltage rises as the load resistance increases. The instantaneous peak output power of the TENG increases from 8.41 μW to 15.21 μW as the resistance changes from 100 MΩ to 400 MΩ and then decreases with the larger load resistance, which indicats that the maximum instantaneous peak output power is located at the resistance of 400 MΩ. The output power of the EMG has the same trend as the TENG, and the instantaneous peak output power of EMG is 1.23 mW under a matched load resistance of 400Ω.

Supplementary video related to this article can be found at https

://doi.org/10.1016/j.nanoen.2019.104440.

Subsequently, the water pump was used to study the effect of amplitude factors on the nanogenerator to harvest the wave energy at the frequency of 2 Hz. The output electricity was studied on the condition of the water wave amplitude ranging from 3 cm to 7 cm, taking the horizontal plane at rest as the zero reference level. The output characteristics of the hybridized nanogenerator were measured under different amplitudes, as diagramed in Fig. 4a. The output voltage, output current, and transferred charges all increased with increasing the amplitude continuously (Fig. 4b), which implies that as the amplitude of the wave goes up, the main pendulum swinging augments the friction area between the gold electrode and PTFE. When the amplitude range from 3 cm to 7 cm, the voltage, current, and charges are separately enhanced to 120 V, 2.8 μA, and 42 nC. The output trend of the EMG is chaotic, and the maximum output electric of EMG is reached 1 V and 4 mA (Fig. 4c). This result indicates that, as the amplitude of the wave rises, the frequency of the pendulum swing rises with the increment of the main pendulum swing amplitude. The short circuit current and the open circuit voltage of TENG2 and EMG2 under the condition of the different amplitude are depicted in Fig. S1(Supporting Information). Under the excitation of the amplitude of 7 cm, the short circuit current and the open circuit voltage of TENG and EMG are diagramed in Fig. S2 (Supporting Information), respectively. Furthermore, the harvester was tested in the actual condition, Jialing River was chosen (Fig. 4d, Video S4), and the output electricity was depicted in Fig. S3(Supporting Information). The input energy of the river is random, and the nanogenerator transferred the random force into power energy, the wide responsivity to react randomness is better than that of linear systems in the actual environment. Based on the above analysis, water wave excitation with a frequency of 2 Hz and an amplitude of 7 cm were chosen for the next experiments. In addition, the durability of the TENG in the experiment of water is presented in Fig. 4e. To demonstrate the efficiency of energy harvesting, the output voltage of TENG and EMG under a trigger is shown in Fig. S4 in the supporting information, and the

