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Effect of Electrospun PVDF-Fibers Orientation for Vibration Sensing

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Abstract. Advanced Structural Health Monitoring (SHM) systems require the use of high performing, ultra-thin and light weight flexible sensing devices to reduce impact in a hosting material or structure. In this paper piezoelectric polyvinylidene difluoride (PVDF) electrospun fibers were investigated to realize advanced vibration sensors. The microscale structure of the fabricated sensors is of a porous nature and consists of an aggregation of microfibers that are either randomly distributed or oriented. Being piezoelectric these fibers are capable to detect mechanical stress or strain over time in terms of a voltage signal. To investigate the reliability of piezoelectric fibers as vibration sensors, tests of a dynamic nature were conducted. It is found that the developed sensors are capable to detect a cantilever vibration over time with great accuracy and that the microfibers orientation is an important factor to maximize the sensor performance.

1. Introduction

Structural health monitoring (SHM) systems are very promising to improve reliability and integrity of structures during their life-time. These systems typically consist of sensors that are surface mounted or embedded into a structure. Sensors signal is gathered by a conditioning system and analysed by ad-hoc designed algorithms that are capable to reinterpret the acquired signal as a structural health status. Various physical changes, such as displacement, velocity, acceleration, tension, deformation, force, can be used for this scope. Piezoelectric-based devices are among the most widely used for SHM applications. These devices are made of piezoelectric materials that are characterized by an electromechanical response: they produce a voltage when they are strained or, vice versa, they strain when a voltage is applied. In other words, piezoelectric-based devices can work as both sensing and actuating elements within an SHM system. The working principle is that sensors and actuators are mounted on a structure in a specific and predefined array. Actuators send a diagnostic signal (strain waves) into the hosting structure and this signal, that is influenced by the structural integrity, is then detected by the surrounding sensors. The problem is that the most common commercially available piezoelectric sensors are relatively large in size, require time-consuming assembling procedures and can only be applied in a small number on large structural surfaces (low sensors density). Device size is critical not only in terms of an overall weight increase that can impact advanced light weight structures, but also because it can compromise structural integrity when sensors/actuators are conceived as embedded devices. In addition, piezoelectric ceramics are rigid in their nature and this limits their application to rigid structures that are affected by ultra-low strain levels.

The above limitations could be overcome by reducing the sensors/actuators size, weight and rigidity. To this end, the excellent traits of polyvinylidene difluoride (PVDF), low production cost, high

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chemical resistance and excellent piezo and pyroelectric properties, makes it very attractive for fabricating lighter and flexible film devices for SHM applications [1]. In the past, PVDF has been widely used for pressure [2], strain [3] and vibration sensing [1,4] as well as to implement SHM systems for composite structures [5].

PVDF has four crystalline phases, one of which, the β phase, is characterized by the highest electro-active properties. In nature this material is present in the *non-polar* phase and to attain its piezoelectric properties it must undergo into a *polarization process*, which involves subjecting the material to an elongation while applying a high voltage. This process leads to an orientation of the internal material dipoles. However, despite the excellent properties of this material, its usage for SHM systems carries most of the above-mentioned limitations except for the acquired device flexibility and partial weight reduction. To make PVDF a major candidate for SHM embedded systems, it is mandatory to drastically reduce the material size and density. Both of which have in fact the potential to further reduce the overall device weight.

In this paper we propose to change the PVDF film microstructure taking advantage of an electrospinning process. Electrospinning is a technique by which a polymer, in solution form, can be spun into smaller-diameter fibers (micro-nanometres) due to a very high electric field. One of the appreciable features of electrospinning is the simplicity of the process apparatus consisting of a syringe pump, syringe, high-voltage source and a collector. The polymeric solution contained in a syringe fitted to the syringe pump passes through the needle with a regulated and a steady flow. A very high electric field is applied between the needle and the collector. As the voltage increases, the meniscus of the solution at the needle tip deforms, creating a Taylor cone. When the electric field reaches a critical value, the repulsive forces overcome the forces of surface tension and from the Taylor cone a jet of polymer emanates and dries up during flight. The formed fibers get deposited on a collector as aggregated fiber [6]. The use of this technique to electrospin a PVDF solution [7,8,9] has the advantage that the mechanical elongation and the strong electrical field applied during electrospinning, tend to align the PVDF dipoles producing a direct *in-situ* polarization of the material [10]. Therefore, electrospinning transforms the non-polar alpha phase of PVDF into the electro-active polar beta phase with an ease.

