3D network structure and sensing performance of woven fabric as promising flexible strain sensor

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Abstract

A flexible strain sensor was developed through weaving conductive yarns to 3D woven fabric. The relationship between the sensing performance of the woven fabric and its 3D network structure containing yarn shrinkage and arrangement density, as well as fabric interweaving, was investigated according to Pierce's fabric geometry model and the assumption of elastic strain of yarn. Based on such models and assumption, the theoretical results were verified by the experimental data from uniaxial stretching, and the trends of both results were consistent. The sensitivity of woven fabric on its elastic strain is relatively small ($GF < 2$) and nonlinearity. With the deformation of fabric geometry structure (Stage I) caused by stretching on warp direction, the shrinkage of weft yarn (c_w) and interweaving points (n_w) decreased or the arrangement density of warp yarn (N_j) increased, resulting in improved sensitivity on warp direction. At yarn deformation stage (Stage II), the increase in interweaving points (n_w) or the decrease in arrangement density of warp yarn (N_j) could improve the sensitivity on warp direction. All the results provide a theory basis for the design and development of flexible strain sensor with promising application as wearable electronic device.

Keywords Strain sensor · Woven fabric · Pierce's fabric geometry model · Elastic strain

1 Introduction

Recently with the rapid development of wearable electronic devices, more researches were focused on textile-based electronic named electronic textiles (E-textiles) [1–5]. Because it was made of flexible materials and special 3D network structure, E-textiles not only fit the comfort requirement of human body, but also can adapt to strain caused by human body movement. Unfortunately, our daily textiles did not have electrical functions especially sensing performance. To achieve full E-textiles systems, it was necessary to integrate the advantages of 3D network

of textiles with electronic functions. During the past decade, a large amount of approaches had been tried and now two different featured E-textiles systems had been developed. One was to embed the simple electronic devices onto off-the-shelf textiles substrates [6–8]; the other was to integrate the electronic function with fibers which can be further processed to textiles [9, 10]. Although the integration of simple electronic devices onto textile substrate was easier to fabricate, the accessibility, comfort, durability, flexibility and stretchability of prepared E-textiles are extremely deteriorated due to mismatch between rigid electronics devices and flexible textiles [11]. On the

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contrary using textile technology was more suitable for processing the flexible fiber with electronic function to complex structure and area-scalable E-textiles [12].

Fabric as one of the main textiles, if made from flexible and electrical yarns had been demonstrated sensing performance because of its 3D network structure. Sensitivity was normally introduced to evaluate the sensing performance which is expressed as gauge factor ($GF = \frac{dR}{R\epsilon}$, where dR is the change rate of resistance, R is the initial resistance, and ϵ is applied strain) [13]. Three main 3D network structures of fabric (woven, knitting, and non-woven) can be used as strain sensor of E-textiles, of which woven fabric sensor was characterized by relatively high sensitivity and low stretchability due to the relatively tight texture [14–17]. Du et al. [15] prepared a non-woven structure-based strain sensor by coating graphene on the surface of non-woven fabric which exhibited a relatively low sensitivity ($GF < 7.1$) and low stretchability ($\epsilon < 10\%$). Seyedin et al. [18] used the electrical conductive PU/PEDOT: PSS fibers to fabricate knitting structure-based strain sensor which exhibited high stretchability (strain up to 160%) but relatively low sensitivity ($GF = 1$). Yan et al. [19] prepared woven structure-based strain sensor by carbonizing polyacrylonitrile nanofiber yarns of fabric which exhibited high sensitivity ($GF = 77.3$) and relatively low stretchability (strain $< 12\%$). For above sensing performance, E-textiles based on woven structure can accurately monitor the small strain such as heartbeat, pulse, and voice facial expression recognition due to its relatively high sensitivity [20–22]. However, at present there were few studies on the influence of woven fabric geometric structure change and yarn deformation on its sensing performance. Ma et al. [23] studied the resistance of woven fabric and its change during stretching only on the experiment results, but the relationship between fabric structure parameters and resistance changes had not been studied. In order for the well application of woven fabric strain sensors based on its 3D network structure, it is necessary to study the relationship between the structure parameters of woven fabric and its sensing performance under stretching.

In this work, the Pierce fabric geometry model was introduced for the first time to study the relationship between sensing performance and network structure parameters of woven fabric [24]. At first the relationship between the interlacing rules of warp and weft yarns and the electrical conductivity of woven fabrics was studied. Then, the geometric structure model of Pierce was introduced to study the relationship between sensing performance and structure parameters on uniaxial stretching and the mathematical relationship was derived. Finally, the reliability of the above results was verified experimentally.

We expected these studies can guide the design, development and application of woven fabric strain sensor based on its 3D network structure.

