Research Article

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Effect of Contact-separation Frequency on the Output of Triboelectric Nanogenerator

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Abstract

In this study, we investigated the impact of the contact separation frequency on the electrical output performance of triboelectric nanogenerators (TENGs). Because TENGs convert mechanical energy into electrical energy through the triboelectric effect, the frequency at which the two triboelectric surfaces interact plays a pivotal role in determining the efficiency and magnitude of the generated output. Understanding the relationship between the frequency and output is crucial for optimizing TENG performance in various applications, particularly where dynamic mechanical stimuli are involved. This research aims to explain how variations in frequency influence the electrical output parameters, thereby providing insights into the design and deployment of more effective energy-harvesting devices.

Keywords: Triboelectric Nanogenerator (TENG), Contact-Separation Frequency, Triboelectric Materials, Charge Accumulation, Electrostatic Potential Difference, Energy Harvesting Efficiency

Introduction

Triboelectric nanogenerators (TENGs) have emerged as a promising and versatile technology for converting mechanical energy into electrical energy by harnessing the triboelectric effect, whereby certain materials generate electric charges upon contact and separation [1]. This capability has positioned TENGs as key players in the development of self-powered systems and energy-harvesting devices, particularly in the context of the Internet of Things (IoT), wearable electronics, and environmental monitoring [2, 3]. Various types of TENGs, including contact-separation, single-electrode, and sliding modes, have been developed to accommodate a wide range of energy harvesting scenarios [4]. Each type of TENG is designed to maximize the energy conversion efficiency under specific conditions, with the choice of mode depending on the application and nature of the mechanical energy source. For instance, contact-separation mode TENGs are commonly used for harvesting energy from vertical movements, whereas sliding-mode TENGs are more effective for capturing energy from lateral movements [5]. The performance of TENGs is influenced by several factors, including the choice of triboelectric materials, surface area of the materials, environmental conditions such as humidity and temperature, and operational frequency [6]. The selection of materials is particularly crucial because different materials exhibit varying degrees of charge affinity, which affects the overall efficiency of energy conversion [7]. Moreover, environmental factors can significantly alter the triboelectric effect, thereby affecting the output performance of the TENGs. For example, high humidity levels can reduce charge retention, whereas temperature variations can affect material properties and triboelectric processes [8]. Among these factors, the frequency of contact and separation between triboelectric surfaces is a critical parameter that directly influences the electrical output of the TENG. Higher frequencies generally lead to more frequent charge generation events, potentially increasing output voltage, current, and power. Despite significant advancements in the design and material optimization of TENGs, a comprehensive understanding of how frequency influences their output characteristics remains essential for optimizing their performance across various applications.

This study focuses on exploring the impact of frequency on the output performance of TENGs by fabricating and testing devices with different sizes of triboelectric materials. By systematically varying the frequency of operation, we aim to provide insights into the relationship between the frequency and output, which could inform the design of more efficient TENGs for specific applications.

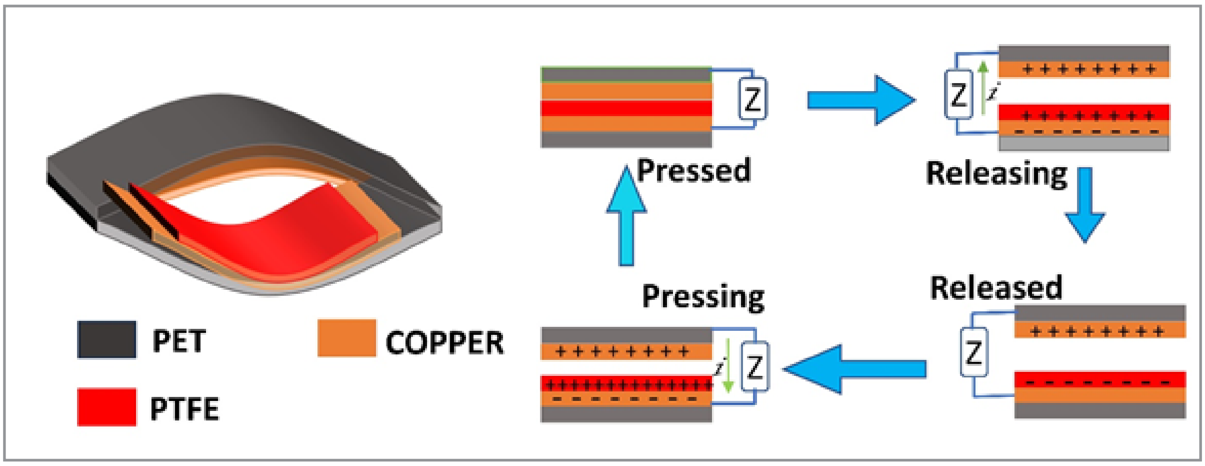

Figure 1: Device schematic and working mechanism of the device.

