Detection and measurement of impacts in composite structures using a self-powered triboelectric sensor

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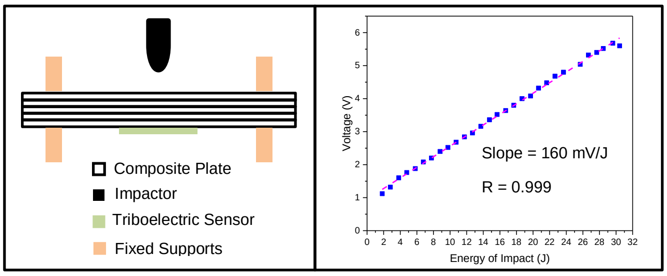
Abstract:

Composite structures as e.g. aircrafts, wind turbines or racing cars are frequently subjected to numerous impacts. For example, aircrafts may collide with birds during take-off and landing or get damaged due to the impact of hailstones. These impacts harm the integrity of the composite laminates used in their structures which results in delamination and other failures which are usually very difficult to detect by visual inspections. Hence, the detection and quantification of impacts is of vital importance for monitoring the health state of composite structures. Recently, triboelectric sensors have been demonstrated to detect touches, pressures, vibrations and other mechanical motions with the advantages of being self-powered, maintenance-free and easy to fabricate. However, there is no research focusing on the potential of triboelectric sensors to detect impacts in a wide energy range. In this paper, a self-powered triboelectric triboelectric sensor is developed to measure impacts at high energy in structures made of composite materials. This could be particularly benefitial for the detection of bird strikes, hailstones and other high energy impacts in aircraft composite structures. For that purpose, composite plates are subjected to various energy impacts using a drop weight impact machine and the electric responses provided by the developed triboelectric sensor are measured in terms of voltage and current. The idea is to evaluate the sensitivity of the electrical signals provided by the sensor to changes in the impact energy. The results prove that the generated electric responses are affected by the energy of the impact and their amplitude increases linearly with the impact energy. The voltage and current sensor responses demonstrate a very good impact sensitivty of 160 mV/J and a strong linear relationship to the impact energy (R = 0.999) in a wide energy range from 2 to 30 J. This work suggests a novel approach to measure the magnitude of the impacts in composite structures using the newly developed triboelectric sensor. The findings of this work demonstrate that the developed triboelectric sensor meets the urgent needs for monitoring high energy impacts for aeronautic and civil composite structures.

Graphical abstract



Keywords: Triboelectric sensor; Self-Powered systems; Impact monitoring; Electrospinning; Nanofibers

1. Introduction

Structures made of composite materials as aircrafts, wind turbines or bridges are frequently subjected to impacts. For example, aircrafts may collide with birds during take-off and landing. Composite structures like e.g. wind turbines can be seriously affected by the impact of hailstones. These impacts damage the integrity of the composite materials used in the structures which results in a significant loss of their structural integrity and stiffness. Furthermore, the delamination caused is almost impossible to detect by visual inspections and requires sophisticated inspection methods for its detection such as ultrasounds [1], infrared thermography [2], shearography [3], radiography [4] or rigorous mathematical tools [5]. Hence, impact sensors are vital to detect and quantify impacts as well as assess their location.

An impact sensor is a crucial component for vehicle safety [6], structural health monitoring [7], impact monitoring [8], and emergency locations of persons in distress [9]. According to its working mechanism, an impact sensor can be generally classified into piezoelectric [10, 11], capacitive [12], optical [13] and resistive types [14]. Among these, the sensors based on the piezoelectric effect have attracted considerable attention because they do not require external power supply or battery to power the sensor. However, the fabrication procedure is rather expensive and requires additional processing steps as annealing (a thermal treatment to increase the crystallinity of the material) and electrical poling (the application of a high electrostatic field at elevated temperature to align the dipoles) [15]. Thus, it is necessary to explore new approaches to develop sensors that does not rely on external power supply and can be produced using a low-cost and easy fabrication procedure.

Very recently, triboelectric sensors (TES) have attracted much research interest as a simple, sustainable, and cost-efficient technology can be used to develop self-powered sensors for pressures [16-18], vibrations [19, 20], accelerations [21, 22], velocities [23-24], magnetic fields [25, 26], gases [27, 28], object motions [29], and surface topographies [30]. However, there are only a few papers to analyse the potential of triboelectric sensors for impact energy detection. For example, [31] reported a triboelectric sensor which can detect the impacts applied between a little ball and the sensor in the energy range from 20 to 210 millijoules (mJ). The authors from [32] reported a self-powered triboelectric sensor which can detect the energy impacts below 105 mJ applied on a fixed table using a free-falling ball. One of the limitations in the above-mentioned studies is that they only evaluate a small range of energies between 10 and 210 mJ, which is far from the energy of the impacts in practical applications (e.g. automobile crash, bird-strikes or hailstorms). In this regard, it is necessary to investigate the capabilities of self-powered triboelectric sensors for detection of impacts at higher energies and wider detection ranges.

In this paper, we present a new class of self-powered triboelectric sensor prepared using polyvinyl fluoride (PVDF) and polyvinyl pyrrolidone (PVP) nanofibers, which can detect impacts in a wide energy range from 2 to 30 J. PVDF nanofibers are chosen as one of the frictional mats due to their strong tendency to attract electrons from other materials. This behaviour is attributed to the large composition of fluorine in PVDF that has the highest electronegativity among all the elements [33]. On the other hand, PVP nanofibers are selected as the other frictional mat due to their strong ability to donate electrons [34]. Furthermore, the rough and porous surfaces of the nanofibers extend the contact area between the frictional materials which results in an increment of the triboelectric effect [35]. The technique of electrospinning was used to prepare both layers of nanofibers due to its low cost, versatility and simplicity for the fabrication of nanofibers using a wide variety of triboelectric mats [36].

The main aim of this work is to investigate the ability of the developed triboelectric sensor to detect and quantify mechanical impacts applied to composite structures. For this purpose, composite plates are subjected to various impacts in the energy range from 2 to 30 J using a drop weight impact machine. Then, the electric responses of the triboelectric sensor adhered to the composites are measured in the form of voltage and current. The idea is to study the changes in the resultant electrical signals due to the variations in the impact energy. As was already mentioned, the experimental results confirm the dependence of the sensor electric responses on the impact magnitude. The measured voltage and current both demonstrate a strong linear relationship (R^2= 0.99) with the energy and the force of the impact. In addition, the sensor outputs show a very high sensitivity of 160 mV/J in a wide measurement range of energies from 2 to 30 J. Finally, the paper compares the performance of the developed triboelectric sensor with a commercial one.

