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A simulation model of electrical resistance applied in designing conductive woven fabrics

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Abstract

Numerous studies have performed analyses of knitted fabric integrating conductive yarn in textile-based electronic circuits, some of which established simulative models such as the resistive network model for knitting stitches. Compared to conductive knitted fabrics, limited studies have been presented regarding the resistive theoretical model of conductive woven fabric. In this paper, a simulation model was derived to compute the resistance of conductive woven fabric in terms of the following fabric parameters: structure, density and conductive yarn arrangement. The results revealed that the model is well fitted (P value < 0.01) and can predict the resistance of woven fabrics, which makes it possible to estimate the fabric parameters and thus to meet the required resistance. Based on this model, thermal conductive woven fabric with maximum energy management and cost control can be efficiently designed.

Keywords

conductive woven fabric, electrical resistance, electronics, conductive properties

Fabric integrating conductive yarn has been applied in various fields, such as the sensory field, electromagnetic shielding field and thermal field. Plenty of researchers have reported on the use of conductive fabric as a pressure sensor, textile sensor, medical sensor, etc.[1–4] The studies of the electromagnetic shielding area present electromagnetic textiles and related research of electromagnetic shielding effectiveness.[5–8] Thermal fabric embedded with conductive yarn can be utilized for the development of electronic textiles or smart garments, which are desired in the areas of health care, medicine, sports and outdoor activities.[9] Current research on this topic can be classified into three parts: electrical resistance modeling,[10,11] characteristic analysis[12,13] and application development.[14] It is worth noticing that knitted fabric embedded with conductive yarn has been extensively studied, whereas limited research can be found on woven fabric, not to mention the lack of a theoretical model in electrical resistance.

This paper proposes a resistive simulation model used for designing the conductive woven fabrics with different densities of conductive yarns in the warp and weft, based on three basic weave structures. A series of experiments were designed and conducted to verify the ability of the proposed model to simulate the conductive fabric. Simultaneously, the effect of the conductive yarns' density in the warp and weft on the resistance of conductive woven fabric was studied. An analytical equation was derived to calculate the resistance of conductive woven fabric. A comparison of the experimental and theoretical results shows that the resistive simulation model can effectively approximate the equivalent electrical resistance. More advantages and profits can be achieved if the electrical resistance of conductive woven fabric with various parameters can be systematically predicted, calculated and designed, which would make it possible to meet the high demands of rapid prototype design and reduce costs.

Resistive simulation model of conductive woven fabrics

Unit model

One unit of conductive yarn can be treated as a building block for current conduction, as shown in Figure 1. For example, the conductive yarn with a length of L_0 can be regarded as a resistor with resistance R_0. R_0 is given as below, where ρ is the resistivity of the conductive yarn, L_0 is the length and S_0 is the cross-sectional area:

$$R_0=\rho\frac{L_0}{S_0} \qquad (1)$$

Figure 1. Schematic diagram of the unit model.

Single yarn model

As illustrated in Figure 2, a single conductive yarn can be regarded as an assembly of multiple resistors connected in series. Assuming all resistors have equal resistance values, then

$$L_N = NL_o \text{ and} \quad (2)$$

$$R_N = NR_0 = \frac{R_0}{L_0} L_N, \ (R_0 = R_1 = R_2 = \ldots = R_n) \quad (3)$$

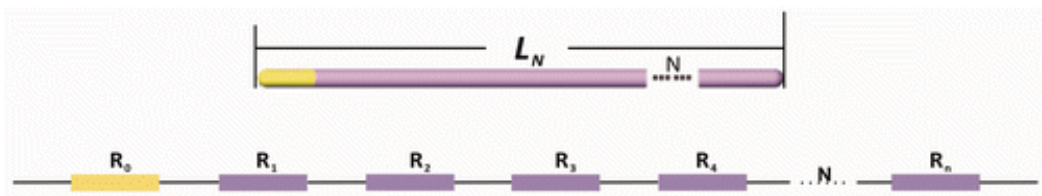


Figure 2. Schematic diagram of the single yarn model.

Calculation of the length of weft yarn in different woven structures

If R_0 is known, L_N is the key factor to estimate the entire resistance of this single yarn. Considering the adjacent two warp yarns as a group, the whole length of the weft yarn consists of two parts: l_r (mm) and l_s (mm). Ideally, part of the weft yarn overlaps the warp yarn and the other part remains straight; meanwhile, the warp yarn is inextensible and remains circular in shape. Draw a perpendicular line starting from the center of the warp yarn to the corresponding tangent point with the weft yarn, and draw another line from the same point and ending at the vertices of the weft yarn. Relevant values include the length of the radius, r (mm), and the angle between these two radiuses, θ(radian). As illustrated in Figure 3, the equations are given as follows:

$$\{ l_r = \theta r \quad l_s = \sqrt{2rs + s^2} \quad \sin\theta = \frac{r}{r+s} \quad (4)\ (5)\ (6)$$

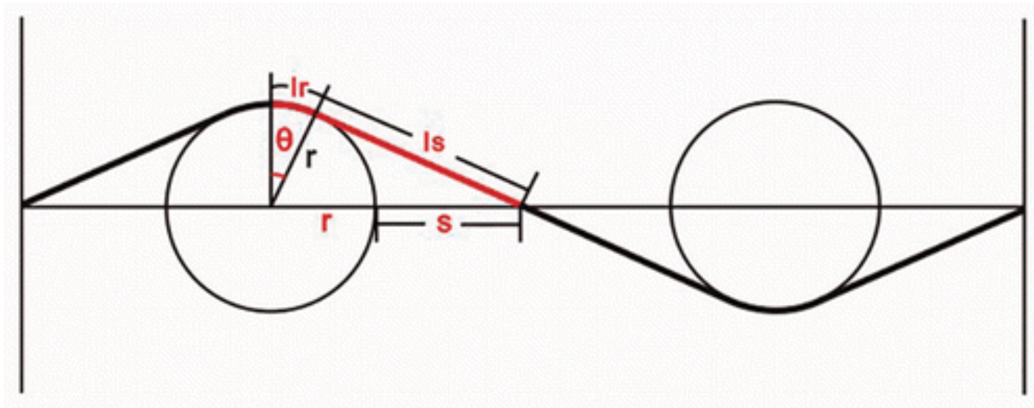


Figure 3. Schematic diagram of l_r, l_s and θ.

