Real-time diagnosis of small energy impacts using a triboelectric nanosensor

Cristobal Garcia [a, b, c, *], and *Irina* Trendafilova [a]

[a] University of Strathclyde, Department of Mechanical and Aerospace Engineering, 75 Montrose Street, G1 1XJ, Glasgow, UK.
[b] IMDEA: Madrid Institute for advanced studies of materials, C/ Eric Kandel 2, 28906, Madrid, Spain.
[c] FIDAMC: Foundation for the Research, Development and Application of Composite Materials, Avda. Rita Levi Montalcini 29, 28906, Madrid, Spain.
E-mail address: cristobal.garcia@strath.ac.uk

Abstract: Recently, triboelectric nanogenerators (TENGs) are generating increasing interest due to their important applications as energy harvesters and self-powered active sensors for pressures, vibrations and other mechanical motions. However, there is still little research within the research community on their potential as self-powered impact sensors. This paper considers the development of a novel triboelectric nanogenerator, which is prepared using a simple and economic fabrication process based on electrospinning. Furthermore, the paper studies the changes in the generated electric response caused by small energy impacts. For the purpose, the TENG electric outputs generated by the impact of a free-falling ball dropped from different heights are investigated. The idea is to investigate the relation between the electric responses of the nanogenerator and the energy of the impact. The experimental results demonstrate that the voltage and current outputs increase linearly with the increase of the impact energy. Moreover, the electric responses of the triboelectric nanogenerator show a very high sensitivity (14 V/J) to the changes in the impact energy and good repeatability. The main achievements of this paper are in the development of novel triboelectric nanogenerator composed of polyvinylidene fluoride nanofibers and a thin film of polypropylene, and its successful application as an impact sensor for real-time assessment of small energy impacts.

Keywords: Triboelectric generator; Impact detection; Self-powered device; Nanotechnology

1 Introduction

An impact sensor plays a critical role in vehicle safety, fast medical assistance of elderlies and structural health monitoring. For example, in the event of a car crash an impact sensor detects the collision to release an air-bag for the protection of the passengers. In the case of falls in the elderly, an impact sensor can be used to inform about the accident and provide a fast-medical assistance. Other practical examples could be detection of impacts in hail storms, where impacts are responsible for a considerable number of accidents in aircrafts, wind turbines and other civil infrastructures. Therefore, the sensing and the quantification of impacts is of vital importance for a number of applications as impacts can seriously affect the health and safety of humans.

Recently, various approaches have been developed and applied for detection and measurement of impacts in environment as for example piezoelectric sensors [1, 2], capacitive sensors [3], optical sensors [4], acoustic sensors [5] and vibration sensors [6]. Special attention deserves the works of Yang's group [7, 8] which investigates the applications of flexible piezoelectric sensors for detection and measurement of pressures, which can be used for important applications as sleeping monitoring, tactile measurements, or sensing of human heartbeats. Additionally, other authors as [9] investigated the potential of piezoelectric nanogenerators as acceleration sensors for real-time collision monitoring, which has important applications as vehicle safety monitoring. However, most of these technologies require an external power supply or battery to sense the impact which is a disadvantage of the non-self-powered operation which leads to limited life-time and increased maintenance cost. Therefore, an environmentally friendly self-powered technology is very much desired for the detection of impacts.

In the last five years, triboelectric nanogenerators (TENGs) are gaining a lot of popularity within the scientific community, which results in a considerable amount of research on the potential of triboelectric nanogenerators as energy harvesters [10-13] and self-powered active sensors for vibrations [14, 15], accelerations [16, 17], touches [18, 19], pressures [20-23], magnetic fields [24, 25], and environmental changes [26, 27]. However, until now, there are almost no works to report about the potential of triboelectric nanogenerators for detection and evaluation of impacts [28]. Therefore, it is urgently needed to investigate the potential applications of triboelectric nanogenerators for detection and measurement of impacts.

The working principle of triboelectric nanogenerators is based on the contact electrification and electrostatic induction [29, 30]. The contact electrification occurs when two materials with different electron affinities are brought into contact with each other, which induce positive and negative charges in the surfaces of the contacted mats. The amount of charge transferred between the two materials is related to the area of the materials in contact and their differences in electron affinities [31]. The electrostatic induction takes places when the two materials with opposite and equivalent triboelectric charges are separated, which result in a dipolar moment and a strong potential difference.

The present paper investigates a novel triboelectric nanogenerator prepared by a membrane of polyvinylidene fluoride (PVDF) nanofibers and an ultra-thin layer of polypropylene (PP). The triboelectric nanogenerator is designed with PVDF due to its strong tendency to gain triboelectric charges from almost any other mats [32]. This behaviour is attributed to the large amount of fluorine in PVDF that has the highest electronegativity among all the elements [33]. As a result, the surfaces of PVDF and polypropylene become negative and positive charged after the contact, respectively. The design of the TENG was based on nanofibers because it is one of the practical ways to increase the effective contact area between the triboelectric materials, which is beneficial to increase the generation of triboelectric charges of the TENG [34]. To the best of our knowledge, this is the first work to report a triboelectric nanogenerator based on the combination of these triboelectric mats.

Furthermore, the paper studies the potential applications of the developed TENG as self-powered impact sensor. For that purpose, the triboelectric sensor is impacted at various energies using a free-falling ball dropped from five different heights. The idea is to study if the electric responses of the nanogenerator are affected and how by the magnitude of the impacts. The experimental results demonstrate that the electric responses of the triboelectric nanogenerator are influenced by the energy of the impacts and are directly proportional to it so that higher electric outputs are found with increased energy impacts. Furthermore, the voltage and current outputs show a very high sensitivity, linearity and reproducibility, which demonstrates the potential of the TENG as self-powered impact sensors. In our view, this work presents an innovative approach for self-powered impact detection, which has important implications in multitude of areas as e.g. vehicle safety, structural health monitoring or urgent medical attention of elderlies.

2. Fabrication of the triboelectric nanogenerator

The fabrication process of the triboelectric nanogenerator is schematically shown in Fig. 1(a) and can be divided into three main steps: preparation of the top and the bottom sections of the TENG and assembly of the nanogenerator. Initially, a 2 mm thin film of PVDF nanofibers is deposited on a copper foil via electrospinning to form the TENG top section. After that, an ultra-thin film of polypropylene with a thickness of 25 µm is attached with copper foil using double side copper tape to form the TENG bottom section. Lastly, the two prepared sections are placed face to face and sealed with polyethylene terephthalate film to form the triboelectric nanogenerator. A digital photography of the TENG with a small size of 55 x 55 x 3 mm and the low-weight of 6.75 g can be seen on Fig. 1(b). It is worthy to note that the small size and weight of the device are beneficial for the practical applications of the sensor.

