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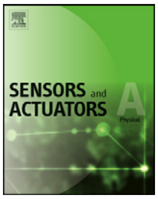

Parametric design of yarn-based piezoresistive sensors for smart textiles

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ABSTRACT

In our previous paper, the yarn-based sensors are shown capable of measuring the respiration signals. In comparing with fabric-based sensors, the yarn-based sensor is more comfortable in wearing, and easily fabricated by conventional textile process. In this paper, we aim at the analysis of the design parameters of the yarn-based sensors that were fabricated by double wrapping the polyester, elastic, and piezoresistive fibers. The performances of the yarn-based sensor under different compositions have been experimentally evaluated. It is shown that the soft-core yarn sensors achieve high gain factors with low linearity. The sensors consisting of high-density piezoresistive fibers achieve high linearity with low gain factor. It was also shown that the nonlinearity of the sensors that is mainly due to the irregular characteristics of the yarn structure exits at the low strain region. As at the high strain region, the high linearity of the yarn-based sensors is found regardless of material compositions. To further reduce irregular characteristics of the yarn structure, to increase the preload and to choose the stiffer core yarn and the harder piezoresistive fibers are suggested.

1. Introduction

Smart textiles with embedded sensors to monitor, actuate and adapt to environment change become more and more popular in these years [1]. One advanced study was to integrate smart textures with semiconductors to develop a wearable-computing technique [2–4]. The other study was to develop smart textiles which can detect environmental change, and thus they can be used to measure and monitor the physiological conditions of the wearer. Although promising results were shown in utilizing the smart textures, those issues of complicated manufacturing process, performance deterioration after washing or repeated folding, and difficulty aesthetic design still hinder the way of commercialization.

One type of fabric-based sensors using piezoresistive fabrics was developed in which the fabrics were coated by a thin layer of piezoresistive materials, such as polypyrrole (PPy, a $\prod$-electron conjugated conducting polymer) or a mixture of rubbers and carbons, on conventional fabrics [5–9]. The sensors behave like flexible strain gauges which measured strain or stress and were used to capture posture or motion [6,10–12]. It was shown that the coated fabrics were highly dependent upon knitting or weaving topology and the performance of the sensors might degrade a lot after repeated folding or washing. To improve the stability of the sensors, another method was to knit conductive fibers with nonconductive base fibers [8,13,14]. The integration of conductive fibers with the base fibers can improve the sensing performance even after washing. However, only the knitting process can be adopted to fabricate the sensors which might constrain the freedom when designing modern clothes.

Besides fabrics-based sensors, yarn-based sensors were another approach which could have the advantages such as more comfortable in wearing, easier to be fabricated by conventional textile process, better in style design, higher space resolutions and possible to measure distributed strain. Instead of using fabrics as base elements, the yarn itself is the base element. The yarn is fabricated by using piezoresistive fibers, elastic, and polyester fibers [15,16]. Our previous paper showed that the yarn-based sensor using the double wrapping method can achieve higher linearity than the single wrapping approach. The sensor could measure the respiratory signals precisely [16]. To extend the applicability of the sensor, more studies should be performed to provide guideline in designing the yarn-based sensors. The issues of using different core yarns and piezoresistive fibers are explored to provide more understandings in designing yarn-based sensors.

In this paper, the yarn-based sensors were fabricated by polyester, elastic and piezoresistive fibers using the double wrapping methods with different compositions. Different polyester, piezoresistive fibers, and the fabrication process (twist per meter,

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TPM) are chosen as the design parameters. Performances of the designed yarn-based sensors were experimentally evaluated by measuring their resistance change under various elongation for linearity and gain factor. To interpret the nonlinear characteristics of the sensor, an analysis method is proposed to calculate the force distribution between the core yarn and the carbon-coated fiber (CCF). It was shown that the soft-core yarn sensors achieve high gain factors at low linearity. The nonlinearity of the yarn-based sensors mainly comes from the irregular characteristics of the yarn structure specifically at the low strain region. Physical interpretations are given to illustrate the behavior of the yarn-based sensor with different compositions.