Experiment

In this study, we fabricated three different sizes of triboelectric nanogenerators (TENGs) using copper (Cu) and polytetrafluoroethylene (PTFE) as triboelectric pairs with dimensions of 2 cm × 2 cm, 3 cm × 3 cm, and 4 cm × 4 cm. These materials were chosen because of their well-known triboelectric properties, where copper acts as a positive triboelectric material and PTFE acts as a negative triboelectric material. The performance of these TENGs was evaluated by varying the frequency of the contact-separation cycles, and the resulting output voltage, current, and power were measured.

Result and Discussion

Contact-separation Mode Teng Working Mechanism

The contact-separation mode triboelectric nanogenerator (TENG) operates based on the cyclic contact and separation of two triboelectric materials, typically a metal like copper (Cu) and a polymer such as polytetrafluoroethylene (PTFE). The working mechanism of this TENG involves four key stages: Pressed, Releasing, Released, and Pressing. Here's a detailed explanation of each stage:

Pressed Stage

In the pressed stage, the two triboelectric materials (Cu and PTFE) are brought into direct contact with each other. When these materials touch, electrons transfer from the Cu (which tends to lose electrons) to the PTFE (which tends to gain electrons), due to their differences in triboelectric affinities. This electron transfer causes the Cu surface to become positively charged and the PTFE surface to become negatively charged. At this moment, no external circuit is connected, so no current flows, but the surfaces remain charged due to the triboelectric effect, Figure 1.

Releasing Stage

As the two surfaces begin to separate, the distance between the Cu and PTFE layers increases. During this separation, the electrostatic potential difference between the positively charged Cu and the negatively charged PTFE drives electrons through an external circuit to balance the charges. This movement of electrons generates an electrical current. The more the surfaces are separated, the greater the potential difference, and consequently, the larger the current generated.

Released Stage

In the released stage, the Cu and PTFE layers are fully separated, maximizing the distance between them. At this point, the electrostatic charges on the surfaces remain, but no further electron flow occurs because the separation has reached its maximum. The potential difference between the Cu and PTFE layers is at its peak, but the circuit is in a state of equilibrium with no current flowing. The charges on the surfaces are stored as potential energy.

Pressing Stage

In the pressing stage, the Cu and PTFE layers begin to move back toward each other, reducing the distance between them. As the surfaces come closer, the electrostatic potential difference decreases, causing electrons to flow back in the opposite direction through the external circuit to re-establish charge balance. This reverse current continues until the two surfaces make contact again, completing the cycle. The charges on the surfaces are neutralized when the materials touch, and the process is ready to repeat from the pressed stage.

Effect of Frequency on Output Voltage

In this study, we fabricated and tested three different triboelectric nanogenerators (TENGs) with active material areas of 2 × 2, 3 × 3, and 4 × 4 cm. The devices were subjected to three different operational frequencies (2, 3, and 4 Hz) to evaluate the effect of frequency on the output voltage. The triboelectric materials used in all devices were copper (Cu) and polytetrafluoroethylene (PTFE), which were selected for their significant triboelectric contrast.

Voltage Output Analysis

The output voltage measurements revealed a clear dependence on both the size of the TENGs and operational frequency. Specifically:

- The 2 cm × 2 cm TENG generated peak voltages of 1.5, 4, and 6.4 V at 2 Hz, 3 Hz, and 4 Hz, respectively, Figure 2(a).

- The 3 cm x 3 cm TENG produced higher peak voltages of 2 V, 5.4 V, and 10.6 V at the corresponding frequencies, Figure 2(b).
- The 4 cm × 4 cm TENG exhibited the highest output, generating 5 V, 11.34 V, and 19 V at 2, 3, and 4 Hz, respectively, Figure 2(c).

