Dual Mode Rotary Triboelectric Nanogenerator for Collecting Kinetic Energy from Bicycle Brake

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Regenerative braking system is a promising technology for electrical vehicles, in which the excess kinetic energy can be effectively collected and utilized. As a new energy technology based on contact electrification, triboelectric nanogenerator (TENG) is suitable for harvesting dissipated kinetic energy in braking systems. Herein, a dual mode rotary TENG (DMR-TENG) is reported, which is installed on the bicycle disc brake for collecting kinetic energy in riding mode and braking mode. First, the electric generation mechanism of DMR-TENG is analyzed and then the characteristics in different structural and kinematic parameters by simulation and experiment are investigated. Furthermore, a linkage mechanism is designed for two modes switching by controlling the distance between two triboelectric layers of the DMR-TENG. The results illustrate that the DMR-TENG can simultaneously illuminate 156 serial LEDs as a warning signal while riding and braking. In addition, it can charge a 300 μF capacitor and act as a power source to drive a speedometer, which can measure the bicycle speed in real time. Herein, a considerable prospect in vehicle kinetic energy collecting is demonstrated and may have potential application in intelligent transportation.

1. Introduction

The electricity is one of the most significant technologies that was rising during the second industrial revolution.[3] Recent years, with the development of Internet of things (IoTs),[2] large-scale centralized power plants may not be able to meet all the demands of distributed electronic equipment, according to the distributed energy entropy theory.[3] Tens of thousands of sensor nodes in sensor networks, big data, and intelligent transportation need to be powered by collectable distributed energy.[4] More specifically, in the area of unmanned driving, large amount of sensor data needs to be exchanged and calculated between cars, transportation facilities, and cloud data platforms.[3] The energy supply problem of these distributed sensors cannot be effectively solved by simply relying on wiring. Thus, harvesting mechanical energy from working environment[6] is an ideal solution for powering the numerous distributed sensors and electronic equipments in intelligent transportation.[7–11]

The discovery of triboelectrification phenomenon can be traced back to 600 B.C. However, this kind of electricity could not be utilized until the invention of triboelectric nanogenerator (TENG) in 2012.[12] Originating from the second term of Maxwell’s displacement current,[13,14] the TENG with appropriate power management strategy[15,16] has incomparable advantages in harvesting low frequency and micro-amplitude mechanical energy[17] from environment on account of its flexible structure[18] and intrinsic electrical characteristics. Therefore, its applications in wind,[19–21] ocean wave,[22–24] raindrops,[25–27] mechanical vibration,[28–30] human body movements,[31–33] etc. have been reported during the past few years. Collecting kinetic energy from brakes is a new technology in electric vehicles[34,35] which has inspired researchers to use TENG as a collection method.[36] In 2014, Wang and coworkers proposed a disc-based TENG for mechanical energy harvesting as a simulated braking system in the laboratory.[37] However, the electrical output performances...
dependence on structural parameters still need to be investigated. It is also expected that the TENG can be integrated on actual braking system for energy recovery.

Herein, we report a dual mode rotary TENG (DMR-TENG), which is installed on the bicycle disc brake for collecting kinetic energy in riding mode and braking mode. We first analyze the electric generation mechanism of DMR-TENG and then investigate the characteristics in different structural and kinematic parameters by simulation and experiment. Furthermore, a linkage mechanism is designed for two modes switching by controlling the distance between two triboelectric layers of the DMR-TENG. The results illustrate the DMR-TENG can simultaneously illuminate 156 serial LEDs as a warning signal while riding and braking. In addition, it can charge a 300 μF capacitor and act as a power source to drive a speedometer, which can measure the bicycle speed in real time. This work demonstrates a considerable prospect in vehicle kinetic energy collecting and may have potential application in intelligent transportation.

