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Equivalent Model of the DC Resistance of Nonwoven-Based Embroidery Conductive Lines with Embroidery Parameters

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Abstract

Although embroidering technology is generally used to manufacture electronic components, previous works only give the fitting relationship between embroidery parameters and their direct current (DC) resistance. However, to manufacture embroidered electronic components in scale, the relationship between their DC resistance and embroidery parameters must be known in the computer aided embroidery system. This study investigated the effect of embroidery parameters, including stitch spacing, stitch length and embroidery tension, on the DC resistance of embroidery conductive lines using a peripheral needle, and established their equivalent resistance model in terms of the properties of conductive yarns and embroidery parameters. To verify the model, conductive lines with different embroidery parameters were embroidered on polyester nonwoven, and their DC resistance were tested and fitted. The results show that DC resistance can be effectively controlled by adjusting embroidery parameters. The model proposed is verified and can be used to predict the DC resistance of conductive lines with predesigned parameters.

Key words: *textiles, conductive line, embroidery parameters, direct current resistance.*

Introduction

Flexible wearable devices have recently gained considerable attention among researchers and industry players with the fast growing and wide range of wireless body centric systems, including sports, security, healthcare and military applications [1, 2]. As one of the essential components of wearable electronic products, transmission lines are one of the most basic forms of transmission signals in frequency technology. Generally, there are four approaches: attaching to a fabric using an adhesive [3], weaving [4, 5] or knitting [6] the fabric with conductive yarn, printing [7, 8] a conductive layer on fabric, and embroidering [9, 10]. Among these, the embroidery technique can accurately and easily embroider conductive threads on fabrics by using a digital embroidery machine with a computer aided design pattern, which is a good way to fabricate electronical devices, such as antennas [11, 12], electrodes [13], transmission lines [14] and RFID tags [9, 15].

Recently, the selection of conductive yarns and the effect of embroidery parameters on the performance of wearable electronics have been mainly investigated. Acti et al. used a novel copper yarn, the results of which showed that the use of copper yarn with higher conductivity improved antenna efficiency compared to Amberstrand [11]. Kiourti et al. employed thinner E-fibres to improve geometrical accuracy and increase embroidery density to boost surface conductivity [16]. Ouyang also showed that the direct current (DC) surface resistance is inversely proportional to the conductive thread density [4]. Bahadir demonstrated that the linear resistance of conductive yarns and the type of weave structure significatly influence the signal trasferring capability of the transmission line [17]. Choi et al. studied embroidery fabrics with different conductive yarn directions, the results of which showed that the conductive fabrics had less resistance when aligned in the direction of current propagation [18]. In addition, Wang investigated the effect of embroidery parameters on the DC resistance of embroidery transmission lines and gave the fitting relationship between embroidery parameters and the DC resistance of electronic components. The results showed that embroidery parameters had a significant impact on the DC resistance of the transmission line [19]. In short, these papers select conductive yarns with high conductivity and increase the embroidery density or change embroidery parameters to boost surface conductivity. However, there is still a lack of a determinant relationship between embroidery parameters and the DC resistance of conductive lines.

To establish the relationship between the DC resistance of embroidery conductive lines and embroidery parameters in the CAD system, conductive lines with different embroidery parameters (stitch spacing, stitch length and embroidery tension) were embroidered on a nonwoven textile, and the DC resistances of the embroidery conductive lines were tested and analysed. The relationships established will help to parametrically design conductive lines and other electronic components by embroidering techniques with the CAD system.

Experiment design and method

Materials

Silver-plated nylon multifilament thread was used as the conducting material due to its superior strength. The thread is composed of 36 identical filaments. The resistance measurement of one silver-plated nylon thread is 455 Ω/m. The resistance of conductive yarn can be obtained from

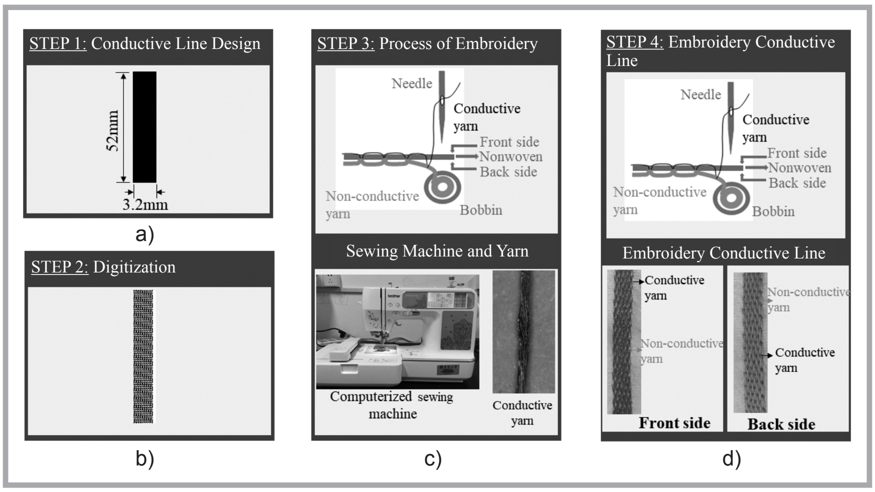

***Figure 1.** Fabrication flowchart of embroidery conductive line: a) STEP 1: conductive line design; b) STEP 2: digitization; c) STEP 3: process of embroidery; d) STEP 4: embroidery conductive line.*

