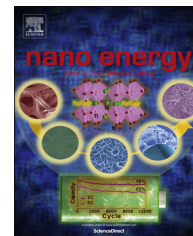




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FULL PAPER

Kinematic design for high performance triboelectric nanogenerators with enhanced working frequency



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Received 1 September 2015; received in revised form 10 December 2015; accepted 19 December 2015
Available online 13 January 2016

KEYWORDS

Kinematics;
Triboelectric nano-
generator;
Enhanced frequency;
Power conversion
efficiency

Abstract

Triboelectric nanogenerators (TENGs) can harvest a variety of environmental energies including sound, waves, wind, and human motions, but low input energies normally generate low output power although TENGs have high power conversion efficiency (PCE). In this study, we report the kinematic design of TENGs for improving the PCE. By adopting a gear train in a TENG system, the frequency (f_w) at the working gear could be larger than that (f_{in}) at the input gear. Finally, the output energy of TENGs with a higher working frequency could be improved, thus providing enhanced PCE. We investigated the output performance of our gear-based TENG system under input frequencies of 1.5, 3, and 4.5 Hz by controlling the gear ratio (i.e. 1, 1.7, and 5). Under the input frequencies, the output voltage and current from our gear-based TENG system were enhanced up to the maximum of 3.6 times and 4.4 times, respectively. It was analyzed that the PCE was improved up to 7.57 times at the gear ratio of 5 under the input frequency of 1.5 Hz. In order to clearly understand improved performance of the gear-based TENG system, we used our TENG system to charge a capacitor by rectifying the output voltage. Under the input frequency of 4.5 Hz, we obtained a 3 times enhanced rectifying voltage at a gear ratio of 5. Interestingly, capacitor charging voltage was enhanced up to about 8 fold in using our TENG system. It is attributed that our gear-based TENG system could improve simultaneously the magnitude as

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well as the generation time of output power, finally enhancing output energy. Therefore, our gear-based TENG system provided an effective way to enhance the PCE of TENGs operating at a given input energy.

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Introduction

Triboelectric nanogenerators (TENGs) have great potential to produce electrical energy by harvesting environmental energy from air flow, wind, waves, vibrations and even human motion [1-6]. To date, many researchers have studied the working mechanism of TENGs, have shown enhancements in TENG output power, and have used TENGs in various electronic, biomedical, and sensing device applications [7-12]. Many studies for developing high performance TENGs have been performed and are still on-going. TENG operation is based on the sequential processes of triboelectrification and electrostatic induction [13-16]. Triboelectrification occurs when two materials that have relatively different polarities come into contact with each other [17,18]. After separation of the contacted materials, the charge balance collapses and an electric field is formed in each material. The transferred charge density is dependent on the material properties such as capacitance and electron affinity. The surface morphology also plays a significant role in enhancing output power [19-21]. Therefore, many studies have focused on the design and synthesis of novel materials to improve the performance of TENGs [22-25].

Previously, high output power from TENGs has been achieved using high-speed rotating systems, multi-stack systems, and sliding systems [26-30]. In those TENG systems, high output power was achieved if a high input energy was captured via high contact frequencies or high contact loads. However, it is difficult to constantly supply high energy because the environmental energy depends on region, weather, population and other factors. Furthermore, obtaining high output power based on high input energy can result in low power conversion efficiency (PCE), which is defined as the ratio of output energy to input energy. Therefore, our goal is to improve the output energy using the same materials and the same input energy to provide a high PCE for future TENG systems.

Kinematics describes the motion of points, bodies, and systems. Thus, we can control the motion of a system through a kinematic design. It is well known that two or more gears working in a sequence, called a gear train, can change the speed, torque, and direction of a power source. The most common situation is for a gear to mesh with another gear, where the smaller gear is rotating faster. In this study, we report such a gear-based kinematic design for a TENG system to enhance output energy at a given input energy. We connect a small gear (i.e., a working gear, r_w) with a moving TENG element, and the working gear meshes with a larger gear (i.e., an input gear, r_{in}), which is connected to an input source. The frequency (f_w) of the working gear increases beyond the frequency of the input gear (f_{in}) by controlling the gear ratio (r_{in}/r_w), thus providing enhanced output energy from our

TENG system. We design gear ratios of 1, 1.7, and 5 and examine the output performance of the gear-based TENGs. Since the input energy is fixed, the PCE of our TENG system could be improved by enhancing the TENG output energy. Finally, we demonstrate the enhanced performance of our gear-based TENG system through the behaviors of capacitor charging. Our results may offer an effective design for TENG systems to generate enhanced PEC for traditional TENGs.

Experimental section

TENG fabrication

We fabricated our TENGs using a polydimethylsiloxane (PDMS) thin film with a nanostructured surface as an electron acceptor and an aluminum (Al) thin film as an electron donor. The PDMS was 200 μm thick, had a length of 4 cm and a width of 1 cm. To achieve a nanoscale morphology on PDMS, we first prepared an aluminum hydroxide ($\text{Al}(\text{OH})_3$) nanotemplate as a mold. Since the $\text{Al}(\text{OH})_3$ surface is superhydrophilic, we treated the surface with hydrophobic molecules, i.e., heptadeca-fluoro-1,1,2,2 tetrahydrodecyl trichlorosilane (HDFS), to facilitate subsequent PDMS separation. After pouring a PDMS solution onto the HDFS-treated $\text{Al}(\text{OH})_3$ nanotemplate, we used a doctor blade technique to create a thin film with a uniform thickness. The PDMS was dried in a convection oven for about 8 h at 70 $^\circ\text{C}$. After detaching the nanostructured PDMS from the nanotemplate, the PDMS was bonded to an Al electrode by using a PDMS solution as a glue. Finally, a nanostructured PDMS film on an Al electrode was achieved for use as an electron acceptor element. The detail processes are shown in Figure S1.

Design of gear-based TENG system

We designed our TENG system based on kinematic models such as gear trains. First, an input gear (r_{in}) was connected to a model input source (i.e., a DC motor). The input gear meshed with a smaller working gear (i.e., $r_w < r_{in}$), and the working gear was connected to a slider-crank with an Al electron donor at the end. The slider moved by rotation of the working gear and contacted the nanostructured PDMS positioned at the counterpart. To avoid an additional triboelectric effect between the slider and guides, we provided a 1 mm allowance to the slider. The slider was designed to move by 26 mm when the working gear is rotated, so the distance between the PDMS and the Al film was set to be 26 mm. By using a smaller working gear than the input gear (i.e., $r_{in}/r_w > 1$), we could enhance the working frequencies ($f_w > f_{in}$) under a given input frequency (f_{in}). Furthermore, we fabricated a contact-type TENG system from a rotating input source by applying a slider-crank mechanism.

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