The triboelectric nanogenerator has a multi layered structure with two main sections as detailed in Fig. 1. It consists of two sections- a lower and an upper one. In the lower section is made of a film of polypropylene is adhered to copper foil to act as one of the triboelectric materials. In the upper section, nanofibers of polyvinyl fluoride are deposited on copper foil and this serves as the other oppositely charged triboelectric material. The roles of PVDF nanofibers and polypropylene film is to act as frictional materials while the copper foils serve as electrodes for the nanogenerator owing to the low cost and the high electrical conductivity of the copper.

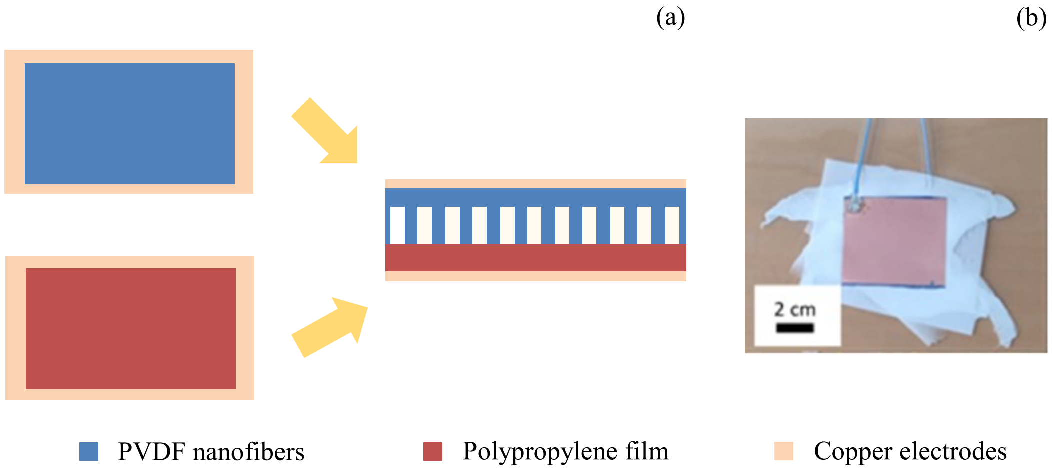

Fig. 1. (a) Fabrication process of the triboelectric nanogenerator: (i) Preparation of the top section. (ii) Preparation of the bottom section and (iii) structure of the nanogenerator. (b) Digital photography of the triboelectric nanogenerator as-fabricated.

From a fabrication point of view, this procedure is simple, low-cost and can be easily scaled-up for large scale production, which is desired for the practical applications of the device.

3. Preparation and characterization of PVDF nanofibers

This paragraph describes the preparation of the PVDF fibres used for the fabrication of the triboelectric nanogenerator, which is used here as an impact sensor. As was mentioned above the TENG and the current sensor are prepared using PVDF and PP nanofibers.

The film of PVDF nanofibers is prepared using the technique of electrospinning because is a simple and economic way to prepare triboelectric mats with large surface area [35]. The preparation of the nanofibers can be summarized as follows: First, the polymer solution for electrospinning is prepared by dissolving 2g of PVDF pellets (MW=275,000 gmol-1) in 10 ml solvent mixture of N,N- dimethylformamide (DMF) and acetone (40/60). Second, the polymer solution is inserted into a plastic syringe to be spun in a commercial electrospinning machine (Nanon-01A) using the following processing parameters: applied voltage of 15 kV, needle tip-collector distance of 15 cm, feed rate of 1 ml/h, 21G steel needle and a static collector. As a result, a 2 mm thin layer of interconnected PVDF nanofibers is deposited on the surface of a copper electrode. A schematic description about the electrospinning process used to prepare the nanofibers can be found on Fig. S1.

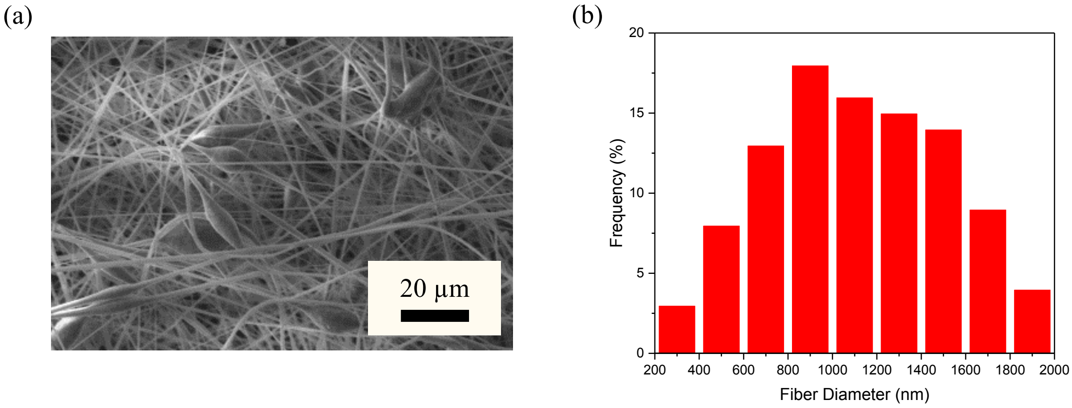

Fig. 2 Preparation of nanofibers via electrospinning: (a) SEM image of PVDF nanofibers and (b) fibre diameter distribution of PVDF fibers.

The design of the sensor was based on nanofibers because it is one of the practical ways to increase the effective contact area between the frictional materials, which is beneficial to enhance the generation of triboelectric charges [34]. Fig. 2 (a) shows a scanning electron microscopy image of the PVDF nanofibers prepared by electrospinning. From the image, it can be clearly appreciated a dense population of interconnected fibres of PVDF, which will result in a very large surface area. The nanofibers are distributed randomly in the membrane and show a few bead defects, which can be associated to the nature of the polymer solution and the high voltages used during the electrospinning [36].