The radius *r* (mm) can be found based on the diameter *d* (mm) of the yarn, which can be calculated with the following equation if the yarn title (tex) is the only information known.[15] Take cotton, for example, which will be further used in the experiments:

$$\text{Forsingleply: } d = 0.037\sqrt{\mathrm{Tt}} \tag{7}$$

$$\text{Fordoubleply: } d = 0.045\sqrt{\mathrm{Tt}} \tag{8}$$

where T_t is the yarn title using tex as the unit of measurement.

The half-length *s* (mm) between two adjacent yarns can be used to find the warp density, M_W (ends/inch):

$$2(r+s) = \frac{25.4}{M_W} \quad (1\text{inch}\approx 25.4\text{mm}) \tag{9}$$

Hence,

$$s = \frac{12.7}{M_W} - r \tag{10}$$

Plain weave, twill weave and satin weave are the three basic types of weaving by which the majority of woven fabrics are formed. Different structures lead to variations of length in the weft yarn when the warp density remains constant. If the conductive yarn is much finer than the yarn with which it is woven, the effect of the thickness in the length calculation can be ignored.

Plain weave (1/1)

In the plain weave, represented as 1/1, the warp yarn and weft yarn form a simple criss-cross pattern that is firm and resistant to yarn slippage. Each weft yarn crosses the warp yarn by going over one, then under the next and so on.[16] As shown in Figure 4, when the fabric contains N_{WA} ends of warp yarn, the length of one weft yarn is as follows:

$$L_P = 2N_{WA}(l_r + l_s) = 2N_{WA}(\theta r + \sqrt{2rs + s^2}) \qquad (11)$$

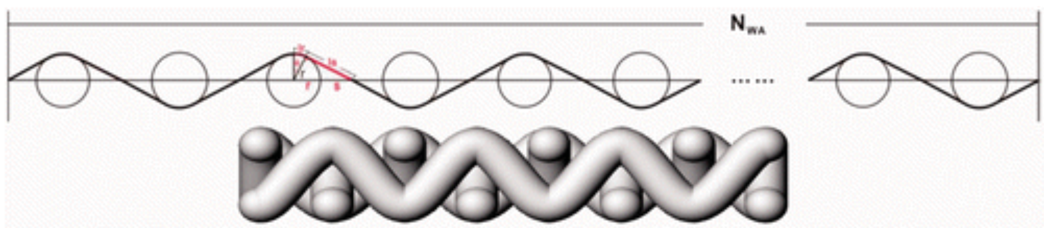


Figure 4. Schematic diagram and three-dimensional image of plain weave (1/1).

Twill weave (n/m)

In the twill weave, designated as n/m, each weft yarn floats across the warp yarns in a progression of interlacing to the right or left, forming a distinct diagonal line. A float is a portion of yarn that crosses over two or more yarns from the opposite direction.[17] With twill 1/3 ($n = 1$, $m = 3$), for example, the numerator indicates the number of yarns that are raised (in this example, one), and the denominator indicates the number of yarns that are lowered when a filling yarn is inserted (in this example, three). As shown in Figure 5, if the twill weave is n/m, containing N_{WA} ends of warp yarn, then

$$L_T = \frac{N_{WA}}{m+n}[4(l_r+l_s)+2(s+r)(n-1)+2(s+r)(m-1)] = \frac{2N_{WA}}{m+n}[2\theta r+2\sqrt{2rs+s^2}+(s+r)(n+m-2)] \qquad (12)$$

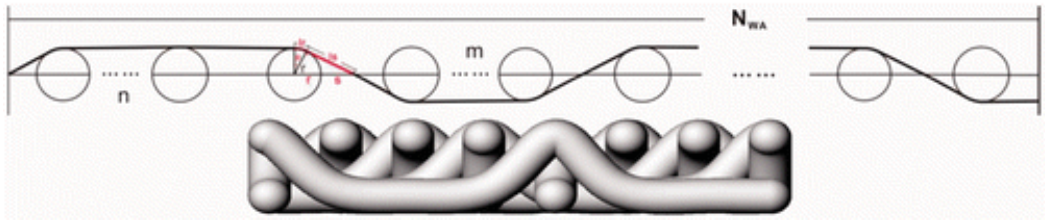


Figure 5. Schematic diagram and three-dimensional image of twill weave (1/3).

Satin weave (q ends)

In the satin weave, expressed as having q ends, only one end is up on each pick, it being in this respect similar to the twill weave, but the interlacing of each end is at least one pick apart from the interlacing of either of the several ends next to it.[18] As shown in Figure 6, the cross-section view shows that a q-end satin with N_{WA} ends of warp yarn contains N_{WA}/q ups and $(q-1)\ N_{WA}/q$ downs. The length of one weft yarn is as follows:

$$L_S = \frac{N_{WA}}{q}\ [4(l_r+l_s)+2(s+r)(q-2)] = \frac{2N_{WA}}{q}\ [2\theta r+2\sqrt{2rs+s^2}\ +(s+r)(q-2)] \tag{13}$$

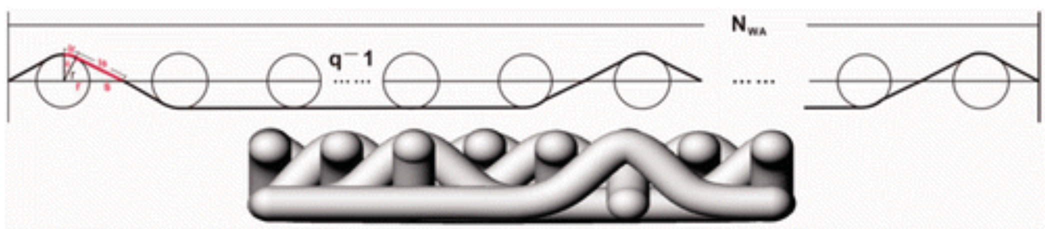


Figure 6. Schematic diagram and three-dimensional image of satin weave (8 ends).

