Triboelectric nanogenerator with deceleration strip for harvesting vibration energy

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Abstract. To achieve the peaking of carbon emission and carbon neutrality, optimizing the energy structure and accelerating the energy transformation has become an inevitable choice to tackle global climate change and promote sustainable development. The search for sustainable clean energy is urgently needed. In this paper, a triboelectric nanogenerator with deceleration strip (DS-TENG) is proposed to harvest the vibration energy in the environment. The DS-TENG comprises a displacement platform, a base plate, and six springs. The experimental data show that the output performance of DS-TENG: the open-circuit voltage 309 V, short-circuit current 16.6 μA, and transferred charge is 96.6 nC. Meanwhile, the DS-TENG can power the LED board with “20” pattern by harvesting energy from human movement. It can be seen the DS-TENG can harvest energy from low-frequency mechanical energy in the environment. Simultaneously the DS-TENG shows its potential application value in the field of energy collection and expands the application space of TENG in the human living environment.

1. Introduction

To achieve the peaking of carbon emission and carbon neutrality, optimizing the energy structure and accelerating the energy transformation has become an inevitable choice to tackle global climate change and promote sustainable development[1-2]. It also forces people to find sustainable clean energy to deal with the problem of energy shortage[3-4]. In the past decades, a variety of clean natural energy sources, such as solar energy, wind energy, marine energy, and mechanical energy, have been widely used to solve energy problems. Among them, vibration, as a typical mechanical motion, widely exists in the environment and our daily life, such as vehicle driving, bridge vibration, and human motion. In recent years, various types of energy harvesting devices based on electromagnetic and piezoelectric effects have been developed. At the same time, these devices can only work well at higher frequencies. However, the vibration frequency in the environment is relatively low, and the frequency is usually less than 10 Hz, which makes these devices not particularly suitable for harvesting energy from low-frequency mechanical energy. Therefore, to better harvest and utilize the low-frequency mechanical energy, it is of great significance to develop the equipment that can be used to harvest the low-frequency vibration energy.

Recently, the triboelectric nanogenerator (TENG) for harvesting mechanical energy in the environment has been proposed by Wang Group. TENG is a new method to convert mechanical energy into electrical energy[5]. TENG equipment shows good performance in collecting low-frequency
motion energy in the environment[6-9]. In recent years, TENG has become a research hotspot due to its various advantages, such as a wide range of materials, diverse working modes, low cost, and diverse structures[10]. Meanwhile, TENGs with various mechanical structures based on different working modes are widely used in the collection of wind energy[11-13], waves energy[14-17], and vibration energy[18-20]. Therefore, it is very promising to collect energy from low-frequency vibration by using TENG with good performance and low cost in the low-frequency environment[21].

In this study, triboelectric nanogenerator with deceleration strip (DS-TENG) for harvesting low-frequency vibration energy is proposed. The DS-TENG has the advantages of simple structure, easy installation, and lightweight. The working mode of the DS-TENG is the contact-separation mode. The DS-TENG comprises a displacement platform, a base plate, and six springs. The bottom of the displacement platform is covered with copper film, and a foam layer is attached to the base plate. A copper film with fluorinated ethylene propylene (FEP) is attached to the foam. Under the action of external excitation and springs, the electrode on the displacement platform and the electrode on the base plate produce contact-separation motion, which makes the DS-TENG output electrical signal. The experimental results show that the open-circuit voltage ($V_{OC}$), short-circuit current ($I_{SC}$), and transferred charge ($Q_{SC}$) of the DE-TENG are 309 V, 16.6 μA, and 96.6 nC. Simultaneously, the DS-TENG can power the LED board with “20” pattern by harvesting energy from human movement. The experimental results demonstrate that the DS-TENG can collect mechanical energy from the low-frequency motion, and demonstrate it has application in vibration energy harvesting. At the same time, it expands the application space of TENG in the human living environment.

2. Results and discussion

2.1. Structure
The overall structure of the DS-TENG is demonstrated in Figure 1(a). The DS-TENG comprises a displacement platform, a base plate and six springs. When the external excitation acts on the displacement platform, the displacement platform moves downward. When the external excitation disappears, the displacement platform returns to the initial position with the help of the springs. The movement of the displacement platform will make the electrode attached to the displacement platform contact and separate from the electrode attached to the base plate. The complete prototype of the DS-TENG is shown in Figure 1(b). Simultaneously, details of the base plate are presented in Figure 1(c). The displacement platform is shown in Figure 1(d).

Figure 1. Basic structure of the DS-TENG: (a) overall structure, photographs of (b) DS-TENG, (c) the structure of displacement platform, and (d) base plate.
2.2. Working principle
The DS-TENG adopts contact-separation mode, and its specific working principle is demonstrated (Figure 2). In the initial state, the top copper electrode and FEP film are separated with the help of spring [Figure 2a(i)]. When the copper electrode gradually approaches the FEP film, the potential difference between the copper electrode and FEP film will drive electrons from the top electrode to the bottom electrode, and the load circuit will generate current [Figure 2a(ii)]. When the top copper and FEP film are in full contact, equal amount of opposite charges are generated between the copper film and the FEP film [Figure 2a(iii)]. When the two surfaces of the top electrode and FEP film are separated again, the electrons return from the bottom electrode to the top electrode, and the reverse current is generated [Figure 2a(iv)]. The top electrode makes reciprocating linear motion under external excitation and spring action. This will make the two surfaces of the top copper film and the bottom FEP film contact and separate, so electrical signals are generated in the load circuit. Simultaneously, the change of potential difference (Figure 2b) was simulated by using COMSOL Multiphysics 5.5 software.