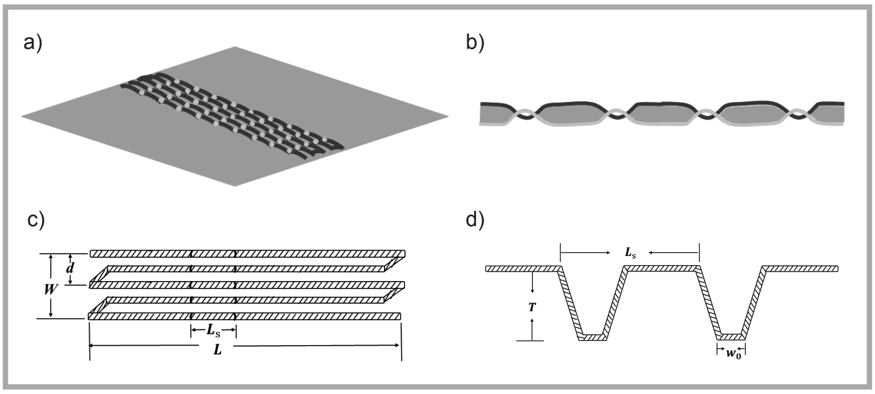

***Figure 2.** Embroidery conductive lines with a peripheral needle: a) sketch of top view, b) sketch of side view, c) schematic of top view, d) schematic of side view.*

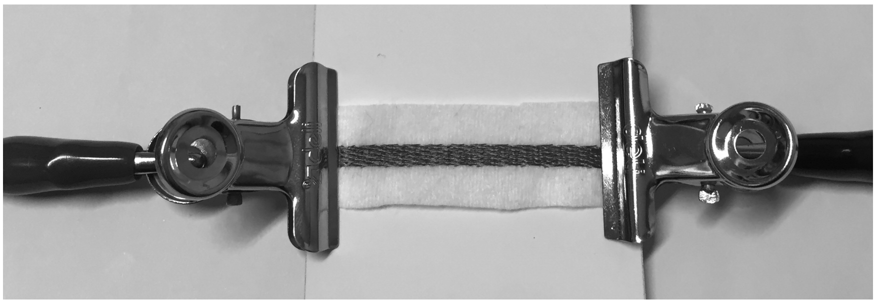

***Figure 3.** Test diagram of conductive line.*

$$R = \rho \frac{L}{A} \qquad (1)$$

Where, L is the length of the given thread, ρ the resistivity of the given thread, and A is the cross-sectional area of the conducting layer of the given thread.

The conductive threads were embroidered onto a 100% polyester nonwoven substrate, whose thickness was 0.698 mm, measured by a fabric thickness gauge (YG141N, China) according to the GB/T3820-1997 (Determination of the thickness of textiles and textile products) standard. The resonance method based on a split post dielectric resonator was used to measure [20] the relative permittivity and loss tangent of the polyester nonwoven. The values measured are 1.134 and 0.0014 at a frequency of 1.11 GHz, respectively.

Design of conductive lines

As the upper signal track of the microstrip line, the conductive line should be appropriately designed. For a line designed with a characteristic impedance of 50 Ω, the width of the line can be calculated with reference to [21]. Thus, the width of the conductive line is around 3.2 mm. The length of the line is set to 52 mm. Embroidery conductive lines were fabricated by a computerised embroidery machine (Brother NV 950, Japan) as shown in ***Figure 1***. Wilcom computer aided design software was used to design the conductive lines. Conductive yarn was used as the top line and non-conductive yarn as an assistant yarn.

DC resistance measurement on conductive lines

For the conductive lines with a peripheral needle, shown in ***Figure 2***, embroidery parameters such as the stitch spacing d, stitch length L_s and embroidery tension are the main parameters that result in different electrical resistances. Therefore, to study the relationship between the DC resistances of nonwoven-based embroidery conductive lines with a peripheral needle and each of the embroidery parameters, the resistances of the conductive lines designed were measured by digital multimeter (PROVA 901, China) according to the GB/T 351-1995 standard (metallic materials-resistance measurement method), shown in ***Figure 3***.

Equivalent resistance model

To study the relationship between the DC resistance of nonwoven-based embroidery conductive lines with a peripheral needle and the embroidery parameters, an equivalent circuit of embroidery conductive lines with a peripheral needle needs to be presented, shown in ***Figure 4.a*** [22] where R_s is the resistance of the single stitch length. Although the R_s values are not all identical due to the embroidery tension and accuracy, the difference between the R_s values is very small and can be assumed to be same. R_c represents the contact resistance between two adjacent stitches and is determined by the stitch spacing. It can be neglected for the reason that the contact resistance is small, and the current prefers to follow the stitch direction rather than jump between yarns [23]. Then, the equivalent circuit model of the conductive line can be simplified, shown in ***Figure 4.b***.

