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Development of hysteresis-free and linear knitted strain sensors for smart textile applications

B. Bozali*[a], J.J.F. van Dam[a], L. Plaude[a], K.M.B. Jansen[a]
[a] Faculty of Industrial Design Engineering
Delft University of Technology, The Netherlands
Email: B.Bozali@tudelft.nl

Abstract— **Smart textiles have been attracting considerable interest in imparting a wide range of functions to traditional clothing ranging from sensing, actuation, data processing, and energy storage. In the case of textile-based strain sensors, most of the studies proved that they can work in principle, however, producing strain sensors with desirable properties such as stable sensitivity, small hysteresis, large enough working range, and good repeatability still remains a challenge necessitating the developments of novel technologies for soft sensors. This paper conducts a systematic approach to investigate the electromechanical properties of the knitted strain sensors to find out the optimum process parameters. We found a repeatable and robust method to produce knitted strain sensors with low hysteresis at a working range of at least 40%.**

Keywords—knitted strain sensors; hysteresis-free sensors

I. Introduction

Significant attention has been devoted to smart textiles in the past years, among which recent research has been focusing on various applications such as textile-based antennas [1], energy harvesting [2], electromagnetic shielding, and health monitoring [3]. Integrating various smart functions in garments helps to capitalize upon the intrinsic qualities of textiles such as comfort, stretchability, and washability. Thus, textiles provide appropriate platforms as a host for human interaction because they fit the shape of the human body, allowing for easy implementation to the functionality of the electrical components incorporated within [4]. Benefiting from this advantage, various applications of strain sensing can be realized in garments. Strain sensors commonly used for mechanical engineering applications are typically limited to strain not larger than 1 %. For the on-body applications, we need to be able to measure strains up to 30-40% [5]. In addition, for unobtrusive monitoring of the sensors need to be breathable, washable, and stretchable.

Knitted strain sensors have been ideal candidates achieving a seamless integration to the garments and utilized for the applications such as elbow and knee motion monitoring [6] or respiratory monitoring [7] thanks to their good elastic recovery and stretchability. Nevertheless, due to the unstable characteristics of knitted structures, which result in high hysteresis values, poor sensing performance, and narrow working range, they are currently not commonly integrated into practical applications and mostly remain as a patch form [8]. To be able to apply the knitted strain sensors in practical applications, they must fulfill several requirements such as low hysteresis, linear resistance vs. strain relationship over a certain working range up to 40%, and stable sensor properties with high sensitivity [5].

Many studies in which the parameters of fabricating reliable sensors have been reported by incorporating conductive yarns within a non-conductive fabric construction. A study by Atalay and Kennon pointed out that manufacturing parameters such as yarn tension, the properties of elastomeric yarn, and knit structure had a significant impact on the performance of the sensor [9]. This was also reported for interlock fabrics proving how the elastic yarn characteristics affect the reliability of the sensors [10]. The effect of the aspect ratio of 1x1 rib knitted samples was evaluated by Raji et al. They found out that plain rectangular sensors showed higher repeatability and sensitivity with low noise levels. Moreover, they stated that the initial resistance can be controlled by the sensor design with different aspect ratios [11]. The same group also reported that the use of covered elastic yarn instead of bare ones has resulted in higher sensitivity [12]. The effect of basic loop units such as loop head and loop feet on strain sensor optimization was also studied by Tohidi, Zille, Catarino, and Rocha. They achieved that higher loop lengths in knitted structures create a more stable structure, resulting in better sensor performance with lower noise values [13].

While all these studies have identified the most essential parameters for knitted strain sensors, most of them still need additional improvements in terms of durability and stability. In our study, we were able to find out a way to manufacture a linear and hysteresis-free knitted strain sensor and this paper explains the systematic work that led us to produce it.

II. EXPERIMENTAL SECTION

A. *Materials*

In this paper, we conducted a study on the electromechanical performance of knitted strain sensors in which the material and process parameters were varied systematically. From the previous studies, it turned out that conductive yarns made of steel filaments undermined the performance of sensors with a low narrow working range and low sensing behavior [14]. Therefore, we started to work with silver-coated yarns which are more comfortable and soft for wearable applications and have shown good washability results [15]. Silver-plated nylon yarns from Shieldex and Amann group were selected to have a wide range of resistivity values whereas two types of elastic yarns were used as non-conductive elastic filament (Uppingham and Yeoman). The detailed properties and notations of the conductive yarns used in this paper are listed in TABLE I.

TABLE I. PROPERTIES OF CONDUCTIVE YARNS

Yarn Type	***Conductive Yarn Properties***		
	Notation	***Linear Density***	***Resistivity***
Shieldex ®	S235	235/36 dtex	600 Ω/m
	S117	117/17 dtex	< 1.5 kΩ/m
	S76	78/20 dtex	< 3.5 kΩ/m
Amann ®	A96	Tex 96	<85 Ω/m
	A62	Tex 62	<150 Ω/m
	A28	Tex 28	< 530 Ω/m

The strain sensors used in this study have been weft-knitted on a Stoll CMS 530 flat knitting machine with an E8 machine gauge and 0.30 m/s carriage speed. A rib-knit design was chosen that combined a high extension potential with good elastic recovery. The samples were produced for machine NP settings ranging from 6 to 12, which result in a series of fabrics with different the knitting densities or fabric counts. Fabric counts were determined as calculating the loop numbers per unit distance both in wale and course directions.