Fig. 2 (b) displays the fibre diameter distribution of the nanofibers. The preparation of the fiber diameter histogram can be summarized as follow: Initially, the diameters of 100 nanofibers are measured from the SEM image using the software Image J. After, the numbers of fibers which correspond to a certain diameter range (e.g. 800-1000 nm) are counted. The histogram reveals that the diameter of the fibers is not uniform and varies between 200 and 2000 nm. The wide distribution of diameters in the fibers is attributed to the nature of the electrospinning process. From the histogram, it can be deducted that the diameter of the fibers varies between 800 and 1000 nm with a probability of about 18%. As a result, the average fibre diameter of the nanostructures is 1087 nm with a standard deviation of 419 nm.

PVDF is a well-known piezoelectric material when there is betha crystalline phase and the ferroelectric domains of β-phase are well oriented [37]. To find out if the electric response of the PVDF nanofibers is also attributed to the piezoelectric effect X-ray diffraction (XRD) spectroscopy were performed on the membranes of polyvinyl fluoride fibres to identify the crystalline phase. The XRD pattern is shown in Fig. S2. From the XRD pattern, it can be clearly observed three intense peaks at $2\theta = 18.43°$, $20.06°$, and $26.75°$ which are associated to the (0 2 0), (1 1 0) and (0 2 1) planes of the alpha crystalline phase. Thus, it can be concluded that the crystalline phase of PVDF is the non-piezoelectric alpha phase, and the electric response detected from the PVDF nanofibers is not caused by the piezoelectric effect.

4. Operating principle of the triboelectric nanogenerator

Fig. 3 illustrates the working principle of the triboelectric nanogenerator, which is based on the contact-separation mode reported by Wang’s group [38- 41]. The electric responses of the TENG are generated due to the conjunction between contact electrification and electrostatic induction of two materials with different electron affinities [42, 43].

At the initial state (Fig. 3 (a)), there is no contact and separation between the film of PVDF nanofibers and polypropylene, which results in non-electric response. When the ball hits the sensor, the TENG configuration changes from the original to the contact state as shown in Fig. 3 (b). Since PVDF has a higher electronegative behaviour than polypropylene, the electrons are transferred from polypropylene to PVDF. Therefore, net negative charges are generated on the PVDF surface and equal amount positive ones in the polypropylene film. When the ball rebounds, the device changes from the contact to the separation state as described in Fig. 3 (c). In this configuration, the opposite triboelectric charges are separated, and a potential drop is generated between the two electrodes. As a result, there is transference of electrons between the bottom electrode and the upper one through the external circuit. Finally, the deformation of the sensor decreases, and the sensor returns to its original state (Fig. 3 (a)), which causes the voltage output drop back to zero.

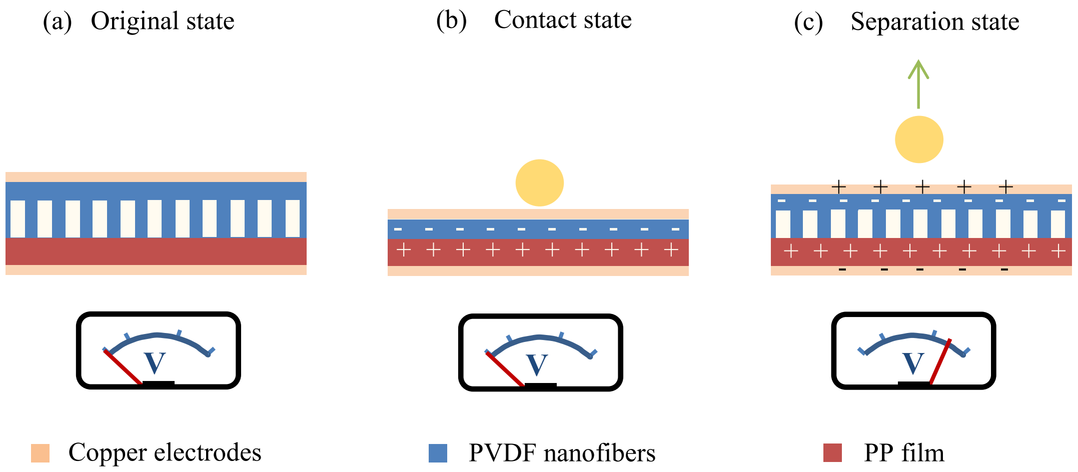

Fig. 3. Operating principle of the triboelectric nanogenerator: (a) The original state of the TENG prior to the ball impact. (b) The state of the TENG during the ball impact and (c) the state of the TENG after the impact.

5. Experimental investigation of the triboelectric nanogenerator

The aim of this section is to describe the experiment used to evaluate the response of the manufactured sensor to impacts. To carry out this investigation, a drop ball impact test is used to investigate the relation between the electric responses of the nanogenerator and the impacts of a free-falling ball. The main goal of this experimental study is to study if and to what extent the voltage and current outputs of the triboelectric nanogenerator are affected by the energy of the impacts.

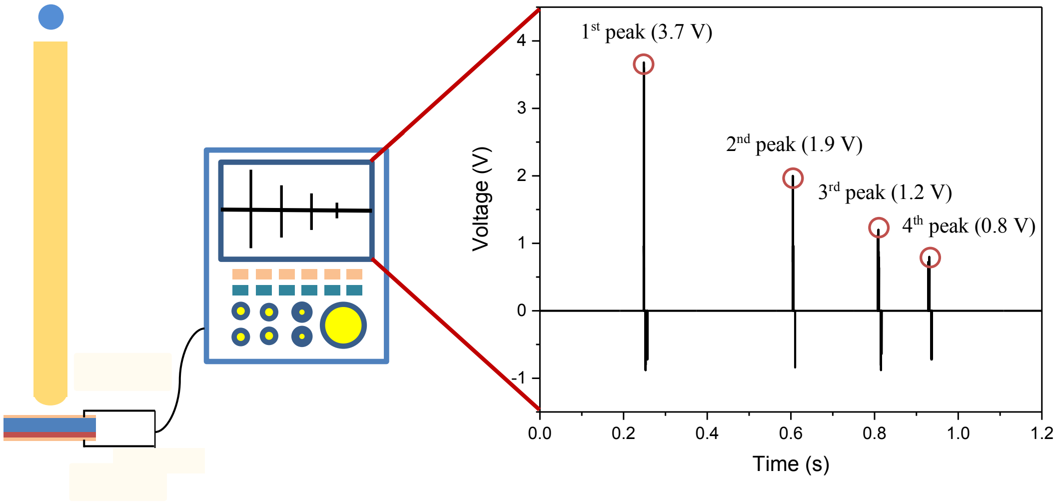

Fig. 4 Experimental testing of the triboelectric nanogenerator: Schematic description of the experimental setup. The inset of the figure shows the electric outputs of the triboelectric nanogenerator due to the ball impact.