2 Materials and methods

2.1 Materials

The electrical conductive yarn (plied yarn) made of silver nanoparticles (AgNPs)-coated polyester staple yarns by ply twisting was kindly supplied by Shenzhen Huizheng new materials Ltd. China. (Fineness 120tex, Coefficient of twist 260 ± 10 , Density 0.93 g/cm^3 , Diameter 0.40 mm).

2.2 Measurement for the electrical resistance of yarn

The axial and radial resistance of yarn was measured, respectively, by Keysight 34461A universal digital meter (Digital multi-meter, 34461A, Agilent Technologies Inc. USA.); each sample was tested three times to get the average value. The axial and radial resistivity ρ_a, ρ_r can be derived by equation $R = \rho \frac{L}{S}$ (Support Information S1).

2.3 Preparation of woven fabric

As shown in Fig. 1, the electrical conductive yarns were fabricated to 3D network structure of woven fabric by semi-automatic sample loom (Y208W Changzhou No.2 textile instrument factory China). The arrangement density of warp and weft is 100–110 roots/10 cm and 90–100 roots/10 cm, respectively; the woven fabric structure is $\frac{1}{1}$ plain weave and $\frac{1}{2}$ twill weave for comparison.

2.4 Measurement of the electro-mechanical performance of woven fabric under uniaxial stretching

The strain (ϵ_j) of woven fabric was measured using Instron 5943 Tensile Testing Machine (Instron Inc. UK) according to ASTM D882-10 at room temperature, while the resistance change rate (dR/R_0) was measured by Keysight 34461A universal digital meter (Digital multi-meter, 34461A, Agilent Technologies Inc. USA). The sensitivity index of gauge factor ($GF = dR/R_0\epsilon$) was used to evaluate the sensing performance of woven fabric strain sensor. The measurement of strain on weft direction (ϵ_w), the shrinkage of warp and weft yarn (c_j, c_w) during stretching on warp direction can be reviewed on Support Information S2.

Fig. 1 3D network of woven fabric as **a** plain weave, **b** twill weave

3 Result and discussion

3.1 The electrical resistance of conductive yarns

Woven fabric is made by interweaving two sets of electrical conductive yarns that intersect vertically (warp and weft); electric currents can flow through the axial direction of the yarns or through from the radial direction of one set of yarns to another. As shown in Fig. 2a, the axial resistance of the yarns (R_a) can be expressed according to the mathematical expression of the surface specific resistance as

$$R_a = \rho_a \frac{L}{S} = 4 \frac{\rho_a L}{\pi D^2} \quad (1)$$

where ρ_a is the axial resistivity of yarn; L is the length of yarn; S is the area of yarn cross section $S = \frac{\pi D^2}{4}$; and D is the diameter of yarn.

Accordingly the axial resistances of warp and weft yarns can be expressed as:

$$R_{aj} = \frac{4\rho_a L_j}{\pi D_j^2}; \quad R_{aw} = \frac{4\rho_a L_w}{\pi D_w^2} \quad (2)$$

where D_j and D_w are the diameters of warp and weft; L_j and L_w are the lengths of warp and weft.

As shown in Fig. 2b, the radial resistance of yarns can be viewed as a series of small radial resistors with angle $d\theta$ in parallel and the resistance of each resistor (R_i) can be expressed as

Fig. 2 Graphic analysis of **a** axial resistance, **b** radial resistance, **c** the parallel of radial resistor, **d** contacted resistance of R_{cw} , **e** contacted resistance of R_{cj}

$$S = L \times r d\theta; \quad R_i = \rho_r \frac{r}{L r d\theta} = \rho_r \frac{1}{L d\theta} \quad (3)$$

where ρ_r is the radial resistivity of the yarn; r is the radius of yarn; and L is the length through which radial current flows.

Because the radial resistor with angle $d\theta$ is in parallel (Fig. 2c), the total radial resistance R_r of yarn can be expressed as:

$$\frac{1}{R_r} = \sum \frac{1}{R_i} = \frac{L}{\rho_r} \sum d\theta = \frac{L}{\rho_r} \int_0^{2\pi} d\theta = \frac{2\pi L}{\rho_r}; \quad R_r = \frac{\rho_r}{2\pi L} \quad (4)$$

On woven fabric, the electric currents flow through from one set of yarns to another; the resistance is related to the angle of contact at which the yarns intersect. The resistance where the current flows radially from weft to the warp is called the contact resistance R_{cw} (Fig. 2d), while the resistance where the current flows radially from warp to weft is called the contact resistance R_{cj} (Fig. 2e). According to Eq. (4), R_{cj} and R_{cw} can be expressed as:

$$R_{cw} = \frac{\rho_r}{\theta_w D_w}; \quad R_{cj} = \frac{\rho_r}{\theta_j D_j} \quad (5)$$

where θ_j is the contacted angle of warp covers on weft; θ_w is the contact angle of weft covers on warp; and the diameters of warp and weft D_j and D_w correspond to L of Eq. (4).

