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Electromechanical Behavior of Helical Auxetic Yarn Strain Sensor †

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Abstract: Three-component strain sensors based on helical auxetic yarn (HAY) structure were designed. HAYs comprise elastic core yarn, wrapped by the composition of multifilament Nylon 66 and conductive spun yarns with three different electrical resistance. The electromechanical behavior of samples was investigated. The cross-section of samples was studied to investigate the aerial density of conductive fibers at different strain ranges. The results indicated that gauge factors of HAY strain sensors significantly depend on the electrical resistance of the conductive component. Therefore, a new generation of efficient wearable textile-based strain sensors is introduced, based on the adjustable and flexible nature of the auxetic yarns.

Keywords: auxetic sensor; wearable sensor; negative Poisson's ratio; smart textile; strain sensor

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1. Introduction

Conventional electronic wearable sensors are formed by the traditional systems being attached to the garment in some way. However, the new generation of smart textiles is produced from conventional textile materials. Therefore, among other wearable sensors, smart textiles are advantageous due to the preservation of textile properties such as flexibility, breathability, conformability, and cost-affectivity [1–3].

Auxetic materials are materials that exhibit negative Poisson's ratio. It is generally accepted that the auxetic phenomenon potentially contributes to the development of highly advanced functional materials [4]. Helical auxetic yarn (HAY) is a core-wrap yarn design that is both technically and practically advantageous. This is not only due to the ease of yarn properties control but also relatively simple production adjustments during the spinning of auxetic yarn. Additionally, HAY can be spun using conventional textile raw materials and textile processing machines. More importantly, the production of auxetic yarns is by no means restricted to using auxetic components [5].

HAY comprises a central low-modulus thick core helically wrapped by a high-modulus fine strand wrap. The low-stiffness HAY is stretchable, durable, and sensitive. Furthermore, it seems to be capable of adjusting response and recovery time. Additionally, HAY can be woven and form an auxetic fabric [6,7] with the potential of synclastic curvature [4]. In this regard, Cuthbert et al. [8] introduced a HAY capacitive strain sensor containing a conductive copper wire and investigated the effect of HAY structural properties on sensor performance. Furthermore, Wu et al. [9] manufactured an auxetic interlaced yarn sensor containing conductive silver-coated PA yarns to develop a sign-language-translation glove.

This research aim to introduce a HAY strain sensor containing conductive yarns to further serve as a cost-effective sensing element in wearable smart textiles with advanced breathability and conformability.

2. Experimental

2.1. Material

Figure 1 represents the three-component HAY strain sensor. The HAY strain sensor comprises Polyester-covered spandex core yarn (0.6 mm diameter, 120 tex) wrapped by the composition of high-modulus Nylon 66 multifilament (0.16 mm diameter, 100D/24f) and conductive low-modulus stainless steel/polyester (SS/PES) yarns.

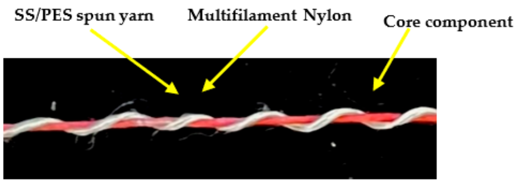

Figure 1. Three-component HAY strain sensor.

2.2. Methods

Three conductive HAY samples with a nominal initial wrap angle of 35°, utilizing equivalent yarn composition except for a conductive yarn in the wrap, were prepared. The conductive wrap components contained 28%, 40%, and 80% stainless steel (SS) fibers with an electrical resistance of 29.82, 23.07, and 5.31 Ω/cm, respectively. The HAY samples composed of conductive wrap components contained 28%, 40%, and 80% SS fibers were coded A, B and C, respectively. The HAY strain sensors were prepared manually to ensure an accurate and consistent initial wrap angle of 35° [10]. During the preparation of the HAY samples, the core component was centrally fed under tension and wrapped by the side-by-side wrap components. The mechanical behavior of samples was evaluated using Zwick tensile tester model 1446 equipped with knurled-face clamps according to ASTM D2256. Tensile tests were conducted at the tensile rate of 50 mm/min and 100 mm gauge length under the CRE principle. The test was ceased up on the breakage of the conductive wrap component. The dimensional changes of HAY samples were detected based on suggested literature adjustments [6,7].

The cross-section of HAY sensors at different strains was studied to investigate the configuration of steel fibers of the conductive yarn. First, the cross-section of samples was obtained based on the microtomy method. Then, the stereo microscope was used to evaluate the prepared cross-section of samples. The electrical properties of HAY strain sensors during the tensile test were determine using pre-programmed microprocessor and a computer. In this regard, an electronic board consisting of AVR microprocessor and 5 volts power supply was used. Then, HAY was part of circuit in series with a reference resistance (R_{ref}). Using Code Vision AVR, the circuit output voltage (V_{out}) during the tensile test was recorded. The sampling rate was 10 per sec, corresponding to a 10 Hz frequency. The sensor resistance can be calculated according to Equation (1). Finally, in order to compare the electromechanical behavior of different samples, the variation of output voltage during the tensile test ($\Delta V = V_i - V_0$) in relation to the sample voltage at the onset of tensile test (V_0), was calculated. Finally, the acquired data were smoothed using the polynomial fitting method.

$$R_{sensor} = R_{ref}(5 - V_{out})/V_{out} \tag{1}$$

3. Results

Figure 2 shows the normalized voltage variation of HAY strain sensor samples versus strain. Both the original and smoothed diagram is shown in Figure 2. The result points to the effect of electrical resistance of the conductive component on the electromechanical behavior of the HAY strain sensor. Results show that the sensitivity of the HAY strain sensors depends on two significant factors, namely the helical wrap angle and the conductive fiber percentage in yarn structure. Figure 2 shows that the voltage variation of all samples resembles each other and can be divided into four separate sections, Phases 1 to 4. The result shows that an increase in HAY strain results in a brief initial reduction in voltage variations (Phase 1) followed by a notable long-lasting increase (Phase 2). Then, voltage variations continued more smoothly (Phase 3). Finally, variations sharply decreased (Phase 4).

