Magnetically Levitated-Triboelectric Nanogenerator as a Self-Powered Vibration Monitoring Sensor

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ABSTRACT: This paper presents a magnetically levitated-triboelectric nanogenerator to harvest mechanical energy and detect acceleration of the vibration in the surroundings. Based on the effective conjunction of triboelectrification and electromagnetic induction, maximum power density of 3.23 W m^{-2} is obtained at $100 \text{ M}\Omega$ and 10 m s^{-2} for the triboelectric part, while the electromagnetic part can provide power density of 2.25 W m^{-2} at $1 \text{ K}\Omega$ and 10 m s^{-2} . The hybridized nanogenerator also exhibits a good stability for the output performance and a good charging performance. This hybridized nanogenerator can light up 40 commercial light-emitting diode bulbs and charge a $470 \text{ }\mu\text{F}$ capacitor by using a power management circuit. Furthermore, due to the magnetically-levitated structure, the hybridized nanogenerator has been utilized as a vibrometer. It can clearly detect the vibration with the acceleration less than 30 m s^{-2} and amplitude less than 7.5 mm . This work not only presents a novel approach in the field of mechanical energy harvesting, but also a solid step towards self-powered monitoring technology.

1 Introduction

Sensors for monitoring quantities such as vibrations, temperature, ammonia concentrations, and micro-differential pressure are widely employed in the field of bridge construction and working environment supervision. These devices are convenient aides to work and life, but they also cause an increase in energy demand. Although the power consumption of these devices is low and generally provided by batteries, they are difficult to operate for extended periods of time. By contrast, harvesting energy from the surrounding environment is a promising way to power electronic devices.¹⁻⁴ In recent years, electromagnetic, piezoelectric and electrostatic generators have been fabricated to convert mechanical energy into electricity, increasing battery life and reducing the maintenance costs of the monitoring systems.

Recently, the triboelectric nanogenerator (TENG), which couples the effects of contact electrification and electrostatic induction, has been proved to be an effective means of energy harvesting.⁵⁻²⁰ The vertical contact-separation TENG has a high open-circuit voltage, which can be easily achieved. This makes its use convenient in any application requiring high voltage; however, the short-circuit current of the TENG is relatively low, which limits its applications. When the size is reduced, the output will be lower. It has been shown that an effective way to compensate the low short-circuit current of TENGs consists in coupling two or more energy conversion mechanisms.²¹⁻³⁰ Nonetheless, the complicated structure required to complete the conversion still limits their application.

In this work, we demonstrated the use of an magnetically levitated-triboelectric nanogenerator to convert mechanical energy into electricity. The device integrates two TENGs and one electromagnetic generator (EMG). It is worth mentioning that an magnetically levitated generator (MLG) has been put forward. The magnetically levitated component of the hybrid nanogenerator has high efficiency and sensitivity, due to the main magnet that can keep the suspension in the middle-position. The main magnet has two important roles. The first is to move up and down repeatedly, which is essential for the contact-separation between the two friction materials. The second is to change the induced

electromotive force in the coils repeatedly and quickly, efficiently converting the mechanical energy to electricity. A characterization of the outputs of the triboelectric and magnetically levitated components has been conducted systematically. It was found that the power generated could instantaneously light up 40 LEDs, indicating that a high output can be obtained. Moreover, owing to the high sensitivity and good recovery performance of the magnetically-levitated structure, this nanogenerator was also demonstrated as a self-powered vibration monitoring system, which can be mainly employed to detect acceleration. Vibrations characterized by accelerations lower than 30 m s^{-2} and amplitudes below 7.5 mm can be detected. This work not only presents a novel approach in the field of mechanical energy harvesting, but also a solid step towards self-powered monitoring technology.