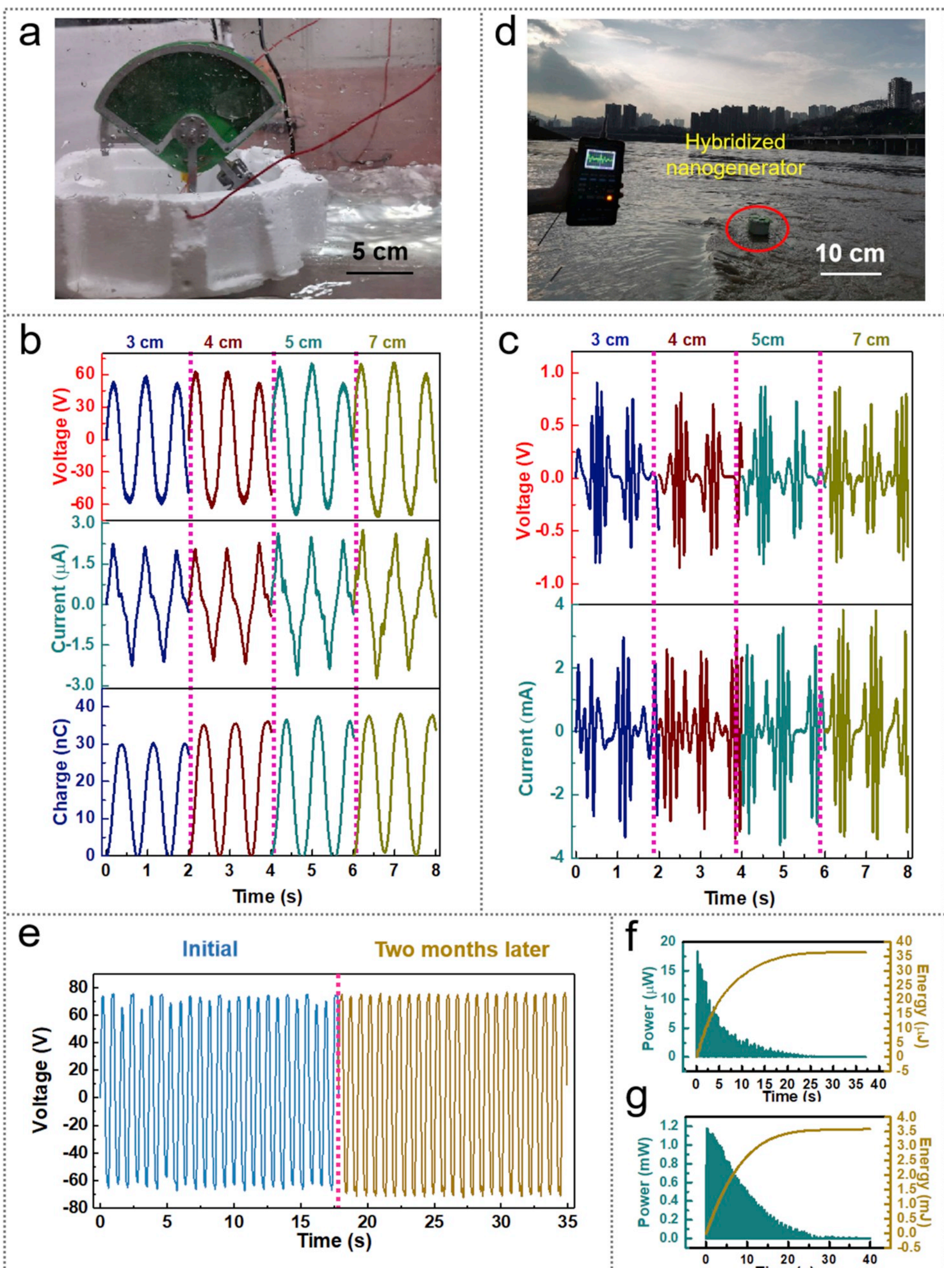

Fig. 4. Electrical measurement results of TENG and EMG, and a water pump is used to control the movement of the device, also in the actual environment. a) Test in the wave energy. b) The output voltage, the short-circuit current and the transfer charge of the TENG under different amplitude. c) The output voltageand the short-circuit current of the EMG under different amplitude. e) Stability of the triboelectric nanogenerator. f) Output power and converted energy of TENG for a trigger with impedance of 400 MΩ. g) Output power and converted energy of EMG for a trigger with impedance of 400 Ω.

output power and converted energy of EMG for a trigger with impedance are demonstrated in Fig. 4f–g.

The charging capability of the hybridized nanogenerator was investigated, the external excitation of the frequency was 2 Hz and the amplitude is 7 cm in this experiment. We set the targeting voltage at 3 V. It is found that the smaller the capacitance (10 μF) of the capacitor is the shorter charging time is used (10 s) to achieve the target, while the larger capacitance (100 μF) of the capacitor is, the longer charging time is used (200s). Fig. 5a presents the results of the charging time. On account of the chaotic pendulum triboelectric-electromagnetic hybridized nanogenerator having excellent electrical output, about 100 LEDs are connected in parallel and lighted by the hybridized nanogenerator (Fig. 5b). Also, the frequency and amplitude of the external excitation are 2 Hz and 7 cm, respectively. The experiment demonstration could be found in a Video S5 (Supporting Information).

Supplementary video related to this article can be found at https://doi.org/10.1016/j.nanoen.2019.104440.