2. Results and Discussions

2.1. The Overview of DMR-TENG

The 3D schematic of the DMR-TENG is shown in Figure 1a. The steel plate not only works as a brake disc but also as a rotator of the DMR-TENG. The other triboelectric layer is the polytetrafluoroethylene (PTFE) film as a stator. Steel is the original brake disc material which is used to maintain the original braking performance and mechanical properties. According to the triboelectric sequence table, there is a large difference in electronegativity between PTFE and steel. In addition, PTFE has excellent heat resistance, corrosion resistance, and wear resistance. Last but not least, PTFE is an electret material and has a strong storage capacity for charge, which is conducive to the stable output of DMR-TENG in the separated state. The radial electrodes were made by printed circuit board (PCB) technology. The sponge can guarantee the close contact between the flexible PTFE triboelectric layer and the steel. Larger contact area leads to higher surface charge density thus enhance the output. Based on the aforementioned design, we fabricated a DMR-TENG and assembled into the bicycle brake, as shown in Figure 1b and Figure S1, Supporting Information. The black clamp is the clamp I in the inset of Figure 1c, which mainly works as the brake. Three brake clamps are connected with one cable which forms a linkage mechanism. Clamp I works as a brake to generate friction torque between the pad and the disc brake. Clamp II and clamp III can push the stator closer to the rotator while braking, which can recycle the dissipated mechanical energy and convert it into electrical energy. In the rear view, the original brake disc was redesigned. The dual mode switching of the DMR-TENG and output waveforms during accelerating and decelerating is shown in Video S1, Supporting Information. We combined the radial-arrayed rotary TENG and disc brake, and proposed a DMR-TENG for collecting braking kinetic energy. As shown in Figure 1c, this device can power a speedometer to measure the real-time velocity and display it on the screen. If we switch the power supply line to the LED array, it can illuminate 156 serial LEDs simultaneously when riding and braking. The circuit diagram is shown in Figure S2, Supporting Information. The LED array can work as a stoplight warning signal with higher brightness while braking. The working principle and characteristics will be further discussed in the following part.

2.2. Theoretical Model and Finite Element Simulation

To fully understand the output performance of DMR-TENG dependence on structural parameters, we simplified the

![Figure 1](https://www.advancedsciencenews.com/wps/wcm/connect/6372ab8f-saving-wcm-content-60647234/2000113-2/00011320001132000113)
DMR-TENG and build a 2D model in COMSOL Multiphysics. A single sector unit of the DMR-TENG was selected and the cutaway view (taking the red plane as the cut surface) is shown in Figure 2a, in which the thickness of the PTFE film, length of electrode and gap distance between electrodes are fixed. Figure 2b,c shows the working principles in braking and riding mode, respectively. Because of the difference of electronegativity and the effect of contact electrification, when the steel plate contacts with the PTFE film and slides, the electrons in the steel plate will transfer to the PTFE film. When the steel plate is aligned with the left electrode, the negative charge in left electrode is induced. However, there is no charge transfer between the two electrodes until the movement of the steel plate. The negative free charges in copper of PCB keep moving between the two electrodes because of the electrostatic attraction generated by the positive charge on the steel plate. Thus, when the steel plate moves from left side to the middle, the current direction of external circuit is from right to left. When the steel plate moves from middle to right, the current reverses. The charge transfer mechanism in both modes is similar. However, the induced charges on the electrodes in braking mode is less than that in braking mode because of the lower electrostatic induction in the separation status.[18]

Figure S3a,b, Supporting Information are the potential distribution in open-circuit state, which directly show the charge distribution state. The net charge on the electrodes keeps constantly at zero because they are isolate from each other. The potential on the left and right electrode is defined as $U_L$ and $U_R$, respectively, then the potential difference between the two electrodes can be calculated by Equation (1)

$$V_{OC} = U_R - U_L = \pm \frac{2\sigma}{\varepsilon_0 \varepsilon_r}$$  \hspace{1cm} (1)  

where $t$ is the thickness of the PTFE film, $\sigma$ is the triboelectric charge density on the surface of PTFE film, $\varepsilon_0$ is the dielectric constant of vacuum, $\varepsilon_r$ is the relative dielectric constant of the PTFE film. When the PTFE film coincides with the left electrode, open-circuit voltage ($V_{OC}$) is greater than zero, when the PTFE film coincides with the right electrode, $V_{OC}$ is less than zero.

The following two parameters in the model are changed to explore their influence on the $V_{OC}$ and short-circuit transfer charge ($Q_{SC}$): the displacement of the steel plate ($D$) and the gap distance between the steel plate and the PTFE film ($d$). Simulation results illustrated $V_{OC}$ and $Q_{SC}$ both show positive correlation with $D$, as shown in Figure 2d. Also, $Q_{SC}$ is proportional to displacement $D$. However, $V_{OC}$ shows nonlinear relationship with $D$. Figure 2e shows that with the increasing $d$, $V_{OC}$, and $Q_{SC}$ presents a downward trend from steep to gentle. The reason is the weakening of electrostatic induction effect.