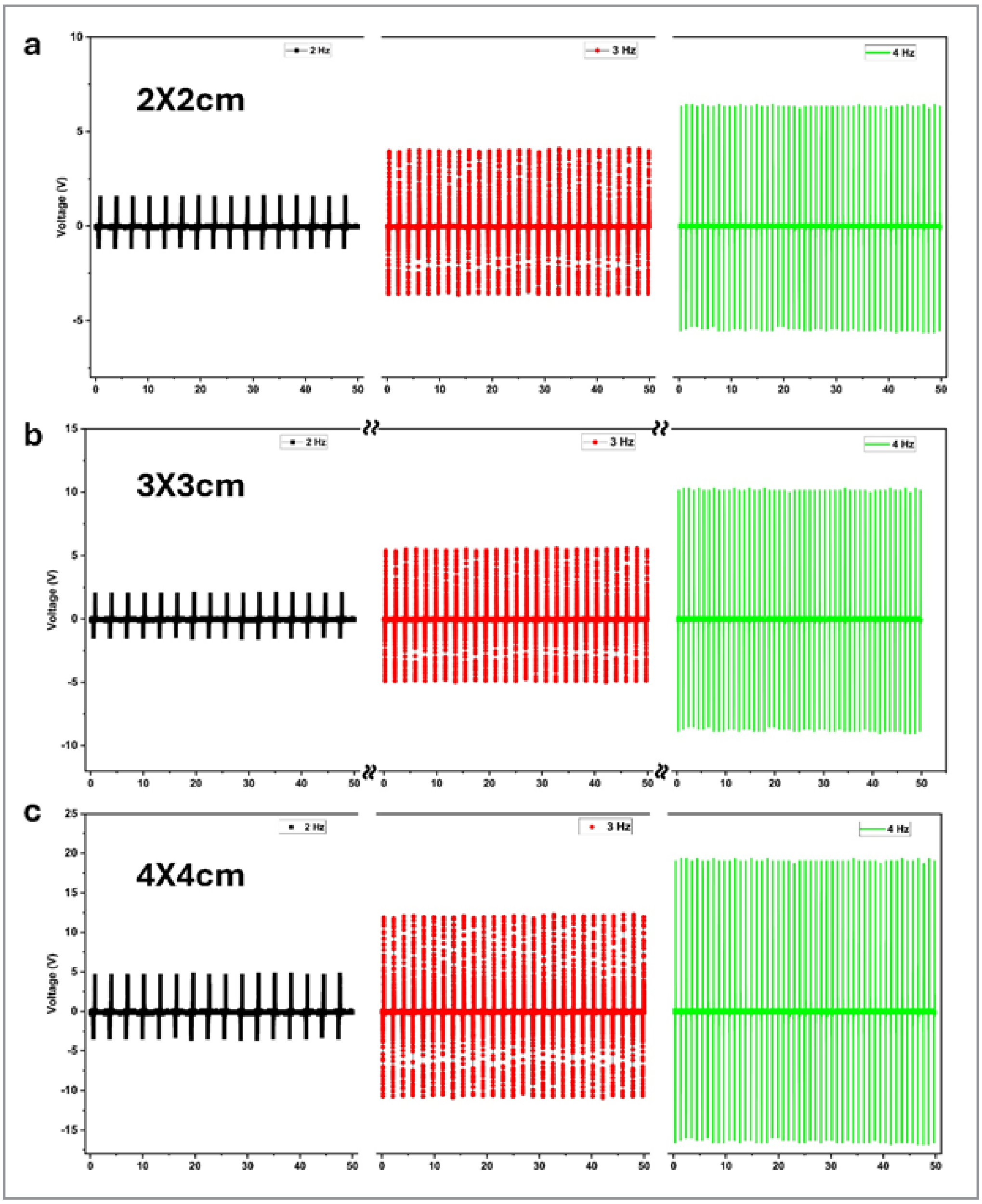

Figure 2: Electrical characterization: (a) Open circuit voltage of 2 x 2cm device at different frequencies; (b) Open circuit voltage of 3 x 3cm device at different frequencies; Open circuit voltage of 4 x 4cm device at different frequencies.