Fig. 4 shows a schematic representation of the experimental setup. From the figure, it can be appreciated that the experiment utilizes a simple setup which consist of an impact ball, a plastic tube and a triboelectric nanogenerator connected to an apparatus to measure the electric responses. In the experimental test, a 21 g glass ball with a diameter of 2 cm is dropped on the top surface of the triboelectric sensor. The idea is to drop a glass ball from five different heights ranging from 20 to 100 cm (with a drop height interval of 20 cm) by using plastic tubes of different lengths and record the voltage and current responses of the triboelectric nanogenerator as result of the impacts by using a Tektronix 2012B commercial oscilloscope and Agilent 34410A digit multimeter. The main goal of the experiment is determinate if the amplitude of TENG electric signals is affected by the height of the ball impact.

Our experimental method was inspired by [44] and represents a simple and low-cost procedure to analyse the impact sensitivities of TENGs. The experimental procedure can be divided into the following three steps: First, a 2 cm diameter glass ball with a weight of 21.22 g is dropped from five different heights of 20, 40, 60, 80 and 100 cm which correspond to five different impact energies. Second, the plastic tube holds on a heavy metallic base which is used as a fall guide for the glass ball to have a direct impact on the triboelectric nanogenerator. Finally, the voltage and current responses of the triboelectric sensor are measured in order to analyse if the amplitude of the sensor electric outputs is affected by the energy of the impact. It is also important to mention that the energy of the impacts for the different impact balls is calculated using equation (1):

$$E = mgh \qquad (1)$$

where m represents the mass of the glass ball, g is the acceleration due to the gravity and h indicates the impact height. For the sake of simplicity, the drag forces caused by the air resistance during the ball drop and the side walls of the plastic tube are neglected.

Fig. 4 also includes the variations of voltage caused by the impact of a free-falling ball dropped at 100 cm drop height. From the graphic, it can be clearly seen four peaks which are associated to the multiple collisions of the impact ball. The largest peak is the first peak, which correspond to the highest impact energy of the ball falling on the TENG. The amplitude of the subsequent peaks decreases proportionally for the following bounces due the reduction of the impact energies. The figure also shows the time interval between the ball bounces, where it can be observed a lower time-intervals for the lower impact energies. For the sake of simplicity, the experimental results presented in the results and discussion section only show the first peak attributed to the first bounce of the ball.

6. Results and Discussion

This section shows and discusses the experimental results obtained from the drop ball impact test. Initially, the effect of the energy of the impacts on the electric outputs of the nanogenerator is analysed. After, the repeatability of the voltage and current responses of the TENG for five repetitions of the same energy impact is discussed.

6.1 Effect of the impact height on the TENG voltage output

As stated in the previous section, the triboelectric nanogenerator is subjected to various energy impacts using a drop ball impact test and the voltage outputs of the TENG are measured using a commercial oscilloscope. The aim of the experiment is to analyse if the TENG voltage outputs are affected by the energy of the impacts.

Fig. 5 (a) shows the voltage outputs of the triboelectric nanogenerator when the ball was dropped from five different heights of 20, 40, 60, 80 and 100 cm respectively. The graph shows that when the ball was dropped from greater heights, the amplitude of the TENG voltage responses increases. Therefore, it can be clearly seen that the peak-to-peak voltage increases from 2.4 to 4.7 as the drop height increased from 20 to 100 cm. This trend is in good agreement with other works. For example, the authors of [45] analysed the effect of controlled height impact balls on the voltage outputs of a TENG based on PVDF nanofibers and a mercury droplet. The results reveal that the electric responses of the TENG increased from 1.3 to 10.4 as the impact height is raised between 10 and 100 cm. Other works as [46] obtained similar results using a triboelectric nanogenerator composed of nanofibers of polyvinylidene fluoride and polyvinylpyrrolidone. To the best of our knowledge, [45, 46] are the only two works that have investigated the effect of ball impacts in the voltage responses of triboelectric nanogenerators.

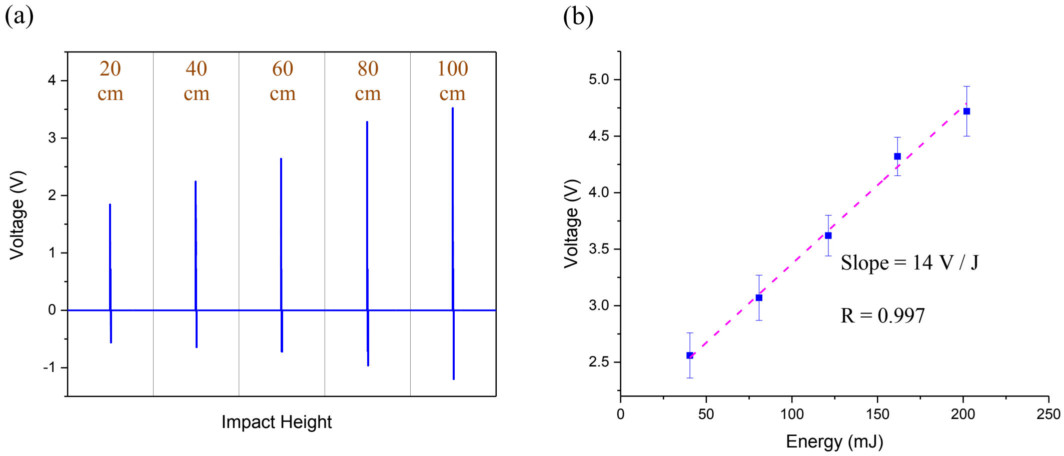

Fig. 5 Influence of the impacts on the voltage responses of the new TENG: (a) Voltage outputs as a function of the time for the different ball impacts. (b) Voltage amplitudes as a function of the impact energy.

Fig. 5 (b) displays the peak-to-peak voltages of the triboelectric nanogenerator as a function of the impact energy. The graph includes the average peak-to-peak voltage and corresponding standard deviations for five repetitions of each energy impact. The results show that the peak-to-peak voltage responses increase gradually under higher energy impacts in the measurement range 40-200 mJ. This behaviour can be explained by the fact that the voltage outputs of a TENG are strongly affected by the contact surface between the frictional mats [47, 48]. Therefore, higher energy impacts lead to a more intimate contact between the frictional mats, which results in higher electric outputs. From the results, it can also be seen a strong linear correlation for the relationship between voltage and energy with a high Pearson coefficient of 0.997. Furthermore, the sensitivity of the TENG is calculated using the slope of the interpolated straight line and a very high sensitivity of 14 V/J is found on the detection range 40-200 mJ.