### 2.3. Electric Measurements

To investigate how rotation velocity $V$ and distance $d$ influence the output performance, a 1D axis is defined, as shown in Figure S4, Supporting Information. It is perpendicular to the surface of the PTFE film and the horizontal position of the PTFE film surface is defined as the zero point. When the rotator separates from the PTFE film, the distance between the bottom of the rotator and surface of the PTFE film is positive. When rotator contacts with the PTFE film, the sponge is compressed. At this time, the coordinate of the PTFE film surface is negative. The adjustment of gap distance is explained in Experimental Section.

The output performance is measured with $d$ as a variable at fixed velocity of 150 rpm. The peak to peak voltage ($V_{PP}$), surface charge density ($\sigma_{SC}$), and short-circuit current ($I_{SC}$) dependence

![Figure 2.](image)  
Figure 2. a) Two simulated parameters on the single grid. Theoretical model of the DMR-TENG in b) braking mode and c) riding mode. Trend of open-circuit voltage ($V_{OC}$) and short-circuit transfer charges ($Q_{SC}$) by different d) displacements of steel and e) interval length between steel and PTFE membrane.
on $d$ are shown in Figure 3a–c, the insets are the corresponding waveforms. $I_{SC}$ can be calculated by Equation (2)

$$I_{SC} = \frac{dQ_{SC}}{dt}$$ (2)

$\sigma_{SC}$ can be calculated by Equation (3)

$$\sigma_{SC} = \frac{Q_{SC}}{S}$$ (3)

In which $S$ is the area of triboelectric layer.

The test results show the $V_{P-P}$, $\sigma_{SC}$, and $I_{SC}$ decrease with the increasing $d$, which is consistent with the finite element simulation result. The insets are the waveforms at $d = -1.0$ mm. The detailed waveforms at other contact conditions is shown in Figure S5a–c, Supporting Information.

Figure 3d,g,h shows the changing trend of $I_{SC}$, $\sigma_{SC}$, and $V_{P-P}$ with rotation velocity $V$. When measuring output performance with velocity as a variable, riding mode is controlled precisely at $d = 0.5$ mm and braking mode is controlled at $d = -0.5$ mm. $\sigma_{SC}$ and $V_{P-P}$ hardly change with the increase in velocity, and $I_{SC}$ shows a linear increase trend, which can be explained that $I_{SC}$ can be calculated by the differential of $Q_{SC}$ to time, as shown in Equation (2). Figure 3e,f are the waveforms of $I_{SC}$ in riding and braking mode, respectively. The frequency and amplitude of the waveforms increase with the increase in rotation velocity.

The frequency can be calculated by Equation (4)

$$f = \frac{180\nu}{\alpha_0}$$ (4)

where versus is the rotation velocity ($r$ sec$^{-1}$), $\alpha_0$ is the sector angle of a single electrode. Figure S5 d–g, Supporting Information, are the waveforms of $\sigma_{SC}$ and $V_{OC}$.

The general output of DMR-TENG in braking mode is higher than that in riding mode, which can be attributed to higher surface charge density and stronger electrostatic induction during the sliding process.
Furthermore, output characteristics with different external resistive load of the DMR-TENG in the two states of riding and braking is shown in Figure 3i. At riding state, the distance between rotator and stator is 0.5 mm. The power reaches its peak value of 0.3 mW at 46 MΩ. At braking state ($d = -0.5$ mm), the peak power of 2.29 mW is obtained at the matched load of 20 MΩ. The average power $P$ is calculated by the current $I(t)$, as in Equation (5)

$$ P = \frac{R}{a} \sum_{i=1}^{a} I_i^2 $$

where $R$ is the resistance of external circuit, $a$ is the number of sampling points, $I_i$ is the discrete current. The measured current under different resistances is shown in Figure S6, Supporting Information. To avoid the asymmetry of single-electrode power generation, the resistance is divided into two equal parts and connects them to both ends of the electrometer probe. After that, we tested the DMR-TENG’s ability to charge capacitors, as shown in Figure S7, Supporting Information. The rotation rate is set at 200 rpm and three different capacitors were chosen. The voltage growth rate in braking mode is larger than that in riding mode, and the voltage of smaller capacitor increases faster in the same charging time. In general, the power in braking mode is higher than that in riding mode. In addition, the time varying curve of storage energy illustrates that higher speed leads to higher output power.