However, according to ***Figure 2.d***, the actual usage of the conductive thread is longer than its horizontal length due

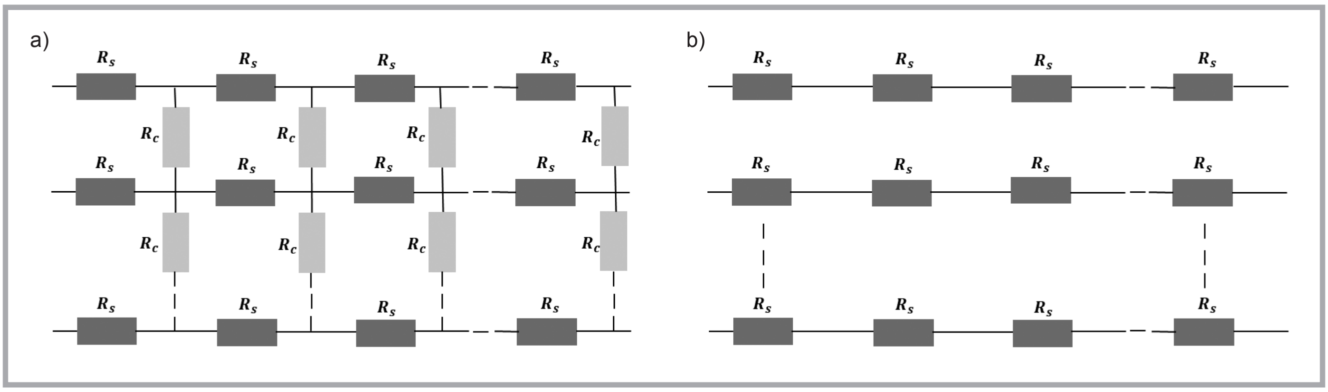

Figure 4. *Embroidery conductive lines using a peripheral needle:a) equivalent circuit model, b) simplified model.*

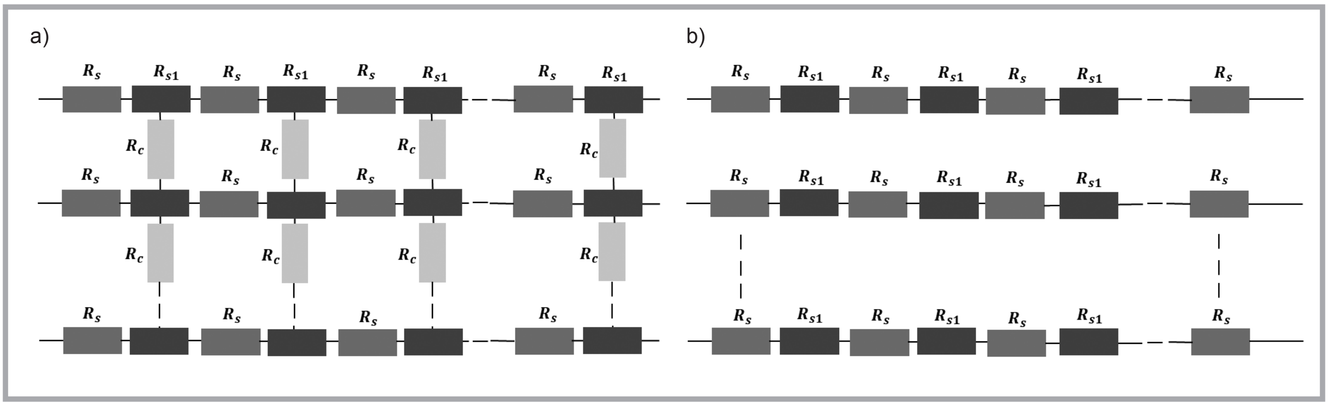

Figure 5. *Embroidery conductive lines with a peripheral needle: a) new equivalent circuit model, b) new simplified model.*

to the presence of the textile fabrics. The depth of the embroidery thread inserted into fabric is approximately equal to the thickness of the fabric substrate. Compared with the total horizontal length, the total depth of the embroidery thread inserted into the fabric cannot be neglected due to its large number of stitch holes as well as its depth. Thus, the resistance of the depth of the inserted embroidery thread affects that of the conductive line. R_{s1} represents the resistance of the depth of the embroidery thread inserted into the fabric back and forth. To more accurately establish the relationship between the resistance of the embroidery conductive lines and embroidery parameters, R_{s1} should be considered. Based on the equivalent circuit model above, a new equivalent circuit model of the conductive line including R_{s1} is presented in ***Figure 5.a***, which can be simplified as shown in ***Figure 5.b***. Thus, the equivalent resistance of the conductive line R_e can be approximately determined by

$$R_e = \frac{1}{n} \times R_s' \qquad (2)$$

Where, the number of parallel yarns n is that of the embroidery needle back and forth which is determined by the stitch spacing; R_s' represents the total resistance of each single conductive yarn, determined by the total length of a single conductive yarn in relation to the stitch length.

What is more, to establish the relationship between the DC resistances of the embroidery conductive lines and embroidery parameters, there is still a need to determine the relationship between embroidery parameters and the number of parallel yarns (n) as well as that between the embroidery parameters and stitch length of each line (m).