The output electricity of the TENG and EMG is alternating current, and that output mode cannot be used to power the sensing nodes. Thus, the power management circuit was designed to convert the time-varying electric output into a constant voltage, and the output characteristics of the TENG and EMG, a high output voltage and a high output current, were utilized to simplify the design of the power management circuit powering for the applications. The whole circuit consists of the rectifier bridge, the storage capacitor (47 μF), the control circuit, and the voltage regulator module, used to process, store and control the energy, as displayed in Fig. 5c. While the hybridized nanogenerator started to generate electricity, the rectifier bridge and electrolytic capacitor was used to store the energy generated by the TENGs and EMGs. For the purpose of efficiently storing energy into the capacitor, the power management circuit was utilized to improve the efficiency of collecting the output electricity of nanogenerator. While the transistor, diode and N-channel MOSFET together with LDO voltage regulators (MAX 666) were set to monitor the storage capacitor voltage. We calculated the power demand for subsequent experiment of wireless sensing nodes transmission, and the proper setting of the charge voltage limit is critical and ranges from 3 V to 11 V one cycle, as presented in Fig. S5. While power supply output voltage exceeds its setting, the hardware switches on, and the discharge power of the capacitor power (about 2.6 mJ once time) is connected with voltage regulator module LDO, regulating the voltage to 3.3 V to power the wireless sensing nodes. The wireless sensing node system consists of a temperature sensor, a radio frequency (RF) module transmitter, a radio frequency receiver and a monitor system on the laptop. The picture of the module is displayed in Fig. 5d–e. The data sender includes the temperature sensor and the radio frequency module transmitter. The temperature of the surrounding conditions is detected via the temperature sensor and is transferred through the RF module transmitter, while the energy consumed by the processing of

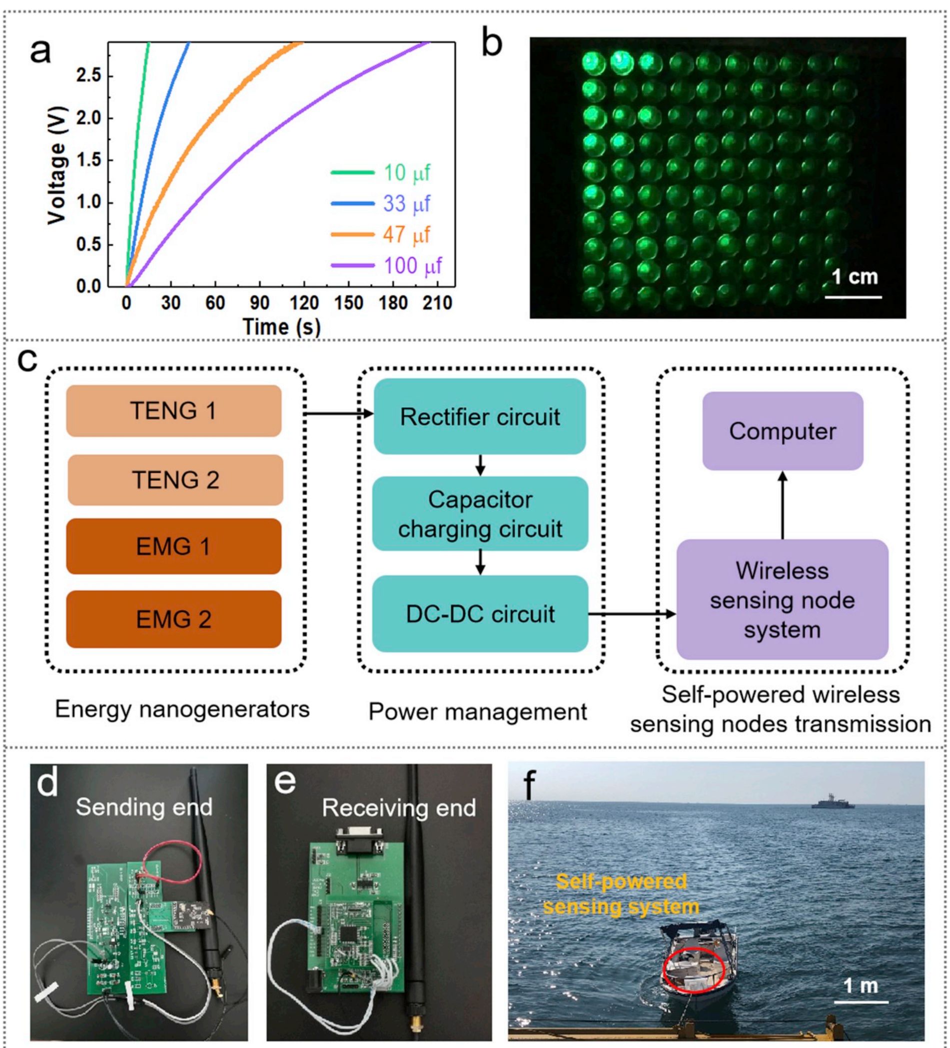

Fig. 5. Application of the hybridized nanogenerator. a) The charge time of the hybridized nanogenerator for different capacitors. b) Powering 100 light-emitting diodes (LEDs) in parallel. c) The schematic circuit diagram of the self-powered wireless sensing nodes transmission system. d-f) Self-powered wireless sensing nodes transmission system enabled by the hybridized nanogenerator in Bo Hai.