This study to suggests a new approach to detect and measure a wide range of energy impacts in composite structures using a self-powered triboelectric sensor. The findings of this work demonstrate that triboelectric sensors can be used for real-time detection of impacts in composite structures as aircrafts, wind turbines or bridges. The main application of the triboelectric sensors is to monitor high energy impacts in composite structures. This could be practically used for the detection of bird strikes, hailstones and other high energy impacts in aircrafts and civil structures. Alternatively, the amount of damage generated because of these impacts is proportional to the amount of energy involved in the impact. Therefore, the amplitude of the electric responses of the energy sensor could be also used to estimate the health state of the composite structures.

The rest of the paper is organized as follows: Section 2 explains the fabrication process of the newly developed triboelectric sensor [16]. Section 3 introduces the experiment used to study the capability of the triboelectric sensor to detect and quantify impacts in composite structures. The analysis of the experimental results is presented and discussed in section 4. Some conclusions are drawn in the final section 5.

2. Fabrication of Triboelectric Sensor

This section details the fabrication of the triboelectric sensor. It is divided into two subsections. The first subsection gives a brief overview of the electrospinning procedure used to prepare the triboelectric nanofibers, while section 2.2 explains the design and the assembly process of the triboelectric sensor.

2.1. Preparation of triboelectric nanofibers

This section describes the production process used to prepare the nanofibers which served as frictional layers in the triboelectric sensor. The sensor is prepared by layers of PVDF and PVP which are made of nanofibers. The nanofibers are prepared via electrospinning because it is a simple and economic way of preparing a wide variety of polymer nanofibers [37]. Moreover, the large active surface of the electrospun nanofibers can efficiently generate triboelectric charges [38], which enhance the output performance of the triboelectric sensor. A schematic description of the electrospinning process utilized can be found in supplementary Fig. S1.

In the preparation of PVDF fibres, polyvinylidene fluoride pellets with a molecular weight of 275,000 g mol-1, dimethylformamide (DMF) and acetone from Sigma-Aldrich were used. To prepare the solution for electrospinning, PVDF pellets were dissolved in a solvent mixture of DMF and acetone (40/60) at 20% w/v. After, the homogenous solution was placed to a plastic syringe to be spun in Nanon-01A using the following operational conditions: a high voltage of 15 kV, a spinning distance of 15 cm, a feed rate of 1 ml/h, a 21 G steel needle and a static collector. Finally, a dense array of randomly distributed PVDF nanofibers with an average diameter of 953 ± 360 nm was obtained as shown in Fig. 1(a). From the figure, it can also be observed a few beads which are attributed to the nature of the polymer solution.

For preparing the PVP fibres, polyvinyl pyrrolidone powder and ethanol were provided by Sigma-Aldrich. The polymer solution was prepared by dissolving 1 g PVP powder (MW = 360,000 g mol-1) in 10 ml of ethanol. The obtained homogenous solution was then spun using the following conditions: applied voltage of 18 kV, feed rate of 0.5 ml/h, spinning distance of 12 cm, a 21G steel needle and a static collector. As result, good quality PVP

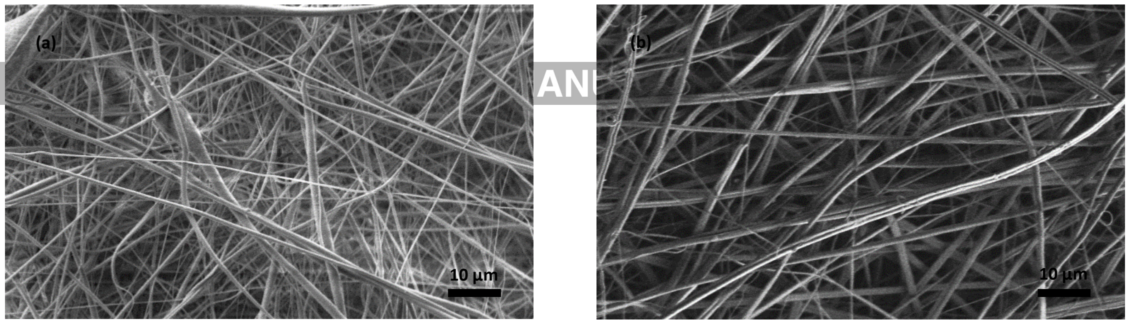


Fig. 1. Scanning electron images of the nanofibers prepared by electrospinning: (a) SEM image of the PVDF nanofibers. (b) SEM image of the PVP nanofibers.

nanofibers with an average diameter of 1545 ± 349 and random orientations are obtained and they are shown in Fig. 1(b).

2.2. Design and assembly of triboelectric sensor

The structural design of the triboelectric sensor consists of two layers of polymer nanofibers and copper electrodes as displayed in Fig 2(a). The role of the copper films is to act as electrodes for the triboelectric sensor, while the PVDF and PVP nanofibers served as the frictional mats. PVDF is selected as one of the frictional mats due to its strong ability to charge negatively (attract electrons) when in contact with almost any other materials [39]. In contrast, PVP is chosen as the other frictional material due to its strong tendency to charge positively (lose electrons) [34]. Therefore, the contact between the layers of PVDF and PVP nanofibers generates charges as a result of the triboelectric effect. The abilities of PVDF and PVP and other common triboelectric materials to produce negative and positive triboelectric charges respectively, are displayed in the triboelectric series given in supplementary figure Fig. S2.

It also important to mention that the nanofibers used in the triboelectric sensor are very rough with the aim to increase the area of contact between the frictional materials and enhances the electric responses [40]. To verify the effect of the contact surface, the electric responses of a triboelectric sensor with smooth and rough frictional surfaces are compared. Fig. S3 shows the electric responses of two triboelectric sensors prepared by frictional materials with smooth and rough nanostructured surfaces. The voltage amplitude of the triboelectric sensors with smooth and rough frictional mats are 0.78 V and 4.44 V, respectively, under the same mechanical impact. As a result, the electric responses of the nanostructured sensor with rough surfaces are six times larger due to the higher contact surface of the nanofibers. This confirms that the use of rough nanostructured surfaces is an excellent method for improving the performance of the triboelectric sensor. These results are in very good agreement with previous studies [40, 41]. For example, F.R. Fan et al. [40] fabricated triboelectric sensors using frictional materials with different types of micropatterned arrays: film, lines, cubes and pyramids. The results show that the sensors patterned with geometric features (lines, cubes and pyramids) show from five to ten times larger electric responses than the film patterned sensor. Other studies as [41] compared the electric responses of identical triboelectric devices prepared with nanofibers and flat films. The results demonstrate that the electric responses of the device with nanofibers are seven times higher as compared the flat films.