3.2 The resistance of woven fabrics on warp and weft direction

As shown in Fig. 3a, when the resistance on the warp direction measured on both ends of the warp can be regarded as two equal potential points, the resistance of the whole warp system can be approximately regarded as the resistance of the fabric on warp direction. Similarly, the resistance of the whole weft system can be approximately regarded as the resistance of the fabric on the weft direction. The resistance of warp system (R_j) contains the sum of the resistances of the two current paths; one is currents directly flowing through whole warp yarns ($R_{j \rightarrow j}$), the other is the currents flowing from weft to warp ($R_{w \rightarrow j}$), where weft was interwoven with warp. As shown in Fig. 3b, c, the $R_{j \rightarrow j}$ can be regarded as each warp resistor in parallel, while the $R_{w \rightarrow j}$ can be regarded as each weft resistor in parallel. The resistance of each weft is the sum of the contact

Fig. 3 Schematic diagram of **a** resistance measurement on warp direction, **b** circuit diagram, **c** equivalent resistance of whole resistance on warp direction

resistance where the weft interwoven with the warp (R_{cw}) and the resistance of the weft (R_{aw}).

The latter two factors are the main causes of hysteresis of fabric sensors [2, 25]. Therefore, the rapid elastic strain

$$R_{j \rightarrow j} = \frac{R_{aj}}{N_j}; \quad R_{w \rightarrow j} = \frac{R_{cw} + R_{aw}}{n_w}; \quad R_j = R_{j \rightarrow j} + R_{w \rightarrow j} = \frac{R_{aj}}{N_j} + \frac{R_{cw} + R_{aw}}{n_w} \quad (6)$$

where R_{aj} and R_{aw} are the axial resistance of each warp yarn or weft yarn according to Eq. (2); R_{cw} is the contact resistance of each interlacing point, where current flows through weft to warp according to Eq. (4); n_w is number of interlacing points weft cover on warp which is related to the total number of weft yarns (N_w) and the basic structure of the fabric. For example, as $\frac{1}{1}$ plain weave, the number of weft yarns in base structure is 2, interlacing point is 1, $n_w = \frac{N_w}{2} \times 1$; as $\frac{1}{2}$ twill weave, the number of weft yarns in base structure is 3, interlacing points is 1, $n_w = \frac{N_w}{3} \times 1$.

Accordingly, the resistance of woven fabric on weft direction (R_w) can be expressed as

$$R_w = \frac{R_{aw}}{N_w} + \frac{R_{cj} + R_{aj}}{n_j} \quad (7)$$

where N_w is the total number of weft yarns; n_j is number of points warp interwoven with weft; and R_{cj} is the contact resistance of each interlacing point, where current flows through warp yarn to weft according to Eq. (4).

According to Eqs. (6) and (7), the resistance of woven fabric is related to axial resistance of yarn (R_{aj} , R_{aw}), the contact resistance of the yarn (R_{cj} , R_{cw}), the density of the yarn arrangement (N_j , N_w), and the number of interweaving points (n_j , n_w), by increasing the yarn arrangement density and number of interlacing points or decreasing the contact resistance and axial resistance of yarn which can reduce the resistance of the woven fabric.

3.3 The sensing performance of woven fabric strain sensor on uniaxial stretching

Woven fabrics are made of interwoven warp and weft yarns, when the fabric is subjected to uniaxial stretching; the different strains on warp or weft direction will occur due to different interactions (friction, shear) between the warp and weft yarns. These strains include quick-elastic strain that can be recovered immediately, time-dependent slow-elastic strain and non-recoverable plastic strain.

range is an ideal working area for fabric sensors. For the sake of research, the following assumptions are made: (1) The section of yarn remains circular and volume remains unchanged during stretching. (2) The yarn structure is uniform, strain is within the elastic strain range of the fabric (stretching below the yield stress), and the fabric did not arch or fold.

When the fabric is subjected to uniaxial stretching (if on warp direction), two different stages of strain will be occurred: on first stage, the geometrical structure of woven fabric changes and the necking phenomenon occurs, that is shrinkage of warp and weft yarns changes, while the warp and weft yarns diameters remain unchanged (as shown in Fig. 4a). On second stage, the warp shrinkage reaches the minimum value ($\theta_j \rightarrow 0$) and the weft shrinkage reaches the maximum value ($\theta_w \rightarrow \pi$) (as shown in Fig. 4b, c); further stretching on warp direction, the warp yarn is deformed, while the deformation of weft is very small because of maximum shrinkage and the tight structure of fabric on weft direction [26, 27].

The sensitivity of woven fabric sensor can be expressed as:

$$GF = \frac{dR}{R_0 \varepsilon} \quad (8)$$

where $\frac{dR}{R_0}$ is the rate of resistance change on applied force; ε is the strain.