data collection and transmission is around 0.75 mJ, a lower energy. And the data is received at the interface of the monitoring system on the notebook computer by means of RF receiver, however, the receiving end is powered by the computer. The data remote transmission capability exceeds 300 m, and the wirelesses was tested in the laboratory (Fig. S6), also was tested in the Bohai installed on the boat (Fig. 5f). The self-powered wireless sensing nodes transmission system enabled by the hybridized nanogenerator is displayed in the laboratory (Video S6)and in Bohai (Video S7), and the tested temperature is shown in Fig. S7 in the supporting information. The results of the above experiments indicate that the hybridized nanogenerator is a practical application in marine ecosystem monitoring, otherwise, this designed nanogenerator could be widely used in other small offshore platforms powering sensing node.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.nanoen.2019.104440.

3. Conclusion

In summary, to efficiently scavenge mechanical energy from blue energy, a chaotic pendulum triboelectric-electromagnetic hybridizedizied nanogenerator and self-powered wireless sensing nodes system is proposed. The nanogenerator possessing the advantages of low working frequency and high electromechanical conversion efficiency was investigated to scavenge the mechanical vibration for powering wireless sensor node under different experimental conditions. The maximum output power of the TENG and EMG on wave excitation forces conditions are 15.21 μW and 1.23 mW, respectively. The nanogenerator can illuminate about 100 LEDs. Moreover, the nanogenerators can power the wireless sensing node of the marine environment monitoring system on the buoy and the self-powered sending end transfer the monitoring data to base station. The design of the chaotic pendulum triboelectric-electromagnetic hybridized nanogenerator provides an innovative and effective method toward blue energy harvesting. This work demonstrates a new direction to scavenge the low-frequency, chaotic vibrations in the other ambient environment.

4. Experimental section

Fabrication of the nanogenerator: The nanogenerator is manufactured through machining technicality, and the structure of the nanogenerators is fabricated by aluminum plate (1 mm) and acrylic (3 mm), via precision cutting technology and laser cutting technologies. The device has a total dimension of 167 mm in height and the diameter of support pedestal is Φ100 mm, including the main pendulum and inner pendulum. The TENG is comprised of PTFE (80 μm) attached on the outer side of main pendulum and Au electrode (50 nm) fixed on the outer support, while the inner pendulum and one coil consist of the EMG, and three magnetic spherules of inner pendulum is made up of ferrite magnet.

COMSOL simulation: The magnetic force of spherical magnets with different diameters was numerically calculated by a commercial software COMSOL 5.3a. The flux density and the relative magnetic permeability for the magnet were set as 1 T and 1.05 respectively. The magnetic force was calculated at different distances.

Measurement system: The output electric (output voltage, short-circuit current and transfer charge quantity) of the hybridized nanogenerator were measured by a programmable electrometer (Keithley 6514) and a data acquisition card (NIPCI-6259) on a desktop PC. And the hybridized nanogenerator was fixed on the liner motor (DGL200-S3-1300-S). In addition, a wave simulation system and a variable water pump (CX-W3) were simulated for waves in the actual environment, and the hand oscilloscope (Hantek2C42) was used to test the output voltage of nanogenerators in the actual environment.

Wireless sensing node transmission system: The system consisted of temperature sensor (SI7050) integrated with RF data sending module (NRF24LE1-1), data receiving end (NRF24LE1-2) and the monitor system on the laptop. The processor chip within the temperature sensor converted the perceived temperature analog signal into digital signal and transmited it to the remote transmitter, the digital signal was processed by 51 MCU in the data sending module transmitting to the data receiving end and display in the laptop.

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.