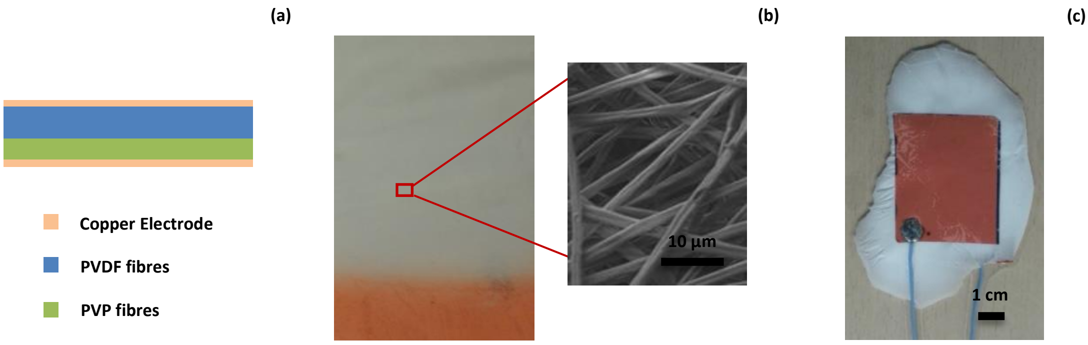


Fig. 2. Fabrication process and structure of the self-powered impact sensor: (a) Structure of the triboelectric sensor. (b) Preparation of the bottom part of the sensor. (c) Photography of the fully assembled sensor.

The assembly process of the triboelectric sensor is detailed in Fig. 2 and can be divided into four steps. First, a layer of PVP nanofibers with a thickness of approximately 1 mm was spun on copper foil to form the bottom part of the sensor as shown in Fig. 2(b). Secondly, a 2 mm layer of PVDF nanofibers was deposited on copper foil to form the top part of the sensor. A detailed description of the electrospinning procedure used to prepare the layers of PVDF and PVP nanofibers can be found in Section 2.1. Thirdly, the top and bottom part of the sensor are stacked to assemble the sensor as illustrated in Fig. 2(a). The copper films are located at the top and bottom side of sensor while the layers of nanofibers are placed in between the electrodes. Finally, the sensor is sealed with polyethylene terephthalate film which avoids changes in the sensor electric responses due to environmental changes (humidity, rainy days) and ensure the stable performance of the device. Fig. 2(c) shows a digital photograph of the triboelectric sensor as fabricated with the dimensions of 40 x 40 x 5 mm and a low weight of 5 g. Figure 2(a) shows the final configuration of the developed sensor.

In conclusion, it can be said that the fabrication process of the sensor is very simple and does not require sophisticated processing steps or equipments, which results in important cost-savings. Moreover, the electrospinning procedure is scalable and can be easily upgraded for large-scale production.

3. Detection of impacts in composite structures using the triboelectric sensor

This section explains the working principle of the developed triboelectric sensor and the experiment used to assess its capability to detect and quantify various energy impacts.

3.1. Working principle of the triboelectric sensor

The electric outputs of the triboelectric sensor are generated from the coupling effect of contact electrification and electrostatic induction [42-44]. Fig. 3 shows the working mechanism of the self-powered impact sensor, which is due to the contact-separation principle demonstrated by Wang's group [45-47]. At the original state (Fig. 3(a)), the triboelectric sensor is at rest and no charge is generated, which result in no electric potential difference between the two electrodes. When the composite plates are impacted, the sensor changes from the original state to the contact state as shown in Fig. 3(b). Therefore, the layers of PVDF and PVP nanofibers rub with each other which generate net negative charges on the surface of the PVDF fibers and net positive charges on the PVP fibers. This is attributed to the strong ability of PVDF and PVP nanofibers to gain and lose electrons, respectively. When the impact is released, the triboelectric sensor moves from the contact to the separation states as illustrated in Fig. 3c, d and e. At this stage, the triboelectric sensor is bent downwards due to the inertia of the impact and the opposite triboelectric charges from PVDF and PVP nanofibers are separated. Consequently, a strong potential difference between the top and bottom electrodes is generated in the triboelectric sensor. It is important to note that the potential difference is proportional to the relative distance between the positive and negative charges (electromagnetic induction effect) as can be seen in Fig. 3(c) and (d). Finally, the generation of triboelectric charges stops and the device reverts back to its initial state. This operational mechanism is an innovative alternative to the other conventional sensor working principles due to its independence on external power supply unit, sustainability and low-cost (maintenance-free).

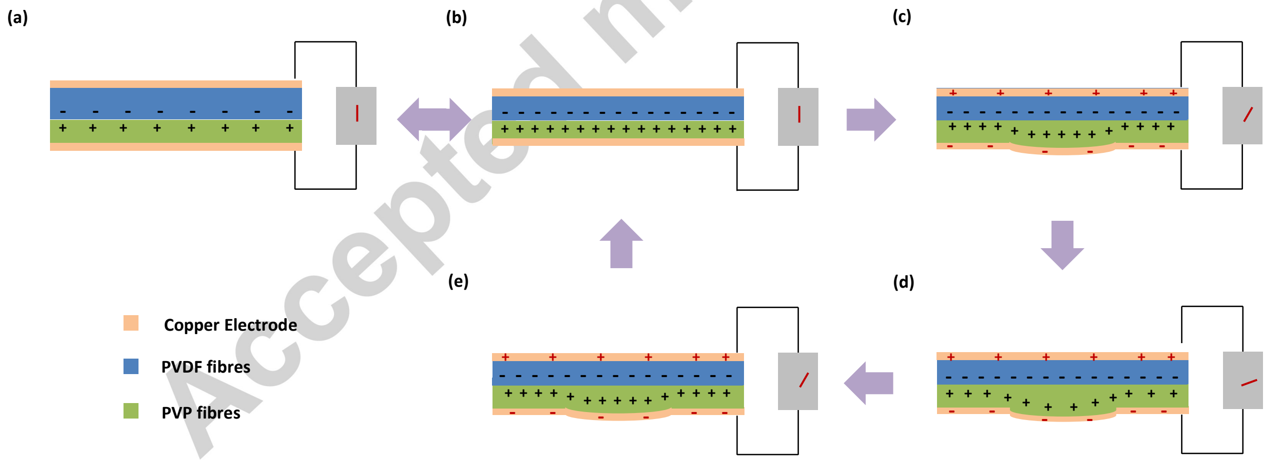


Fig. 3. Working mechanism of the self-powered impact sensor: (a) The original state of the sensor. (b) The contact state of the sensor. (c-e) Various separation states of the triboelectric sensor. The polymer nanofibers are not illustrated in the figure for the purpose of simplification.

3.2. Detection of impacts using the triboelectric sensor

This paragraph shows that the energy of the impacts can be detected and measured using the developed triboelectric sensor. For the purpose, composite plates are subjected to controlled energy impacts using a drop weight impact machine (Instron CEAST 9350) and the sensor electric responses are measured in form of voltage and current using a commercial oscilloscope and digital multimeter respectively. Fig. 4(a) shows a schematic representation of the experiment. The idea of the suggested experiment is to investigate the effect of the energy of the impacts on the electric responses of the developed triboelectric sensor.