Simulative resistance of single conductive yarn

According to the above equations, redefine plain weave, twill weave and satin weave as a unified expression by x/y, which can wholly represent plain weave when $n = 1$, $m = 1$, while satin weave is represented when $n = 1$, $m = q - 1$.

Define A and B as

$$A = s+r \tag{14}$$

$$B = \theta r + \sqrt{2rs+s^2} \tag{15}$$

Thus, the simulative resistance of single conductive yarn in different woven structures is simplified as below:

$$R_N = \frac{R_0}{L_0} L_N = \frac{2R_0 N_{WA}}{L_0(x+y)} [2B+(x+y-2)A] \quad (16)$$

where

{−Plain (1/1), $x = 1$, $y = 1$; −Twill(n/m), $x = n$, $y = m$; −Satin (q ends), $x = 1$, $y = q - 1$.

Woven fabric model

In this paper, the conductive woven fabric shown in Figure 7(a) is equivalent to the fabric model in Figure 7(b). As shown in Figure 8, the whole fabric can be treated as multiple single yarn models connected in parallel. Therefore, the resistance of this conductive fabric is formulated as

$$R_{NM} = \frac{R_N}{M} = \frac{R_0}{ML_0} L_N \quad (17)$$

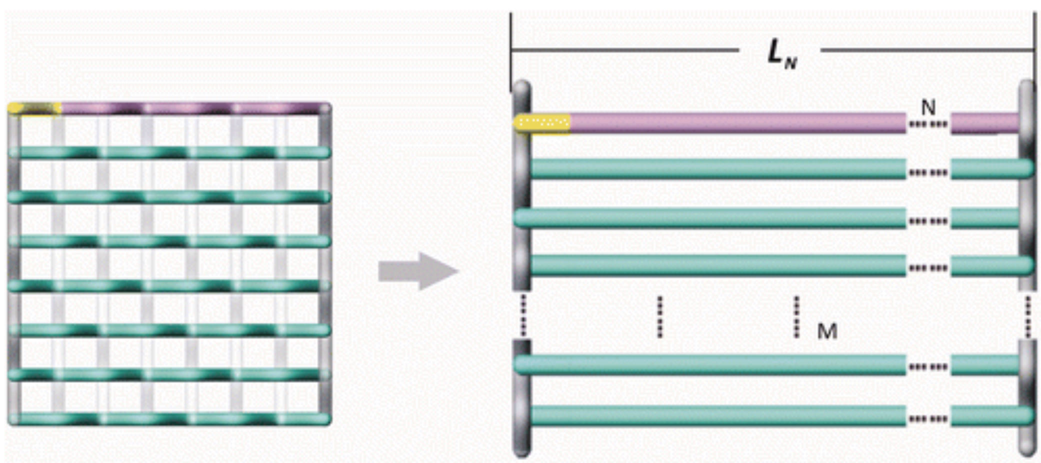


Figure 7. Schematic diagram of woven fabric (a) and woven fabric model (b).

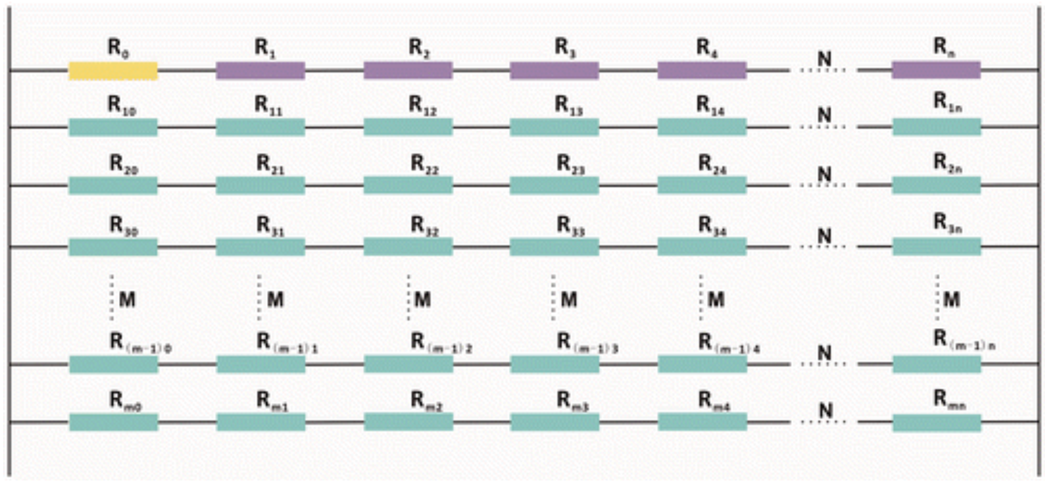


Figure 8. Equivalent resistive network of the woven fabric model.

