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Triboelectric nanogenerator as self-powered impact sensor

Cristobal Garcia [1] *, *Irina* Trendafilova [1], *Roberto* Guzman de Villoria [2], and *Jose* Sánchez del Río [3]

[1] University of Strathclyde, Department of Mechanical and Aerospace Engineering, 75 Montrose Street, G1 1XJ, Glasgow, UK
[2] FIDAMC, Avda. Rita Levi Montalcini 29, 28906, Getafe, Spain
[3] IMDEA Materials Institute, C/ Eric Kandel 2, 28906, Getafe, Spain

Abstract. In recent years, triboelectric nanogenerators (TENGs) are used to harvest mechanical energy from ambient environment. These devices convert ambient energies (e.g. vibrations, breathing-driven, impacts or human body motions) into electricity based on the triboelectric effect. Furthermore, some TENGs can be successfully employed as self-power active sensors because the electric response from the TENG is proportional to the magnitude of the mechanical motion. This study report on the design and development of a novel triboelectric nanogenerator, and its potential application as self-powered impact sensor. To prepare the TENG device, membranes of polyvinylidene fluoride (PVDF) and polyvinylpyrrolidone (PVP) nanofibers are sandwiched between copper electrode films and wrapped on PET films. The TENG works based on the triboelectric interaction between the membranes of nanofibers. After the preparation, the TENGs are subjected to several impacts by the drop-ball impact test. The purpose of the experiment is to analyse if the electric response of TENG is dependent on the energy of the impact. The results of the experiment are presented and discussed. The main contributions of this work are the preparation of a novel nanogenerator (TENG) based on the triboelectric interaction between polyvinylidene fluoride and polyvinylpyrrolidone sub-micron polymer fibers and the investigation of its potential use as a self-powered impact sensor.

1. Introduction

A few years ago, impact sensors are required for a number of applications including structural health monitoring [1, 2]. Such sensors should be designed so that they can detect the impact but also measure some of its characteristics. Recently TENGs as self-powered active sensors are gaining a lot of popularity as they save energy but in the same time some of them can detect touch, impacts, vibrations, pressures and so on. These devices demonstrate excellent sensitivity to certain mechanical motions. Triboelectric nano-generators (TENG) as self-powered active sensors work on the basis of the triboelectric effect [3, 4 and 5]. This type of sensing has shown a number of desirable properties including extremely high output and efficiency in comparison to other sensing devices, low cost production technology, as it does not require highly sophisticated instruments for the manufacturing process, outstanding stability to high temperatures in comparison to piezoelectric devices, as well as environmental friendliness.

Traditional sensors are usually powered by batteries; however, TENGs do not need a power supply unit. The number of sensors used for monitoring different structures and machinery is increasing continuously. In a lot of cases the sensors are distributed across a wide range of area and integrated within the structure, and as such they need to operate wirelessly. For these systems, it is very important for the sensor to have the capability of operating independently, sustainably and maintenance-free. Therefore, the ability of the sensors to perform self-powered operations in a wireless sensor networks is critically important.

Vibrations are one of the most important forms of mechanical motions that can be found in ambient environment. Some examples of these are the motions generated for a washing machine/engine during its operational state or the vibrations produced on buildings and bridges due to an earthquake. Vibrations can directly reflect the working state and the health of the machineries and infrastructures, therefore the sensing of vibrations is of critical importance in equipment maintenance and environment monitoring. Since TENGs can generate electricity from any type of mechanical motions in the natural environment including vibrations

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[*] Corresponding author: cristobal.garcia@strath.ac.uk

[6, 7], human body motions [8, 9], impacts [10, 11], breathing-driven [12] and so on, they can be used to develop self-powered active sensors for all these types of mechanical motions.

In this work we build a novel TENG and investigate its applicability as impact sensor. This device is constructed with the aim to develop a vibration sensor. But at this stage we only investigate its capabilities to detect and measure impact. The developed TENG is based on the interaction between PVDF and PVP fibres. The nano-structured materials are sandwiched between copper electrodes and wrapped in PET films.