3.3.1 The sensing performance caused by fabric geometry structure change (Stage I)

In order to study the relationship between structure and electro-mechanical properties of fabric, Peirce geometric model (PGM) of woven fabric is introduced as shown in Fig. 5. There are some mathematical equations between fabric structural parameters according to PGM as follows [28]:

Fig. 4 Schematic diagram of fabric uniaxial stretching on Stage I **a** extension on warp direction and necking contraction on weft direction, **b** initial state ($c_j = c_{j0}$, $c_w = c_{w0}$), **c** the final state of Stage I ($c_j \rightarrow 0$, $c_w \rightarrow \max$)

Fig. 5 Peirce geometric model of woven fabric

$$h_j + h_w = D_j + D_w \quad (9)$$

$$\frac{h_j}{\alpha_w} = \frac{4}{3} \sqrt{c_j}; \quad \frac{h_w}{\alpha_j} = \frac{4}{3} \sqrt{c_w} \quad (10)$$

$$\theta_j = 212 \sqrt{c_j}; \quad \theta_w = 212 \sqrt{c_w} \quad (11)$$

$$c_j = \frac{L_j}{A} - 1 = \frac{l_j}{\alpha_w} - 1; \quad c_w = \frac{L_w}{B} - 1 = \frac{l_w}{\alpha_j} - 1 \quad (12)$$

$$l_j = \frac{L_j}{N_j}; \quad l_w = \frac{L_w}{N_j} \quad (13)$$

$$\alpha_w = \frac{A}{N_j} = \frac{l_j}{1+c_j} = \frac{L_j}{N_w} \frac{1}{1+c_j}; \quad \alpha_j = \frac{B}{N_w} = \frac{l_w}{1+c_w} = \frac{L_w}{N_j} \frac{1}{1+c_w} \quad (14)$$

where α_w and α_j are the spacing between the adjacent weft or warp; c_j and c_w are the warp and weft shrinkage of fabric; h_j and h_w are the crimp wave heights of warp or weft; l_j and l_w are the crimp wave lengths of warp or weft; L_j and L_w are the lengths of warp or weft; N_j and N_w are the numbers of warp or weft; θ_j and θ_w are the contact angles of warp cover on weft or weft cover on warp; A is the length of the fabric; and B is the width of the fabric.

In Stage I, only the structure of fabric changes and no deformation occurs on warp or weft yarns; so the following equations can set up:

$$dL_j = d\frac{L_j}{N_j} = dl_j = 0; \quad dl_w = d\frac{L_j}{N_w} = dl_w = 0 \quad (15)$$

$$dR_{aj} = 0; \quad dR_{aw} = 0 \quad (16)$$

$$d(D_w + D_j) = d(h_j + h_w) = 0 \quad (17)$$

According to Eqs. (12), (13), (14), and (15)

$$dl_j = (1+c_j)d\alpha_w + \alpha_w dc_j = 0; \quad dl_w = (1+c_w)d\alpha_j + \alpha_j dc_w = 0 \quad (18)$$

$$\frac{d\alpha_w}{\alpha_w} = \varepsilon_j; \quad \frac{d\alpha_j}{\alpha_j} = \varepsilon_w \quad (19)$$

$$dc_j = -(1+c_j)\varepsilon_j \quad (20)$$

$$dc_w = -(1+c_w)\varepsilon_w \quad (21)$$

$$\alpha_w = \alpha_{w0}(1+\varepsilon_j); \quad \alpha_w = \frac{l_j}{(1+c_j)}; \quad \alpha_{w0} = \frac{l_j}{(1+c_{j0})} \quad (22)$$

Rearranging Eq. (22), we get

$$\varepsilon_j = \frac{c_{j0}-c_j}{c_j+1} \quad (\because c_{j0} > c_j, \therefore \varepsilon_j > 0) \quad (23)$$

Similarly

$$\varepsilon_w = -\frac{c_w-c_{w0}}{c_w+1} \quad (\because c_{w0} < c_w, \therefore \varepsilon_w < 0) \quad (24)$$

$$\frac{\varepsilon_w}{\varepsilon_j} = -\frac{(c_w-c_{w0})(c_j+1)}{(c_w+1)(c_{j0}-c_j)} \quad (25)$$

where ε_j and ε_w are the strains of fabric on warp or weft direction; c_{j0} and c_{w0} are the initial shrinkage of warp or weft. α_{w0} is the initial spacing between the adjacent wefts.