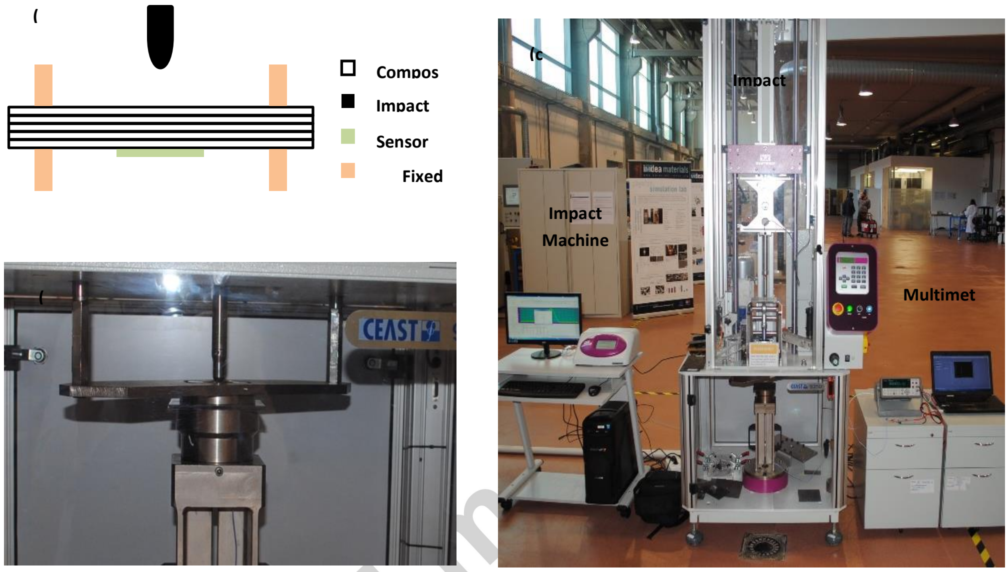


Fig. 4. Description of the experiment used to evaluate the capability of the triboelectric sensor to detect impacts in composite plates: (a) Schematic description of the experimental setup. For the sake of clarity, a transversal view of the experimental setup is given. (b) Digital photography of the experimental setup. (c) The magnitude of the impacts are controlled using the drop-weight impact machine controller and the electric responses of the triboelectric sensor as result of the impacts are measured using a digit multimeter/ commercial oscilloscope.

Fig. 4(b) shows a digital photo of the used experimental setup. From the image, it can be seen that the composite specimens are clamped around the four edges and a controlled energy impact is applied in the centre of the specimen using the striker of the impact machine. The energy of the impacts was varied in a wide range of energies between 2 and 30 joules with small energy increments of 1 J. Finally, the electric responses which the triboelectric sensor produces as a result of the impacts are measured in terms of voltage and current using a commercial oscilloscope (Tektronix 2012B) and a digital multimeter (Agilent 34410A) as illustrated in Fig. 4(c). The main purpose of the experiment is to evaluate the effect of the energy of the impacts on the amplitude of the resultant voltage and current electrical signals. This experiment is a simple and rapid way to evaluate the sensitivity of the developed triboelectric sensor for detection of impacts and quantification.

The composite structures impacted are carbon fibre reinforced square composite plates (CFRP) with the dimensions of (12 x 12 x 0.7) cm. The fabrication process and the characteristics of the carbon fibre composite plates used in this work are described in supplementary Fig. S4.

4. Results and discussion

This section is divided into three parts. The first section 4.1 studies the electric response of the sensor to various energy impacts in the range 2-30 J. In the next section 4.2 the effect of the impact force on the measured voltage and current responses is analysed. Finally in the last section 4.3, the performance of the triboelectric sensor is compared to the performance of a commercial one.

4.1. Effect of the impact energy on the sensor electrical responses

The experimental procedure described in section 3.2 is used to supply various energy impacts to the composite plates tested. The energy of the impacts is varied from 2 to 30 J and the electric responses of the sensor are measured in terms of voltage and current using a commercial oscilloscope and digit multimeter respectively. The aim of this experiment is to find out how the energy of the impacts influences the electric responses of the sensor.

Fig. 5(a) shows the voltage outputs of the sensor when the composite plates are impacted using energies from 2 to 30 J. From the figure, it can be appreciated that the energy of the impacts is increased with small increments of 1 J. As a result, the sensor voltage amplitudes increase gradually from 1.1 to 5.6 V with the increase of the impact energy from 2 to 30 J. This behavior can be attributed to the stronger friction between the PVDF and PVP polymer nanofibers when the composite plates are impacted at higher energy, which results in