To the best of our knowledge, this is the first attempt to produce a TENG using this selection of nano-structured materials. This work investigates the potential application of the newly developed TENG as a self-powered impact sensor. The impact testing is supposed to check and verify the sensor sensitivity to impact. In this respect the output voltage for different impact heights, velocities and energies is measured. There are other studies that test the application of different sensors to impact [13]. As the sensor developed is a novel one this testing and all the results are new. Therefore, this work presents solid progress toward the practical applications of the developed TENG.

The authors plan to use this TENG for purposes of development of an active vibration sensor and investigate its capabilities for vibration-based structural health monitoring in their future work.

The rest of the paper is organised as follows: The second section gives some insight on the fabrication of the necessary polymer nanofibers. &3 is dedicated to the sensor assembly using these nano-structured mats. Section 4 explains the experiments carried out to demonstrate the potential application of the TENG as self-powered impact sensor. The experimental results are introduced and discussed briefly in section 5. The last section offers some conclusions and ideas for extending the research.

2. Nano-material preparation

Electrospinning is a versatile process to produce sub-micron polymer fibers having high surface to volume ratio. Membranes of polyvinylidene fluoride and polyvinylpyrrolidone submicron fibers are prepared via electrospinning. The surface morphology of the fibers was observed using scanning electron microscopy (SEM) from Carl Zeiss (EVO MA15). An SEM image of PVDF nanofibers is given in figure 1 (a). The image shows fibers with different sizes distributed randomly in the membrane. The average diameter of the beaded fibers is about 700 nm. PVP fibers are shown in figure 1 (b). The SEM image shows microfibers with approximately the same diameter which can be measured to be about 1.4 micras.

PVDF in form of pellets is dissolved in DMF/acetone (40/60) mixture solvent to prepare a 20% w/v solution. The PVDF solution was loaded in a 5 mL plastic syringe with 21G steel needle. The electrospinning was carried out under the following conditions: voltage = 15 kV, spinning distance = 15 cm, flow rate = 0.6 ml/h. Membranes of PVDF nanofibers with a thickness of 0.25 mm were deposited on copper foil. PVP powder was dissolved in ethanol to prepare a 10% w/v solution. The PVP solution was transferred to a plastic syringe to be electrospun in Nanon-01 A. The electrospinning was carried out under the following conditions: voltage 18 kV, spinning distance 12 cm, 21 gauge needle and feed rate 0.5 ml/h. Membranes of PVP nanofibers with thickness of 0.12 mm were electrospun on copper foil.

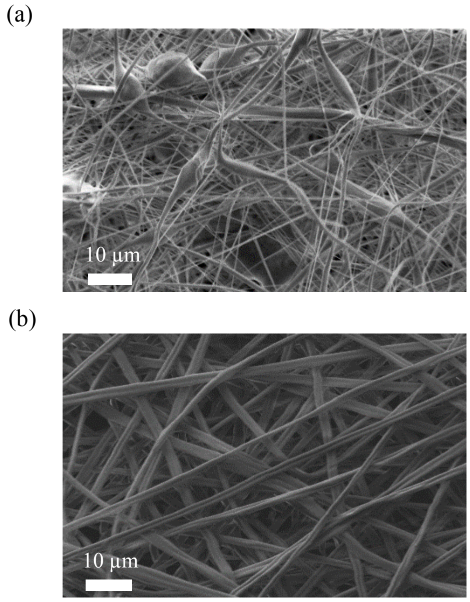


Figure 1: (a) SEM image of the electrospun PVDF fibers and (b) SEM image of the electrospun PVP fibers.

