Study on the Modeling and tensile performance simulation of knitted fabric-based conductive line

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Abstract: Aiming at the problem of easy breakage and low tensile performance during the preparation of flexible conductive lines on the fabric surface, numerical simulation methods are used to establish a medium-scale three-dimensional (3D) model of the knitted fabric-based conductive line. The influence of the shape and width of the conductive line on the tensile properties is studied, and the deformation and fracture processes of knitted fabrics and conductive lines under different stretching directions (horizontal, vertical, and shear) are clarified. The results show that the optimal geometric shape of the conductive line is horseshoe shape, the width of the conductive line is inversely proportional to the tensile performance, the crack section of the conductive line is straight when stretched horizontally, and the cross-section of the crack is sawtooth when stretched vertically, the initial stage of the crack section during shear stretching is the same as that of horizontal stretching, and the later crack development is irregular.

1. Introduction
Wearable smart textile is a new type of textile that highly integrates electronic technology and fabric. It is composed of sensors, actuators, data processing, communication, power supply, and other units, including sensing, communication, and learning functions, and has broad application prospects in aerospace, medical, sports and leisure fields[1-2]. The conductive line serves as a bridge connecting various electronic components, and its performance directly determines whether the wearable textile system can work effectively[3]. However, the prepared conductive line has problems of looseness, low rigidity and poor adhesion. When the fabric matrix is stretched and deformed, it is easy to fall off, tear or break, thereby destroying the integrity of the line, resulting in electrical performance failure. Yuan Wei et al[4] studied the resistance uniformity and tensile resistance stability of micro-electrodes on the surface of silicon substrates based on the microstructure of the electrode surface and discussed the influence of the appearance of the curved structure on the tensile strength of the film. Chang Ruofei et al[5] summarized the flexibility and mechanical design principles of the corrugated box structure and the island bridge structure through experiments and revealed the deformation mechanism. Gonzalez M et al[6] put forward a flexible and stretchable interconnection design by embedding curved electroplated metal wires in a stretchable substrate to achieve 100% conductor ductility. M. Jablonski et al[7] studied the conductivity, bendability, and reliability of different geometrically curved copper conductors packaged in PDMS by combining experiments and numerical simulations. In summary, researches on stretchable conductive lines are mainly focused on flexible substrates that are mostly impermeable flexible materials such as PET or PDMS, while there are few studies on fabric substrates with porous characteristics. In this paper, a numerical simulation method is used to establish a medium-scale 3D physical model of the knitted fabric-based conductive line. According to the static-dynamic theory, the
influence of shape and width on the tensile properties of conductive lines is studied, and the deformation process of conductive lines and knitted fabrics under horizontal, vertical, and shear directions stretching is studied.

2. Physical model

2.1 Establishment of the physical model of knitted fabric

The main structural parameters of knitted fabrics are loop height \( H \), loop width \( W \), and yarn diameter \( D \), and other parameters are derived from these three basic parameters through mathematical expressions. The estimation of geometric parameters is based on ideal elastic yarn, so to simplify the model and facilitate the calculation, the following assumptions are made:

(1) The yarn is a homogeneous elastic cylinder with a constant diameter.

(2) The coil is a 3D structure in space, which is constructed by a piecewise function of the centerline.

By calculating the center line function of the 1/4 coil \((ABCE)\), and then according to the symmetry relationship, the expression of the centerline function of the unit coil can be obtained. As shown in Fig 1, the centerline path of the 1/4 coil can be divided into \( AB, BC, \) and \( CE \). The mathematical expressions of the three paragraphs are as follows:

\[
AB \quad (x \ (y = C/2+R)< x < W/4): \quad z(x) = P - \sqrt{Q - (x - W/4)^2} \\
P = (x_W - W/4)^2 - (x_L - W/4)^2 + z_L^2 + z^2 \\
Q = \sqrt{(x_W - W/4)^2 + (z_L - P)^2} \\
x_L = L - a \left(1 - \frac{R - 0.001}{b}\right), \quad z_L = L - a \left(1 - \frac{R}{b}\right), \\
\left\{ \begin{align*}
H/2 &< y < H/2 + R \\
\left(\sqrt{(G + D/2)^2 - (H/2 + R - 0.001)^2} - (G + D/2)\right) &- \left(\sqrt{(G + D/2)^2 - (H/2 + R)^2} - (G + D/2)\right)
\end{align*} \right.
\]