B. *Measurement Techniques*

The electromechanical performance of the knitted strain sensors was determined by performing five test cycles at 30 mm/min, using a custom-made tensile tester (Fig. 1, left). The resistance changes are determined with the four-point probe measurement principle. In such a system, the current passes through the two outer probes and the voltage difference between them is recorded, as a result of which the change in resistance is measured [16]. The resistance response during tensile extension-relaxation tests was assessed in the course-wise direction under strains of up to 40%.

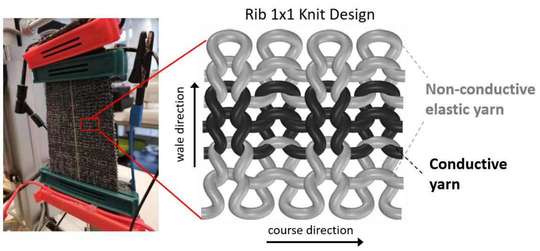

Fig. 1 Tensile tester with knitted strain sensor ((left) Knit design with 2-courses conductive yarn (right)

The electromechanical properties such as gauge factor (GF), hysteresis, and working range were determined for all experiments. The gauge factor or sensitivity is defined as the slope of the relative resistance change against the applied strain. Equation (1) shows the formula of the gauge factor in which $\Delta R = R_{Stretched} - R_0$, R_0=initial resistance, and is the **ε**=strain.

$$GF = \frac{(\Delta R/R_0)}{\varepsilon} \qquad (1)$$

In order to be useful as a strain sensing element the gauge factor should be preferably above unity. Hysteresis values were calculated as the maximum strain difference between stretched and unstretched cycles, scaled to the working range. The working range defines the maximum and minimum strain values that can be measured by the sensor [5].

III. RESULTS AND DISCUSSION

A. *The effect of fabric count and elastic yarn type on the sensor performance*

TABLE II shows the results of knitting samples produced with 2 courses of conductive yarn S235. Two different elastic yarns (U: Uppingham, Y: Yeoman) were used for the non-conductive base fabric. The results show that those produced with lower NP values and high fabric count all show a rather narrow working range of 0-10%, as the separation of knitted loops cannot be achieved easily due to the compact fabric structure. This causes a low resistance change within the tighter structures leading to low sensitivity. Linearity values also indicate a low level of relationship between strain and resistances at low NPs. Furthermore, the applied strain value may not be high enough to expand the conductive area, resulting in the number of contact points remaining unchanged. The samples with lower fabric counts, on the other hand, provide a structure with a wider working range with less noisy signals.

The sensitivity and working range of the sensors remained relatively limited and low at higher fabric counts, even when the type of elastic yarn was changed for co-knitting. Furthermore, all samples had shown significant and high hysteresis values. When the fabric counts increased, gauge factors were increased for both elastic yarns. They became close to a value of one which is suitable for measurements. The samples co-knitted with U elastic yarn appear to be more promising due to their higher elastic recovery performance and lower hysteresis values, whereas samples co-knitted with Y elastic yarn give lower gauge factors. As a result of that, for all next samples, Uppingham yarn was used.

TABLE II. THE EFFECT OF FABRIC COUNT AND ELASTIC YARN TYPE

Elastic Yarn	***Electromechanical properties***					
	NP	***Fabric Count***	***Gauge Factor***	***Working Range (%)***	***Hysteresis***	***Linearity (R^2)***
U	6	22x12	0.20±0.06	0-10	0.17	0.42±0.05
	7	21x10	0.11±0.005	0-10	0.12	0.67±0.02
	8	20x10	0.33±0.01	0-10	0.12	0.56±0.01
	9	19x10	0.70±0.002	6-30	0.15	0.88±0.01
	10	18x10	0.89±0.06	0-30	0.07	0.93±0.01
	12	16x10	0.76±0.04	0-37	0.12	0.96±0.01
Y	6	22x12	0.03±0.007	20-38	0.20	0.52±0.06
	7	21x10	0.06±0.01	25-40	0.25	0.43±0.19
	8	20x10	0.10±0.06	10-15	0.27	0.11±0.03
	9	19x10	0.28±0.05	5-20	0.13	0.78±0.02
	10	18x10	0.58±0.01	0-37	0.17	0.92±0.008
	12	16x10	0.33±0.04	10-37	0.19	0.63±0.01

B. *The effect of conductive yarn type on the sensor performance*

Conductive yarns with a range of initial resistance and linear density values (depicted in TABLE I) were compared for the structures knitted with the value of NP9 and with 2 conductive courses (TABLE III). The sensors knitted of Shieldex yarns with lower initial resistance tended to have higher sensitivity, while gauge factors decreased significantly as initial resistances increased. However, the same trend was not observed for Amann yarns, which at low resistances both low and high gauge factors were reported.