Relationship between stitch spacings and number of parallel yarns

The stitch spacing d refers to the vertical distance between two adjacent needle drop points on the contour lines, shown in ***Figure 4***. The relationship between the stitch spacing d and the number of parallel yarns n was established in [22]:

$$n = \frac{W}{d} \qquad (3)$$

Where, W is the width of the conductive line.

However, ***Equation (2)*** shows that the number of stitch spacings could not stand for the number of parallel yarns n. According to ***Figure 2.c***, the number of parallel yarns was 3 when the number of stitch spacings was 1, and the number of parallel yarns was 5 when the number of the stitch spacings was 2. Thus, the number of parallel yarns was 2n + 1 when the number of stitch spacings was n according to the rule above. However, the number of stitch spacings is the ratio of the conductive line width to the stitch spacing, and is not always an integer. Therfore, the predesigned stitch spacing will be adjusted appropritely to arrange the yarns evenly, and the number of stitch spacings will be 1 larger than the integer part. If the predesigned stitch spacing was $d_1 (d_1 \geq 0.2)$, and the length and width of the conductive line were L & W, respectively, then the number of parallel yarns n is as follows:

$$\mathrm{n} = \left(\left\lfloor \frac{W}{d_1} \right\rfloor + 1\right) \times 2 + 1 \qquad (4)$$

and the number of stitch spacings n_1 is as shown below:

$$n_1 = \left\lfloor \frac{W}{d_1} \right\rfloor + 1 \qquad (5)$$

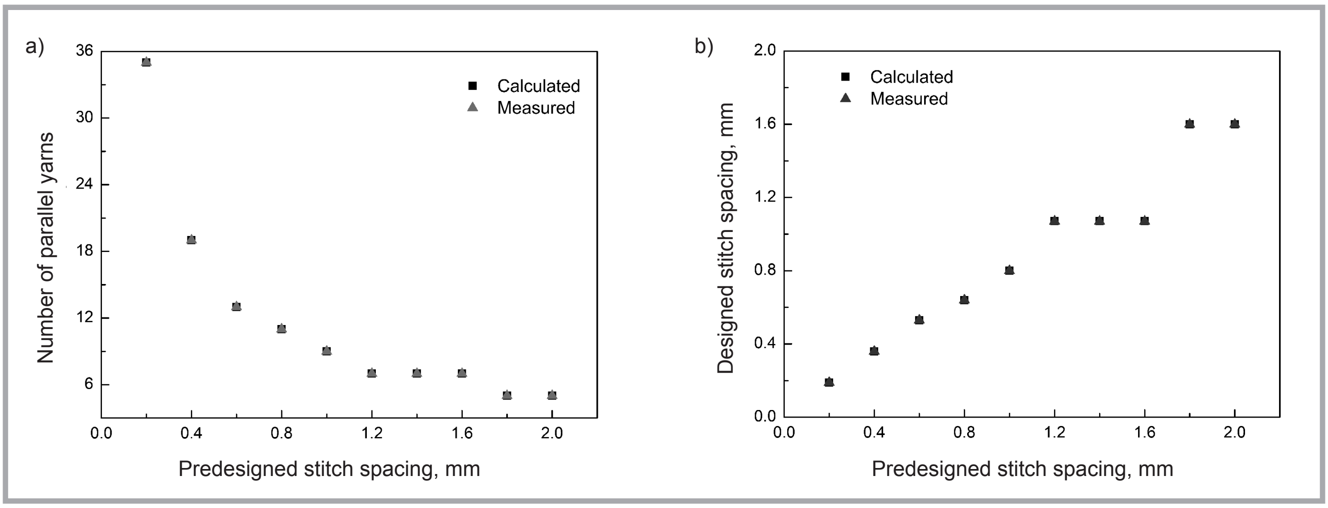

Figure 6. *Calculated and measured values of a) the number of parallel yarns, b) designed stitch spacing.*

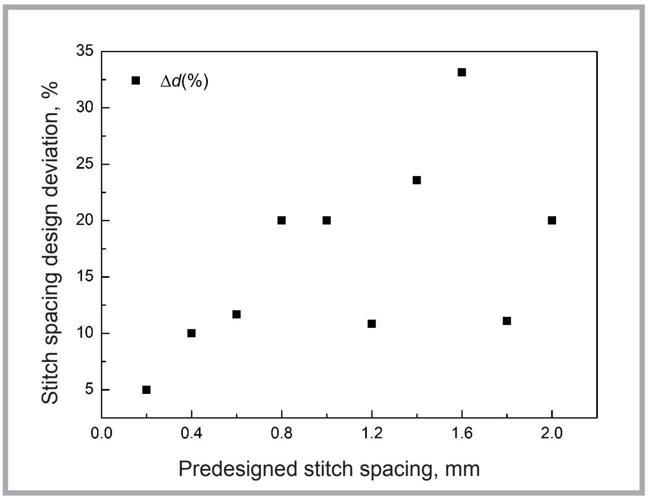

Figure 7. *Percentage of stitch spacing design deviation.*

Then the designed stitch spacing d_2 is

$$d_2 = \frac{W}{\left\lfloor \frac{W}{d_1} \right\rfloor + 1} \quad (6)$$

Thus, the equivalent resistance of the conductive line R_e can be expressed by

$$R_e = \frac{1}{\left(\left\lfloor \frac{W}{d_1} \right\rfloor + 1\right) \times 2 + 1} \times R_s' \quad (7)$$

Relation between the stitch length and number of stitch lengths of each line

The stitch length L_s indicates the distance from the last needle drop point to the next needle drop point i.e. the length of each stitch crossing, shown in ***Figure 2***.