2. Materials and methods

The PVDF solution was created by mixing together PVDF powder, acetone and N, N-dimethylacetamide (DMAc), produced by the Sigma-Aldrich company. The powder was dissolved in a mixture of acetone/DMAc. A syringe, that was filled with a polymer solution, was pressurized with a syringe pump to set the solution flow rate. A high voltage (12 KV) between the needle tip and a metal plate that collects the nanofibers (collector), was applied with a power supply. The needle to collector distance was of 20 cm. The electrospinning setup is shown in figure 1. Changes to the collector configuration were done to produce different types of fibers. In one case, fibers with a random orientation were obtained using a rectangular aluminium foil as a collector (Fig 1a). In the second case, aligned fibers were obtained using two co-planar aluminium electrodes, placed at a specific distance, as collectors (Fig 1b).

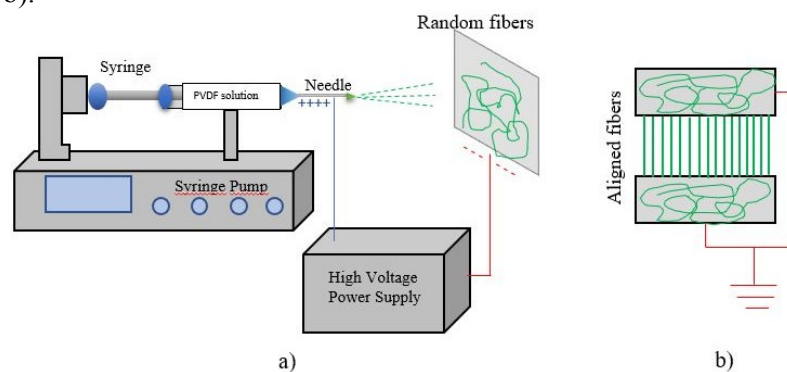


Figure 1: 1a) Set-up to electrospin random PVDF fibers; 1b) Collector set-up to obtain aligned PVDF fibers

The sensing device was fabricated by sandwiching the electrospun fibers between two copper electrodes (Figure 2) onto which electrical wires were soldered for electrical measurements.

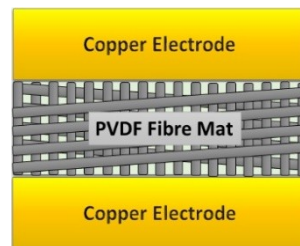


Figure 2: Schematic cross section of the sensor.

3. Results and Discussion

Figure 3 shows an optical microscope image of the resulting PVDF fibers. The fibers showed an average diameter of $3\mu\text{m}$. As expected, the fibers that were electrospun using a single collector, were characterized by a random distribution while the fibers that were electrospun using the co-planar collector configuration, showed a preferential direction of alignment (oriented fibers). The microscopic characterization highlights that with this fabrication method the resulting PVDF film shows a porous microstructure and an overall film thickness of $200\mu\text{m}$.

The functional capability of the microfibers and their piezoelectric response were studied by testing the devices under dynamic loading conditions.

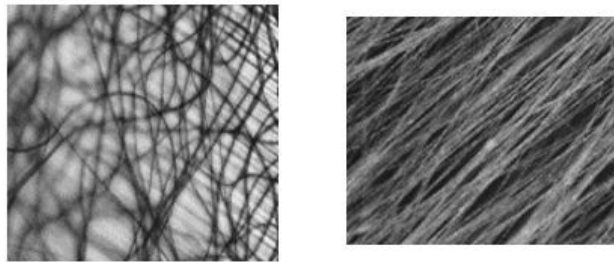


Figure 3: Microscope images of the PVDF porous films formed by random (top image) or aligned (bottom image) fibers.

The fabricated sensors were bonded to a fiber-glass composite cantilever using an epoxy resin (epoxy resin L20). Three sensors of each type (random and aligned) were tested.

The functional capability of the sensors was tested with the setup schematically represented in Figure 4. The cantilever was impulsively stressed by imposing a constant vertical displacement at the free end. The cantilever was then let free to oscillate over time while the electrical output of the sensor signal was recorded with a Digital Storage Oscilloscope (2556, BK Precision). The sensor response was compared with that acquired by a Polytec Laser Vibrometer that was focused at the free end of the cantilever throughout the test duration.

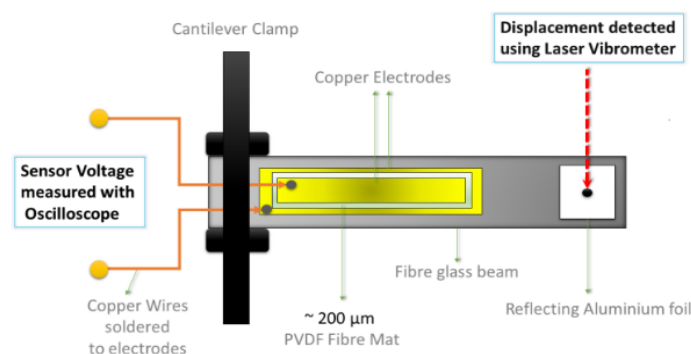


Figure 4: Schematic representation of the test setup.