3. Sensor assembly

The sensor is fabricated by using electrospun nanofiber mats. The electrospun nanofiber mats are deposited at 0.05 mm thick square copper electrodes with a size of 4 x 4 cm^2. The sensor is made of four layers. The first and fourth layers are the bottom and the top copper electrodes respectively. The electrospun nanofiber mats are located as layers in between the electrodes, which face with each other. Eventually, the device is wrapped with polyethylene terephthalate film (PET) using a standard laminator (Inspire A3). The schematic structure of the sensor is shown in Figure 2.

The selection of triboelectric materials was done in accordance to the triboelectric series [14]. PVDF is one of the electronegative materials from the series. Thus, it tends to attract electrons and charge negatively. PVP is an electropositive material in the series, therefore, it tends to give electrons and charge positively. It is known that the contact area between the triboelectric materials affects the performance of the TENG. This is why the authors chose to use nanofibers instead of films. The larger surface increases the generation of triboelectric charges and thus improves the performance of the sensor.

The working mechanism of the sensor is the vertical contact-separation mode described elsewhere [15]. It is out of the scope of this work to assets it, however, we are going to show the sensing mechanism of a TENG based in the schemes of other authors [16, 17]. The basic working principle of the device is schematically depicted in figure 2. In the original state of the device, there is no charge generation and no electric potential difference. Under pressure from an external motion, the two triboelectric layers are brought into physical contact with each other. The contact between the triboelectric layers generates opposite triboelectric charges onto both nano-structured surfaces. Thus, the membranes of PVDF and PVP nanofibers are oppositely charged. When the pressing force is released, the two oppositely charged nanostructured surfaces are separated. The gap between the opposite triboelectric charges creates a dipolar moment with a potential difference across the two electrodes. Last, the material reverts to its original state because the triboelectric charges created disappear. Thus the voltage is created by the contact and the consequent separation of the two PVDF and PVP membranes of nanofibers. The contact and separation result in changes of the measured voltage.

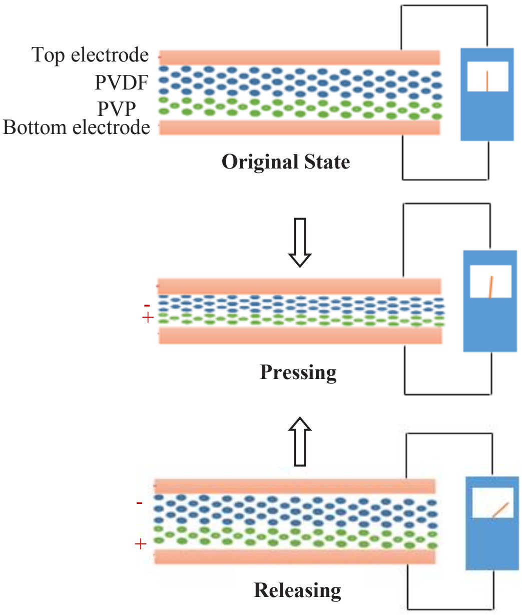


Figure 2: A schematically description of the structure and mechanism of generation of electricity in the TENG

4. Application of the device for impact detection and measurement.

This section describes the experiment used to measure the sensitivity of the manufactured sensor to impact. The prepared self-powered TENG was subjected to impacts with different energies applied via drop ball test. In this test, a free-falling glass ball of 21.22 g is dropped from four different heights: 10, 35, 65 and 100 cm. A schematic description of the experimental set-up is shown in figure 3. The diameter and the density of the ball is 2 cm and 5,06 g/cm^3 respectively. The ball is dropped within a plastic tube so that the impacts were applied perpendicularly to the sensor. The TENG is connected to a commercial oscilloscope to measure the electric output in response to impacts in the form of voltage using Tektronix 2012B commercial oscilloscope.