When there is uniaxial stretching on warp direction, the resistance change rate of the warp system (R_j) can be expressed as:

$$R_{aj} = 4\rho_a \frac{L_j}{\pi D_j^2} = \text{const}; \quad R_{cw} = \frac{\rho_r}{D_w \theta_w} = \frac{\rho_r}{212 D_w \sqrt{c_w}} \quad (26)$$

$$dR_j = \frac{1}{n_w} dR_{cw} \quad (27)$$

According to Eqs. (5) and (11)

$$dR_{cw} = d\frac{\rho_r}{212 D_w \sqrt{c_w}} = -\frac{1}{2} \times \frac{\rho_r}{212 D_w} c_w^{-3/2} dc_w = -\frac{R_{cw}}{2c_w} dc_w \quad (28)$$

Rearranging Eqs. (21), (27), and (28), we get:

$$dR_j = \frac{1}{n_w} R_{cw} \frac{1+c_w}{2c_w} \varepsilon_w \quad (29)$$

According to Eqs. (5) and (6), the initial resistance on warp direction of fabric (R_{j0}) and initial contacted R_{cw0} can be expressed as:

$$R_{j0} = \frac{R_{aj}}{N_j} + \frac{R_{cw0} + R_{aw}}{n_w}; \quad R_{cw0} = \frac{\rho_r}{D_w \theta_{w0}} = \frac{\rho_r}{212 D_w \sqrt{c_{w0}}} \quad (30)$$

$$\begin{aligned} \frac{dR_j}{R_{j0}} &= \frac{R_{cw}}{\frac{n_w}{N_j} R_{aj} + R_{cw0} + R_{aw}} \frac{1+c_w}{2c_w} \varepsilon_w \\ &= \frac{\frac{\rho_r}{212 D_w \sqrt{c_w}}}{\frac{n_w}{N_j} 4\rho_a \frac{L_j}{\pi D_j^2} + \frac{\rho_r}{212 D_w \sqrt{c_{w0}}} + 4\rho_a \frac{L_w}{\pi D_w^2}} \frac{1+c_w}{2c_w} \varepsilon_w \end{aligned} \quad (31)$$

Rearranging (25), (30), and (31), the resistance change rate on Stage I $\left(\frac{dR_j}{R_{j0}}\right)_1$ can be expressed as

$$\left(\frac{dR_j}{R_{j0}}\right)_1 = -\frac{(c_w - c_{w0})(c_j + 1)}{2c_w(c_{j0} - c_j)} \frac{\frac{\rho_r}{212D_w\sqrt{c_w}}}{\frac{n_w}{N_j}4\rho_a\frac{L_j}{\pi D_j^2} + \frac{\rho_r}{212D_w\sqrt{c_{w0}}} + 4\rho_a\frac{L_w}{\pi D_w^2}} \varepsilon_j \quad (32)$$

The sensitivity of woven fabric sensor on warp direction at Stage I (GF_{j1}) can be expressed as:

$$GF_{j1} = -\frac{(c_w - c_{w0})(c_j + 1)}{2c_w(c_{j0} - c_j)} \frac{\frac{\rho_r}{212D_w\sqrt{c_w}}}{\frac{n_w}{N_j}4\rho_a\frac{L_j}{\pi D_j^2} + \frac{\rho_r}{212D_w\sqrt{c_{w0}}} + 4\rho_a\frac{L_w}{\pi D_w^2}} \quad (33)$$

It can be known from the analysis of Eq. (33) as follow:

1. When stretching on warp direction, the GF_{j1} is negative correlation with strain on warp direction (ε_j).
2. GF_{j1} is related to the shrinkage of fabric on warp or weft direction (c_j, c_w), since GF_{j1} is not constant, so the sensitivity of fabric sensors whatever on warp or weft direction is nonlinear at the Stage I.
3. Increasing the shrinkage of warp yarns (c_j) and the number of warp yarns (N_j), or decreasing the shrinkage of weft yarns (c_w) and the number of interweaving points (n_w) can improve the sensitivity of the fabric sensor. For example, twill weave is with relatively few interweave points (n_w) than plain weave; the sensitivity of twill woven fabric strain sensor is higher than plain woven.

3.3.2 The sensing performance caused by deformation of yarn (Stage II)

On second stage, when $\varepsilon_j > \varepsilon_{jc}$ (ε_{jc} is the critical strain when $c_j = 0$), the contact resistance R_{cj} tends to infinity, which means no currents flow through warp to weft and the resistance of fabric on weft direction (R_w) is $\frac{R_{aw}}{N_w}$. Meanwhile the shrinkage of weft (c_w) and the contact angle where weft cover on warp (θ_w) tends to maximum value (c_{wmax}, θ_{wmax} , Fig. 4c) and the contact resistance R_{cw} tends to the minimum value $R_{cwmin} = \frac{\rho_r}{212\sqrt{c_{wmax}}D_w}$. So the resistance of fabric on warp direction (R_j) is $\frac{R_{aj}}{N_j} + \frac{R_{cwmin} + R_{aw}}{n_w}$. Under the condition of small strain, when the warp is stretched, the force on weft yarn is very small and its deformation can be ignored [26]. The resistance change of fabric on warp direction can be expressed as

$$dR_j = \frac{dR_{aj}}{N_j} \quad (\because R_{cwmin} \approx \text{const}, R_{aw} \approx \text{const}) \quad (34)$$

As shown in Fig. 6 according to the assumption (1) that the yarn has no volume change at small strain, the following equation can be derived:

Fig. 6 Schematic diagram of radial and axial strain of yarn ($\varepsilon_y, \varepsilon_x$) on Stage II

$$\frac{1}{4}\pi D_{j0}^2 L_{j0} = \frac{1}{4}\pi D_j^2 L_j; \quad \frac{L_j}{L_{j0}} = \left(\frac{D_{j0}}{D_j}\right)^2; \quad \frac{L_j}{L_{j0}} = \varepsilon_y + 1; \quad \frac{D_{j0}}{D_j} = \frac{1}{\varepsilon_x + 1} \quad (35)$$

$$\varepsilon_x + 1 = \frac{\sqrt{\varepsilon_y + 1}}{\varepsilon_y + 1}; \quad \sqrt{\varepsilon_y + 1} - 1 \approx \frac{\varepsilon_y}{2}; \quad \varepsilon_x \approx -\frac{\varepsilon_y}{2(\varepsilon_y + 1)} \quad (36)$$

And according to surface specific resistance formula of uniform materials

$$R = \rho \frac{L_j}{S}; \quad dR = \rho d\frac{L_j}{S} = \rho \frac{S dL_j - L_j dS}{S^2} = \rho \frac{dL_j}{S} - \rho \frac{dS}{S^2} = R \frac{dL_j}{L_j} - R \frac{dS}{S} \quad (37)$$

$$S = \frac{\pi D_j^2}{4}; \quad dS = \frac{\pi D_j dD_j}{2}; \quad \frac{dS}{S} = 2 \frac{dD_j}{D_j} = 2\varepsilon_x \frac{dD_j}{D_j} = \varepsilon_x \frac{dL_j}{L_j} = \varepsilon_y \quad (38)$$

$$dR = R \left(\frac{dL_j}{L_j} - \frac{dS}{S} \right) = R(\varepsilon_y - 2\varepsilon_x) \approx R \frac{\varepsilon_y(\varepsilon_y + 2)}{\varepsilon_y + 1} \quad (39)$$

$$\frac{R}{R_0} = \frac{\rho \frac{L_j}{S}}{\rho \frac{L_{j0}}{S_0}} = \frac{L S_0}{L_0 S} = \frac{\frac{1}{4}\pi D_{j0}^2 L_j}{\frac{1}{4}\pi D_j^2 L_{j0}} = \left(\frac{L_j}{L_{j0}}\right)^2 = (\varepsilon_y + 1)^2 \quad (40)$$

where $\varepsilon_x, \varepsilon_y$ are the strains of yarn on radial and axial direction; $D_{j0}, D_j, L_{j0}, L_j, S_0$, and S are the diameter, length and section area of yarn at initial state or under stretching.

Rearranging (39) and (40), we get

$$dR \approx R_0 \varepsilon_y (\varepsilon_y + 1) (\varepsilon_y + 2) \quad (41)$$

$$dR_j = \frac{dR_{aj}}{N_j} = \frac{R_{aj0}}{N_j} \varepsilon_y (\varepsilon_y + 1) (\varepsilon_y + 2) \quad (42)$$

$$\left(\frac{dR_j}{R_{j0}}\right)_2 = \frac{R_{aj0}}{R_{aj0} + N_j \frac{R_{cwmin} + R_{aw0}}{n_w}} \varepsilon_y (\varepsilon_y + 1) (\varepsilon_y + 2) \quad (43)$$

where $\left(\frac{dR_j}{R_{j0}}\right)_2$ is the change rate of warp direction resistance on Stage II.

Considering the assumption of the elastic strain of the yarn, the range of ε_y is small, so the higher power of ε_y can be skipped; Eq. (43) can be expressed as:

$$\left(\frac{dR_j}{R_{j0}}\right)_2 \approx \frac{2R_{aj0}}{R_{aj0} + N_j \frac{R_{cwmin} + R_{aw0}}{n_w}} \varepsilon_y \quad (44)$$

Considering the strain already occurred in the first stage, the strain occurred in the second stage should be removed from the strain in the first stage that is

$$\varepsilon_y = \varepsilon_j - \varepsilon_{jc} \quad (45)$$

$$GF_{j2} \approx \frac{2R_{aj0}}{R_{aj0} + N_j \frac{R_{cwmin} + R_{aw0}}{n_w}} \left(1 - \frac{\varepsilon_{jc}}{\varepsilon_j}\right) \quad (46)$$

where ε_{jc} is critical strain when $c_j = 0$; GF_{j2} is the sensitivity on warp direction of woven fabric at Stage II.

It can be known from the analysis of Eqs. (44), (45), and (46):

1. GF_{j2} can be improved by increasing the interweaving points of warp and weft (n_w), increasing the initial resistance of warp (R_{aj0}), or decreasing the initial resistance (R_{aw0}) and the minimum contact resistance of weft (R_{cwmin}), as well as the number of warp yarns (N_j).
2. GF_{j2} values are approximately linear with the strain occurred on stage II (ε_y) but nonlinear with the whole strain of the fabric (ε_j).