Furthermore, the authors investigated the influence of the mass of the ball on the electric responses of the triboelectric nanogenerator. For this study, the device is impacted using balls of different materials (plastic, rubber and glass), which are dropped from the same height. Fig. S3 shows the relationship between the mass of the ball and the sensor voltage outputs. From the graphic, it can be clearly seen that the voltage outputs are strongly affected by the mass of the ball and the voltage outputs increase with the increment of the mass of the impactor. This can be explained by the higher energy of the impact which increases the deformation of the sensors and results in higher electric outputs.

The response time is a very important factor for a sensor as it shows how fast the response can be detected after the excitation (the impact in this case) is applied [7, 8, 23]. The response time of a sensor can be defined as the time required for reaching the maximum voltage output which is calculated as the time period of the voltage output changing from 10% to 90% of its peak value. Fig. S4 displays the response time of the triboelectric sensor for a ball impact from a height of 100 cm. The figure shows that the response time of the triboelectric sensor is very fast 0.5 ms, which means that the triboelectric sensor takes a very short time to respond to the applied impact. Therefore, it can be concluded that the response of the developed sensor to impact is very fast, which is critical for the real time detection of impacts.

On the basis of these results, it can be said that the TENG voltage responses are influenced by the energy of the impacts and increase proportionally in the range between 40 and 200 mJ. Furthermore, the straight lines used to interpolate the voltage responses show a very high sensitivity and linearity of 14 V/J and 0.997, respectively. These characteristics are the utmost importance as sensors with very high impact sensitivity and strong linear response are always preferred.

6.2 Effect of the impact height on the sensor current output

As mentioned in Section 5, a free-falling ball is used to impact the developed TENG at different energy impacts and the current signals of the nanogenerator are measured using a digital multimeter. The main purpose is to investigate if the current electric signals of the TENG are influenced by the energy of the impacts.

Fig. 6 (a) shows the current responses of the developed triboelectric nanogenerator when the free-falling ball was dropped from various heights at 20, 40, 60, 80 and 100 cm. For the sake of simplicity, the electrical outputs of the five different energy impacts are shown in the same graphic. The results show that the TENG current outputs increase significantly when height of the impact is increased. The increase of the current output as the drop impact height increases can be explained by the fact that the deformation of the TENG increases for higher energy impacts. When the TENG is impacted at smaller energies, the deformation of the sensor is smaller, which decreases the contact between the frictional mats and the generation of electricity. When the ball hits the TENG at higher energies, a stronger deformation is caused, which results in a larger contact between the frictional mats and higher current responses.

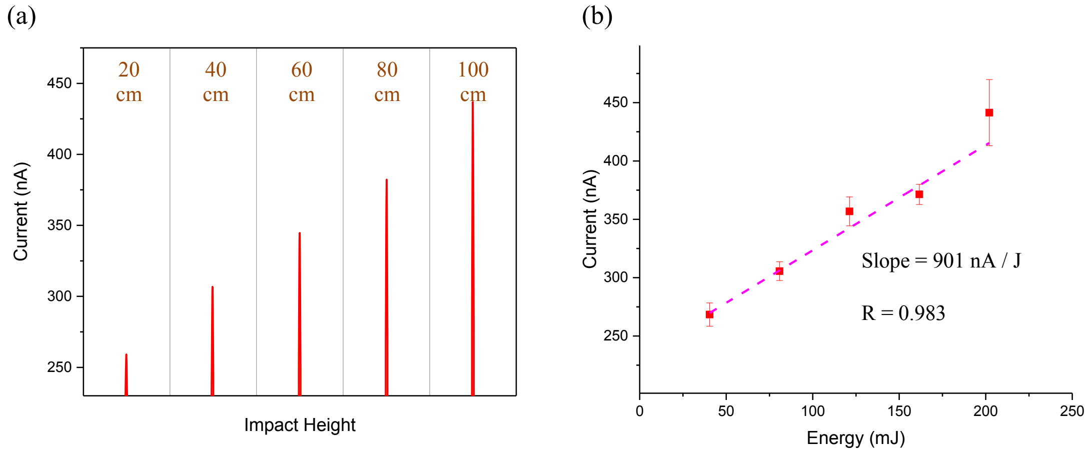

Fig. 6 Effect of the impacts on the current outputs of the fabricated triboelectric nanogenerator: (a) Current responses for impacts at various drop heights of 20, 40, 60, 80 and 100 cm. (b) Current amplitudes as a function of the impact energy.

The waveform shown in Fig. 6 (a) shows only one positive peak instead of the conventional two peaks with opposite directions for each impact. This can be explained by the short duration of the impacts (just a few milliseconds) which induces overlapping peaks in the electrical measurements. Moreover, the current output signal generated by the triboelectric sensor is rectified by the measurement equipment, which converts the negative peaks into positive.

Fig. 6 (b) shows the current amplitudes of the triboelectric nanogenerator as a function of the energy of the impacts. The results given are the average value and corresponding standard deviation for five repetitions of the same energy impact. From the graphic, it can be appreciated that the current responses are strongly affected by energy of the impacts and the amplitude of the current responses increase from 268 to 441 nA as the energy of the impact changes between 40 and 200 mJ. The results reveal that the relation between the energy of the impacts and the TENG current responses is linear and has a high Pearson coefficient of 0.983. Furthermore, the sensitivity of the triboelectric nanogenerator is calculated using the slope of the straight line and a very high impact sensitivity of 901 nA/J is found.

The increase of the voltage and current outputs with the increase of the height of the ball using the law of conservation of energy and the theory of contact mode TENGs. According to the law of conservation of energy, the height of the impact is directly proportional to the energy of the impact. Therefore, when the height of the impacts is increased, the energy of the impacts is higher. As suggested by the theory of contact mode TENGs, the voltage is dependent of the density of triboelectric charges (θ), the distance between the frictional layers (d) and the vacuum permittivity (ε_o) [49].

$$V = \frac{\theta d}{\varepsilon_o} \qquad (2)$$

Therefore, when the nanogenerator is subjected to higher energy impacts, the density of triboelectric charges increases due to the higher friction between triboelectric materials and stronger deformation of the frictional materials, which results in higher voltage outputs. Additionally, the current is proportionally dependent of the capacitance (C) and the voltage (V) of the TENG [49].

$$I = C\frac{\partial V}{\partial t} + V\frac{\partial C}{\partial t} \qquad (3)$$

Therefore, when higher energy impacts are subjected to the nanogenerator, the voltage increase considerably for the reasons stated above (more intimate contact between the triboelectric layers), which results in higher current outputs.