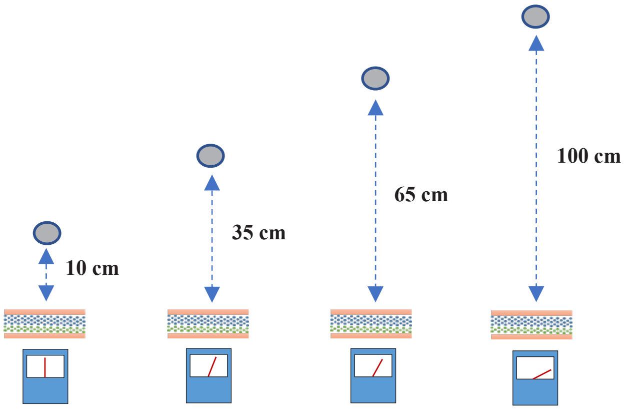


Figure 3: A schematic diagram of the experimental set-up to measure the electrical response to impacts

When the ball hits the sensor, both membranes of sub-micron fibres are brought into physical contact. After the impact, the ball rebounds and the nano-structured membranes revert back to their initial position. Thus, the nano-structured membranes are brought into contact and separation which generates a potential difference between the electrodes.

In the case of a drop ball test, according to the law of conservation of energy the potential energy before the collision equals the kinetic energy after the collision, which can be written as in equation 1, where m is the mass of the ball, g is the acceleration due to gravity, h is the drop ball height and v is the impact velocity. In the experiment, the drag forces caused by the air resistance and the side walls of the plastic tubes during the ball drop were neglected to simplify the analysis. Solving from the law of conservation of energy, the energy of the impact and impact velocity can be calculated using equations 1 and 2 respectively.

$$U = mgh = \frac{1}{2} mv^2 \qquad (1)$$

$$v_{impact} = \sqrt{2gh} \qquad (2)$$

5. Results and discussion

This section presents and discusses the results obtained in the drop-ball test. The TENG fabricated as indicated in section 3 was tested by drop-ball impact test using a free-falling ball. The ball was dropped from four different heights of 10, 35, 65 and 100 cm respectively. Table 1 presents the velocity and energy of the impact calculated theoretically for the particular drop height. The table indicates that when the balls were dropped from greater heights, the velocity and energy of the impact increase.

Table 1: The velocity and energy of the impact calculated theoretically as a function of the drop height.

Drop Height (cm)	*Velocity (m/s)*	*Impact Energy (mJ)*
10	1.40	21
35	2.62	73
65	3.57	135
100	4.43	208

The output voltage responses obtained for the impacts on the sensor are given in figure 4. The graph shows the electric response as a function of the time that result in response to the different impacts. The graph shows the variations of voltage caused by the ball impacts at 10, 35, 65 and 100 cm drop height respectively. The results show that increasing the impact drop height leads to increase of the voltage output. A number of peaks are observed for each impact due to multiple collisions, with the first peak corresponding to the first impact of the ball falling on the sensor. The following peaks correspond to the subsequent rebounds. The graph indicates the drop height for the first impact. The time interval between the bounces is also indicated in figure 4. The time interval between the first impact and the first bounce is the biggest one. However, the time interval between the subsequent bounces decreased gradually.

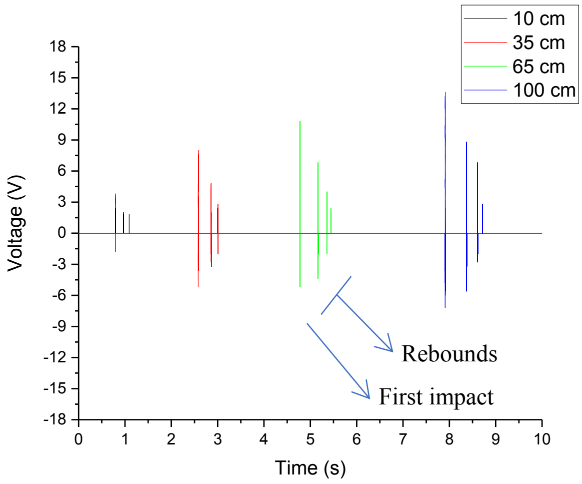
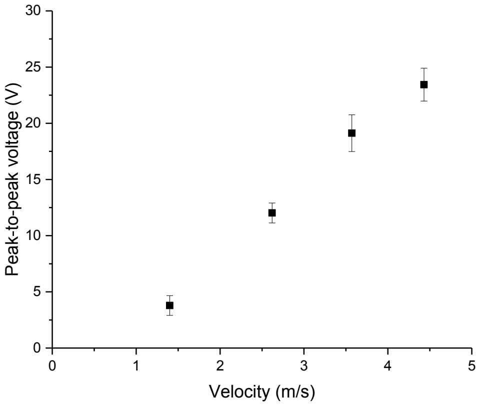