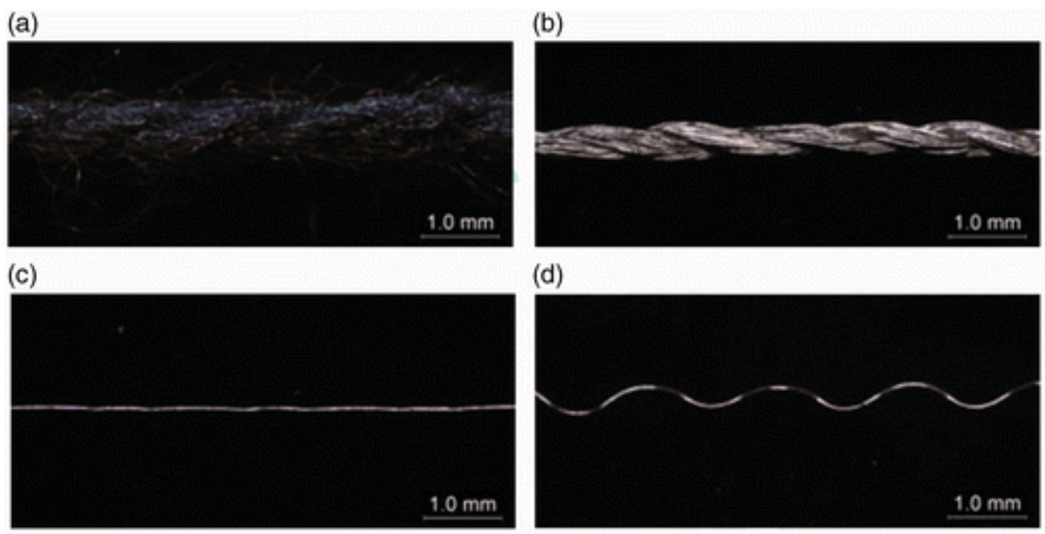


Figure 9. Microscope longitudinal view of cotton yarn (a), silver-coated conductive yarn B (b), silver-coated conductive yarn A (c) and silver-coated conductive yarn A in natural state (d).

The conductive yarn can be woven in a specified number according to the design, of which the picks can easily be calculated by the following equation:

$$N_{WE} = \mathrm{M} = \frac{D_W b}{a} \tag{18}$$

where D_W (picks/inch) is the weft density of the fabric, b (inch) is the length of the fabric and α (picks) is the interval of picks that contain one conductive yarn. For example, if every five picks has one conductive yarn, the value of α is six.

Given

D_W, b, α, R_0 and (16), (17)

Let

$$C = \frac{2\alpha R_0 N_{WA}}{D_W b L_0} \quad (19)$$

Then, the simulative resistance of conductive woven fabric in different structures can be formulated as

$$R_s = \frac{C}{(x+y)}\ [2B+(x+y-2)A] \quad (20)$$

when

$$\begin{cases} -\text{Plain}(1/1), x = 1, y = 1;] \\ -\text{Twill}(n/m), x = n,\ y = m; \\ -\text{Satin}(q\text{ends}), x = 1,\ y = q - 1. \end{cases}$$

where

$$\begin{cases} A = s + r; \\ B = \theta r + \sqrt{2rs + s^2}; \\ C = \dfrac{2\alpha R_0 N_{WA}}{D_W b L_0}. \end{cases}$$

Experimental setup

Materials

One-hundred percent cotton Ne 20/2 yarns were used as the ordinary material. Two silver-coated conductive yarns, A (22/1 dtex single filament,) and B (235/34 dtex 2-ply), with resistances of 72.6 Ω per cm (diameter 0.005 mm) and 1.1 Ω per cm (diameter 0.290 mm), respectively, are used in this experiment. The longitudinal view of each materials under microscope are shown in Figure 9. The raw material for yarn A is Nylon 6, whereas that for yarn B is Nylon 66.

Experimental design

To validate and evaluate the simulation model, the simulative effect and variation, a three-factor-three-level experiment was conducted with selected samples shown in Table 1. In this part, the electrical resistance of these fabrics will be calculated and compared to measured values for further analysis.

Selected sample swatches								
	25				P- Plain		S1	
Weft density	30				T- Twill (1/3)		S6	
(picks/inch)	35		Structure		S- Satin (8 ends)	Arrangement	S11	
P25-S1	**T25-S1**	**S25-S1**	**P25-S6**	**T25-S6**	**S25-S6**	**P25-S11**	**T25-S11**	**S25-S11**
P30-S1	**T30-S1**	**S30-S1**	**P30-S6**	**T30-S6**	**S30-S6**	**P30-S11**	**T30-S11**	**S30-S11**
P35-S1	**T35-S1**	**S35-S1**	**P35-S6**	**T35-S6**	**S35-S6**	**P35-S11**	**T35-S11**	**S35-S11**

Table 1. Sample design information.

Three basic structures of woven fabrics, plain weave, twill weave and satin weave, were designed as 4.8 inches in width and 5.9 inches in length, woven by a CCI tech automatic dobby sampling loom with weft densities of 25 picks/inch, 30 picks/inch and 35 picks/inch, respectively, whereas warp density remained at 40 ends/inch. The head type is a gripper head with a speed of approximately 25 revolutions per min.

In the samples, cotton yarns were used both in the weft and in the warp, as base material. As illustrated in Figure 10, at the left and right edges of the sample, a 0.4 inch-wide strip of yarn B replaced the warp cotton yarn to serve as the power supply in the conductive path due to the much lower resistance in comparison to yarn A. Yarn A was woven with the cotton yarn as heating panels at picks according to three arrangements: every pick, every five picks and every fifty picks, as illustrated in Figure 11. These arrangements of yarn A were selected to represent different situations of electrical resistance change, with details shown in Table 2. N_{WE} was calculated as below, and the result was the integer part of the value:

$$N_{WE} = \frac{D_w \ X\ 5.9(length)}{\alpha} \quad (21)$$

Figure 10. Three-dimensional images and samples of the conductive yarn in different structures.