In order to establish the relationship between the stitch lengths L_s and the total resistance of each single conductive yarn, the relationship between the stitch lengths and the total length L_s of a single conductive yarn of each line L_t should be established first, which was as follows [22]:

$$L_t = L + 2 \times \left(\left\lfloor \frac{L}{L_s} \right\rfloor + 2\right) \times T \quad (8)$$

L is the length of the conductive line, L_s the predesigned stitch length, T the thickness of the fabric, and $\left\lfloor \frac{L}{L_s} \right\rfloor$ stands for the number of stitch lengths of each line.

However, it can be found that the number of stitch lengths of each line is not always $\left\lfloor \frac{L}{L_s} \right\rfloor$. The number of stitch lengths of each line will be $\left\lfloor \frac{L}{L_s} \right\rfloor$, if the ratio of the length of the conductive line to the stitch length is an integer. And if the ratio of the length of the conductive line to the stitch length is not an integer, to arrange the yarns evenly, the predesigned stitch length is adjusted appropritely; then the number of stitch lengths of each line will be 1 larger than the integer part based on the laws of the number of stitch spacings changing with the integer part. In a design using embroidery software, the predesigned stitch length was L_s ($L_s \geq 1.6$), and the length and width of the conductive line were L &W, respectively. Therefore, the number of stitch lengths of each line m is as follows.

$$m = \begin{cases} \frac{L}{L_s} & , \frac{L}{L_s} \text{ is an integer} \\ \left\lfloor \frac{L}{L_s} \right\rfloor + 1 & , \frac{L}{L_s} \text{ is not an integer} \end{cases} \quad (9)$$

Then the designed stitch length L_s'

$$L_s' = \begin{cases} L_s & , \frac{L}{L_s} \text{ is an integer} \\ \frac{L}{\left\lfloor \frac{L}{L_s} \right\rfloor + 1} & , \frac{L}{L_s} \text{ is not an integer} \end{cases} \quad (10)$$

Thus, according to ***Equation (1)***, for the same and uniform conductive yarn R_s', the total resistance of each single conductive yarn can be expressed by ***Equation (11)***.

$$R_s' = \begin{cases} \left[L + 2 \times \left(\frac{L}{L_s} + 2\right) \times T\right] \times R_0 & , \frac{L}{L_s} \text{ is an integer} \\ \left[L + 2 \times \left(\left\lfloor \frac{L}{L_s} \right\rfloor + 3\right) \times T\right] \times R_0 & , \frac{L}{L_s} \text{ is not an integer} \end{cases} \quad (11)$$

$$R_e = \begin{cases} \frac{1}{\left(\left\lfloor \frac{W}{d_1} \right\rfloor + 1\right) \times 2 + 1} \times \left[L + 2 \times \left(\frac{L}{L_s} + 2\right) \times T\right] \times R_0 & , \frac{L}{L_s} \text{ is an integer} \\ \frac{1}{\left(\left\lfloor \frac{W}{d_1} \right\rfloor + 1\right) \times 2 + 1} \times \left[L + 2 \times \left(\left\lfloor \frac{L}{L_s} \right\rfloor + 3\right) \times T\right] \times R_0 & , \frac{L}{L_s} \text{ is not an integer} \end{cases} \quad (12)$$

Equations (11) *and* ***(12)***.