TABLE III. THE EFFECT OF CONDUCTIVE YARN TYPE ON GAUGE FACTOR FOR 2 CONDUCTIVE COURSES

Yarn Type	*Electromechanical properties*	
	Gauge Factor	*Initial Resistance (ohm)*
S235	0.70±0.01	15±0.02
S117	0.61±0.04	88±0.06
S76	0.35±0.02	189±0.66
A62	0.78±0.01	18±0.03
A96	0.38±0.03	10±0.02
A28	0.38±0.05	64±0.30

C. *The effect of conductive yarn conficuration on the sensor performance*

So far, all the samples have been prepared using the same knitting production method. The conductive and elastic yarns were co-knitted and conducted through a yarn feeder with two holes, which assured stable positioning of the conductive yarn in the final fabric structure. In the chosen 1x1 rib structure, the conductive yarn can be positioned either inside or outside in the knitted fabric. More details can be found in the Patent [17] (See Fig. 3). It turned out that the choice of the conductive yarn position had a significant effect on the hysteresis, as becomes evident from Fig. 2. and TABLE IV. After embedding the conductive yarn inside the rib structure, the gauge factor was seen to increase from 0.70 to 1.19, whereas the hysteresis decreased from 0.15 to a value of 0.03. It should be noted that such low hysteresis values have not been reported for knitted strain sensors before.

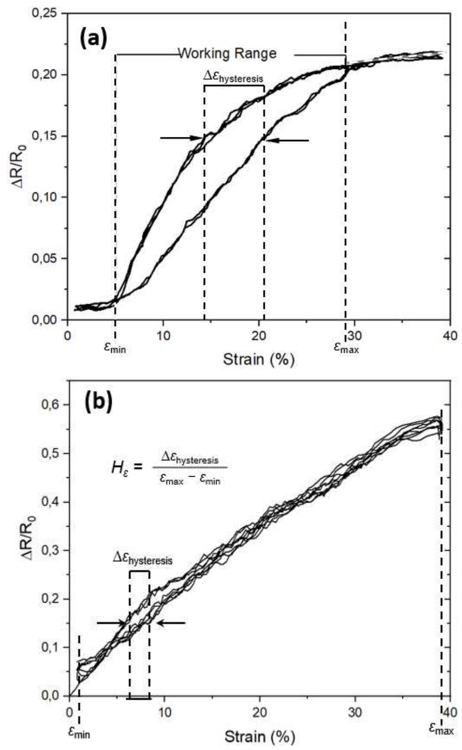

Fig. 2. The resistance versus strain graphs for the samples with hysteresis values of 0.15 (a), and 0.03 (b) for 5 cycles.

TABLE IV. THE EFFECT OF CONDUCTIVE YARN FEED POSITION

Pattern Type	*Electromechanical properties*			
	Gauge Factor	*Working Range (%)*	*Hysteresis*	*Linearity (R^2)*
Inside	1.19±0.04	0-40	0.03	0.98±0.00
Outside	0.70±0.002	6-30	0.15	0.88±0.01

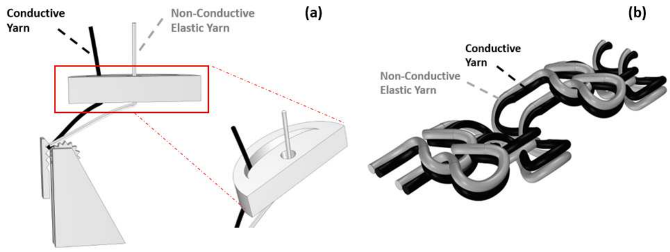

Fig. 3. The schematic view of plating yarn carrier (a), the co-knitted rib 1x1 structure (b)

The drastic decrease of hysteresis can not only be explained by the resistance change of conductive filaments but also the configurational changes of the loops. In the rib 1x1 structure where the loops are placed diagonally, the interlaced loops start to slide relative to each other when they are elongated under deformation. The courses are getting closer after stretching to 40% strain, resulting in the contraction of the fabric in the central region and the increase of the contact between the yarns. The lower loop's head may come into contact with the upper loop's feet, resulting in several inter-yarn contact points between the two loops. In addition, the loop's feet may also come into contact with each other, forming intra-yarn contact points. Generally, when the fabric is stretched, the intra-yarn contact points are pulled apart, resulting in a higher resistance, while the inter-yarn contact points are drawn together, resulting in decreased resistance.

IV. CONCLUSION

In this paper, we performed a systematical study to improve the sensing performance of knitted strain sensors. We compared elastic yarns and six conductive yarns with different characteristics and varied the knit density values and number of conductive courses. The measurement showed that the gauge factor increased when the knit density decreased. The performance of sensors made with different conductive yarns was evaluated, and those with lower initial resistance reported higher gauge factors for Shieldex yarns. By positioning the conductive yarns inside the 1x1 rib structure, a knitted strain sensor with linear performance and a gauge factor of 1.19 and negligible hysteresis was finally developed.

V. FUTURE STUDIES

This hysteresis-free and linear sensor performance will be evaluated in terms of repeatability at actual wearing conditions.

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