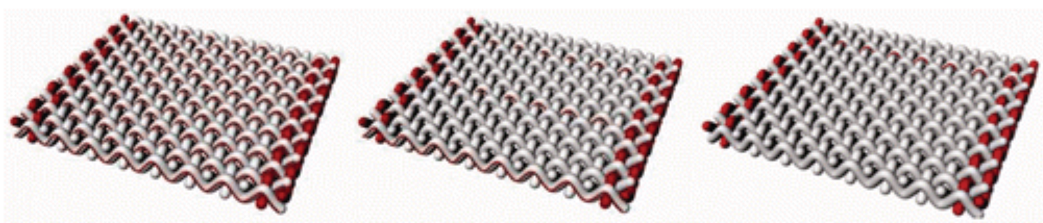


Figure 11. Three-dimensional images of the conductive yarn arrangement in plain weave samples. (a) S1 (Yarn A in every pick), (b) S6 (Yarn A in every 5 picks) and (c) S11 (Yarn A in every 50 picks).

	Sample	S1	S6	S11
D_w	Interval picks	+0	+5	+50
	α	*1*	6	*51*
25	N_{WE}	**147**	**24**	**2**
30		**177**	**29**	**3**
35		**206**	**34**	**4**

D_W – weft density (picks/inch);
α – interval of picks containing one conductive yarn (picks);
N_{WE} – total number of picks of conductive weft yarn (picks).

Table 2. Weaving samples for different weft densities and conductive yarn arrangements in the experiment

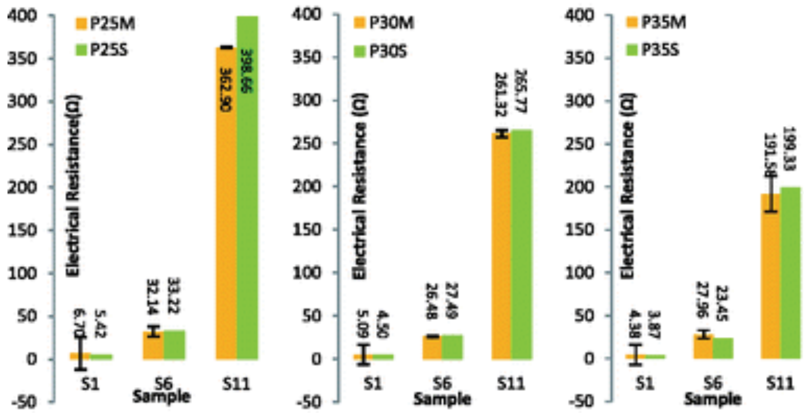
In total, nine types of test samples were created to evaluate the proposed model of electrical resistance; 27 samples with three weft densities were manufactured to test the three samples woven for each set of parameters.

All samples were tested in a control room under the KSON control system with an air pressure of 1 atm, relative humidity of 65 ± 2%, and temperature of 23 ±1°C. For measurement purposes, all samples were placed inside the control room for 24 hours before testing and none of them were treated with washing or ironing before testing. The samples were aligned on an insulated hard board, and electrical resistance was measured using the four-probe method with a Keithley 2010 multimeter with a pre-tension of 0.5 gf/tex.

Result and discussion

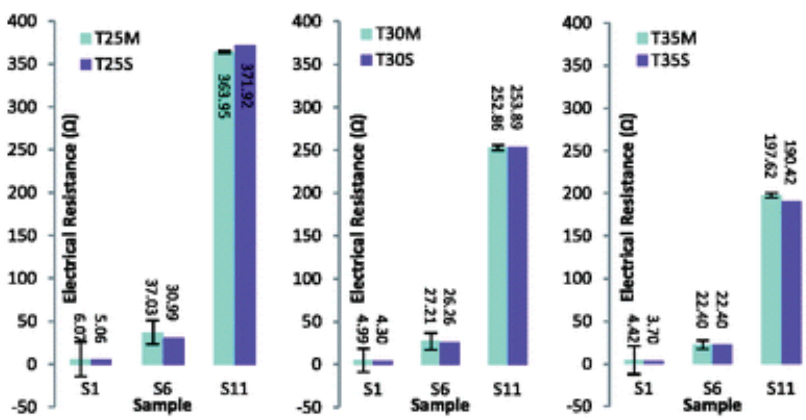
Comparison between simulated and experimental results

Figures 12–14 illustrate the comparison between the measurements and the simulations. M in P25M represents the measured value, and S in P25S is the simulated value. P stands for plain weave, T stands for twill weave and S stands for satin weave, while 25, 30 and 35 indicate the weft density (picks/inch). The error bar in the measurement value represents the standard deviation. Every table attached with these charts shows the percentage error for each kind of sample between the measurement and simulation. The electrical resistance of the testing sample is inversely proportional to the quantity of yarn A as indicated. In other words, the value of the resistance increases as the picks of yarn A change from S1 to S11. Compared to S6, for instance, the picks of yarn A in S1 were sixfold, whereas the resistance value of S1 was almost one sixth. Fewer conductive yarns woven in the weft direction means fewer 'resistors' are connected in parallel, which results in an obvious increase in the value of the resistance of conductive fabrics.



P25 Variation (%)	
S1	19.10
S6	3.36
S11	9.85
P30 Variation (%)	
S1	11.54
S6	3.84
S11	1.70
P35 Variation (%)	
S1	11.67
S6	16.14
S11	4.05

Figure 12. Comparison between the measured and simulated electrical resistance values in plain weave with 25/30/35 picks/inch weft density.



T25 Variation (%)	
S1	20.29
S6	8.22
S11	0.81
T30 Variation (%)	
S1	13.70
S6	3.48
S11	0.40
T35 Variation (%)	
S1	16.39
S6	0.00
S11	3.65

Figure 13. Comparison between the measured and simulated electrical resistance values in twill weave with 25/30/35 picks/inch weft density.