### 2.4. The Electric Measurements of the Combination

The DMR-TENG was assembled into a bicycle to modify the traditional brake. The inner part of the original brake disc is changed to a radial-arrayed steel plate as a stator. Figure 4a,b shows the positional relationship of the DMR-TENG in riding mode and braking mode. The main friction torque is generated by the contact of brake disc and brake pad rather than the contact of the two triboelectric layers, which is driven by the tension of brake cable (red arrows). Thus, it is reasonable to infer that the...
temperature of triboelectric layer will not fluctuate greatly. Meanwhile, the linkage mechanism can drive the contact motion by the other two clamps (II, III in Figure 1b and green arrow in Figure 4b). The PTFE film always first contacts with the steel plate (rotator) and then the sponge is compressed to guarantee the close contact of the two triboelectric layers. The charge density of the two triboelectric layers at braking state is higher than that at riding state. The intermittent contact can not only prolong the service life of the device but also replenish surface charge which escapes into the air.

The DMR-TENG’s output performance \( I_{SC} \), \( V_{OC} \), and \( Q_{SC} \) in accelerating and decelerating states was tested, respectively. Figure 4c is the peak value of \( I_{SC} \). The curve has two stages, at accelerating stages, \( I_{SC-peak} \) increases continuously from zero to 10 \( \mu \)A with the increasing velocity. Once braking at 10th second, the \( I_{SC-peak} \) shows a step growth, which is attributed to the close contact of two triboelectric layers. The contact enhances the electrostatic induction and increases surface charge density thus \( I_{SC} \) increase immediately. At the decelerating stage, from 10 to 14 s, because the rotation velocity declines, the \( I_{SC-peak} \) decreases although the contact of two triboelectric layers is still maintained. The \( V_{OC-peak} \) and \( Q_{SC-peak} \) (in Figure S8, Supporting Information) also have the similar step characteristic while braking. However, \( Q_{SC} \) and \( V_{OC} \) do not show any relevance with velocity, which has been verified by the former experiments in Figure 3g,h. Figure S9a–c, Supporting Information, shows the waveforms of \( V_{OC} \), \( I_{SC} \), and \( Q_{SC} \) during accelerating and decelerating stages. The assembly’s ability to charge a 30 \( \mu \)F capacitor is shown in Figure 4d. Blue curve shows the voltage change and the red one shows voltage change rate. At 24 s, the brake works and the slope of voltage curve increases, which corresponds with the test result in Figure S7, Supporting Information. After 27.9 s, the change rate of voltage drops to zero continuously because of the decrease in rotation velocity. After that, we used the assembled DMR-TENG to charge a 300 \( \mu \)F capacitor as a power source to drive a speedometer. The circuit is shown in Figure 4g. The Zennor diode (stable voltage, 3 V) can ensure that the voltage across the power supply capacitor does not exceed the rated working voltage. The circuit’s energy consumption rate is greater than the DMR-TENG’s generation power, so two switches are added to manually control the on and off modes of the measuring circuit. Figure 4e shows the voltage change of the capacitor, which presents the working stage of the speedometer. At the 119 s, we turned on switch S1 (1.77 V) and the main circuit enters the initialization stage, which leads to the voltage drop from 1.77 to 1.47 V. After that, the perimeter of the tyre need to be set. Then switch S2 is turned on and the speed measurement begins. The capacitor voltage drops from 1.5 to 0.9 V within 13 s. the voltage cannot maintain the circuit’s work and the measurement ends. The velocity is refreshed on the display at 1 Hz. Figure 4f is the \( v-t \) curve. The whole velocity measurement process lasts 15 s. Video S2 and S3, Supporting Information, shows the working process in practical riding process. The assembly’s fatigue and robust performance are tested shown in Figure 4h. \( V_{OC} \) (Figure S10, Supporting Information) and \( Q_{SC} \) were measured before and after a 10 km riding. In the outdoor environment, the friction between airflow and triboelectric layers may take part of the surface charge away and reduces the output. However, contrary to the anticipation, the \( Q_{SC} \) and \( V_{OC} \) are increased by 8.2% and 24.86%, respectively. That can be attributed to the charge replenishment effect by the braking contact. As for the durability of the DMR-TENG, from the previous work\(^{[19]}\) we can know that the performance of the generator remains stable after 10 million cycles. Therefore, it is reasonable to infer that DMR-TENG has excellent fatigue resistance.