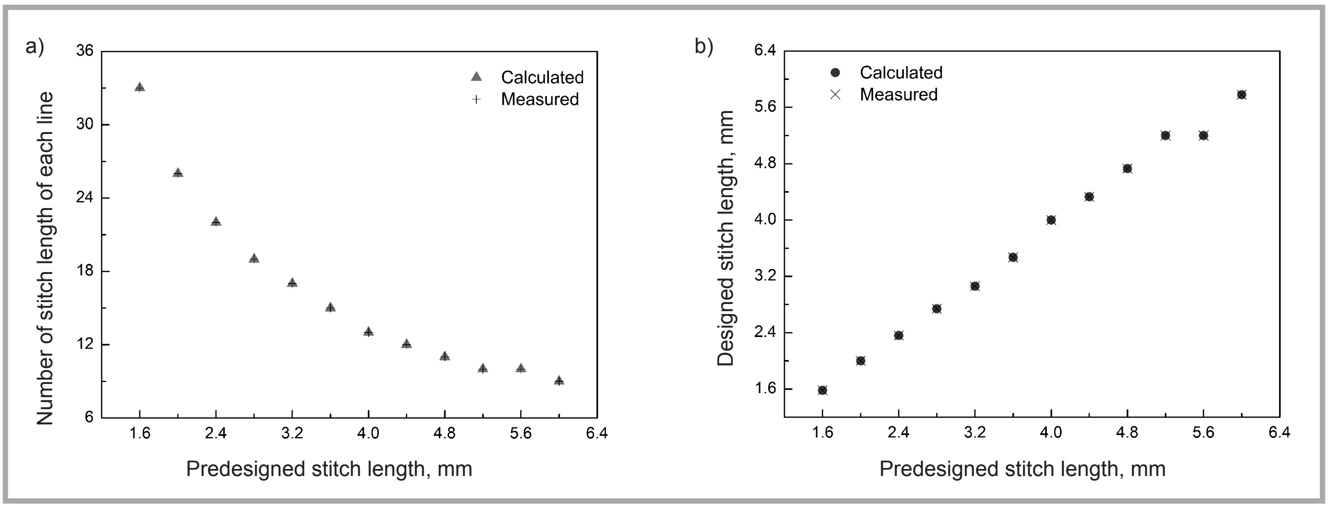

Figure 8. *Calculated and measured values of a) the number of stitch lengths of each line, b) designed stitch length.*

Where stands for the resistance per centimeter.

Thus, combining ***Equation (7)*** with ***Equation (11)***, can be expressed as follows ***Equation (12)***.

Results and discussion

Embroidering technical parameters

Stitch spacings and number of parallel yarns

To verify the relationship between DC resistances and embroidery parameters, the relationship between stitch spacings and the number of parallel yarns should be investigated. Therefore, embroidery conductive lines with different stitch spacings were manufactured, where the length and width of conductive lines, the stitch length and embroidery tension in the control were 52 mm, 3.2 mm, 4 mm and level 1, respectively. Their number of parallel yarns n were counted from the number of embroidery needles back and forth. The predesigned stitch spacing as well as the designed stitch spacing from the embroidery software are shown in ***Table 1***.

As shown in ***Table 1***, the number of parallel yarns decrease as the predesigned stitch spacing increases, and the designed stitch spacing increases along with the presigned stitch spacing. What is more, through ***Equation (4)*** and ***Equation (5)***, the calculated number of parallel yarns and designed spacings can be obtained, and ***Figure 8*** compares the calculated and measured values of the number of parallel yarns and designed spacings. The results indicated that the calculated and measured values of the number of parallel yarns and designed spacings were completely coincident. Thus, the relationship between stitch spacings and the number of parallel yarns can be verified. ***Equations (4)*** to ***(6)*** can be used to calculate accurately the number of parallel yarns, stitch spacing and designed spacings.

Furthermore, the percentage of stitch spacing design deviation from $\Delta d\%$ the software can be obtained by:

$$\Delta d\% = \frac{d_1 - d_2}{d_1} \times 100\% \quad (13)$$

Figure 7 shows the percentage of stitch spacing design deviation, from which it can be seen that the design deviation does not increase as the predesigned stitch spacing increases, and the largest design deviation can reach up to 33.15 % when the predesigned stitch spacing is 1.6 mm. Thus, the stitch spacing design deviation cannot be ignored, and the designed stitch spacing needs to be calculated accurately.

Relationship between stitch lengths and number of stitch lengths

To verify the relationship between DC resistances and embroidery parameters, the relationship between stitch lengths and the number of stitch lengths of each line should also be verified first. To further verify the relationship between stitch lengths and the number of stitch lengths of each line, embroidery conductive lines with different stitch lengths were manufactured, where the length and width of the conductive lines, stitch spacing and embroidery tension, controlled to be the same, were 52 mm, 3.2 mm, 0.4 mm and level 1, respectively. The number of stitch lengths of each line is counted from the number of embroidery needles forth, the predesigned stitch length L_s as well as from the designed stitch length L_s' using embroidery software, shown in ***Table 2***.

According to ***Table 2***, the number of stitch lengths of each line decreases as the predesigned stitch length increases, and the designed stitch length increases along with the presigned stitch length. Moreover, through ***Equation (9)*** and ***Equation (10)***, the calculated number of stitch lengths of each line and designed length can be obtained. ***Figure 8*** compares the calculated and measured values

Table 1. *Embroidery conductive lines with different stitch spacings.*

Sample	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#
d_1, mm	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
n	35	19	13	11	9	7	7	7	5	5
d_2, mm	0.19	0.36	0.53	0.64	0.80	1.07	1.07	1.07	1.60	1.60

Table 2. *Embroidery conductive lines with different stitch lengths.*

Sample	11#	12#	13#	14#	15#	16#	17#	18#	19#	20#	21#	22#
L_s, mm	1.6	2.0	2.4	2.8	3.2	3.6	4.0	4.4	4.8	5.2	5.6	6.0
m	33	26	22	19	17	15	13	12	11	10	10	9
L_s', mm	1.58	2.0	2.36	2.74	3.06	3.47	4	4.33	4.73	5.2	5.2	5.78