2. Results and discussion

2.1. Structure of the magnetically levitated-triboelectric nanogenerator

The hybrid generator consists of two TENGs and one EMG, as schematically illustrated in Figure 1a. Figure 1b shows the electromagnetic component. Figure 1c shows one of the TENGs, which consists of a one-piece membrane structure formed of polyamide, aluminium (Al) electrode, silicone and PET. PET was selected for both the support and substrate layers, mainly due to its decent strength, good machinability and low cost. Its use as substrate layer also promotes the recovery after deformation of the TENG. In addition, to enhance the effective contact area and friction coefficient of the thin film, thus improving output performance, a nylon micro-filtration membrane, with $10 \text{ }\mu\text{m}$ pore size, and a silicone thin film, with $250 \text{ }\mu\text{m}$ thickness and triangular pyramid structure on surface, were used. The Al electrode was manufactured through magnetron sputtering on the back of the nylon membrane and silicone thin film. SEM images are displayed in Figures 1c and 1d (see Figure S1 and Figure S2 in the Supporting Information for details).

Here, we demonstrated a new structure of the MLG, as shown in Figure 2. Three cylindrical

magnets are fixed on the surrounding shell at equal-angle intervals, in order to keep the main magnet in balance. The poles of the main magnet and cylindrical magnets are opposite to each other. In order to clarify the representation of the MLG, Ansoft Maxwell was employed to simulate the magnetic field. As shown in Figures 2a, Figure 2b, Figure 2c and Figure 2d, in the static state, the main magnet stays still in the middle-position. When an external vibration is applied, the magnet moves up and down repeatedly and quickly, until it stops back in the middle-position. The greatest advantage of the MLG is that it can convert mechanical energy to electricity for many times even after only one vibrational excitation (see Figure S3-S10 in the Supporting Information for detailed simulation of the magnetic field). The detailed fabrication process of the TENG and MLG is presented in the Experimental Section.

2.2. Working principle

The basic working principle of the generator can be divided into two parts: the triboelectric part and the electromagnetic part, as schematically depicted in Figure 3. On one hand, the main magnet stays in the static state (Figure 3a). Due to the fact that the main magnet is in a state of suspension, it can nimbly and repeatedly move up and down in response to external vibration. Based on Faraday's law, the change in magnetic flux crossing the coil causes an inductive electromotive force. When the main magnet moves up, the magnetic flux crossing the bottom coil decreases and the magnetic flux crossing the top coil increases, thus inducing current flow into the bottom coil and out of the top coil (Figure 3a). On the contrary, when the main magnet moves down, current flows are induced into the top coil and out of the bottom coil. (Figure 3a). The coils can thus generate electricity.

On the other hand, the basic working principle of the TENG is based on the coupling between contact electrification and electrostatic induction.³¹⁻³⁷ When the external vibration amplitude is greater than 5 mm, the arc gel pad fixed on the top and bottom of the main magnet will press the TENG and cause its deformation, as shown in Figure 3b. When the top substrate of the TENG is pressed by the arc gel pad (Figure 3b), the top nylon micro-filtration membrane and the bottom silicone film are brought in contact with each other, generating triboelectric charges due to their different triboelectricities. As

determined by the triboelectric series,² polyamide is much more triboelectrically positive than silicone, resulting in accumulation of positive charges on the nylon micro-filtration membrane side and of negative charges on the silicone film side (Figure 3b). When the arc gel pad moves up, the nylon micro-filtration membrane and silicone film move apart due to the elastic force of the PET. Meanwhile, electrons flow from the Al electrode on the back of the silicone film to the Al electrode on the back of the nylon film due to electrostatic induction (Figure 3b), generating a current. When the deformation is fully recovered, the charges reach a balanced state (Figure 3b). When the arc gel pad moves down again, electrons flow back from the Al electrode on the back of the nylon film to the one on the back of the silicone film because of the rejection of the electric field (Figure 3b). Thus, the current is generated in the triboelectric component.