Acknowledgements

This work was supported by the National Key Research and Development Program of China (Grant No. 2016YFB0402702, Grant No. 2016YFA0202701), National Natural Science Foundation of China (Grant No. 51605060, Grant Nos. 51472055), the Fundamental Research Funds for the Central Universities (No. 2018CDPTCG0001-5), the Chongqing municipality key research and development program of china (Grant No. cstc2017rgzn-zdyfX0041), the Research Funds from Shanghai Institute of Space Power-source (YF07050118F5655), External Cooperation Program of BIC, Chinese Academy of Sciences (Grant No. 121411KYS820150028), the 2015 Annual Beijing Talents Fund (Grant No. 2015000021223ZK32), Qingdao National Laboratory for Marine Science and Technology (No. 2017ASKJ01),the University of Chinese Academy of Sciences (Grant No. Y8540XX2D2), and the State Education Ministry and Fundamental Research Funds for the Central Universities (2019 CDJSK 04 XK 23).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.nanoen.2019.104440.

References

[1] K. Sherman, Ecol. Appl. 1 (1991) 350–360.
[2] C. Sguotti, X. Cormon, YOUMARES 8 – Oceans across Boundaries: Learning from Each Other, vol. 8, 2018, pp. 155–166.
[3] G. Bailey, N. Flemming, Quat. Sci. Rev. 27 (2008), 0-2165.
[4] G. Xu, W. Shen, X. Wang, Sensors 14 (2014) 16932–16954.
[5] X. Yang, K. Ong, W. Dreschel, K. Zeng, C. Mungle, C. Grimes, Sensors 2 (2002) 455–472.
[6] J. Vesecky, K. Laws, S. Petersen, C. Bazeghi, D. Wiberg, Int. Geosci. Remote Sens. Symp. 7 (2007) 4987–4990.
[7] K. Liu, Z. Yang, M. Li, Z. Guo, Y. Guo, F. Hong, X. Yang, Y. He, Y. Feng, Y. Liu, Comput. Commun. Rev. 14 (2010) 7–9.
[8] C. Albaladejo, F. Soto, R. Torres, P. Sánchez, J. López, Sensors 12 (2012) 9613–9634.
[9] L. Xu, J. Zhang, H. Li, P. Ye, X. Yan, X. Li, J. Netw. 7 (2012) 1900–1907.
[10] C. Albaladejo, P. Sánchez, A. Iborra, F. Soto, J. Lopez, R. Torres, Sensors 10 (2010) 6948–6968.
[11] B. Petolas, R. Mahr, Oceans (1998).
[12] H. Yu, X. He, W. Ding, Y. Hu, D. Yang, S. Lu, C. Wu, H. Zou, R. Liu, C. Lu, Z. L. Wang, Adv. Energy Mater. (2017) 1700565.
[13] Y. Yang, H. Zhang, R. Liu, X. Wen, T. Hou, Z.L. Wang, Adv. Energy Mater. 3 (2013) 1563–1568.
[14] G. Zhao, Algorithms 3 (2011) 46–63.
[15] H. Mitsuyasu, F. Tasai, T. Suhara, S. Mizuno, M. Ohkusu, T. Honda, Phys. Oceanogr. 5 (2010) 286–296.
[16] P. Jiang, H. Xia, Z. He, Z. Wang, Z. Sensors 9 (2009) 6411–6434.
[17] M. Cardei, J. Wu, Comput. Commun. 29 (2006) 413–420.
[18] M. Raul, G. Samuel, A. Miguel, L. António, F. Salviano, P. Ferreira, M. Reis, Comput. Electron. Agric. 64 (2008) 120–132.
[19] Z.L. Wang, Nature 542 (2017) 159–160.
[20] S. Wang, X. Mu, X. Wang, A. Gu, Z.L. Wang, Y. Yang, ACS Nano 9 (2015) 9554–9563.
[21] S. Wang, X. Mu, Y. Yang, C. Sun, A. Gu, Z.L. Wang, Adv. Mater. 27 (2015) 240–248.
[22] L. Gao, D. Hu, M. Qi, J. Gong, H. Zhou, X. Chen, J. Chen, J. Cai, L. Wu, N. Hu, Y. Yang, X. Mu, Nanoscale 10 (2018) 19781–19790.
[23] T.P. Ding, L.L. Zhu, X.Q. Wang, K.H. Chan, X. Lu, Y. Cheng, G.W. Ho, Adv. Energy Mater. 8 (2018) 1802397.
[24] R. Pelc, R. Fujita, Mar. Policy 26 (2002) 471–479.
[25] S. Salter, Nature 249 (1974) 720–724.