\[
BC \ (H/2 < y < H/2 + R): \quad x(y) = L - a \left(1 - \frac{y - H/2}{b}\right), \quad z(y) = \sqrt{(G + D/2)^2 - y^2} - (G + D/2) \\
L = (H/2 - R) \tan(\frac{\pi}{2} - \alpha), G = \frac{(H/2 - R)^2 - (D/2 + 2)^2}{2 - D}
\]

\[
CD \ (0 < y < H/2 + R): \quad x(y) = -\frac{D}{H}y, \quad z(y) = \sqrt{(G + D/2)^2 - y^2} - (G + D/2)
\]

Fig.1 Schematic diagram of the centerline of the knit unit coil

According to the mathematical expressions established above, combined with the main structural parameters of knitted fabrics in the literature\[^{[8]}\]: \( H = 0.4857, \ W = 0.8327, \ D = 0.1845, \ T = 0.072 \), substitute the structural parameters to calculate the centerline of the 1/4 unit coil 7 groups of type value points

\[
\psi_1 : 0.046,0.121,-0.019. \quad \psi_2 : -0.09,0.243,-0.241. \quad \psi_3 : -0.079,0.3,-0.138. \quad \psi_4 : 0.033,0.357,-0.228. \quad \psi_5 : 0.209,0.4,-0.27. \quad \psi_6 : 0.089,0.39,-0.25.
\]

First, the spline curve is used to fit the centerline curve of the 1/4 unit coil, as shown in Fig 2(a), second, the sweep modeling method is used to take the centerline curve as the sweep path, Take the diameter of the coil as the sweep section to realize the 3D model of the 1/4 unit coil, as shown in Fig 2(b), third, according to the symmetry relationship, the mirror feature modeling method is used to establish the 3D model of the
unit coil, as shown in Fig 2(c), with the help of the NX 3D modeling platform,

![Fig.2 Knitted fabric 3D model drawing](image)

Based on establishing the 3D model of the unit loop, using the modeling method of array geometric characteristics to establish the 3D physical model of knitted fabric.

2.2 Physical model of the knitted fabric-based conductive line

Based on the NX 3D modeling platform, assuming that the 3D model is composed of macro-isotropic yarns and conductive lines, using the stretching modeling method, the stretching height $d = 0.3$mm, the knitted fabric is completely covered with the 3D model of the knitted fabric, and the established medium-scale 3D model of knitted fabric-based conductive line is shown in Fig 3.

![Fig.3 Meso-scale 3D model of the knitted fabric-based conductive line](image)

Using static-dynamic theory and sparse matrix method, combined with the manual time step control, performing multi-step static analysis, real-time tracking of the load value in the dynamic process, and setting constraints and displacement constraints to solve the problem, the simulation parameter settings are shown in Table 1.

### Table 1 Simulation parameters of knitted fabric and conductive circuit

| Category        | Density /kg-m$^{-3}$ | Poisson's ratio | Young's modulus /Pa |
|-----------------|----------------------|-----------------|---------------------|
| Knitted fabric  | 2200                 | 0.3             | 18500               |
| Conductive line | 6303.3               | 0.367           | 256.8               |

3. Research on conductive line parameters

3.1 Shapes

8 kinds of conductive line structures were designed as shown in Fig 4.