2.3. Output characterization

The output performance of the hybrid generator was measured on a vibration exciter. The generator was strongly fixed by using a special jig. The open-circuit voltage and short-circuit current were tested with an acceleration of 10 m s^{-2} , amplitude of 5 mm and vibration frequency of 8 Hz. As shown in Figures 4a and Figure 4b, a short-circuit current of 1.4 mA was produced with a peak voltage of 2.6 V. To obtain the output power, the electromagnetic peak voltage was measured under different external load resistances with an acceleration of 10 m s^{-2} and a vibration frequency of 8 Hz. As depicted in Figure 4c, the output voltage decreases dramatically as the external loading resistance varied from 1000 Ω to 10,000 Ω . A maximum output power of 1.6 mW, with the corresponding power density of 2.25 W m^{-2} (considering the area of magnet), was obtained at 1 k Ω . When the amplitude of vibration was greater than 5 mm, the TENG started. Figures 4d-e show the measured open-circuit voltage and short-circuit current of the TENG component with an acceleration of 10 m s^{-2} , amplitude of 7.5 mm and vibration frequency of 6 Hz. The voltage and current reached, respectively, 8 V and 260 nA during the fast contact-separation between the polyamide and silicone film (see Movie S1 in Supporting Information). As depicted in Figure 4f, since the inner resistance of the triboelectric component is high,

the output voltage increases with increasing values of the external loading resistance, especially after a loading resistance of 10 M Ω . Consequently, the TENG possesses a maximum output power of 0.65 μ W, with a resistance of 100 M Ω . For instance, the open-circuit voltages of the MLG and TENG components were measured for more than 1000 s. As shown in Figures 4g and Figure 4h, no obvious decline was found for either component. The reliability in the performance was further verified by the fact that no obvious structural damage was recorded after over 1000 s (see Figure S11 in the Supporting Information).

2.4. Hybrid generator as a self-powered vibrometer

In the contact process of two friction surfaces, the contact area and contact tightness are both different due to the different pressure from the arc gel pad. Thus, accumulation of positive charges on the nylon micro-filtration membrane side and negative charges on the silicone film side are also different. Figure 5 shows the dimension parameters of the TENG and quantity of electricity under different contact areas. As shown in Figures 5c, Figure 5d and Figure 5e, the greater the contact area, the greater the charge, this also means that the output generated by TENG is different. Furthermore, in the vibration sensing process, the acceleration and velocity are constantly changing, resulting in variable speeds of the up-down movement of the main magnet. The greater the change of the magnetic flux that crosses the coil, the greater the inductive electromotive force established in the coils, leading to different electric generation outputs from the MLG. If there is a correspondence between the electric outputs of the generator and the acceleration of the external vibration, the output can be used as a vibration signal. As is well known, the higher the sensitivity of the sensor, the better the performance and the wider the application range. It would be very meaningful to use the magnetically levitated-triboelectric nanogenerator as a vibrometer having high performance and sensitivity.

As mentioned above, the vibrometer was strongly secured by using a special jig, on which an UNI-T-UT312 pocketable vibrometer was also fixed for correlation calibration, as shown in Figure 7a and Figure 7b. Figure 6a shows the measured open-circuit voltage of the MLG component under a vibration

amplitude of 5 mm, where the voltages reached 0.6, 2.5, 2.6, 16, and 22 V with accelerations of 2, 5, 10, 20, and 30 m s^{-2} , respectively. The corresponding short-circuit currents of the MLG reached 250 μA , 860 μA , 1.4 mA, 8 mA, 10.5 mA, as shown in Figure 6b. A good correspondence between the output and the acceleration of vibration can therefore be seen. Figures 6d and Figure 6e show the measured open-circuit voltages and short-circuit currents of the TENG obtained with accelerations of 2, 5, 10, 2, and 30 m s^{-2} and an amplitude of 7.5 mm. The corresponding voltages and currents are, respectively, 1.4, 6, 8, 12, and 15 V and 50 nA, 190 nA, 275 nA, 750 nA, 1.1 μA . It is fairly obvious that the output of the TENG also correlates well with the acceleration of vibration. Meanwhile the power output was also measured. As shown in Figures 6c and Figure 6f, the output power curves of both the MLG and TENG components increased with increasing acceleration and both reached their maximum value at 30 m s^{-2} . The maximum peak output power of the MLG and TENG reached nearly 250 mW and 16 μW , respectively. Thus it can be seen that the output performance of the hybrid generator is good.

From the above analysis, it is obvious that the characteristics of the TENG and MLG are different: the MLG can detect vibrations within 5 mm amplitude very well. The TENG can accurately detect vibrations with amplitude greater than 5 mm. Although the output current of TENG is relatively low, it is sufficient to be employed as a sensing signal. In order to realize the self-powered working mode, the electromagnetic component represents the main power supply of the vibrometer, due to its high efficiency and large current.