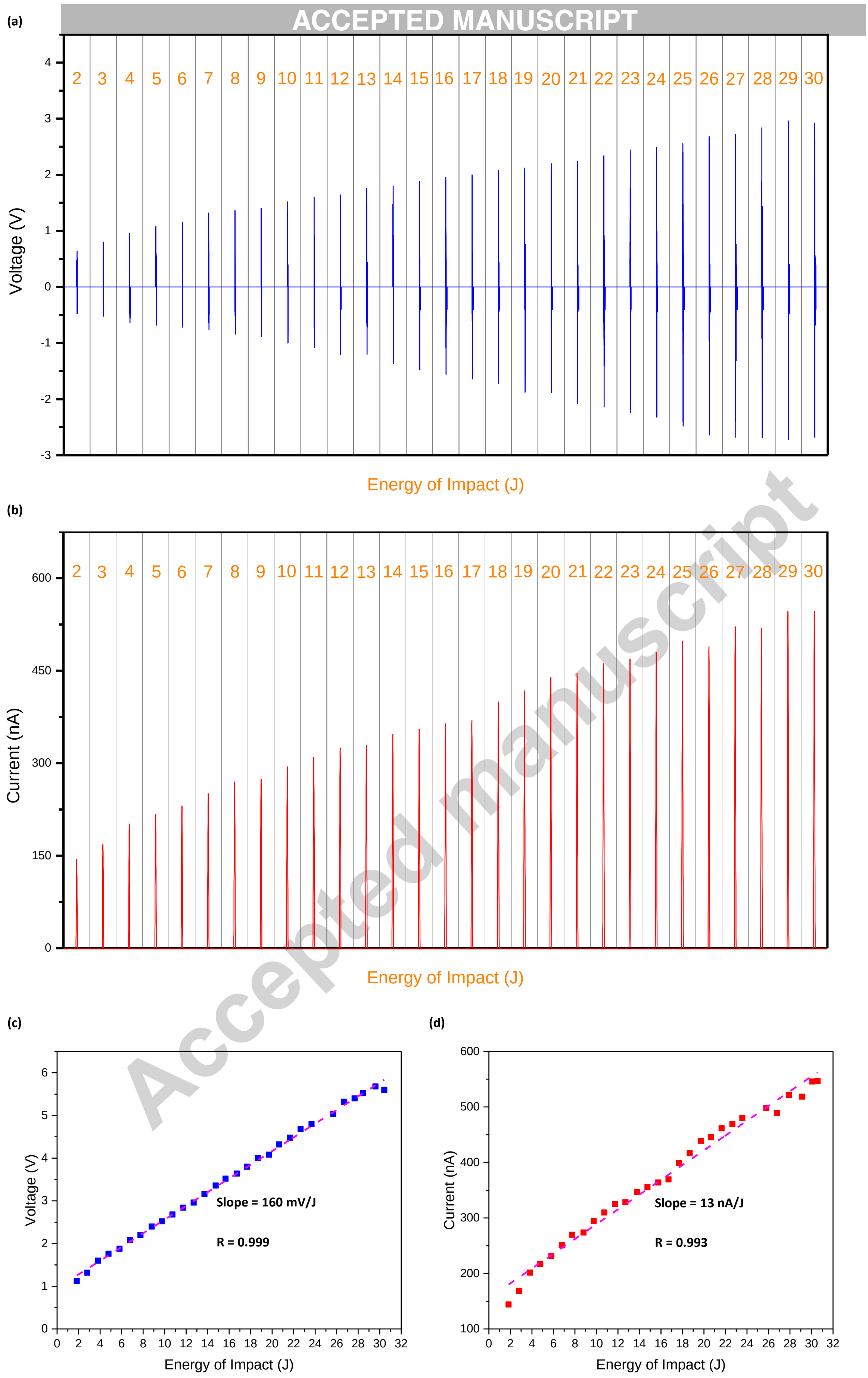


Fig. 5. Effect of the impact energy on the electric responses of the triboelectric sensor: (a) Voltage and (b) current outputs when the composite plates are impacted using controlled impact energy from 2 to 30 J. (b) Voltage and current outputs of the sensor as a function of the energy of the impact.

larger electric responses. In other words, the voltage outputs of the triboelectric sensor can be defined as:

$$V = \frac{\sigma d}{\varepsilon_o} \qquad (1)$$

where σ represents the density of triboelectric charges, *d* is associated to the distance between the layers of polymer nanofibers and ε_0 is the vacuum permittivity. In our triboelectric sensor, the increment of the voltage outputs is attributed to the change in σ and d which results from the increase of the triboelectric charges due to the stronger friction and the higher separation distance between the polymer nanofibers. These experimental results are in good agreement with previous works [31, 32] where it was observed that the voltage responses of triboelectric sensors are directly proportional to the energy of the impact for a small range of energies between 0.02 and 0.2 J, although these results are for much smaller energies. A similar behaviour is reported by [21], where a self-powered acceleration sensor is developed for the purposes of monitoring various high-g impacts for military equipment and automobiles. The results of this work revealed that the electric responses of a PDMS-based triboelectric sensor increase linearly with the acceleration of the impacts in a wide measurement range up to 1.8 x 10^4 g.

Fig. 5(b) also shows the maximum current responses of the triboelectric sensor when the composite specimens are subjected to impacts in the same energy range. From the figure, it can be seen that the current amplitude increases directly and proportionally with energy of impact. From the figure, it can be also seen that the maximum current amplitude raises from 144 to 546 nA as the impact energy increases from 2 to 30 J. As indicated in [43], the current of a triboelectric sensor can be defined as:

$$I = C\frac{\partial V}{\partial t} + V\frac{\partial C}{\partial t} \qquad (2)$$

Where *C* is the capacitance of the triboelectric sensor and *V* is the voltage between the two electrodes. When the composite specimens are subjected to higher energy impacts, the voltage increases, which explains the gradual increase in the current of the triboelectric sensor when the impact energies increase from 2 to 30 J. It is also important to note that the figure shows a positive curve instead of two peaks for each energy impact. This is attributed to the following two reasons: (1) The current output signal generated by the triboelectric sensor is rectified, which results in two positive peaks for the contact and separation states and (2) the duration of the impacts is a very short time (0,003 seconds) and therefore, the two positive current peaks from the rectified signal are overlapping.

Figure 5(c) and (d) display the relations between the energy of the impacts and the obtained maximum current/voltage amplitudes. The graphics show a strong positive linear dependence with the energy of the impacts. The corresponding Pearson coefficients for the energy-voltage and energy-current curves are 0.999 and 0.993 respectively. Thus, very good linear relations between the impact energy and the corresponding voltage and current values can be concluded from our results for the tested energy range (between 2 and 30 J). These linear relationships are ideal as the sensor is used to measure the energy of the impact from the measured voltage/current.

The sensitivity represents the change in output of the sensor per one joule unit change. The sensitivity is also one of the most important parameters of a sensor and it can be calculated using the slope of the straight lines shown in Fig. 5(c) and (d). According to our results, the voltage and current outputs show very high impact sensitivities of 160 mV/J and 13nA/J for a wide energy range from 2 to 30 J as can be seen from Fig. 5 (c) and (d). Accordingly, it can be concluded that the developed sensor features very high sensitivities of both the voltage and the current to changes in the impact energy, which demonstrates the capability of the sensor to to measure the impact energy. It should be also mentioned that these sensitivites are higher than the reported by other authors in other research works [21, 33].

It is also important to mention that for high impact energies (> 26 J), a few small deviations can be seen among the data points on Fig 5(c). and (d). Some possible explanations for these small deviations could be the high energies utilized during the impacts or small dimensional differences of the composite plates impacted.

The results presented above confirm the direct linear proportionality between the applied impact energy and the resultant voltage and current outputs. Thus it can be concluded that the developed sensor can be used to detect impacts and quantify the energy of the applied impacts as well. Furthermore, the produced electric current and voltage signals demonstrate a very high impact sensitivity in a wide detection range, which demonstrates the high performance of the sensor for detection of impacts.

4.2. Effect of the impact force on the sensor electric responses

In this section, we study the effect of the impact force on the voltage and current responses of the triboelectric sensor. As stated above, the composite plates were impacted using energies from 2 to 30 J with a step of 1J. For each energy impact, the drop weight impact machine (Instron CEAST 9350) provides the impact force by means of a sensor incorporated at the tip of the drop-weight impactor (see Fig. 3(b)). With the aim to verify whether the electric response depends on the impact force, the same composite plates together with the sensor attached (see Fig. 3(a)) are impacted using different impact forces which vary between 2000 and 14500 N and the electric outputs are measured as detailed in Section 4.

Fig. 6(a) and (b) show the voltage and current amplitudes as a function of the impact forces applied. It can be clearly seen that the sensor electric responses are affected by the magnitude of the force, and the amplitude of the voltage and the current increase with the increase of the impact force. Therefore, the voltage and current vary from 1.1 to 5.6 V and 144 to 546 nA, respectively, when the impact forces increase from 2000 to 14500 N. As stated above, the increments of the sensor electric responses can be attributed to the higher friction between the PVDF and PVP polymer nanofibers.