In general, it can be concluded that the current outputs of the nanogenerator are strongly influenced by the energy of the impacts and increase linearly under stronger energy impacts. Furthermore, the current-energy relationship shows a very high sensitivity of 901 nA/J for the measurement range between 40 and 200 mJ. As a result, these results indicate the good performance of triboelectric nanogenerators for detection and evaluation small energy impacts.

6.3 Repeatability of the TENG voltage/current outputs

This paragraph of the paper investigates the repeatability of the TENG electric outputs for five repetitions of the same energy impact. The idea is to verify if the triboelectric nanogenerator produces similar electrical responses when the tests are repeated under the same conditions. For this study, the drop ball impact test explained in Section 5 is used to verify the stability of the TENG electric responses for five repetitions of the same impact.

Energy (mJ)	Voltage (V)	S.D. Voltage (V)	C.V. Voltage (%)	Mean Current (nA)	S.D. Current (nA)	C.V. Current (%)
40	2.56	0.20	3.70	268.4	9.9	7.97
81	3.07	0.20	2.62	305.6	8.0	6.54
121	3.62	0.18	3.50	356.8	12.4	4.97
162	4.32	0.17	2.40	371.4	28.3	4.00
202	4.72	0.22	6.41	441.4	6.4	4.64

Table 1 Statics of the electric outputs for five repetitions of the same impact

Table 1 summarizes the average voltage and current outputs for five repetitions of the same impact. From the results, it can be clearly seen that the electric responses are influenced for the energy of the impacts and increase gradually for the impacts at higher energies. Furthermore, the table also includes the standard deviations and coefficient of variations for the five impact repetitions. The standard deviations for the voltage outputs vary between 0.17 V and 0.20 V, while the current standard deviations are increased from 6.4 nA to 28.3 nA. The coefficients of variations are small and vary in the range 2.4 - 7.9 % for the voltage and current outputs. In our view, the variations of the voltage and current responses could be attributed to the drag forces between the ball and the side walls of the plastic tube, which vary randomly for each experiment.

In conclusion, it can be said that the electric responses of the nanogenerator shows a good repeatability with minimum changes in the voltage and current outputs after repeated applications of the same impact. Therefore, it can be concluded that the electric responses of the developed triboelectric nanogenerator are stable and can be potentially used for the quantification of small energy impacts.

7. Conclusions

In summary, this paper presents a novel triboelectric nanogenerator composed of a thin film polypropylene and a membrane of PVDF nanofibers and investigates its application as self-powered sensor for detection of small energy impacts in real time.

The films of electrospun nanofibers used in the nanogenerator are prepared via electrospinning because it is one of the practical ways to increase the performance of the TENG. This fabrication is done for purposes of simplicity and flexibility of the preparation of the triboelectric nanogenerator, which does not require expensive mats or high cost technologies. Furthermore, this procedure can be easily upgraded for large scale mass production, with the advantages of low-cost production.

Furthermore, the paper investigates the practical applications of the TENG as self-powered sensor for detection of small energy impacts. For this purpose, a simple experimental test using a free-falling ball is used to analyse the effect of the energy of the impacts on the electric responses of the triboelectric nanogenerator. The experimental results demonstrate that the voltage and current outputs increase proportionally under higher energy impacts. Furthermore, a strong linear relationship between the electric outputs and the energy of impacts is detected. Additionally, it should be noted the rather high impact sensitivity of 14 V/J and 901 nA/J for the voltage and current outputs, which is persistent in the entire measurement range.

Eventually, the repeatability of the electric responses of the triboelectric nanogenerator for five repetitions of the same energy impact is considered. As per the results, it should be pointed out that the voltage and current outputs of the developed triboelectric nanogenerator shows very small changes (the standard deviations are within the range between 2% and 7%) for repeated applications of the same impact. Therefore, it can be concluded that the electric responses of the triboelectric nanogenerator demonstrate very good repeatability, which is essential for the practical applications of the TENG as self-powered impact sensor.

The results of this experimental study demonstrate and prove that the developed nanogenerator can be used for detection and assessment of small energy impacts. It has the considerable advantages of self-powered operation as compared to most conventional sensors. It should be also noted that the developed sensor is maintenance-free and has the benefit of a simple fabrication method. These results contribute as an excellent initial step toward the development of self-powered impact sensors for multiple applications including vehicle safety, structural health monitoring and urgent medical attention of elderlies.

Conflicts of interest

There are no conflicts of interest to declare.

Acknowledgements

We would like to thank IMDEA Materials Institute for their technical assistance and valuable support in terms of materials and equipment. We also gratefully acknowledge

Dr Roberto Guzman de Villoria for his help and support in this research collaboration between the University of Strathclyde, IMDEA Materials Institute and his research center FIDAMC.

Appendix A. Supplementary data

Supplementary material related to this article can be found in the online version, at doi: [details of any supplementary information available should be included here].

References

[1] M.S. Salmanpour, Z.S. Khodaei, M.H. Ferri Aliabadi, Impact damage localisation with piezoelectric sensors under operation and environmental conditions, Sensors, 17 (2017) 1178.

[2] A. Dixit, S. Bhalla, Prognosis of fatigue and impact induced damage in concrete using embedded piezo-transducers, Sens. Actuator A-Phys., 274 (2018) 116-131.

[3] S. Phan, Z.F. Queck, P. Shah, D. Shin, Z. Ahmed, O. Khatib, M. Cutkosky, Capacitive skin sensors for robot impact monitoring, in: Proceedings to the 24th International Conference on Intelligent Robots and Systems, 25-30 September; San Francisco, CA, USA, 2011, pp. 2992-2997.

[4] D. Liang, B. Culshaw, Fibre optic silicon impact sensor for application to smart skins, Electron. Lett., 29 (1993) 529-530.

