# A simulation model of electrical resistance applied in designing conductive woven fabrics – Part II: fast estimated model

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## Abstract

Limited researches have been proposed regarding the theoretical model of conductive woven fabric. In a previous study, one type of simulation model was derived to compute the resistance of conductive woven fabric. This paper proposed another fast estimated method to obtain the electrical resistance of conductive thermal woven fabrics (CTWFs) based on the previous model but design oriented. This new model has a similar predicted effect, for which the maximum deviation is less than 1.2% compared to the previous one. The cover factor was a major factor in this model, which assists designers to comprehend and manage the method rapidly. The results revealed that the proposed fast estimated model was well fitted (*P*-value < 0.05) and could well simulate the electrical resistance of CTWFs within a certain error variation. According to this model, designers can independently estimate the electrical resistance and design customized products of CTWFs, which will be produced effectively by reducing extra waste of energy and cost.

**Keywords**

Fast estimated model, conductive woven fabric, woven structures, electrical resistance, design oriented

The combination of conductive yarns with electronic components and different textile methods has been receiving much attention in wearable electronics researches. Challenges in creating conductive fabric are as follows: (a) as electrical functions are embedded in textiles it is crucial to retain the flexibility and comfort of the fabrics;[1] (b) fibers/yarns and fabrics have to meet special requirements concerning not only conductivity but also processability and wearability;[2] (c) the electrical property of conductive fabric needs better understanding, such as the issue of electrical resistance in conductive fabric. Before applying electronics to the fabrics by using conductive yarns, we need to model the complex and elastic fabric structures. Previous studies on the electromechanical analysis of conductive yarn in textile-based electronic circuits showed little success in presenting an analytical formulation for equivalent electrical resistance.[4–9] Zhao et al.[1] managed to establish a kind of simulation model of electrical resistance for conductive woven fabric. However, most textile designers or garment designers lack the background knowledge of science and engineering or of other disciplines, and may consider it difficult to design intelligent textile products with a fine aesthetic appearance. Thus, a comprehensive and manageable method that designers can adopt is an urgent requirement.

This paper proposes a fast estimated model of electrical resistance used in designing conductive thermal woven fabrics (CTWFs) with three basic weaving structures – plain weave, twill weave, and satin weave. The weft density of weft silver-coated yarn was changed according to different arrangements. Combined with the result of the previous simulation model, the new model will be an empirical model using only the cover factor as variable. Experiments were designed and conducted to verify the availability of the proposed model. A customized design method of CTWFs can be produced according to this fast estimated model, which can meet the demand of a highly efficient prototype design and conserve costs and energy.

**Calculation of the cover factor**

The fabric cover factor is used to assess the fabric tightness. The warp cover factor, weft cover factor, and fabric cover factor are the areas covered by warp yarn or weft yarn, or both yarns. It can be expressed as the ratio of the area covered by the warp and weft yarn and the total area of the fabric. Under the condition of the same fabric, the greater the fabric cover factor is, the tighter the fabric is. Figure 1 illustrates the maximum cover of 1/3 twill weave, which means the warp yarns are kept in planes so that their projections are touching each other and the weft yarns interlace in between.[3]