![Fig.4 Different geometric shapes](image)

![Fig.5 stress distribution nephogram of different shapes](image)
It can be seen from Fig 5, comparing the four shapes of the sharp tooth, crenelated, trapezoidal, and square wave, when the angle of the straight line is 90°, the maximum equivalent stress is the smallest, and the maximum stress of the crenelated tooth is square wave shape 2.63 times that of the square wave shape, which is because the square wave shape has more angles than the sawtooth shape, which improves the stress dispersion ability. The square wave shape, the arc shape, and the horseshoe shape are composed of a straight line and a straight line, a straight line and a circular arc, and a circular arc and a circular arc. Compared with the straight line, the maximum equivalent stress is reduced by 67%, 75%, and 87.5%, indicating that the geometric structure connecting the arc segment and the arc segment can effectively reduce the stress concentration, so the horseshoe shape is selected as the optimal shape parameter.

3.2 Widths

4 kinds of conductive line width were designed as shown in Fig 6.

![Different geometric widths](image1)

![Stress distribution nephogram of different widths](image2)

It can be seen from Fig 7 that the maximum equivalent stress values (0.04Pa, 0.07Pa, 0.15Pa, 0.22Pa) increase with the increase of line width (1~4mm), which is due to the peak of the arc segment caused by the line width. The increase in stress concentration with the trough indicates that the narrower linewidth has better tensile properties, so 1mm is selected as the optimal line width parameter. Compared with the linear shape, the horseshoe shape reduces the maximum equivalent stress by 87.5% and the maximum equivalent strain by 88.3%, which can effectively improve the tensile performance of the conductive line, laying a foundation for further research on the tensile performance of the knitted fabric-based conductive line.

4. Study on the stretch of knitted fabric-based conductive line

Fig 8 shows the distribution of equivalent strain contours of the knitted fabric and the conductive line stretched in different directions.

It can be seen from Fig 8(a) that the strain distribution area and size corresponding to different stretching directions are also different. The high strain area of horizontal stretching is mainly concentrated in the yarn contact area and the inner side of the loop arc and the equivalent strain value is 0.56, this is because the horizontal stretching causes the coil orientation to deform, the coil arc is straightened, and the initial modulus is low, which makes the deformation easy. The high strain area of the vertical stretching circle is mainly concentrated in the yarn contact area and the inner side of the loop cylindrical section. The equivalent strain value is 1.69, which is higher than the horizontal stretching direction, which is determined by the configuration of the yarn along the stretching direction. As long as the high strain area in the shearing and stretching direction is concentrated in the yarn contact area, the cylindrical and arc sections of the loop, the inside of the top of the loop, and the outside of the middle of the loop, the strain distribution area of the yarn contact area parallel to the shearing and stretching direction is larger than the other In the lateral strain distribution area, the strain value is 0.67.
Fig. 8 Tensile strain profile of a knitted fabric-based conductive line. (a): strain distribution of knitted fabrics in different stretching directions. (b): strain distribution diagram of horseshoe-shaped conductive lines in different stretching directions.

It can be seen from Fig 8(b) that under horizontal stretching, the high strain area is mainly concentrated in the arc segment, the strain value is 0.55, and the conductive line cracks are straight lines and parallel to the cylindrical end of the coil. This is due to the silver layer and the yarn. The adhesion strength of the wire is greater than the tensile strength of silver. Under vertical stretching, the high strain area is mainly concentrated in the connecting section, the strain value is 0.58, and the conductive line cracks are zigzag, which is related to the orientation of the knitted fabric loop. Under shear tension, high strain regions are distributed in the connecting section and the arc section, and the strain value is 0.92. The conductive line is affected by the combined force of the horizontal and vertical directions. Because the initial modulus of the yarn in the horizontal direction is less than the vertical direction, it deforms easily, so the fracture form of the silver layer under shearing and stretching in the initial stage is the same as that of the horizontal stretching. As the elongation increases, the cracks in the silver layer develop in irregular shapes under the action of the resultant force in the later stage.

5. Conclusion
(1) The horseshoe-shaped geometry is most suitable for improving the tensile properties of the conductive line, and the width of the conductive line increases and the tensile resistance decreases.
(2) The crack is straight when stretched horizontally; the crack is zigzag when stretched vertically, and the crack is irregular when affected by multiple directions during the shear stretch.

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