3. Conclusions

In summary, we combine the radial-arrayed rotary TENG and disc brake and propose a dual mode rotary TENG (DMR-TENG) for collecting kinetic energy in riding and braking. The electric generation mechanism of DMR-TENG is analyzed first. Then the electrical output performance dependence on interval length between steel and PTFE film \( d \), displacements of rotator \( D \), and rotation velocity \( v \) is studied through finite element simulations and experiments. Furthermore, the DMR-TENG is installed on a bicycle to demonstrate its mechanical energy collecting performance in practical application scenario. The DMR-TENG can illuminate 156 serial LEDs simultaneously. The intensity of light is high enough to be used as a warning signal in dark night. It can also power a commercial speedometer for real-time velocity measuring and displaying. Finally, the electrical characteristics of the DMR-TENG is measured before and after a 10.4 km cycling. The results demonstrated that the performance of DMR-TENG can not only be maintained but also slightly improved. This work shows the feasibility of TENG’s potential application in automobiles, trains, and various power deceleration systems, which can establish a powerful energy supply for sensor network of intelligent transportation system in the future.

4. Experimental Section

2D finite simulation: Simulation Model Development: The simulations in this study were carried out using the electrostatic module in COMSOL Multiphysics. The electrodes in the simulation model had a length of 5 mm and thickness of 100 \( \mu \)m. The gap between the two electrodes was 100 \( \mu \)m. The PTFE was 10.1 mm in length and 80 \( \mu \)m in thickness. The steel had the same dimensions as the electrodes. The surface charge density on the lower surface of steel was 3.25 \( \mu C/m^2 \) which was twice the surface charge density on PTFE. In the short-circuit state, the two electrodes were included in the same boundary condition (the initial value was a floating potential of 0 V). In the open state, the two electrodes were set to two identical but independent boundary conditions (the initial value was a floating potential of 0 V). After the simulation calculation, the open-circuit voltage can be obtained by calculating the difference between the average value of the potentials on the lower surface of the two electrodes. The amount of short-circuit transferred charge was the difference between the surface charge of the electrode in the final state and the surface charge in the initial state, which can be derived by calculating the line integral value of the surface charge density on the bottom surface of the electrode.

Fabrication of the Rotating Experimental Platform: The stator of the DMR-TENG which assembled on the rotating experimental platform was composed of four layers, as shown in Figure 1d. The first was the acrylic plate (5 mm in thickness and 160 mm in diameter cut by laser cutting machine). The second was the sponge (3 mm in thickness). The third was the circuit board fabricated by a traditional PCB (0.6 mm in thickness with a sector angle of 15°). The fourth is the adhesive PTFE film with a thickness of 80 \( \mu \)m. The first three layers were adhered together by Kapton double side adhesive tape. The stator was bolted to a liner motor.
(LinMot PS01–37×120–C) with an acrylic substrate of the same size. The motor was used to control the gap distance between rotator and stator. The rotor was a stainless-steel plate (3 mm in thickness and sector angle of 15°) cut by laser. It was connected to an AC servo motor (000AA06030–SC3) with an acrylic base and transmission shafts. The rotational speed could be adjusted by the servo controller.

Fabrication of the Linkage Mechanism of DMR-TENG: As shown in Video S1, Supporting Information, and Figure 1b. There were three calipers. One worked as brake and the other two could drive the stator to the rotator while braking. All the three calipers were connected by a wire rope and bolted by an acrylic plate. The plate was bolted on the wheel axle.

Electrical Characterizations of the DMR-TENG: The gap distance between rotator and stator was controlled precisely by the linear motor. To find the $d = 0$ position, we compared the actual position and demand position on the computer control interface. When contact happened, the difference between the actual position and demand position will increase rapidly. All the electric data were measured by an electrometer (Keithley 6514) except the $V_{oc}$ values in Figure 3a, which was measured by an Oscilloscope (Tektronix MDO3024).

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

H.Z., C.L. and Y.G. contributed equally to this work. The authors thank the support of the National Natural Science Foundation of China (51922023, 61874011), Beijing Talents Foundation (2017000021223TD04), Tribology Science Fund of State Key Laboratory of Tribology (SKLTKF19B02), Open Research Foundation of State Key Laboratory of Digital Manufacturing Equipment & Technology (DMETKF2020014) and Guangxi Hundred Talent Program (T3010097923)

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

Keywords

dual mode, intelligent transportation, IoTs, regenerative braking,triboelectric nanogenerators

Received: December 31, 2020
Revised: February 4, 2021
Published online: March 8, 2021

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