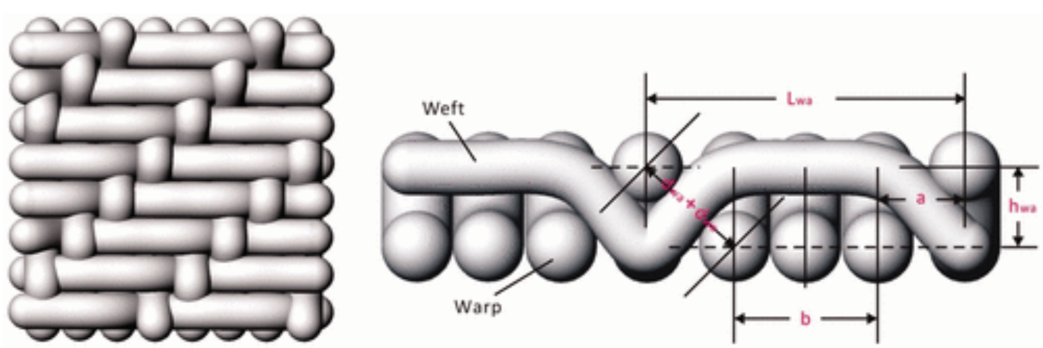


**Figure 1.** Structure diagram of 1/3 twill weave.

Take the following, for example

$$L_{wa} = a + b + a = b + t_{we}a \quad (1)$$

$$a = \sqrt{(d_{wa} + d_{we})2 - h^2{}_{wa}} \quad (2)$$

Because the weft yarn and the warp yarn are in the same surface

$$h_{wa} = d_{we} \quad (3)$$

$$a = \sqrt{d_{wa}^2 + 2d_{wa}d_{we} + d_{wa}^2 - d_{we}^2} = \sqrt{d_{wa}^2 + 2d_{wa}d_{we}} \quad (4)$$

$$b = (R_{wa} - t_{we})d_{wa} \quad (5)$$

where $R_{wa}$ is the cyclic pick of the warp yarn and $R_{we}$ is the same concept for the weft yarn. $t_{wa}$ and $t_{we}$ are the frequencies at which the warp yarn and weft yarn interlace in one cyclic unit.

Substituting into the above equation

$$L_{wa} = (R_{wa} - t_{we})d_{wa} + t_{we}\sqrt{d_{wa}^2 + 2d_{wa}d_{we}} \quad (6)$$

In the same way

$$L_{we} = (R_{we} - t_{wa})d_{we} + t_{wa}\sqrt{d_{we}^2 + 2d_{wa}d_{we}} \quad (7)$$

According to the definition of the cover factor

$$K_{wa}' = \frac{R_{wa}d_{wa}}{L_{wa}} \quad (8)$$

$$K_{we}' = \frac{R_{we}d_{we}}{L_{we}} \quad (9)$$

If the warp density is $d_X$, the weft density is $d_Y$, then $K_{wa}$'Kwa' and $K_{we}$'Kwe' can be calculated as follows:

1. 1/1 plain weave

$$R_{wa} = R_{we} = 2,\ t_{wa} = t_{we} = 2, \tag{10}$$

$$K_{wa}' = \frac{2d_X}{2\sqrt{d_X^2+2d_Xd_Y}} = \frac{d_X}{\sqrt{d_X^2+2d_Xd_Y}} \tag{11}$$

$$K_{we}' = \frac{2d_Y}{2\sqrt{d_X^2+2d_Xd_Y}} = \frac{d_Y}{\sqrt{d_X^2+2d_Xd_Y}} \tag{12}$$

4. n/m twill weave

$$R_{wa} = R_{we} = n+m,\ t_{wa} = t_{we} = 2, \tag{13}$$

$$K_{wa}' = \frac{(n+m)d_X}{(n+m-2)d_X+2\sqrt{d_X^2+2d_Xd_Y})} \tag{14}$$

$$K_{we}' = \frac{(n+m)d_Y}{(n+m-2)d_Y+2\sqrt{d_Y^2+2d_Xd_Y})} \tag{15}$$

7. q ends satin weave

$$R_{wa} = R_{we} = q,\ t_{wa} = t_{we} = 2, \tag{16}$$

$$K_{wa}' = \frac{qd_X}{(q-2)d_X+2\sqrt{d_X^2+2d_Xd_Y})} \tag{17}$$

$$K_{we}' = \frac{qd_Y}{(q-2)d_Y+2\sqrt{d_Y^2+2d_Xd_Y})} \tag{18}$$

**Fast estimated model of electrical resistance**

Three basic structures of woven fabrics, plain weave, twill weave, and satin weave, are designed at certain inches in width and certain inches in length. Regular yarns C were used both in the weft and in the warp, as base material. As illustrated in Figure 2, at the left- and right-hand edges of the fabric, several picks of conductive yarn B replaced the warp yarn C to serve as the power supply in the conductive path. Yarn A was woven with yarn C as heating panels at picks according to different arrangements: every pick, every other picks, every fifth picks, etc.