The sensor time history and its comparison with the laser output is shown in Figure 5 and Figure 6 for the random and oriented fibers, respectively. These data clearly highlight the reliability of the sensor. The signals of the two detection systems are found to be in perfect phase over time. The frequency of the first vibration mode of the cantilever was calculated by means of the Fourier Transforms of the recorded signals. Table 1 shows the frequencies that were calculated from the sensor output voltage and from the laser output.

Table 1: Dynamical test results

	#	f_{laser} [Hz]	f_{sensor} [Hz]	Δf [%]	V_{max} [mV]
Random Fibers	1	90.89	90.24	-0.714	113.128
	2	93.09	93.99	0.967	84.421
	3	95.87	95.04	-0.866	120.142
Aligned Fibers	4	102.97	104.17	1.161	104.275
	5	84.21	84.86	0.761	138.991
	6	94.26	93.99	0.285	109.000

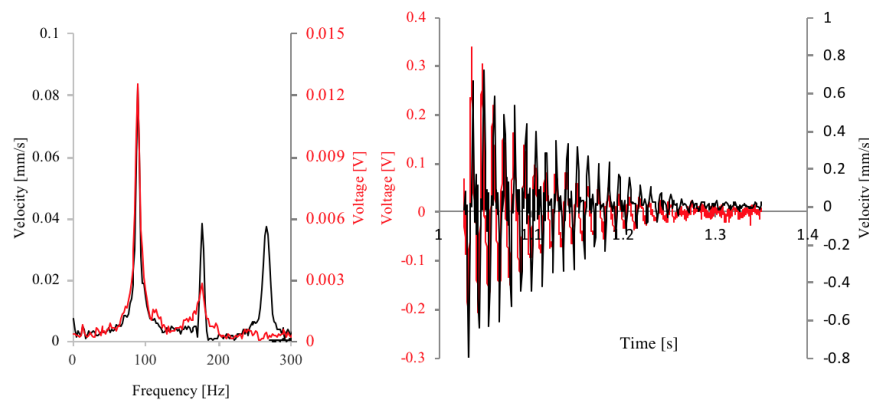


Figure 5: top) Fourier Transform with random fibers; bottom) comparison of the laser response and of the electrospun sensor.

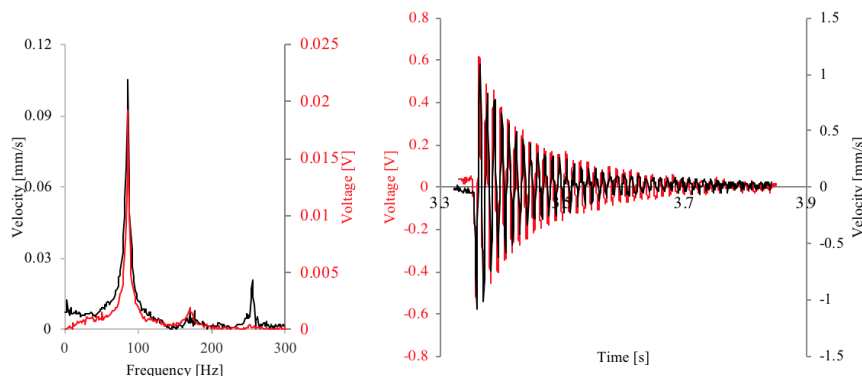


Figure 6: top) Fourier Transform with oriented fibers; bottom) comparison of the laser response and of the electrospun sensor.

As seen in all the tests carried out in this study, the various sensors have a frequency of the first mode of vibration very close to that of the cantilever beam, this indicates their correct operation. Additionally, it is observed that the sensor that has aligned fibers shows a better response compared to that made with random fibers. This can be observed from the time history response as well as the Fourier transform whose peak amplitude is closer to that derived from the laser signal. The percentage frequency variation of the detected signal with that of the laser also highlights the superiority of the sensor with aligned fibers. The latter fibers are in fact characterized by an average 0.7% variation against the average 0.85% of the randomly distributed fibers.

This study shows for the first time that electrospun piezoelectric fibers can be used to monitor dynamic mechanical deformation with a high accuracy. In particular the frequency detected by the PVDF sensor was found to be identical to the frequency that was measured with a sophisticated laser system designed for this purpose. The frequency variation of the proposed sensor was calculated to be less than 1% than that of the laser. In conclusion the developed sensors represent a promising design solution for advanced structural health monitoring systems.

4. Conclusion

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