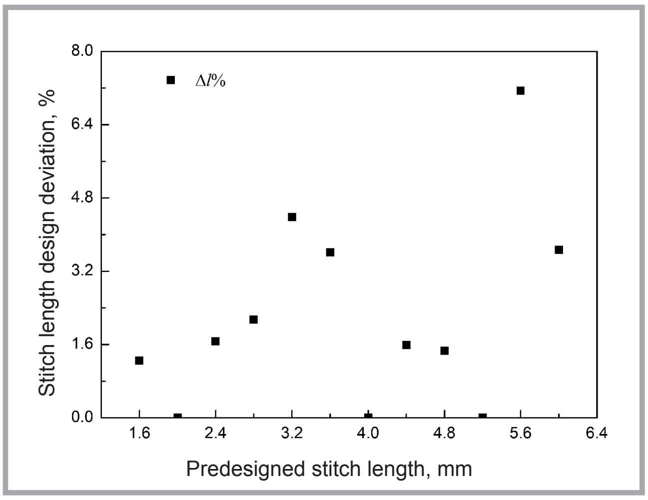

Figure 9. Percentage of stitch spacing design deviation.

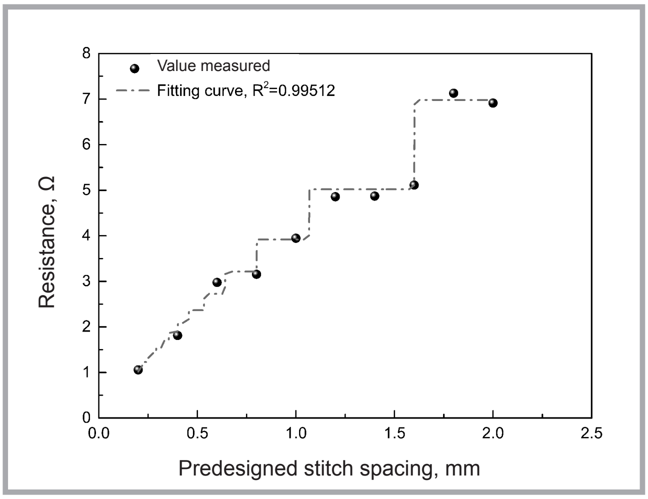

***Figure 10.** Measured resistance of embroidery conductive lines with different predesigned stitch spacings and their fitting curve.*

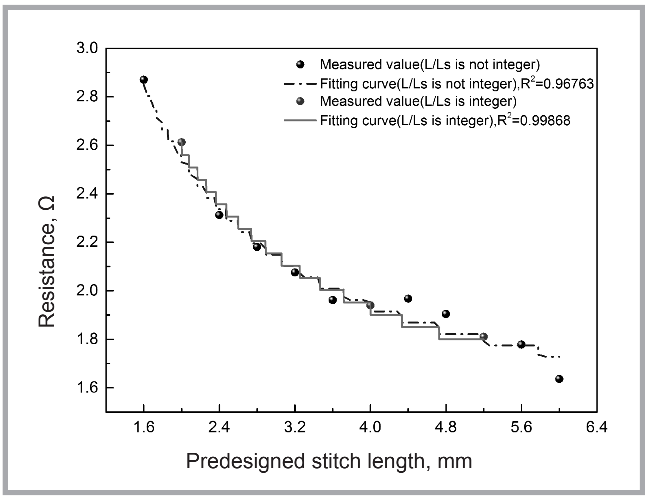

***Figure 11.** Measured resistance of embroidery conductive lines with different predesigned stitch lengths and their fitting curve.*

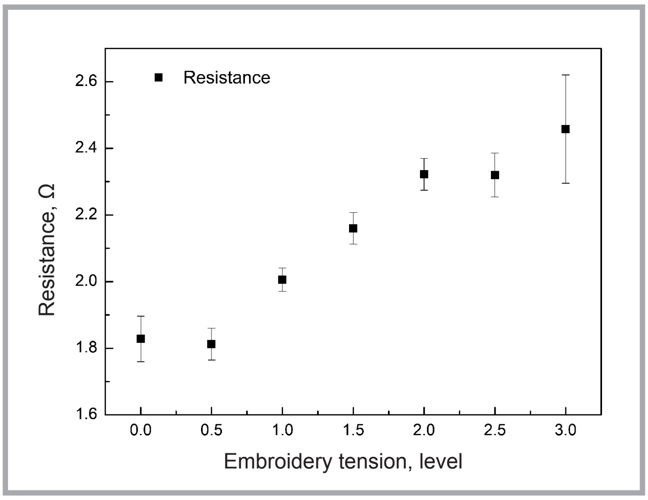

***Figure 12**. Resistance of embroidery conductive lines with different embroidery tensions.*

of the number of stitch lengths of each line and designed length. The results indicated that the calculated and measured values of the number of stitch lengths of each line and designed length were completely coincident. Thus, the relationship between the stitch length and number of stitch lengths of each line can be verified. ***Equations (9)*** to ***(10)*** can be used to calculate accurately the number of stitch lengths of each line and designed length.

Furthermore, the percentage of stitch length design deviation from the software can be obtained by:

$$\Delta l\% = \frac{L_s - L_s'}{L_s}\times 100\% \qquad (14)$$

Figure 9 shows the percentage of stitch length design deviation, from which it can be seen that the largest design deviation is 7.14% when the predesigned stitch length is 5.6 mm. Thus, the stitch spacing design deviation is 4.64 times larger than the the stitch length design deviation, where ***Equations (4)*** to ***(6)*** and ***Equations (9)*** to ***(10)*** play an important role in reducing the design deviation and provide a basis for the equivalent resistance model.