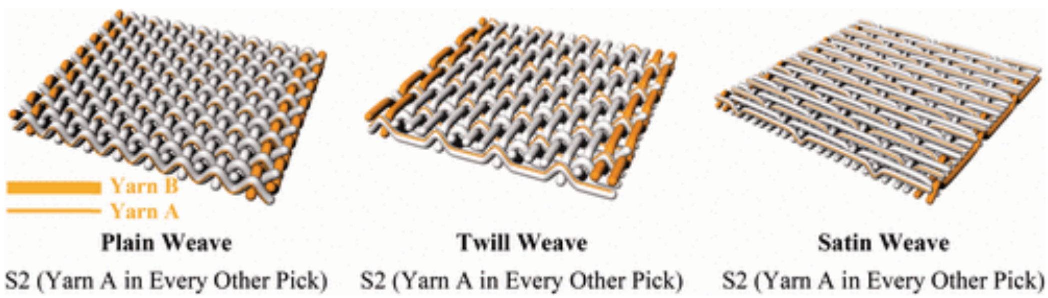


**Figure 2.** Three basic structures of woven fabric.

Almost all the designed fabric above cannot reach the maximum cover and, due to the density change, there exists spacing in every adjacent yarns, as shown in Figures 3(a) and (b). However, for calculation convenience, the structure model can be slightly transformed into Figures 3(c) and (d), with which the internal spacing length $L_i$ will be introduced to the model. Since $N_{\mathrm{waC}}$ represents the picks of weft yarn C, the cyclic unit can be calculated

$$C_{\mathrm{wa}} = \frac{N_{waC}}{R_{wa}} \tag{19}$$

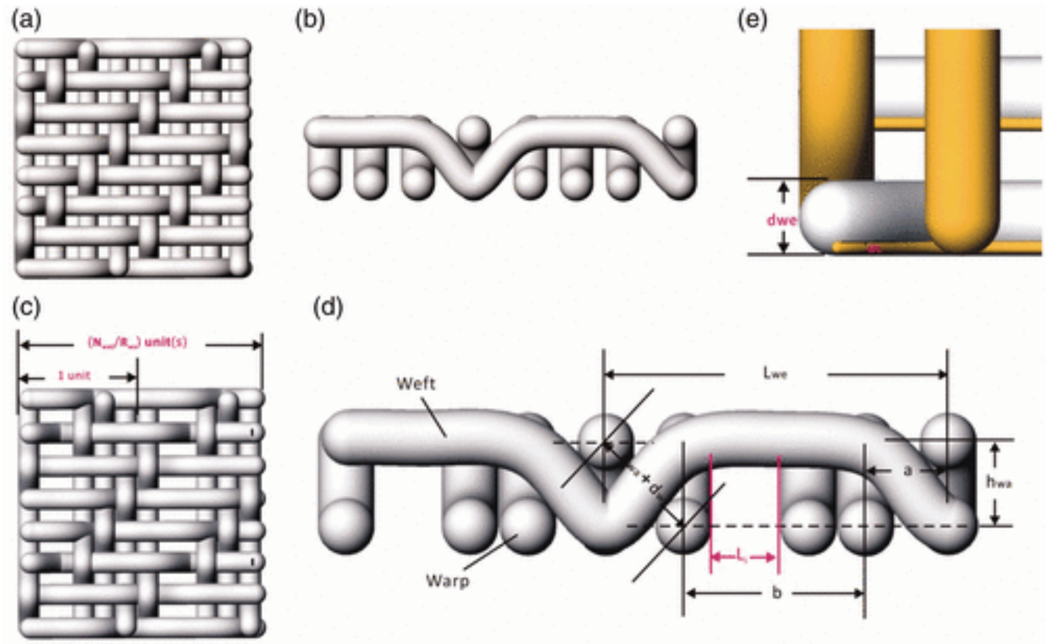


**Figure 3.** Modified structure of woven fabric for calculation purposes.

The internal spacing length $L_i$ will be

$$L_{iwa} = \frac{W - N_{waC} * d_{wa}}{N_{waC}} \tag{20}$$

where $W$ represents the fabric width.