[26] J. Tollefson, Nature 508 (2014) 302–304.
[27] J. Hu, X.J. Pu, H.M. Yang, Q.X. Zeng, Q. Tang, D.Z. Zhang, C.G. Hu, Y. Xi, Nano Res. 12 (2019) 3018–3023.
[28] T. Kim, J. Chung, D.Y. Kim, J.H. Moon, S. Lee, M. Cho, S.H. Lee, S.M. Lee, Nano Energy 27 (2018) 340–351.
[29] X.Q. Wang, C.F. Tan, K.H. Chan, K.C. Xu, M.H. Hong, S.W. Kim, G.W. Ho, ACS Nano 11 (2017) 10568.
[30] D. Heo, T. Kim, H. Yong, K.T. Yoo, S.M. Lee, Nano Energy 50 (2018) 1–8.
[31] H.M. Yang, M.M. Deng, Q. Tang, W.C. He, C.G. Hu, X. Yi, R.C. Liu, Z.L. Wang, Adv. Energy Mater. 9 (2019) 1901149.
[32] C. Saha, T. Donnell, N. Wang, P. McCloskey, Sens. Actuators A Phys. 147 (2017) 248–253.
[33] E. Koukharenko, S. Beeby, M. Tudor, N. White, T. Donnell, C. Saha, S. Kulkarni, S. Roy, Microsyst. Technol. 12 (2006) 1071–1077.
[34] P. Grishchuk, Physics 6 (2003), 0306013.
[35] Z.L. Wang, Mater. Today 20 (2017) 74–82.
[36] J. Chung, H. Yong, H. Moon, Q.V. Duong, S. Choi, D. Kim, S.M. Lee, Adv. Sci. 5 (2018) 1801054.
[37] Y. Xi, H.Y. Guo, Y.L. Zi, X.G. Li, J. Wang, J.N. Deng, S.M. Li, C.G. Hu, X. Cao, Z. L. Wang, Adv. Energy Mater. 7 (2017) 1602397.
[38] T. Zhou, X. Li, C. Zhang, C. Han, Z.L. Wang, L. Zhang, T. Jiang, Nano Energy 22 (2016) 87–94.
[39] P. Cheng, H. Guo, Z. Wen, C. Zhang, X. Yin, X. Li, D. Liu, W. Song, X. Sun, J. Wang, Z.L. Wang, Nano Energy 57 (2019) 432–439.
[40] G. Liu, H. Guo, S. Xu, C. Hu, Z.L. Wang, Adv. Energy Mater. (2019) 1900801.
[41] Z.L. Wang, Y. Yao, L. Zhang, T. Xiao, T. Jiang, L. Xu, Nano Energy 31 (2016) 560–567.
[42] H. Guo, Z. Wen, Y. Zi, M. Yeh, J. Wang, L. Zhu, C. Hu, Z.L. Wang, Adv. Energy Mater. 6 (2016) 1–7.
[43] L.L. Zhu, T.P. Ding, M.M. Gao, C.K.N. Peh, G.W. Ho, Adv. Energy Mater. 9 (2019) 1900250.
[44] H. Shao, P. Cheng, R. Chen, L. Xie, N. Sun, Q. Shen, X. Chen, Q. Zhu, Y. Zhang, Y. Liu, Z. Wen, X. Sun, Nano-Micro Lett. 10 (2018).
[45] X.Q. Wang, C.F. Tan, K.H. Chan, X. Lu, L.L. Zhu, S.W. Kim, G.W. Ho, Nat. Commun. 9 (2018) 3438.
[46] Z.M. Lin, B.B. Zhang, H.Y. Guo, Z.Y. Wu, H.Y. Zou, J. Yang, Z.L. Wang, Nano Energy 64 (2019) 103908.
[47] C. Hou, T. Chen, Y. Li, M. Huang, Q. Shi, H. Liu, L. Sun, C. Lee, Nano Energy 63 (2019) 103871.
[48] Y. Wu, X. Wang, Y. Yang, Z.L. Wang, Nano Energy 11 (2015) 162–170.
[49] Y. Zhu, A. Yu, R. Cao, R. Wen, M. Jia, Y. Lei, Y. Zhang, Y. Liu, J. Zhai, Adv. Electron. Mater. 4 (2018) 1800161.
[50] K. Zhang, Y. Wang, Y. Yang, Adv. Funct. Mater. (2018) 1806435.
[51] M. Gitterman, The Chaotic Pendulum, 2010.
[52] L. Gregory Baker, Am. J. Phys. 63 (1995) 832.