Demonstration of equivalent resistance model

Resistance of conductive lines with different predesigned stitch spacing

The resistances of a conductive line with different predesigned stitch spacings were measured, shown in ***Figure 10***.

It can be seen that the resistance increases as the stitch spacing increases, and fits well to the theoretical model of equivalent resistance. Comparing the theoretical and measured values, the resistance measured is slightly larger than the theoretical resistance in terms of long stich spacing, which can be explained by the fact that the conductive yarns are slightly stretched under tension, making the resistance larger, and slightly worn by the machine, which reduces the quality of the silver plating on the surface of the conductive yarn and increase resistance. It indicates that the major current of the conductive line with a peripheral needle follows the direction of the stitches. In addition, the data measured were fitted to the equivalent resistance ***Equation (12)***, where the fitted relationship between the resistance of the conductive line and the predesigned stitch spacing is:

$$R_e = \frac{1}{0.05592\times\left\lceil\frac{3.2}{d_1}\right\rceil + 0.08736} \qquad (15)$$

The correlation coefficients R^2 is 0.99512 and RMSE is 0.12483. Therefore, the equivalent resistance model of the conductive line in terms of its resistance and predesigned stitch spacing can be verified.

Resistance of conductive lines with different predesigned stitch lengths

The resistances of a conductive line with different predesigned stitch lengths were measured, displayed in ***Figure 11***. Apparently, the resistance measured is far larger than the theoretical resistance, which may be the reason why the conductive yarns are slightly stretched under tension, making the resistance larger, and are slightly worn by the machine, which reduces the quality of the silver plating on the surface of the conductive yarn. What is more, at the beginning and end of the embroidery, a few repeated stitches for reinforcement make the resistance larger, indicating that the current flows not only over the surface of the conductive line but also throughout its entire length. As mentioned before, R_s' represents the total resistance of each single conductive yarn, determined by the total length of single conductive yarn in relation to the stitch length. If the current flows only over the surface of the conductive line of certain surface length, R_s' will not change along with the stitch length. Thus, R_e also will not change. However, R_e is not fixed and varies along with the stitch length. Thus, the current flows not only over the surface of the conductive line but throughout its entire length. In addition, according to the equivalent resistance ***Equation (12)***, the fitted relationship between the resistance of the conductive line and the predesigned stitch length is ***Equation (16)***.

$$R_e = \begin{cases} \frac{0.05059}{\left\lceil \frac{52}{L_s} \right\rceil} + 1.29429 \quad , \frac{L}{L_s} \ \text{is an integer} \\ \frac{0.04671}{\left\lceil \frac{52}{L_s} \right\rceil} + 1.35474 \quad , \frac{L}{L_s} \ \text{is not an integer} \end{cases} \quad (16)$$

Equations (16).

When L/L_s is an integer, the correlation coefficient R^2 is 0.99868 and RMSE is 0.009106. When L/L_s is not an integer, the correlation coefficients R^2 is 0.96763 and RMSE is 0.0570. Therefore, the equivalent resistance model of the conductive line can be used to predict the DC resistance of conductive lines of predesigned length.

Resistance of conductive lines with different embroidery tensions

Figure 12 shows the measured resistance of conductive lines with different embroidery tensions. The results show that the resistance increases approximately as the embroidery tension increases, which can be explained by the fact that as the tension increases, the conductive yarn is elongated and becomes thinner, thus making the resistance larger. And the conductive yarn is worn more seriously under larger tension, so that the quality of the silver-plating on the surface of the conductive yarn is reduced more seriously and the resistance increases more substantially. The resistance is largest when the tension is set to level 3, with the variance fluctuation also being maximum. This indicates that the tension is too large to make the conductivity of the conductive yarn stable. Although the resistance is minimum under a tension of level 0.5, the difference in resistances of the conductive line under different tensions (except level 3) is small. The surface of the conductive line under too small tension is loose, making its conductivity unstable, while the conductive yarn will be seriously worn under too large tension, making the resistance large and conductivity unstable. Thus, the embroidery tension can be set to around level 1 to make the resistance small and conductivity stable.

Conclusions

In this work, the DC resistance of embroidery conductive lines with different embroidery parameters was tested and analysed. And an equivalent resistance model of conductive lines in terms of embroidery conductive lines and embroidery parameters (stitch spacing and stitch length) was established and verified. The results show that resistance can be effectively controlled by adjusting the embroidery parameters and can also be approximately predicted by predesigned parameters. In addition, the relationships between embroidery parameters, the number of parallel yarns and the number of stitch lengths of each line were established and verified. They can be used to calculate the designed embroidery parameters using predesigned embroidery parameters. Through the relationships established, for simple electronic elements of a given size, such as conductive lines, but not limited to the, their structures in terms of the arrangement of conductive yarns are clear. Their designed parameters can be calculated using predesigned parameters, and their resistance can also be predicted.

Acknowledgements

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