2. Fabrication of the yarn-based sensors

In this paper, the yarns were fabricated by wrapping the polyester fibers, elastic, and piezoresistive fibers into a skein. The piezoresistive fiber was chosen as the CCF. The fabrication process was to combine polyester fibers with elastic fibers into a composite core yarn. The length of the elastic fiber (Lycra, 22dtex) was stretched three times in the process before the combination. The elastic fiber is to improve the elasticity of the sensing yarn. Then one CCF was used to wrap the core yarn in the clockwise direction and the other CCF is to wrap the core yarn in the counterclockwise direction to form a double wrapping yarn as shown in Fig. 1. The diameter of the yarn was less than 0.2 mm. The twist density of the CCF fiber warping on the core yarn is normally described by the TPM. For example, TPM 450 means the length of every twist is 1000/450 = 2.22 mm. The lower TPM implies the longer twist. Although the single wrapping process can also be used, the double wrapping method was proven to be more effective as the yarn-based sensor [16].

One objective of this paper is to identify better design of the yarn-based sensors. Since the yarn consists of the polyester, elastic, and piezoresistive fibers, two different kinds of commercial polyester fibers, 56dtex/144f and 56dtex/48f, were chosen to fabricate the core yarn. Here the dtex denotes the gram per 10,000 m and f denotes that number of filaments is contained. Moreover, two types of the CCF fibers (RESISTAT F901, MERGE S022 (24dtex) and RESISTAT F901, MERGE D044 (49dtex)) were utilized to investigate the piezoresistive effects on yarn-based sensors.

Besides using different types of the fibers, the TPM was also chosen as another factor. The effects of the TPM under different combinations of polyester/piezoresistive fibers were investigated.

As shown in Table 1, nine different types of samples were fabricated. The samples are named as DXXX/YYf/ZZ, where XXX denotes the values of the TPM, YYf as the number of filaments of the polyester, and ZZ denotes the dtex of the CCF. For example, D150/48f/24 means that the TPM is 150, the number of the filament of the polyester fibers is 48 and the dtex of the CCF fiber is 24. In the next section, experiments were conducted to evaluate the performances of the samples.

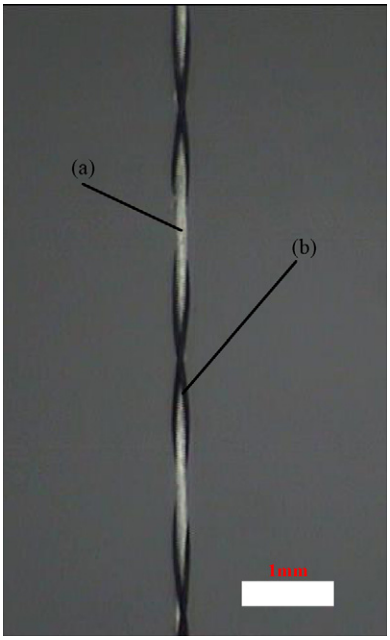

Fig. 1. The structure of yarn-based sensors: (a) core yarn and (b) CCF.

3. Analysis method and experimental results

To evaluate the performance of the yarn-based sensors, experiments on resistance change under different elongation were conducted in this section. The length of the samples is chosen to be 60 mm and the preload of 0.02 kg were used. The total stretched length was 14 mm. During the elongation, the force and resistance were simultaneously measured. Tensile forces were recorded by the Mini44 INSTRON and resistances were recorded by the Fluke189 multi-meter. After the measurement, the resistance and force curve were fitted by either the first or the second regression models as shown in Tables 2 and 3. The first coefficient of the first regression model and its R^2 value are used to evaluate the gain factor and linearity, respectively. The gain factor is the sensitivity of the yarn-based sensor under the given strain. The higher the gain factor means that the designed sensor can provide more sensitivity and stronger noise resistance. Therefore, the gain factor and linearity

Table 1
Nine types of samples for experiments

Type	D150/48f/24	D275/48f/24	D450/48f/24
TPM (twist per meter)	150	275	450
No. of filaments of polyester	48	48	48
Dtex of the CCF (gram per 10 km)	24	24	24
Type	D150/144f/24	D275/144f/24	D450/144f/24
TPM (twist per meter)	150	275	450
No. of filaments of polyester	144	144	144
Dtex of the CCF (gram per 10 km)	24	24	24
Type	D150/144f/49	D275/144f/49	D450/144f/49
TPM (twist per meter)	150	275	450
No. of filaments of polyester	144	144	144
Dtex of the CCF (gram per 10 km)	49	49	49