Effect of Frequency on Voltage Output

Across all three devices, the output voltage increased substantially with an increase in frequency. This increase can be attributed to the higher rate of contact-separation cycles at higher frequencies, which leads to more frequent charge generation and accumulation on the surfaces of the triboelectric materials. As the contact-separation frequency increased, the time available for charge leakage or dissipation between cycles decreased, allowing for a more efficient build-up of surface charges. This, in turn, results in a higher potential difference between the copper and PTFE layers, manifesting as an increased peak voltage. The observed trend aligns with the understanding that at higher frequencies, the rapid succession of contact-separation events enhances the charge density on the surfaces, leading to a stronger electric field and, therefore, a higher voltage output.

Effect of the Device Size on Voltage Output

The data also show that the larger TENGs consistently produce higher output voltages at each frequency. This is expected because larger contact areas between the triboelectric materials allow for a greater amount of charge to be generated during each contact-separation event. For instance, the 4 cm × 4 cm TENG generated peak voltages more than three times higher than those of the 2 cm × 2 cm TENG at each frequency, indicating that the increase in surface area significantly amplifies the energy harvesting capability. This suggests that the energy-harvesting performance of TENGs can be effectively scaled by increasing the active area of the triboelectric materials. However, the impact of frequency is consistently observed across all device sizes, with higher frequencies leading to substantial voltage increases, regardless of the dimensions of the TENG.

Combined Influence of Frequency and Size

The combination of increasing the frequency and larger device size resulted in a synergistic effect on the performance of the TENG. For example, at the highest frequency of 4 Hz, the 4 cm × 4 cm TENG produced a peak voltage of 19 V, which is a significant increase compared to the 6.4 V generated by the 2 cm × 2 cm device at the same frequency. This nearly threefold increase in voltage illustrates that both frequency and surface area are critical factors that can be optimized to maximize the output of TENGs.

Our results indicate a clear and significant increase in the output voltage of TENGs with increasing frequency. The output voltage is directly linked to the amount of charge transferred between the copper and PTFE layers during each contact-separation cycle. As the frequency of these cycles increased, the rate at which charges were generated and separated also increased, leading to a higher accumulation of charges on the surfaces of the materials. This increased charge accumulation results in a stronger electric field, and consequently, a higher output voltage. In the case of our TENGs, as the frequency increased, the time interval between successive contact and separation events decreased, which minimized the charge dissipation that can occur during longer intervals. This means that at higher frequencies, there is less time for the charges to leak away or neutralize, allowing for more efficient charge retention and a stronger build-up of the potential difference between the copper and PTFE surfaces. The result was a higher peak voltage output, which was consistently observed across all three device sizes.

Effect of Frequency on Output Current

Similar to the voltage, the output current of the TENGs showed an increasing trend with increasing frequency. The current generated in the TENG was proportional to the rate at which the charge was transferred. At higher frequencies, the rapid succession of contact-separation events leads to faster charge transfer rates, thereby increasing the current output. This is because during each contact, a certain amount of charge is transferred from one material to another. When the frequency increases, these transfers occur more frequently within a given period, leading to a higher overall current, which facilitates a more continuous and stable flow of charges across the circuit as the intermittent gaps between the charge transfer events become shorter. This enhanced continuity in charge flow contributed to an increase in the average current generated by the TENGs.

Effect of Frequency on Power Output

The power output, which is a product of the voltage and current, naturally increases with frequency as both of these parameters are enhanced. The rise in power output with frequency is particularly important for practical applications where the energy harvested needs to be maximized for power electronic devices or charge storage systems. In our experiments, as the frequency increased, the power output of the TENGs exhibited a nearly exponential growth, highlighting the effectiveness of high-frequency operation in boosting the energy-harvesting capacity of these devices, which can be attributed to the combined effects of higher charge density (resulting in higher voltage) and more efficient charge transfer (resulting in higher current). Copper and PTFE are particularly effective in this context because of their strong triboelectric contrast, which further amplifies the charge generation process, especially under high-frequency conditions.

Conclusion

The results clearly demonstrate that both the operational frequency and size of the TENG significantly influence the output voltage. Higher frequencies and larger device sizes lead to enhanced charge generation and retention, resulting in greater voltage output. These findings underscore the importance of optimizing both the frequency of operation and the dimensions of the triboelectric materials to achieve the maximum energy harvesting efficiency in TENGs. This understanding is vital for the design and development of more effective TENGs for various applications, particularly those that require scalable energy solutions.

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