3.4 Experimental verification

Two different fabric structures (twill and plain weave) were prepared for the comparison and verification of its sensing performance experimentally. The theoretical value of c_{j0} , c_{w0} , c_j , c_w , R_{cw} , $\left(\frac{dR_j}{R_{j0}}\right)_1$, $\left(\frac{dR_j}{R_{j0}}\right)_2$, GF_{j1} , GF_{j2} can be derived by relevant equation and is listed in Tables 1 and 2. As shown

Table 1 The calculated values of fabric structure and electrical properties (twill weave)

ε_j (%)	c_j (%)	B (cm)	ε_w (%)	c_w (%)	R_{cw} (Ω)	R_j (Ω)	$\frac{dR_j}{R_{j0}}$ (%)	GF_{j1}
<i>Stage I</i>								
0	c_{j0}	1.50	0	c_{w0}	0.269	0.1042	–	–
1	6.34	1.47	–2.00	12.24	0.243	0.1029	–1.26	–1.26
2	5.29	1.42	–5.33	16.19	0.213	0.1011	–2.29	–1.15
3	4.27	1.36	–9.33	21.32	0.183	0.0993	–2.74	–0.91
4	3.27	1.31	–12.67	25.96	0.167	0.0984	–2.89	–0.73
5	2.29	1.25	–16.67	32.00	0.151	0.0974	–2.90	–0.58
6	1.32	1.18	–21.33	39.84	0.134	0.0964	–2.83	–0.47
7	0.37	1.13	–24.67	46.02	0.124	0.0958	–2.74	–0.39
7.4	0	1.11	–26.00	48.65	0.121	0.0956	–2.71	–0.37
ε_j (%)	$\varepsilon_j - \varepsilon_{jc}$	B (cm)	ε_w (%)	c_w (%)	R_{cw} (Ω)	R_j (Ω)	$\frac{dR_j}{R_{j0}}$ (%)	GF_{j2}
<i>Stage II</i>								
8	0.6	1.10	–26.67	50.00	0.120	0.0956	0.88	0.11
9	1.6	1.10	–26.67	50.00	0.120	0.0956	2.36	0.26
10	2.6	1.09	–27.33	51.38	0.118	0.0955	3.80	0.38
11	3.6	1.09	–27.33	51.38	0.118	0.0955	5.26	0.48
12	4.6	1.09	–27.33	51.38	0.118	0.0955	6.72	0.56
13	5.6	1.08	–28.00	52.78	0.116	0.0954	8.18	0.63
14	6.6	1.08	–28.00	52.78	0.116	0.0954	9.64	0.69

Known parameter

$A_0 = 5$ cm, $L_{j0} = 5.37$ cm, $\varepsilon_{jc} = c_{j0} = 7.40\%$, $B_0 = 1.5$ cm, $L_{w0} = 1.65$ cm, $c_{w0} = 10\%$, $N_j = 100/10 \times 1.5 = 15$, $N_w = 102/10 \times 5 = 51$, $n_w = N_w/3 = 17$ (plain weave), $R_{cwmin} = \frac{\rho_t}{212\sqrt{c_{wmax}D_w}} = 0.123$ Ω , $R_{cw0} = \frac{\rho_t}{212\sqrt{c_{w0}D_w}} = 0.269$ Ω , $R_{aj0} = 1.05$ Ω , $R_{aw0} = 0.315$ Ω , R_{j01} (at Stage I) = 0.104 Ω , R_{j02} (at Stage II) = 0.0965 Ω , $D_w = D_j = 0.4$ mm

Table 2 The calculated values of fabric structure and electrical properties (plain weave)