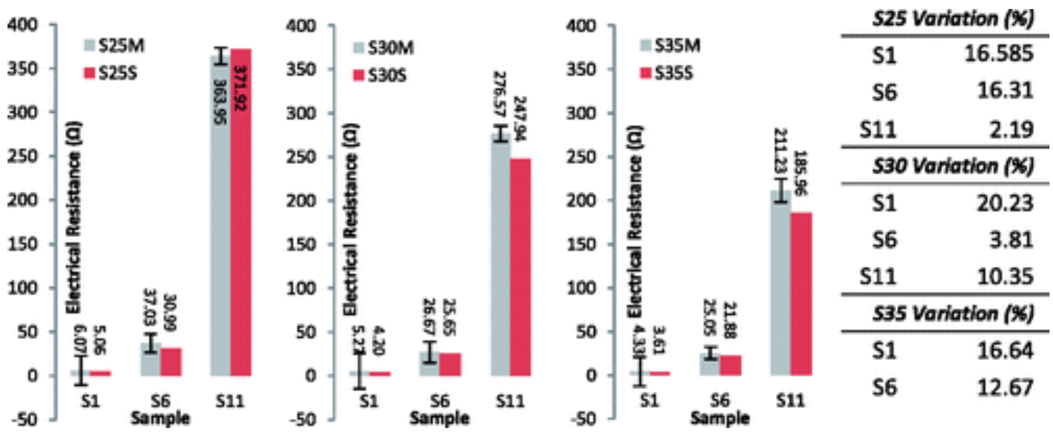


Figure 14. Comparison between the measured and simulated electrical resistance values in satin weave with 25/30/35 picks/inch weft density.

Suppose that

$$R_M = A + B * R_S \tag{22}$$

where the suffixes *M* and *S* refer to the measurement value and simulated value; *A* is the intercept, which represents the deviation of the simulated value, and *B* is the coefficient, which represents the degree of linear fit. The degree of linear fit is better when the coefficient is closer to 1. In Figure 15, the linear regression analyses show that all the coefficients *B* are close to 1, which means the models are quite fit to the measurements. However, the intercepts *A* of all these formulas are different, in particular indicating that the deviation grows as the resistance increases. The percentage of variation decreases when lesser amounts of yarn A are arranged in the weaving.

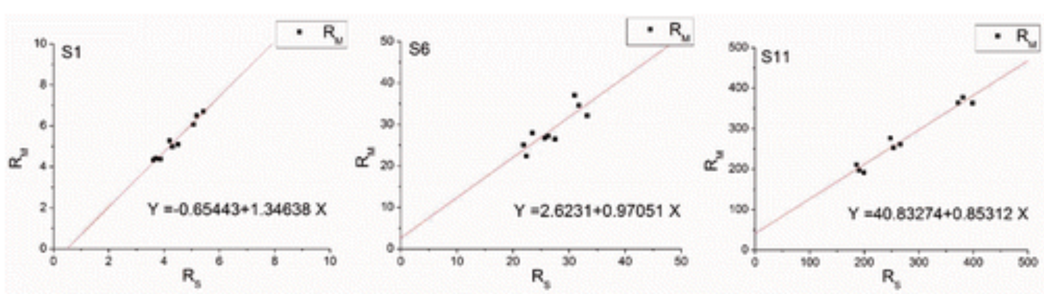


Figure 15. Linear regression analyses of the measured and simulated resistance.

The analysis of variance (ANOVA) table (Table 3) indicates that all the 'Probe > *F*' values are less than 0.01, which means the results are considered statistically extremely significant and the models are well fitted.

Sample	Item	Degree of freedom	Sum of squares	Mean of squares	*F* statistic	Probe > *F*
S1	**Model**	1	6.4044	6.4044	154.0591	<0.01
	Error	7	0.2910	0.0416		
	Total	8	6.6954			
S6	**Model**	1	131.5472	131.5472	18.8256	<0.01
	Error	7	48.9138	6.9877		
	Total	8	180.4610			
S11	**Model**	1	42,149.8542	42,149.8542	174.2541	<0.01
	Error	7	1693.2116	241.8874		
	Total	8	43,843.0658			

Table 3. Analysis of variance table of S1

As shown in Figure 16, the solid line represents the measured value, and the dashed line is the simulated value. The differences in electrical resistance are apparent as the weft density and arrangement change, whereas alternative structures cause only minor variation.