Figure 4: Voltage output response in time domain for the different ball impacts

Figure 4 also shows the peak-to-peak voltage values for the first impact and the next three rebounds. The highest voltage amplitude corresponds to the first ball impact. The peak-to-peak voltage values decrease gradually for the subsequent rebounds. The voltage generated at all the impacts from the different drop heights follow the same trend.

Figure 5 (a) and (b) shows the peak-to-peak voltage amplitude (V) for the first impact as a function of the velocity and the energy of the impact respectively. Five impacts tests were done for each drop height. The results given are the average voltage response and the standard deviation for the five tests.

(a)



(b)

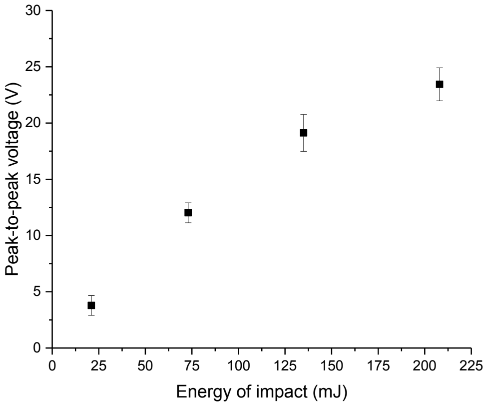


Figure 5: Peak-to-peak voltage response as a function of the velocity (a) and impact energy (b)

Impacts at higher velocity and energy lead to increase in the voltage response in the range from 1 to 5 m/s and 20 to 225 mJ respectively. When the ball hits the sensor at a small energy and velocity, the nano-structured rough membranes prevents completely close contact. Therefore, large areas of PVDF nanofibers are not in contact with PVP nanofibers which decreases the generation of electricity. When a higher energy and velocity is applied, the sensor deformation increases leading to more contact area between the membranes and this increases the voltage response.

The relation between the velocity of the impact and the voltage as per figure5 (a) is approximately linear. While the relation between the energy of the impact and the voltage does not seem to be linear and it looks as if for the higher energies the relative changes in the voltage are smaller as compared to the changes at lower energy.

6. Conclusions and future research

In this work, we demonstrated the potential applications as self-powered impact sensor of a TENG based on triboelectric interaction between submicron fibres of PVDF and PVP. An electrospinning method was utilized to fabricate nanofiber-networked membranes of both polymers, which was beneficial to enhance the performance of the TENG. The sensor is composed by four layers. The first and the four layers are the bottom and top copper electrodes respectively and the middle layers are the membranes of polymer fibres. The sensitivity of the manufactured TENG to impacts was analysed using the drop ball test. The experimental results showed that the TENG was very sensitive to impacts and it can clearly discriminate between impacts at different energies and velocities in the ranges between 0 and 225 mJ, and between 1 and 5 m/s, respectively.

For the future, authors plan to analyse the sensitivity of this TENG to mechanical compressions. For such analysis, the dynamic mechanic analyser (DMA; Q800; TA Instruments) equipped with the compression clamp used. The DMA equipment can apply mechanical compressions with forces in the range from 0.1 to 18 N. Moreover, DMA equipment can also apply mechanical compressions with different frequencies in the range between 0.10 to 20 Hz. Authors will study the electric output response of the TENG in response to different compressive forces and frequencies.

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