![Figure 2. The operating principle of DS-TENG: (a) schematic diagram of electron transfer, and (b) electrical potential distributions.]

2.3. Output performance
The output performance of the DS-TENG is studied by different experiments. Firstly, the effects of different electrode materials on the output performance of the DS-TENG are studied. As shown in Figure 3(a), the output performance of the DS-TENG is different when different electrode materials are used. When electrode materials of the DS-TENG adopt copper film and FEP film, the output performance is the best and the $I_{SC}$ is 11.7 μA, the $V_{OC}$ is 302 V and the $Q_{SC}$ is 94.5 nC. The experimental results show that the electrode material has a great influence on the output performance of the DS-TENG. Copper film and FEP film were used as electrode materials in subsequent experiments.

As shown in Figure 3(b), with the increase of external excitation frequency, short-circuit current increases, but open-circuit voltage and transferred charge remain unchanged. When the frequency is 1.5 Hz, the $I_{SC}$ of the DS-TENG is 16.6 μA, the $V_{OC}$ is 309 V and the $Q_{SC}$ is 96.6 nC.
To determine the reasonable maximum distance between the top electrode and bottom electrode, the influence of the maximum distance between the top electrode and bottom electrode on the output performance of the DS-TENG is studied. The output performance of the DS-TENG is studied by changing the maximum distance which is defined as $h$ between the top electrode and bottom electrodes. As shown in Figure 4, with the increase of the spacing between the top and bottom electrodes, the open-circuit voltage and transferred charge of the DS-TENG increase slightly, but the short-circuit current remains unchanged. When the spacing between the top electrode and bottom electrode is 6 mm, the $I_{SC}$ of the DS-TENG is 10.2 μA, the $V_{OC}$ is 307 V, and the $Q_{SC}$ is 90.5 nC.

To verify the output performance of the DS-TENG, the experiments of charging different capacitors to 3 V and power LEDs by the DS-TENG were carried out. As shown in Figure 5(a), when the external excitation frequency is 1 Hz, it takes only 162 seconds for the DS-TENG to charge a 47 μF capacitor to 3 V. As shown in Figure 5(b), the DS-TENG can harvest the energy from human movement and power 87 LEDs in series with the help of bridge rectifier. The experimental results show the DS-TENG can be used as an effective energy harvesting device to power low-power devices. Figure 5(c) shows common
vibration scenarios in the environment, such as human walking and cars passing through the deceleration strip. The DS-TENG can harvest this energy to drive LEDs and micro energy sensors.

3. Conclusions
In this work, a triboelectric nanogenerator with deceleration strip (DS-TENG) is proposed to harvest vibration energy in the environment and our daily life, such as human movement and cars passing through deceleration strip. The DS-TENG mainly composes a displacement platform, a base plate, and six springs. The experiments of the DS-TENG with different electrode materials, different electrode spacing, and different excitation frequencies were conducted. It is shown that the electrode material has a great influence on the output performance of the DS-TENG, and when the electrode material is the copper film and FEP film, the DS-TENG has better output performance. The open-circuit voltage and transferred charge of the DS-TENG are affected by the distance between the top electrode and the bottom electrode, while the short-circuit current is affected by the excitation frequency. The \( V_{OC} \) that the DS-TENG can output is 309 V and the \( I_{SC} \) is 16.6 \( \mu \)A and the \( Q_{SC} \) is 96.6 nC. Simultaneously, the LED board with “20” pattern can be powered by the DS-TENG by harvesting human movement energy. It is proved that the DS-TENG can harvest vibration energy from the environment and supply power for low-power equipment, which shows the potential application value of the DS-TENG in the field of environmental energy harvesting. The proposed method not only provides an effective way to collect vibration energy from the environment but also expands the application field of TENG.

4. Experimental section

4.1. Fabrication
The dimension of the DS-TENG is 150 mm (length) \( \times \) 120 mm (width) \( \times \) 30 mm (height). The DS-TENG comprises a displacement platform, a base plate, and six springs. The displacement platform and base plate were all made with a three-dimensional printer, and the raw material was polylactic acid (PLA). The raw material of the spring commonly adopted spring steel. The dimension of foam, FEP films, and the copper electrode is 120 mm (length) \( \times \) 33 mm (width). The thickness of the foam, the FEP, and the copper electrode are 2 mm, 100 \( \mu \)m, 65 \( \mu \)m respectively.

4.2. Electrical measurements
External excitation is provided by the linear motor (J-5718HBS401, Aokong, China). Meanwhile, the electrical signal of the DS-TENG was collected by a programmable electrometer and a data acquisition system. The model of the programmable electrometer was 6514, Keithley, USA and the data acquisition system was USB-6218, National Instruments, USA. Finally, the electrical signals is transmitted to the computer through LabVIEW.

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