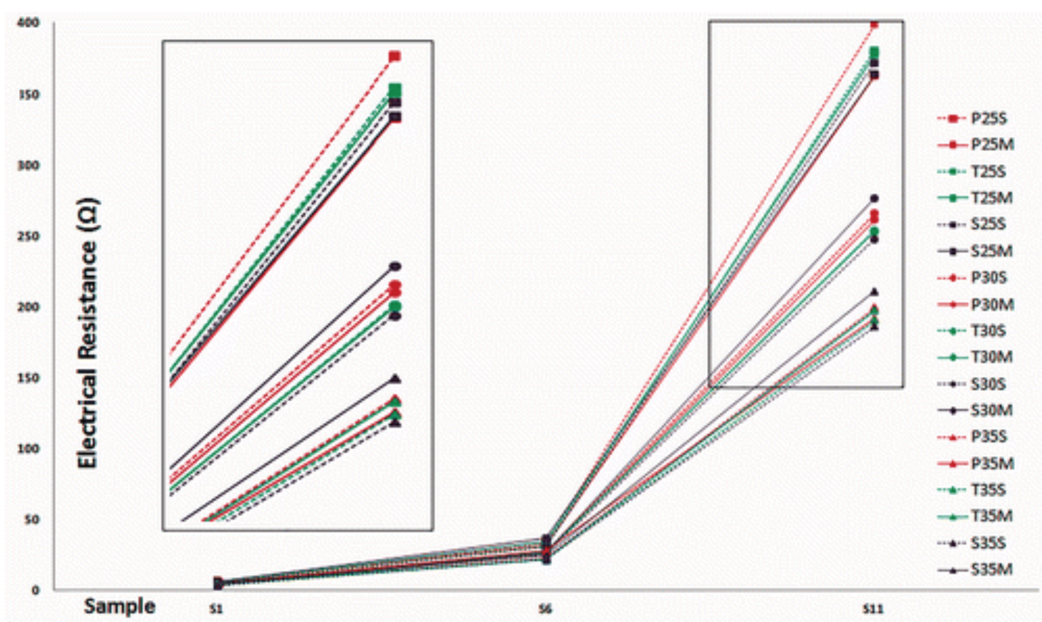


Figure 16. Comparisons between the measured and simulated electrical resistance.

Influence of weft density

Figure 17 demonstrates that the electrical resistance of the fabric decreases as the weft density increases under the same arrangement of conductive yarn, which means the length of yarn A is shorter according to Equations (17) and (18). It is obvious that a change in weft density results in significant variation in electrical resistance when the structure remains the same. As a result, the resistance of the conductive fabric will thus decrease. The decreasing trend becomes gentle as the conductive yarn arrangement changes from S11 to S1. This is due to conductive yarn being woven every single regular yarn: weft density will have the smallest effect on the resistance value. In contrast, in the case of conductive yarn being woven every 10 regular yarns, the effect due to the weft density will become more prominent.

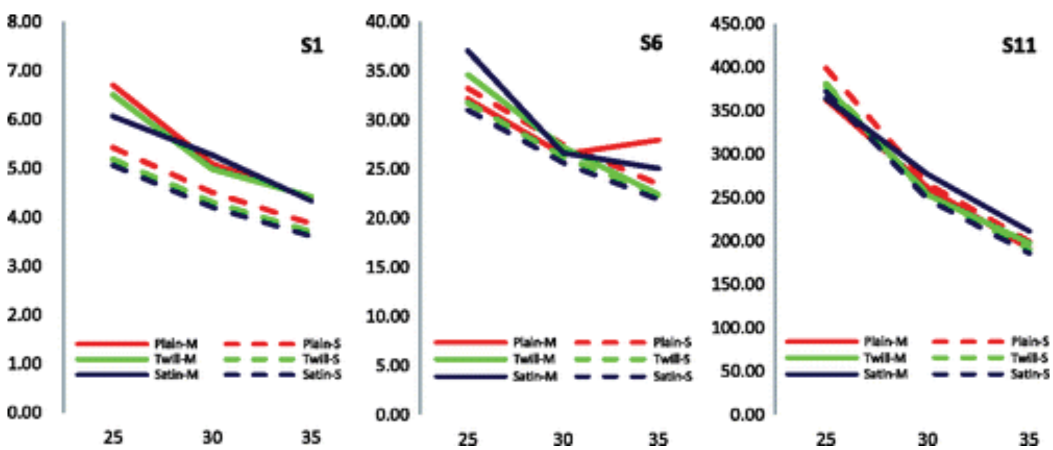


Figure 17. Comparisons between the measured and simulated resistance by weft density.

Influence of structure

Similarly, in Figure 18, when the weft density remains constant, a change in the structure also leads to limited variation in electrical resistance in this situation. The structure alternates from the plain weave to the twill weave and then to the satin weave, reducing the electrical resistance, which also stands when a shorter length for yarn A is used.

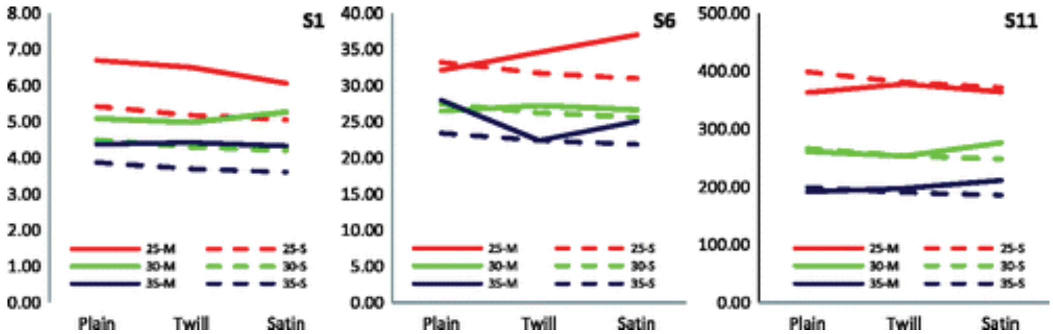


Figure 18. Comparisons between the measured and simulated resistance by structure.

In Figure 19, take S1 for example, as the structure changes, the linear regression analyses show that all the coefficients B are close to 1, which means the models are fit to the measurements. The absolute values of the intercepts A decrease, which means in the same arrangement, the model has a better linear fit in the satin weave than in the plain weave, with a small deviation.

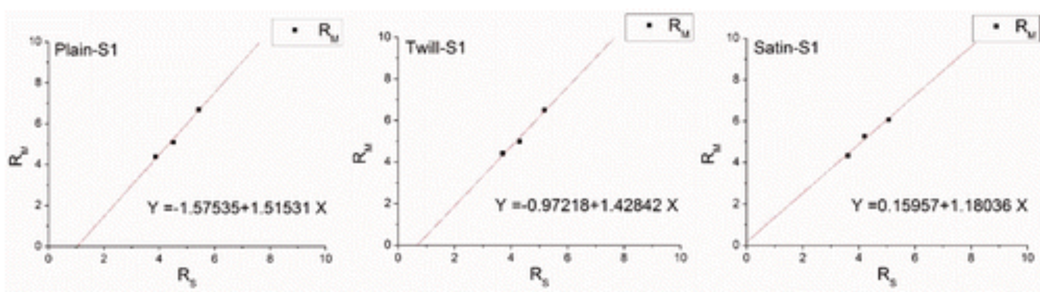


Figure 19. Linear regression analyses of the measured and simulated resistance of S1.