2.5. Hybrid generator for practical applications

To prove the capacity of the hybrid generator as a sustainable power source and vibration sensor, four sets of practical applications were demonstrated. As shown in Figure 7c, the hybrid generator can completely light up 40 LEDs (which are connected in parallel) with an amplitude of 5 mm (see movie S2 in Supporting Information). Figures 7d and Figure 7e indicate the charging curves of the hybrid generator for a capacitor of 470 μF . The highest voltages were obtained by the hybrid generator, indicating that its charging performance is good under external vibration with both high and low

accelerations. In this process, by using a power management circuit, the triboelectric component can also steadily charge the capacitor (see movie S3 and Figure S12 in the Supporting Information). Furthermore, to demonstrate the sensitivity of the hybrid generator as a self-powered vibrometer, it was used to detect the slight vibrations caused by slap, ball drop and spanking (see movie S4, movie S5 and movie S6 in Supporting Information), which indicated that even slight vibrations could be detected due to the electromagnetically levitated structure. In addition, it also can be used as a self-powered and wireless vibration sensor by connecting it with a micro-control unit which is integrated with analog-to-digital conversion module and wireless transmission module. Thus its application prospect is very broad.

The development of modern life involves ever-increasing exposure of the human body to the action of unfavourable environmental factors, especially vibration and noise. Many people are exposed to vibration in vehicles: cars, buses, trains, ships and airplanes, on a daily basis. It was confirmed that vibration caused discomfort, fatigue and physical pain. There have been several reports that describe how vibration interferes with people's working efficiency, safety and health.³⁸ The vibration strength humans can bear is divided into three levels: Limit Standard Value, Fatigue Standard Value and Uncomfortable Standard Value. Besides, the buildings such as bridge also has a certain degree of tolerance to vibration. Once the vibration amplitude or acceleration are close to or more than the threshold, it will produce the risk of damage. Thus it can be seen that this vibrometer based on the hybridized nanogenerator can be used as a self-powered warning or alarming device.

3. Conclusions

In summary, a newly designed hybrid generator was developed for the first time, by integrating TENG and MLG, for high-efficiency harvesting of mechanical energy from friction and electromagnetic induction. The suspended structure in the hybrid generator can produce energy many times in response to a single external vibration. On the basis of the design, the output signals from the MLG and TENG has the characteristics of a wide working bandwidth and high sensitivity. Thus we demonstrated this

hybrid generator as a vibrometer with a 0 - 30 m s⁻² detection range. Even slight vibrations caused by slap, ball drop or spanking can be detected clearly. Moreover, the hybrid generator's charging performance makes it suitable not only to charge a 470 μ F capacitor, but also to sustainably power LEDs. The hybrid generator has potential applications for mechanical energy harvesting and self-powered monitoring sensors. The vibrometer based on the hybrid generator is expected to be applied in the next generation of low-powered or completely self-powered vibrometers. Thus it could play in the future a unique role in the field of bridge, construction, seismic monitoring, working environment monitoring and portable electronic devices.

4. Experimental Section

Preparation of silicone film: The process to prepare the silicone film was divided into two steps: (1) Silicone film surface modification. (2) Back electrode deposition. A 200 nm thick aluminium layer, acting as a back electrode, was deposited on the other side of the silicone film by using magnetron sputtering. Silicone film surface modification: Firstly, SiC sandpaper, with triangular pyramid arrays on its surface, was pasted on the mirror plate. Then silicone was evenly coated on the sandpaper with a ratio between base gum and curing agent of 100:2 and a thickness of 250 μ m. It was then placed in a vacuum drying oven and heated for 2 h at 70 °C. After complete curing, the film could be stripped off..

Fabrication of the TENG: The PETs were die-cut into circles with diameter of 36.5 mm and annulus with inner diameter of 32 mm and external diameter of 36.5 mm. Lead wires were connected to the surface of the aluminium electrode in the back of the silicone film and nylon membrane.