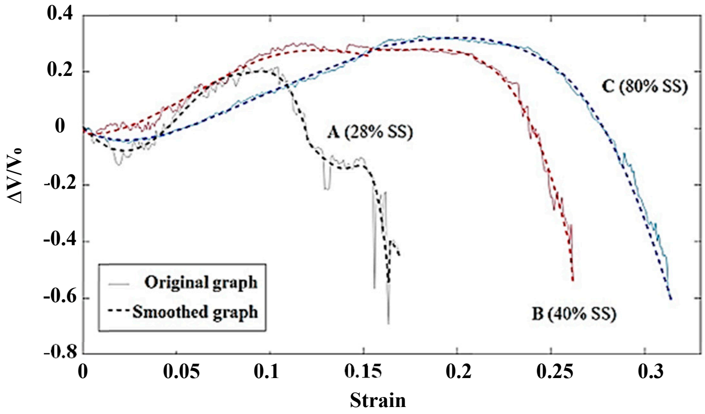

Figure 2. Voltage variation of HAY strain sensors under tensile loading: (A) sensor contained 28% SS in the conductive wrap component, (B) sensor contained 40% SS in the conductive wrap component, (C) sensor contained 28% SS in the conductive wrap component.

Figure 3 shows the cross-section of HAY strain sensors at two different strain ranges. A comparison of the cross-section of HAY samples at non-tensioned and tensioned states in Figure 3 clearly indicates the increase in aerial density of steel fibers after tension.

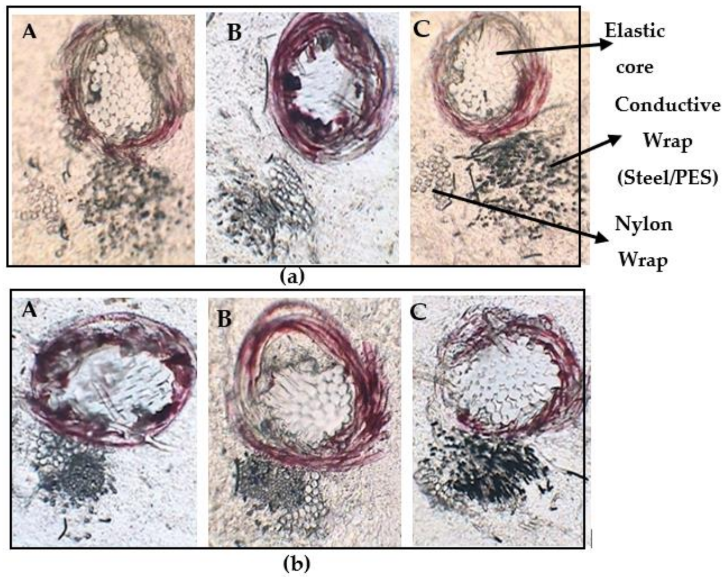

Figure 3. Cross-section of HAY strain sensors at two different strains: (**a**) zero strain, (**b**) and 0.2 strain; (A) sensor contained 28% SS in conductive wrap component, (B) sensor contained 40% SS in conductive wrap component, (C) sensor contained 28% SS in conductive wrap component.

4. Discussion

In these conductive yarn structures, every parameter that increases steel fiber connection, increases output voltage and vice versa. Under tensile loading of the HAY sensor, conductive wrap yarn experiences longitudinal tension and transverse compression. The longitudinal tension is proportional to the wrap angle. The Nylon 66-wrapped yarn in the HAY structure tends to straighten under tensile loading, forcing the elastic core yarn to deform helically. Therefore, Nylon 66 wrap migrate into the yarn center and elastic yarn crimps. Meanwhile, the conductive wrap yarn follows the Nylon 66 wrap migration into the HAY center and compresses in the transverse direction. Hence, connections of steel fibers improve, and output voltage increases. The latter claim is confirmed by Figure 3.

At the beginning of HAY tensile loading, there is poor conformance between the wrap and the core components. Therefore, the applied tensile force leads to tightening the wrap component. However, due to a considerable difference between the elastic modulus of conductive SS/PES and Nylon 66 yarns, the applying tensile force on side-by-side wraps, leads to an slight longitudinal extension of SS/PES wrap and voltage reduction (Phase 1). Then, the steel fiber's contact increases due to conductive yarn compression, increasing the output voltage (Phase 2). In Phase 3, the conductive yarn probably is straightened in the yarn center. Furthermore, it is compressed enough in the transverse direction. Thus, the steel fiber sliding is perhaps not as easy as in Phase 1. Hence, the voltage variation shows a moderate slope during tensile loading. More importantly, the high tenacity adjacent straightened Nylon 66 yarn is defining the HAY tensile behavior in this phase. By rapturing the high tenacity Nylon 66 at the end of Phase 3, the conductive yarn does not resist the elongation, hence, rapid reduction in steel fiber's contact. Therefore, an immediate drop in voltage is observed (Phase 4).

5. Conclusions and Outlook

Results show that the HAY structure containing the different conductive wrap yarns could represent strain sensors with various sensitivities. In this research, a new generation of cost-effective wearable strain sensors with advanced breathability and conformability was introduced. This is not only due to the adjustable and flexible nature of the auxetic yarn but also the fibrous structure of conductive yarn component.

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