Influence of arrangement

In the different arrangements, S1 has significant variation between the measurement value and simulative value, whereas S11 has the slightest variation. As demonstrated in Figures 19 and 20, as the arrangement of yarn A changes, the coefficient *B* becomes closer to 1, indicating a better linear fit, whereas the intercept *A* increases, indicating larger deviation.

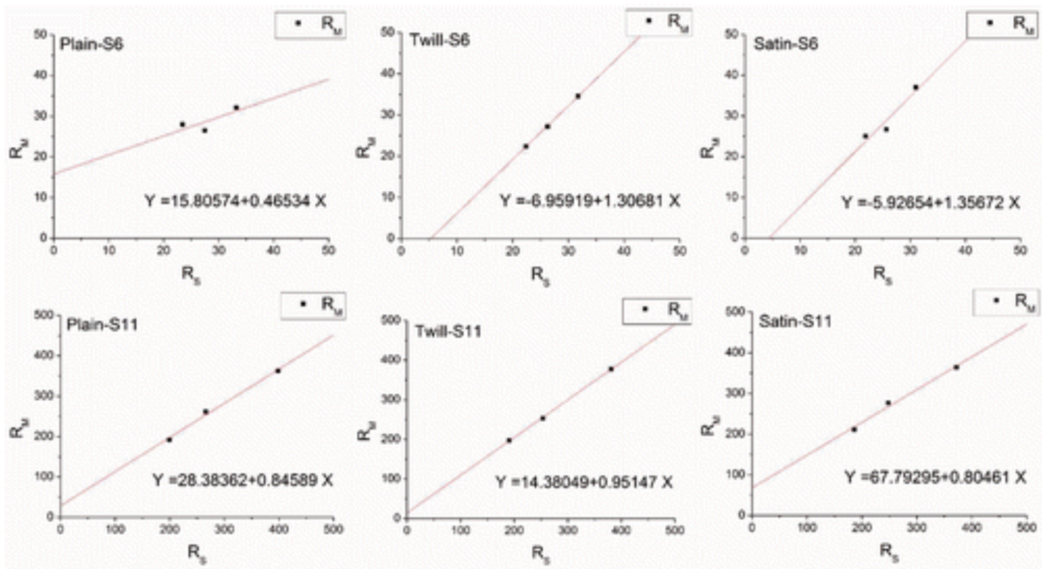


Figure 20. Linear regression analyses of the measured and simulated resistance of S6 and S11.

As demonstrated in Figures 12–14, basically, the error percentage of the satin weave is higher than those of the other two, which is mainly because of the inherent structure of the satin, which has more float yarns and less overlap, which may not be perfectly arranged, as assumed by the model. In addition, yarn A has additional length in its natural state due to its own special characteristics, increasing the resistance of the fabric. It is certain that after replacing the CCI sampling loom with a professional weaving machine and using straight yarn A rather than a wavy one, the simulated result will be more accurate.

In this paper, contact resistance was not considered. However, comparing the measured and simulated resistance, the contact resistance of the device needle and conductive yarn B may be one factor that affects the deviation in the result, especially for sample S1. It is notable in the Table 4–Table 6 (refer to the Appendix) that every S1 has a high error percentage, all beyond 10%. The electrical resistance of S1 is lower than 7 Ω, whereas that of S11 can reach almost 400 Ω, which means the contact resistance has a great impact on S1 and decreases when electrical resistance increases.

To a large extent, the tension of the machine itself influenced the experimental results. The tension of the CCI sampling loom cannot remain constant; however, that of a professional weaving machine in a factory can. Different tension results in different lengths for the embedded yarn, thereby influencing the electrical resistance. The error bar shown in the Figures 12–14 show the standard deviation of the measured electrical resistance. Apparently, the variations are not stable. Some of the variations, which are in relation to each type of testing sample, are quite considerable. In this paper, there may be different tension, affecting the error variation. Another factor that influences the result is the weaving shrinkage. Every fabric has the possibility of shrinkage during the weaving procedure, which will also cause variation in the simulation between measurements.

Beyond what has been mentioned, the most vital factor leading to variation is considering the fact that the actual length of yarn A is longer than what we hypothetically calculated. This is related to the special feature of yarn A. According to Figure 9 (d), yarn A is wave shaped, rather than straight, in its natural state, which apparently adds length, thereby increasing the actual electrical resistance we measured. Especially in the satin weave, more float yarns and less overlaps result in limited tensile force for yarn A, thereby causing higher electrical resistance than we had simulated, in which the model had regarded the yarn as straight.

Conclusion

A theoretical model was proposed to simulate electrical resistance for conductive woven fabrics. An analytic equation was derived based on an equivalent length of conductive yarn woven in three basic woven structures with three different weft densities. Once the radius of the warp yarn and the resistance of one unit of conductive yarn are known, the electrical resistance of woven conductive fabric can be readily computed. The results show that the simulative equation can predict the resistance of woven fabrics, which allows designers to estimate the fabric parameters to meet the required resistance. The differences in electrical resistance become apparent as the weft yarn density and arrangement change, whereas alternative structures cause only minor variation. Moreover, electrical resistance can be controlled by different structures and arrangements under the same size fabric. Because the contact resistance, so far, has not been considered in our research, further research will be conducted to more accurately model and compute resistance and therefore achieve an improved version of the proposed resistive model.

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