Fabrication of the MLG: The pedestal of the MLG was quickly produced by using laser forming technology to prototype resin moulds. Finally, three cylindrical NdFeB permanent magnets were inserted into the longhole on the pedestal. The circular NdFeB permanent magnet can be kept levitated among the cylindrical magnets. Copper coils were fixed above and below the pedestal.

Characterization of the vibrometer: The morphologies of the samples were characterized by field emission scanning electron microscopy (ZEISS EVO18, Carl Zeiss Jena, Germany). The dynamic process of the vibrometer was tested on the vibration exciter. The output voltage and current were measured by a low-noise voltage preamplifier (Keithley 6514 system electrometer) and a low-noise current preamplifier (Stanford Research SR570).

Supporting Information

Supporting Information Available: (1) The surface macroscopic images of silicone film and nylon membrane; (2) The simulation of the magnetic field; (3) The reliability in the performance; (4) The power management circuit; (5) Supporting movie of the short-circuit current of the TENG with the acceleration of 10 m s^{-2} and the vibration frequency of 6 Hz.; (6) Supporting movie of continuously lighting up 100 commercial light-emitting diode bulbs; (7) Supporting movie of the charging performance of the TENG; (8) Supporting movies of that self-powered vibrometer can detect slight vibration caused by slap, ball drop and spanking.

Conflict of Interest: The authors declare no competing financial interest.

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Figure 1. Magnetically levitated-triboelectric nanogenerator. a) Schematic illustration of the hybrid generator, which consists of two TENGs and one EMG. b) Schematic illustration of the magnetically levitated generator. c) A basic unit of the TENG: one-piece membrane structure consisting of polyamide, aluminium electrode, silicone and polyethylene terephthalate (PET). d) SEM image of nylon membrane. e) SEM image of silicone thin film.

Figure 2. Finite element simulation of MLG motion. a) Simulation of the magnetic field in the middle-position. b) Simulation of the magnetic field in the high-position. c) Simulation of the magnetic field in the middle-position. d) Simulation of the magnetic field in the low-position. e) 3D layout of the circular magnet and three cylindrical magnets.

Figure 3. Working principle of the generator. a) Schematic diagram of the generation process of electricity, indicating the relationship between the direction of current flow and the movement of the magnets when the amplitude is less than 5 mm. b) Schematic diagram of the generation process of electricity when the amplitude is greater than 5 mm.

Figure 4 a) Open-circuit voltage of the MLG with acceleration of 10 m s^{-2} , vibration frequency of 8 Hz, amplitude of 5 mm. b) Short-circuit current of the MLG. c) Open-circuit voltage of the TENG with acceleration of 10 m s^{-2} , vibration frequency of 6 Hz, amplitude of 7.5 mm. d) Short-circuit current of the TENG. e) Electromagnetic peak voltage and power under different external load resistances with acceleration of 10 m s^{-2} , vibration frequency of 8 Hz, amplitude of 5 mm. f) Triboelectric peak voltage and power under different external load resistances with acceleration of 10 m s^{-2} , vibration frequency of 6 Hz, amplitude of 7.5 mm. g) Open-circuit voltage of the MLG was measured for more than 1000 s. h) Open-circuit voltage of the TENG was measured for more than 1000 s. Note: the time is limited by the storage of our measuring instrument.

Figure 5. Dimension parameters of the TENG and quantity of electricity under different contact areas. a) Diagram of the TENG. b) Dimension parameters of the TENG in larger view. c-e) Quantity of electricity under different contact areas.

Figure 6. a) Open-circuit voltages of the MLG with vibration amplitude of 5 mm and different accelerations. b) Short-circuit current of the MLG with vibration amplitude of 5 mm and different accelerations. c) Open-circuit voltage of the TENG with different accelerations. d) Short-circuit current of the TENG respectively with different accelerations. e) Output power curve of the MLG under different accelerations. f) The output power curve of the TENG with different accelerations.

Figure 7. a) Vibration modelling test platform. b) Photo of the hybrid generator. c) The generator can completely light up 40 LEDs. d) Generator charge a 470 μF . e) Charging curves.