A strong linear relationship between the impact force and the electric voltage/current output with a high sensitivity are desired for the quantification of the impact force. From the results given in Fig. 6(a) and (b), it can be observed that a strong linear relationship between the impact force and the electric current and voltage as the data points for both cases can be interpolated using a straight line with a Pearson coefficient of 0.99. Furthermore, the electric voltage and current demonstrate sensitivities of 0.4 mV/N and 0.03 nA/N, respectively, for a very wide range of impact forces between 2000 and 15000 N. Therefore, the fabricated triboelectric sensor is capable to transform the impact force into electric current and voltage, with a sensitivity higher than the sensitivity of other conventional sensors [48].

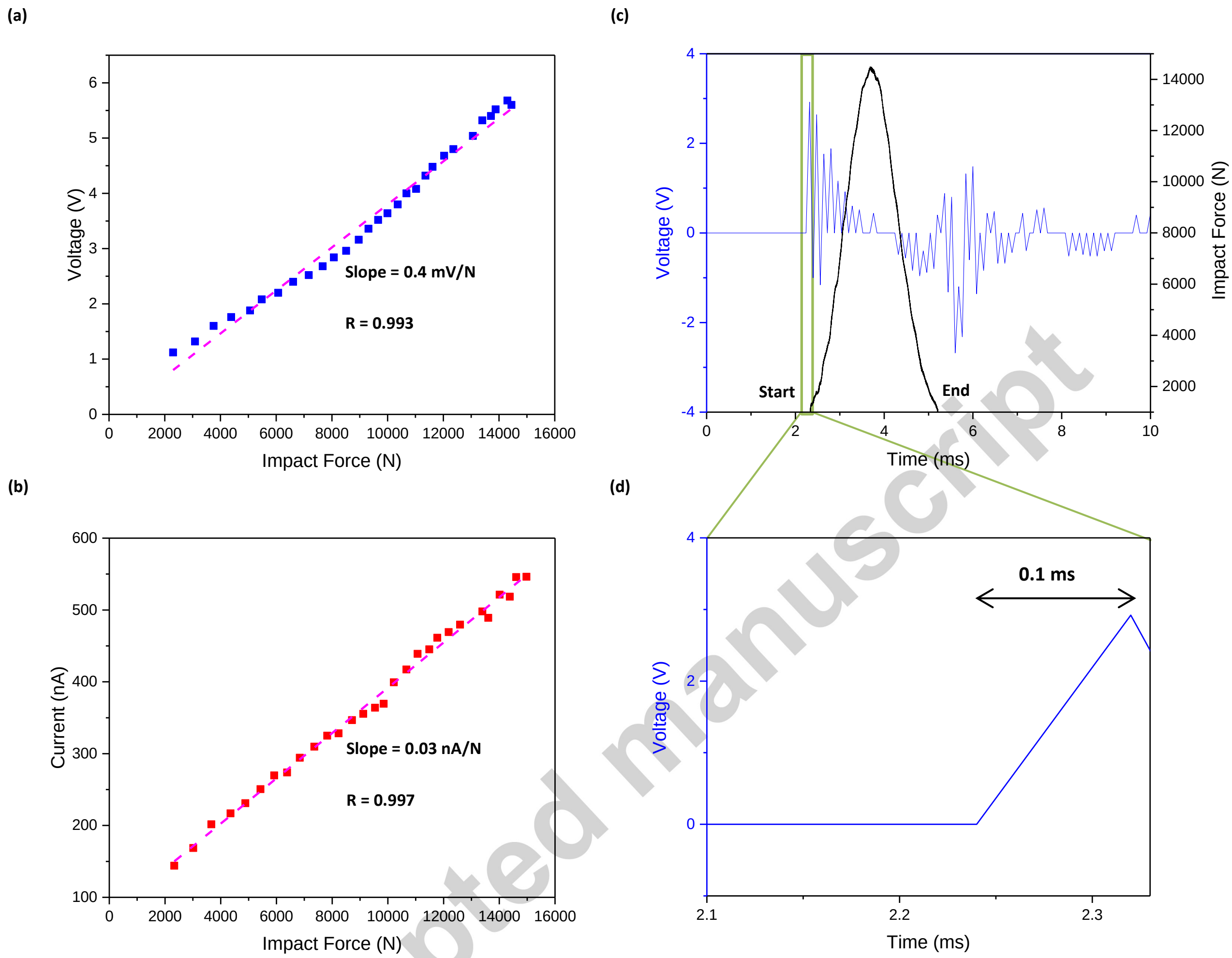


Fig. 6. Effect of the impact forces on the electric responses of the triboelectric sensor: (b) Voltage and (c) current output of the sensor as a function of the impact force. (c) Output voltage of the triboelectric sensor under an impact force of 14500 N. (d) Response time of the triboelectric sensor by enlarging the voltage output signal.

The strong linear relationship between the impact force/energy and the sensor's electric response can be explained using the theory of small deformations [49] and the basics of contact mode TENGs [44]. According to the theory of small deformations [49], the deformation of the composite laminates increases linearly with the energy of the impacts, when the deformation of the composite plates is much smaller than the relevant dimensions of the specimens. This behaviour can be assumed for our composite plates as the deformation of the specimens due to the impacts are very small as a result of the thickness and the high stiffness of the carbon composite plates. Therefore, it can be assumed that the deformation of the triboelectric sensors adhered to the composites increases linearly with the energy of the impacts. As suggested by the theory of contact mode TENGs [44], the voltage outputs of the sensor are strongly influenced by the density of triboelectric charges and separation of triboelectric materials (see equation 1). As the deformation of the sensor increases linearly with the impact force, the generated triboelectric charges and separation of the frictional layers are linearly proportional to the sensor deformation, then it can be concluded that the generated voltage will be hence linearly proportional to the applied impact force.

The developed triboelectric sensor maintains linearity at full scale because the relationship between deformation displacement and impact force is linear in the whole measurement range. Figure S5 shows the force-displacement curve in whole experimental measurement range. From the figure, it can be observed that there is a strong linear relationship between the impact force and the deformation with a high coefficient of Pearson of 0.999. Therefore, it can be said that the electric responses of the sensor show linearity at the full scale because the deformation of the composite is linear. We have also analysed the effect of the deformation of the triboelectric sensor on the sensor electric responses. For the purpose, the voltage output as a function of the deformation are plotted on Fig. S6. The results show that there is a linear relationship (R= 0.991) between the deformation and the voltage outputs. As the deformation of the sensors is increased linearly, the generation of triboelectric charges and separation of the frictional materials is increased proportionally, which results in a linear increment of the sensor electric responses at the full scale.