Xin Chen received the M.S. degree from the School of Measurement and Communication at Harbin University of Science & Technology, China, in 2018. She is currently pursuing the Ph.D. degree under the supervision of Prof. Xiaojing Mu at Chongqing University, China. Her research interests focus on energy harvester.

Lingxiao Gao received the M.S. degree from the Chongqing University in 2014. She is currently a Ph.D. candidate under the supervision of Prof. Xiaojing Mu at Chongqing University, China. Her research interest mainly includes the synthesis of flexible films and energy harvester.

Junfei Chen received the B.E. degree from Department of Electrical engineering at Southwest Petroleum University, China, in 2017. He is currently pursuing his M.S. degree from Instrumentation Engineering in Chongqing University, China. His research interests focus on energy harvesting devices and system.

Shan Lu received the M.S. degree from the Chongqing University of China, Chongqing, in 2016. He is currently pursuing the Ph.D. degree at the Key Laboratory of Optoelectronic Technology & Systems Ministry of Education, International R & D center of Micro-nano Systems and New Materials Technology, Chongqing University, Chongqing, China. His research interests mainly include energy harvester and its power management.

Hong Zhou received the B.Eng. degree from Department of Mechanical Engineering at Central South University, China, in 2013. He is currently pursuing his Ph.D. in Instrument Science and Technology with Chongqing University, China. His research interests focus mainly on nanophotonics, IR metamaterials and their sensing applications.

Tingting Wang is an engineer of unmanned underwater vehicles (UUVs) at China Academy of Aerospace Aerodynamics (CAAA). She obtained her master degree from Beihang University at 2017. Her research interests include guidance navigation and control (GNC), technology of ocean energy application of UUVs.

Aobo Wang is an engineer of unmanned underwater vehicle (UUV) at China Academy of Aerodynamics(CAAA). He obtained his master degree of Ship Building and Ocean Engineering from Harbin Engineering University at 2015.His research interests include design and application of modular UUV, autonomous recovery, energy system of UUV.

Dr. Zhifei Zhang is an associate professor of vehicle engineering at Chongqing University. He obtained his Ph.D. Degree from Chongqing University in 2008. He was a visiting researcher at University of Southampton. His research interests include vehicle vibration and control, vehicle noise and control, and vehicle dynamics.

Dr. Shifeng Guo is currently a full professor affiliated with Shenzhen Institutes of Advanced Technology (SIAT), Chinese Academy of Sciences. He received his Ph.D. degree in mechanical engineering from the National University of Singapore in 2013, and worked as a research scientist from 2012 to 2018 in Institute of Materials Research and Engineering (IMRE), A*STAR, Singapore. His research interests include flexible sensors and sensor networks, smart materials and structures, nondestructive evaluation (NDT) and structural health monitoring (SHM).

Dr. Xiaojing Mu is currently a full professor affiliated with College of Optoelectronic Engineering, Chongqing University. He is also the deputy executive director of "Defense Key Disciplines Lab of Novel Micro-nano Devices and System Technology" in Chongqing University. He received his Ph.D. degree in mechanical engineering from the National University of Singapore in 2013, and worked as a research scientist from 2013 to 2015 in Institute of Microelectronics (IME), A*STAR, Singapore. His research interests include energy harvester, Surface Acoustic Wave (SAW) sensor/filter, and M/NEMS technologies. He has published over 70 SCI journal papers, and authorized/applied 40 patents, including 4 international patents.

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

Prof. Ya Yang received his Ph.D in Materials Science and Engineering from University of Science and Technology Beijing, China. He is currently a professor at Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, China. He has developed various new hybridized and multi-effects coupled nanogenerators, opening up the new principles of the device design and coupled effects, and the new approaches of improving electric generation performances. His main research interests focus on the field of pyroelectric, piezoelectric, triboelectric, photovoltaic, and thermoelectric nanogenerators for energy conversion, storage, self-powered sensing, and some novel applications.