[5] M. Eaton, M. Pearson, K. Holford, C. Featherston, R. Pullin, Detection and location of impact damage using acoustic emission, in: Proceedings to the 2nd International Conference on Advanced Composite Materials and Technologies for Aerospace Applications, June 11-13; Wrexham, UK, 2012, pp. 29-33.

[6] R. Ouckama, D.J. Pearsall, Evaluation of a flexible force sensor for measurement of helmet foam impact performance, J. Biomech., 44 (2011) 904-909.

[7] W. Deng, T. Yang, L. Jin, C. Yan, H. Huang, X. Chu, Z. Wang, D. Xiang, G. Tian, Y. Gao, H. Zhang, W. Yang, Cowpea-structured PVDF/ZnO nanofibers based flexible self-powered piezoelectric bending motion sensor towards remote control of gestures, Nano Energy, 55 (2019) 516-525.

[8] C. Yan, W. Deng, L. Jin, T. Yang, Z. Wang, X. Chu, H. Su, J. Chen, W. Yang, Epidermis-inspired ultrathin 3D cellular sensor array for self-powered biomedical monitoring, ACS Appl. Mater. Interfaces, 10 (2018) 41070-41075.

[9] L. Jin, S. Ma, W. Deng, C. Yan, T. Yang, X. Chu, G. Tian, D. Xiong, J. Lu, and W. Yang, Polarization-free high-crystallization β-PVDF piezoelectric nanogenerator toward self-powered 3D acceleration sensor, Nano Energy, 50 (2018) 632-638.

[10] L. Jin, W. Deng, Y. Su, Z. Xu, H. Meng, B. Wang, H. Zhang, B. Zhang, L. Zhang, X. Xiao, M. Zhu, W. Yang, Self-powered wireless smart sensor based on maglev porous nanogenerator for train monitoring system, Nano Energy, 38 (2017) 185-192.

[11] L. Jin, J. Chen, B. Zhang, W. Deng, L. Zhang, H. Zhang, X. Huang, M. Zhu, W. Yang, Z.L. Wang, Self-Powered safety helmet based on hybridized nanogenerator for emergency, ACS Nano, 10 (2016) 7874-7881.

[12] B. Zhang, J. Chen, L. Jin, W. Deng, L. Zhang, H. Zhang, M. Zhu, W. Yang, Z.L. Wang, Rotating-disk-based hybridized electromagnetic-triboelectric nanogenerator for sustainably powering wireless traffic volume sensors, ACS Nano, 10 (2016) 6241-6247.

[13] L. Zhang, B. Zhang, J. Chen, L. Jin, W. Deng, J. Tang, H. Zhang, H. Pan, M. Zhu, W. Yang, Z.L. Wang, Lawn structured triboelectric nanogenerators for scavenging sweeping wind energy on rooftops, Adv. Mater., 28 (2016) 1650-1656.

[14] Q. Liang, Z. Zhanga, Xiaoqin Y., Y. Gu, Y. Zhao, G. Zhang, S. Lu, Q. Liao, Y. Zhang, Functional triboelectric generator as self-powered vibration sensor with contact mode and non-contact mode, Nano Energy, 14 (2015) 209-216.

[15] S. Wang, S. Niu, J. Yang, L. Lin, Z.L. Wang, Quantitative measurements of vibration amplitude using a contact-mode freestanding triboelectric nanogenerator, ACS Nano, 8 (2014) 12004-12013.

[16] C. Xiang, C. Liu, C. Hao, Z. Wang, L. Che, X. Zhou, A self-powered acceleration sensor with flexible materials based on triboelectric effect, Nano Energy, 31 (2014) 469-477.

[17] K. Dai, X. Wang, F. Yi, C. Jiang, R. Li, Z. You, Triboelectric nanogenerators as self-powered acceleration under high-g impact, Nano Energy, 45 (2018) 84-93.

[18] G. Zhu, W.Q. Yang, T. Zhang, Q. Jing, J. Chen, Y.S. Zhou, P. Bai, Z.L. Wang, Self-powered, ultrasensitive, flexible tactile sensors based on contact electrification, Nano Lett., 14 (2014) 3208-3213.

[19] T. Li, J. Zou, F. Xing, M. Zhang, X. Cao, N. Wang, Z.L. Wang, From dual-mode triboelectric nanogenerator to smart tactile sensor: A multiplexing design, ACS Nano, 11 (2017) 3950-3956.

[20] L. Dhakar, S. Gudla, X. Shan, Z. Wang, F.E.H. Tay, C.H. Heng, C. Lee, Large scale triboelectric nanogenerator and self-powered pressure sensor array using low cost roll-to-roll UV embossing, Sci. Rep., 6 (2016) 22253.

[21] K. Parida, V. Bhavanasi, V. Kumar, R. Bendi, P.S. Lee, Self-powered pressure sensor for ultra-wide range pressure detection, Nano Res., 10 (2017) 3557-3570.

[22] K.Y. Lee, H.J. Yoon, T. Jiang, X. Wen, W. Seung, S.W. Kim, Z.L. Wang, Fully packaged self-powered triboelectric pressure sensor using hemispheres-array, Adv. Energy Mater., 6 (2016) 1502566.

[23] J. Yang, J. Chen, Y. Su, Q. Jing, Z. Li, F. Yi, X. Wen, Z. Wang, Z.L. Wang, Eardrum-inspired active sensors for self-powered cardiovascular system characterization and throat-attached anti-interference voice recognition, Adv. Mater., 27 (2015) 1316-1326.

[24] Y. Yang, L. Lin, Y. Zhang, Q. Jing, T.C. Hou, Z.L. Wang, Self-powered magnetic sensor based on a triboelectric nanogenerator, ACS Nano, 6 (2012) 10378-10383.

[25] S. Qi, H. Guo, J. Chen, J. Fu, C. Hu, M. Yu, Z.L. Wang, Magnetorheological elastomers enabled high-sensitive self-powered tribo-sensor for magnetic field detection, Nanoscale, 10 (2018) 4745-4752.

[26] Y. Su, G. Xie, S. Wang, H. Tai, Q. Zhang, H. Du, H. Zhang, X. Du, Y. Jiang, Novel high-performance self-powered humidity detection enabled by triboelectric effect, Sens. Actuator B-Chem., 251 (2017) 144-152.

[27] Z.H. Lin, G. Zhu, Y.S. Zhou, Y. Yang, P. Bai, J. Chen, Z.L. Wang, A self-powered triboelectric nanosensor for mercury ion detection, Angew. Chem. Int. Ed., 52 (2013) 5065-5069.