Fig. 6(c) shows the impact force history (in black) together with the voltage response of the sensor (in blue) when the composite plates are subjected to an impact force of 14500 N. The largest positive and negative peaks in the figure indicate the start and end of the impact, respectively. From there it can be assumed that the triboelectric sensor could be also used to estimate the duration of the impact (3 ms) which is the time between the two highest peaks of the voltage history. These results show the potential of this triboelectric sensor for detection and monitoring of impacts in real time. The multiple voltage peaks observed during the impact (see Fig. 6(c)) are attributed to multiple contact-separations of the layers of polymer triboelectric nanofibers caused by the impact. Furthermore, it should be also mentioned that the largest positive and negative peaks of the voltage signal show a minimum separation with the start and end of the impact force, which demonstrates that the sensor can be used to measure impacts in real time. Fig. 6(d) shows the amplified voltage signal for the 14500 N force impact. From the figure, it can be seen that the response time of the sensor is very fast (0.1 ms), which is defined as the time between zero to the maximum voltage.

In conclusion, it can be said that the sensor’s electric response (in terms of voltage and current) are both linearly proportional to the impact forces and both the current and the voltage are characterized by high sensitivity for a rather wide detection range of the impact force. Furthermore, it should be also mentioned that the response of the developed sensor is very fast and shows a negligible delay to the application of the impact energy.

4.3. Comparison between triboelectric sensor and commercial sensor

The present section aims to compare the performance of the developed triboelectric impact sensor with a piezoelectric commercial sensor which is used for measuring impact force/energy. This is done by comparing the sensitivity, the Pearson coefficient (strenght of the linear relationship between the impact force and the corresponding electric voltage), and the response time for both the developed triboelectric impact sensor and the piezoelectric sensor. For the purpose, both sensors, the developed one and the piezoelectric one were subjected to the same experiment as presented in section 3,which was used to determine their sensitivity, linearity and response time.

Fig. 7(a) shows the voltage output of the piezoelectric comercial sensor, when the same composite plate with the piezoelectric sensor attached to it (see Fig. 3(a)) is subjected to an impact force of 14500 N. The voltage output signal shows positive and negative peaks, which can be observed during and after the impact, with the highest peaks being refered to the start and the end of the impact, respectively. Additionally, the time interval between the highest positive and negative peaks is 3 ms, which can be associated to the duration of the impact. Figure 7(b) shows the response time of the commerical sensor, which is defined as the time interval between zero and the maximum voltage response, which is the time taken by the sensor to reach the maximum voltage corresponding to the applied impact force. From the figure, it can be seen that the response time of the commercial sensor to an impact of 14500 N is 0.3 ms. Similar results found for the fabricated triboelectric sensor where the response time is 0.1 ms for the same mechanical impact as displayed in Fig. 6(d). Therefore, it can be concluded that the response time of both sensors to impact, the new triboelectric sensor and the piezoelectric one, are rather short (less than one 1 ms), which means it takes both sensors a very short time to respond to the applied impact.

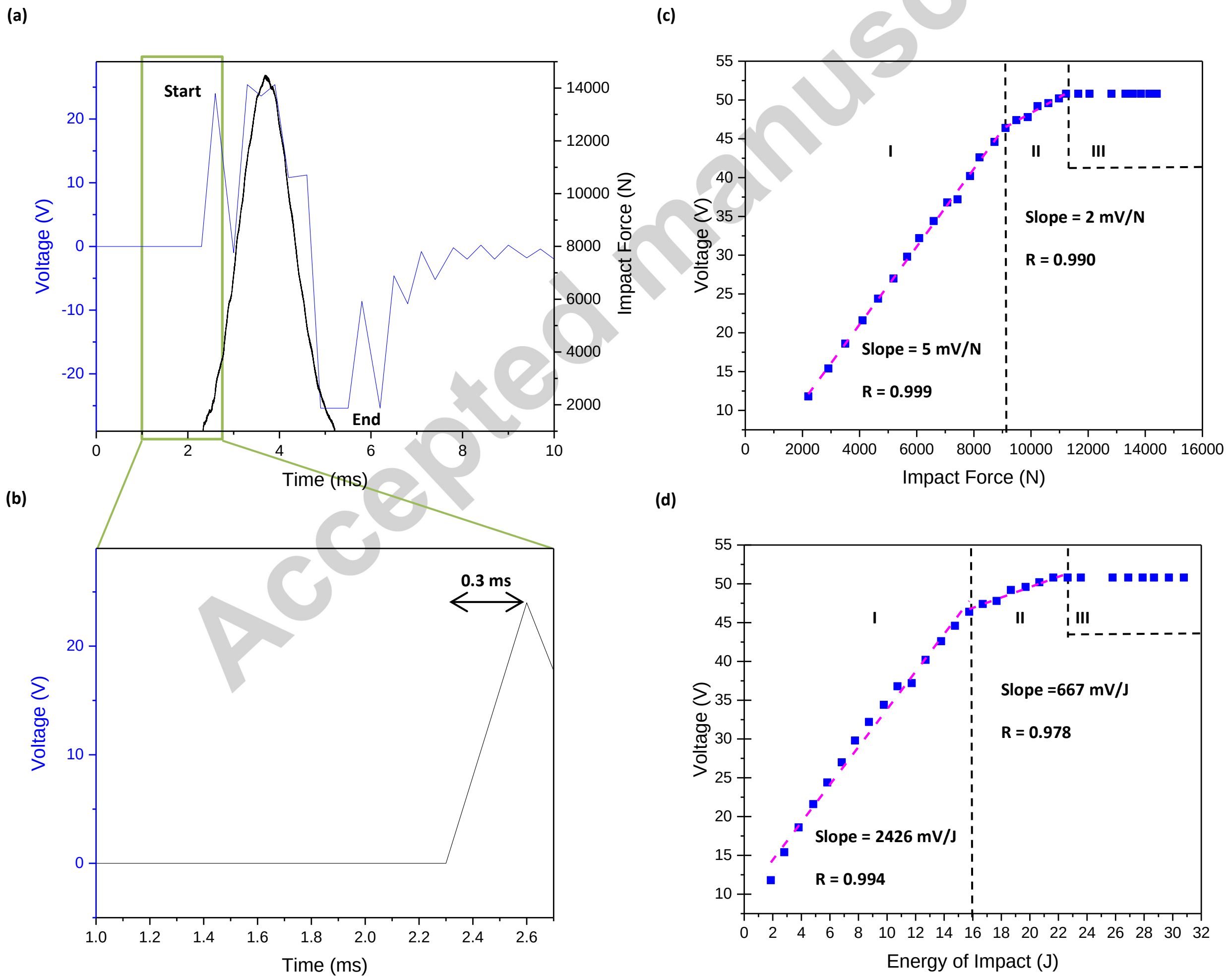


Fig. 7. Performance of the commercial sensor: (a) Output voltage of the piezoelectric sensor under an impact force of 14500 N. (b) The response time of the commercial sensor by enlarging the output voltage signal. Voltage outputs as a function of the impact forces (c) and energy of the impact (d).