ε_j (%)	c_j (%)	B (cm)	ε_w (%)	c_w (%)	R_{cw} (Ω)	R_j (Ω)	$\frac{dR_j}{R_{j0}}$ (%)	GF_{j1}
<i>Stage I</i>								
0	8.60	1.50	0	c_{w0}	0.245	0.0933	–	–
1	7.43	1.48	– 1.33	13.51	0.230	0.0927	– 0.53	– 0.53
2	6.47	1.45	– 3.33	15.86	0.216	0.0921	– 1.17	– 0.58
3	5.44	1.38	– 8.0	21.74	0.183	0.0907	– 1.65	– 0.55
4	4.42	1.30	– 13.3	29.22	0.158	0.0897	– 2.08	– 0.52
5	3.43	1.23	– 18.0	36.58	0.140	0.0890	– 2.11	– 0.42
6	2.45	1.19	– 20.7	41.24	0.132	0.0886	– 2.09	– 0.35
7	1.50	1.16	– 22.67	44.83	0.125	0.0883	– 2.03	– 0.29
8	0.56	1.13	– 24.67	48.68	0.120	0.0881	– 2.02	– 0.25
8.6	0	1.11	– 26.00	51.35	0.118	0.0880	– 2.17	– 0.25
ε_j (%)	$\varepsilon_j - \varepsilon_{jc}$	B (cm)	ε_w (%)	c_w (%)	R_{cw} (Ω)	R_j (Ω)	$\frac{dR_j}{R_{j0}}$ (%)	GF_{j1}
<i>Stage II</i>								
9	0.4	1.10	– 26.67	52.73	0.116	0.0879	0.64	0.07
10	1.4	1.10	– 26.67	52.73	0.116	0.0879	2.26	0.23
11	2.4	1.09	– 27.33	54.13	0.115	0.0878	3.82	0.35
12	3.4	1.09	– 27.33	54.13	0.115	0.0878	5.41	0.45
13	4.4	1.09	– 27.33	54.13	0.115	0.0878	7.00	0.54
14	5.4	1.08	– 28.00	55.56	0.113	0.0876	8.59	0.61
15	6.4	1.08	– 28.00	55.56	0.113	0.0876	10.18	0.68
<i>Known parameter</i>								
$A_0 = 5$ cm, $L_{j0} = 5.43$ cm, $\varepsilon_{jc} = c_{j0} = 8.6\%$, $B_0 = 1.5$ cm, $L_{w0} = 1.68$ cm, $c_{w0} = 12\%$, $N_j = 100/10 \times 1.5 = 15$, $N_w = 96/10 \times 5 = 48$, $n_{w1} = N_w/2 = 24$ (plain weave), $R_{cwmin} = \frac{\rho_t}{212\sqrt{c_{wmax}D_w}} = 0.118$ Ω , $R_{cw0} = \frac{\rho_t}{212\sqrt{c_{w0}D_w}} = 0.245$ Ω , $R_{aj0} = 1.05$ Ω , $R_{aw0} = 0.315$ Ω , R_{j01} (at Stage I) = 0.0933 Ω , R_{j02} (at Stage II) = 0.088 Ω , $D_w = D_j = 0.4$ mm								

in Fig. 7, the experimental measurement curve of $\frac{dR_j}{R_{j0}} \sim \varepsilon_j$ and GF_j are basically consistent with the value obtain by Eqs. (32), (33), (44), and (46), which prove the credibility of theoretical results derived by Pierce geometry model of fabric and assumption of elastic strain of yarn. In addition, the sensitivity of the strain sensor based on woven fabric structure is relatively small ($|GF_j| < 2$) no matter theoretical derivation or experimental verification. At the first stage, the change of resistance is negatively correlated with strain (strain increases and resistance decreases), while in the second stage, the change of resistance is positively correlated with strain (strain increases and resistance

increases). After the second stage of stretching, the plastic deformation may be caused by the fabric structure damage (staple slipping, fabric folding etc.), resulting in the fluctuation of the resistance value and the instability of the sensing performance; therefore, it should not be included in the reliable working strain range of the fabric strain sensor. It is necessary to note that the small GF value of our results are probably due to the electrical conductive plied yarns to weave fabric sensor in our experiment was made of continuous entangled and twisted conductive staple yarns with large aspect ratio, its connection-disconnection state between the fibers is less changed. Therefore the sensitivity of our woven fabric sensor is affected mainly by

Fig. 7 Experimental curve and the calculated value derived by the theoretical formula **a** $dR_j/R_j - \varepsilon_j$ of twill weave, **b** $dR_j/R_j - \varepsilon_j$ of plain weave, **c** $GF_j - \varepsilon_j$ of twill weave, **d** $GF_j - \varepsilon_j$ of plain weave

the geometric effect sensing mechanism, secondary by the connection-disconnect sensing mechanism as it does in the case of coating graphene on the surface of fabric which often exhibits high sensitivity [5, 29]. Finally, what needs further explanation is that different fabric structures exhibit different GF values and resistance change rate (Fig. 8a, b); twill weave normally has a larger resistance change rate and GF value than plain weave mainly because twill weave is prone to deformation during stretching and its current path is less than plain weave.

4 Conclusion

Based on the fabric geometry model of Pierce and the assumption of elastic strain of yarn, the relationship between the parameters of 3D network structure of woven fabric strain sensor and its sensing performance on uniaxial stretching was studied and the mathematical relationship was derived; these theoretical conclusions were verified by uniaxial stretching experiment. It can be found that the sensitivity was relatively small and nonlinear if

Fig. 8 Comparison experimental curve of different fabric structures (plain, twill weave). **a** $dR_j/R_j - \varepsilon_j$ curve, **b** $GF_j - \varepsilon_j$ curve

only geometric effect sensing mechanism works. In order to improve the sensitivity and linearity of woven fabric strain sensor on warp direction, in addition to adjusting the structural parameters of the fabric (N_j , n_{wr} , c_w), other sensing mechanisms, such as connection disconnection effect and piezoresistive effect, should be adopted.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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