Therefore, the modified formula for cover factor is

$$K_{wa}' = \frac{R_{wa} d_{wa}}{L_{wa} + L_{iwa}} \tag{21}$$

$$K_{we}' = \frac{R_{we} d_{we}}{L_{we} + L_{iwe}} \tag{22}$$

$$K_{wa}' = \frac{(N+M) d_X}{(N+M)2) d_X + 2\sqrt{d_X^2 + 2 d_X d_Y}) + \frac{W - N_{waC} * d_{wa}}{N_{waC}}} \tag{23}$$

$$K_{we}' = \frac{(N+M)d_Y}{(n+m-2)d_Y+2\sqrt{d_Y^2+2d_Xd_Y}+\frac{W-N_{weC}*d_{we}}{N_{weC}}} \quad (24)$$

when $N = 1$, $M = 1$, plain weave; $N = n$, $M = m$, twill weave; and $N = 1$, $M = q - 1$, satin weave.

This formula may appear complex, but most of the components are constant numbers, which can be easily calculated.

According to the special design, yarn A was woven with yarn C at specific picks. The core of the fast estimated model is to gather the cover factor of yarn A. By means of the cover factor of yarn C, the target value can be calculated. As demonstrated in Figure 3(e), the relation of diameter between yarn A and yarn C can be described as

$$d_{we} = n*d_A \quad (25)$$

Thus, the cover factor of yarn A is

$$K_{weA}' = \frac{(N+M)d_Y}{(n+m-2)d_Y+2\sqrt{d_Y^2+2d_Xd_Y}+\frac{W-N_{weC}*d_{we}*n^{-1}}{N_{weC}}} \quad (26)$$

According to the different arrangement of yarn A and different density of the fabric, the picks of yarn A used can be calculated as shown in Table 1. Six samples are selected to use in the fast estimated model set-up. The weft density of yarn A is listed in Table 2. All the samples are fabricated according to the parameters shown in Table 1.

| Sample | | S1 | S3 | S5 | S9 | S11 |
|---|---|---|---|---|---|---|
| Weft density | Interval picks | +0 | +2 | +4 | +20 | +50 |
| 25 | Picks of total yarn A | 147 | **49** | **29** | 7 | **2** |
| 30 | | 177 | **59** | 35 | **8** | 3 |
| 35 | | **206** | 68 | 41 | 9 | 4 |

**Table 1.** Weaving samples for different weft densities and conductive yarn arrangements in the experiment

| Sample | 35S1 | 25S1 | 30S3 | 25S5 | 30S9 | 25S11 |
|---|---|---|---|---|---|---|
| Weft density of yarn A (picks/inch) | 35 | 25 | 10 | 5 | 1.43 | 0.49 |
| New sample code | K35 | K25 | K10 | K5 | K1.5 | K0.5 |

**Table 2.** Weft density of yarn A of selected samples

| Sample | $K_P$ | $R_P$ (Ω) | $K_T$ | $R_T$ (Ω) | $K_S$ | $R_S$ (Ω) |
|---|---|---|---|---|---|---|
| K35 | 0.5131 | 3.870 | 0.5297 | 3.700 | 0.5384 | 3.610 |
| K25 | 0.3731 | 5.420 | 0.3825 | 5.180 | 0.3870 | 5.060 |
| K10 | 0.1486 | 13.510 | 0.1527 | 12.910 | 0.1549 | 12.610 |
| K5 | 0.0736 | 27.490 | 0.0755 | 26.260 | 0.0763 | 25.650 |
| K1.5 | 0.0202 | 99.670 | 0.0207 | 95.210 | 0.0210 | 92.980 |
| K0.5 | 0.0051 | 398.660 | 0.0052 | 380.830 | 0.0053 | 371.920 |

**Table 3.** Cover factor and electrical resistance of conductive thermal woven fabrics

| | Sum of squares | *df* | Mean square | *F* | Sig. |
|---|---|---|---|---|---|
| Plain weave | | | | | |
| Regression | 15.681 | 1 | 15.681 | 330,619.465 | .000 |
| Residual | .000 | 4 | .000 | | |
| Total | 15.681 | 5 | | | |
| Twill weave | | | | | |
| Regression | 15.741 | 1 | 15.741 | 755,414.803 | .000 |
| Residual | .000 | 4 | .000 | | |
| Total | 15.741 | 5 | | | |
| Satin weave | | | | | |
| Regression | 15.715 | 1 | 15.715 | 1,268,518.710 | .000 |
| Residual | .000 | 4 | .000 | | |
| Total | 15.715 | 5 | | | |