[28] C. Garcia, I. Trendafilova, J. Sanchez del Rio, Detection and measurement of impacts in composite structures using a self-powered triboelectric sensor, Nano Energy, 56 (2019) 443-453.

[29] A. Yu, L. Chen, X. Chen, A. Zhang, F. Fan, Y. Zhan, Z.L. Wang, Triboelectric sensor as self-powered signal reader for scanning probe surface topography imaging, Nanotechnology, 26 (2015) 165501.

[30] W. Song, B. Gan, T. Jiang, Y. Zhang, A. Yu, H. Yuan, N. Chen, C. Sun, Z.L. Wang, Nanopillar arrayed triboelectric nanogenerator as a self-powered sensitive sensor for a sleep monitoring system, ACS Nano, 10 (2016) 8097-8103.

[31] W. Li, J. Sun, M. Chen, Triboelectric nanogenerator using nano-Ag ink as electrode material, Nano Energy, 3 (2014) 95-101.

[32] Y. Hao, Y. Bin, H. Tao, W. Cheng, W. Hongzhi, Z. Meifang, Preparation and optimization of polyvinylidene fluoride (PVDF) triboelectric nanogenerator via electrospinning, in: Proceedings to the 15th International Conference on Nanotechnology, July 27-30; Rome, Italy, 2015, pp. 1485-1488.

[33] C. Garcia, I. Trendafilova, R. Guzman de Villoria, J. Sanchez del Rio, Self-powered pressure sensor based on the triboelectric effect and its analysis using dynamic mechanical analysis, Nano Energy, 50 (2018) 401-409.

[34] Y. Zheng, L. Zheng, M. Yuan, Z. Wang, L. Zhang, Y. Qin, T. Jing, An electrospun nanowire-based triboelectric nanogenerator and its application in a fully self-powered UV detector, Nanoscale, 6 (2014) 7842.

[35] F. Zhang, B. Li, J. Zheng, C. Xu, Facile fabrication of micro-nano structured triboelectric nanogenerator with high electric output, Nanoscale Res. Lett., 10 (2015) 298.

[36] J.M. Deitzel, J. Kleinmeyer, D. Harris, N.C. Beck Tan, The effect of processing variables on the morphology of electrospun nanofibers and textiles, Polymer, 42 (2001) 261-272.

[37] M. Zaccaria, D. Fabiani, A. Zucchelli, J. Belcari, O. Bocchi, T. Cramer, B. Fraboni, Electret Behaviour of Electrospun PVDF-based fibers, in: Proceedings to the IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), 2016, pp. 137-140.

[38] Z.L. Wang, Triboelectric nanogenerators as new energy technology and self-powered sensors – Principles, problems and perspectives, Faraday Discuss., 176 (2014) 447-458.

[39] S. Niu, S. Wang, L. Lin, Y. Liu, Y.S. Zhou, Y. Hu, Z.L. Wang, Theoretical study of contact-mode triboelectric nanogenerators as an effective power source, Energy Environ. Sci., 6 (2013) 3576.

[40] Z. L. Wang, J. Chen, and L. Lin, Progress in triboelectric nanogenerators as a new energy technology and self-powered sensors, Energy Environ. Sci., 8 (2015) 2250-2282.

[41] S. Niu, and Z. L. Wang, Theoretical systems of triboelectric nanogenerators, Nano Energy, 14 (2015) 161-192.

[42] Y. Xi, H. Guo, Y. Zi, X. Li, J. Wang, J. Deng, S. Li, C. Hu, X. Cao, Z.L. Wang, Multifunctional TENG for blue energy scavenging and self-powered wind-speed sensor, Adv. Energy Mater., 7 (2017) 1602397.

[43] Y. Su, G. Zhu, W. Yang, J. Yang, J. Chen, Q. Jing, Z. Wu, Y. Jiang, Z.L. Wang, Triboelectric sensor for self-powered tracking of object motion inside tubing, ACS Nano, 8 (2014) 3843-3850.

[44] S. Joshi, G.M. Hedge, M.M. Nayak, K. Rajanna, A novel piezoelectric thin film impact sensor: Application in non-destructive material discrimination, Sens. Actuator A-Phys., 199 (2013) 272-282.

[45] B. Zhang, L. Zhang, W. Deng, L. Jin, F. Chun, H. Pan, B. Gu, H. Zhang, Z. Lv, W. Yang, Z.L. Wang, Self-powered acceleration sensor based on liquid metal triboelectric nanogenerator for vibration monitoring, ACS Nano, 11 (2017) 7440-7446.

[46] C. Garcia, I. Trendafilova, R. Guzman de Villoria, J. Sanchez del Rio, Triboelectric nanogenerator as self-powered impact sensor, in: Proceedings to the International Conference on Engineering Vibration, 4-7 September; Sofia, Bulgaria, 2017, MATEC Web. Conf., 2018, 148, 14005.

[47] T. Huang, M. Lu, H. Yu, Q. Zhang, H. Wang, M. Zhu, Enhanced power output of a triboelectric nanogenerator composed of electrospun nanofiber mats doped with graphene oxide, Sci. Rep., 5 (2015) 13942.

[48] Y.S. Choi, Q. Jing, A. Datta, C. Boughey, S. Kar-Narayan, A triboelectric generator based on self-poled Nylon-11 nanowires fabricated by gas-flow assisted template wetting, Energy Environ. Sci., 10 (2017) 2180.

[49] Y. Wang, Y. Yang, Z.L. Wang, npj Flexible Electronics, 1 (2017) 10.

Biographies

Cristobal Garcia received his Ph.D. in Mechanical and Aerospace Engineering from Strathclyde University in Scotland, United Kingdom. He is currently a research and development engineer at TSI. His main research interests are synthesis and characterization of nanomaterials, design and development of nanogenerators and self-powered nanosensors. He also works on nanocomposites with advanced properties and finite element modelling analysis. He has published more than 10 papers in peer-reviewed international journals and has participated in several industrial research projects for the aeronautical and naval industry.

Irina Trendafilova received her Ph.D. from Sofia University in Bulgaria. She is a reader at the University of Strathclyde in Glasgow. Her research track record is in vibrations of structures made of composites, structural dynamics and structural and machinery vibration-based health monitoring, nonlinear dynamics and signal processing methods. She has published more than 85 papers in leading international journals and 3 book chapters. She is and editor of the Elsevier Journal of Sound and Vibration, https://ees.elsevier.com/jsv/.