Fig. 7(c) and (d) illustrate the voltage outputs of the piezoelectric sensor, when the composite plates with the sensor attached are impacted using different forces/energies, which vary in the range between 2000 and 14500 N (2 -30 J). The figures show that the peak-to-peak voltage increase together with the raise of the impact force /energy and finally saturate at 50.8 V,at an impact force of 11200 N (22 J). These results indicate that the relation between the impact energy/force and voltage is linear for the regions I and II and nonlinear over the whole measurement range.

On the other hand, our results showed that the developed triboelectric sensor has a nearly perfect linear relationship between the impact energy/force and the electric sensor responses over the whole measurement range. From the results given in Section 4.1 and 4.2, it can be observed a strong linear relationship between the impact force-voltage and impact energy-voltage relationships, which are both characterised by a Pearson coefficient of 0.99 in the detection range (2-30 J and 2000-14500 N). This means that the developed sensor can be used to quantify the energy/force of the impacts by measuring the resulting voltage in a wider force/energy range than the commercial piezoelectric sensor.

The sensitivity of the voltage outputs measured by piezoelectric sensor are calculated in the same way as this was done with the developed triboelectric sensor using the slope of the corresponding straight lines shown in Fig. 7(c) and (d). Fig. 7(c) exhibits three distinct regions. In the first region when the impact forces are below 9500 N, it is noticed that the sensor shows a very high impact sensitivity of 5 mV/N. In the second region, between 9500 to 11200 N, the impact sensitivity decreases to 2 mV/N . In the region above 11200 N, the output voltage saturates at 50.8 V and the piezoelectric sensor reachs a limit point after which it can no longer register changes in the applied impact force. As can be seen from Fig. 7(d), the sensitivity of the commercial sensor is 2426 mV/J in the low impact energy region, below 16 J while the sensitivity is 667 mV/J in the higher impact energy region from 16 to 22 J. In conclusion, it can be said that the comercial piezoelectric sensor shows a very high impact sensitivity in the low energy/forces region.

The electric responses generated by the triboelectric sensor are approximately ten times smaller as compared to the piezoelectric commercial sensor. In our view, this is not a limitation because the electric responses of the triboelectric sensor can be increased significantly by the incorporation of a separator between the layers of polymeric nanofibers [50,51]. For example, T.C. Hou et al. [50] proved that the electric outputs of a triboelectric nanogenerator can be increased around 700% by adding a 3 mm spacer between the frictional layers. Similar results were found on [51] where the output voltage raises from 13 to 160 V, when the spacer distance increases from 0.5 to 6.5 mm. Additionally, this hypothesis is also verified by equation 1, where it can be appreciated that the output voltage will increase with increasing the distance between the layers of nanofibers (e.g. by adding a spacer in the triboelectric sensor).

Table 1: A comparison of the triboelectric and commercial sensor characteristics for impact energy detection.

Characteristic	*Units*	*Triboelectric Sensor*	*Commercial Sensor*
Response time	ms	0.1	0.3
Linearity	dimensionless	0.999	0.978 - 0.994
Sensitivity	mV/J	160	667 - 2426
Detection Range	J	2-30	2-22

Finally, the measurement range from the developed triboelectric sensor and commercial sensor is compared. As can be seen in Fig. 7(c) and 7(d), the commercial sensor shows a smaller detection range from 2 to 22 J as compared to the triboelectric sensor (2 - 30 J). This characteristic is the utmost importance as impact sensors are required to measure in a wide detection range.

In summary, this section compares the performance of the triboelectric sensor with a standard commercial sensor. For that purpose, the response time, linearity, sensitivity and detection range of the developed triboelectric sensor and comercial sensor are compared as can be seen in Table 1. The results reveal that the response times of the developed and triboelectric sensor are very fast (less than 1 ms). From the table, it can be observed that the developed triboelectric sensor shows smaller impact sensitivity respect to the commercial sensor. However, the sensitivity of the triboelectric sensor is constant over the whole detection range while the sensitivity for the piezoelectric commercial sensor vary for the different regions (see Fig. 7(d)). Finally, the triboelectric sensor shows a higher linear response and wider measurement range as compared to the commercial sensor. These findings can be used to demonstrate that a triboelectric sensor can be used to detect and measure impacts with a similar performance than a commercial sensor.

Additionally, we demonstrate the practical application of the triboelectric sensor for real-time detection and measurement of hailstone impacts in composite structures. As shown in the video S1 in the supplementary information, the electric signal of the triboelectric sensor generated at the moment of the hailstone impact collisions, which verifies that the sensor can measures impacts in real-time. Fig. S7 shows the voltage outputs for three different hailstone impacts. According to the voltage-energy relationship showed in Fig. 5 (c), the energy of the three hailstone impacts are about 2.5 J, 5.4 J and 8.1 J. The results from the drop weight impact and hailstone tests demonstrates the commercial applications of the triboelectric sensor for monitorization of impacts in aircrafts, wind turbines and other structures made of composite materials.

5. Conclusions

Aircrafts, wind turbines and other composite structures are frequently subjected to impacts or collisions. In this work, we have demonstrated for the first time that a triboelectric sensor can be successfully used to detect and measure impacts in structures made of composite materials. The findings of this study indicate that the developed triboelectric sensor shows good sensitivity to impacts in a wide range of energies and impact forces between 2-30 J and 2000-14500 N, respectively. Moreover, it was shown that the voltage and current outputs show a strong linear relationship with the energy of the impacts (R=0.99). It has been also demonstrated that the current and the voltage outputs show a very fast response to the impacts. This is very important as it indicates that the developed sensor can be used to measure impacts in real time with a negligible delay.

From a fabrication point of view, the preparation of the triboelectric sensor is very simple and does not require sophisticated processing steps. Moreover, this procedure can be easily upgraded for large-scale production. From an innovation point of view, the triboelectric sensor is a potential alternative to other conventional impact sensors due to their independence of an external power supply unit and lower cost due to the cheap materials used and easy fabrication. From a technical point of view, the sensor shows very high sensitivity and linearity in a wide detection range which is comparable to other commercial sensors.

In conclusion, our work has proved for the first time an innovative approach to detect and measure the magnitude of the impacts in composites structures. The present findings demonstrate that the developed triboelectric sensors can be successfully utilized for real-time detection and measurement of the energy and/or the force of impacts in structures made of composite mats. This can have important applications for monitoring of impacts in composite structures as aircrafts, wind turbines or bridges.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at (link to find the information).

Video Supplementary 1. The video of the hailstone impact test.

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Highlights

- This study investigates the potential of triboelectric sensors for detection and measurement of impacts in composites structures for the first time.
- The triboelectric sensor presents a very large energy detection range (140 times wider as compared other impact triboelectric sensors).
- The voltage and current outputs show good sensitivity, high linearity and fast response time.
- Great potential for impact monitoring in composites structures as aircrafts or wind turbines.
- The performance of a triboelectric and commercial sensor for monitoring of impacts is compared.