**Table 4.** Analysis of variance table of curve fitting

| | Weft density and arrangement | | |
|---|---|---|---|
| Structure | 30S1 (K30) | 30S2 (K15) | 35S5 (K7) |
| Plain | 3 | 3 | 3 |
| Twill | 3 | 3 | 3 |
| Satin | 3 | 3 | 3 |

**Table 5.** Sample design information

The fabric tightness is in direct proportion to the cover factor, so the equation can be described as

$$R = \mathrm{m}K^{n} \tag{27}$$

Since the fast estimated model is an experience model based on previous data, the data we use to establish the model is listed in Table 3. The $K$ values are calculated by the method in the previous part. The $R$ values are calculated by the method in previous research.[1]

Taking all the data into equation (27), the fast estimated model to simulate the electrical resistance of CTWFs is

$$R_{\mathrm{KP}} = 1.994K^{-0.997} \tag{28}$$

$$R_{\mathrm{KT}} = 1.968K^{-0.999} \tag{29}$$

$$R_{\mathrm{KS}} = 1.994K^{-0.998} \tag{30}$$

The figures of the curve fit are demonstrated in Figure 4. The $R$ value of each fit is all 1.000. The analysis of variance (ANOVA) table (Table 4) indicates that the $P$-values are less than 0.001, which means the results are considered statistically extremely significant and the curves are well fitted.

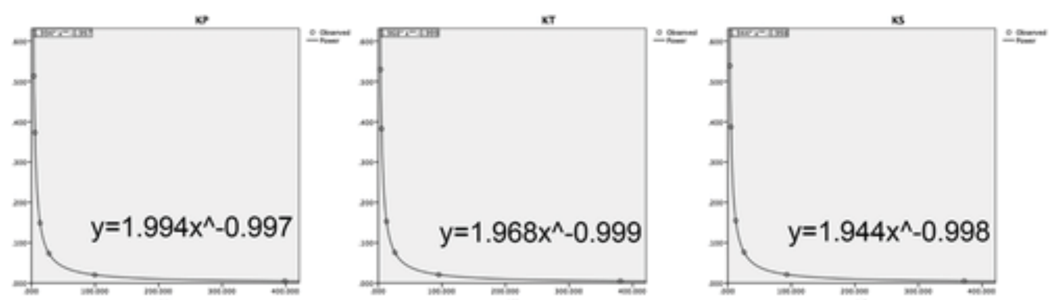


**Figure 4.** Curve Fitting for plain weave, twill weave, and satin weave.

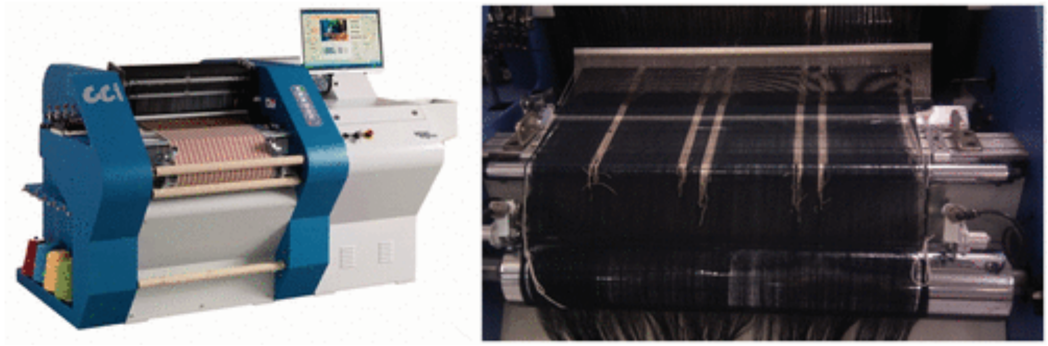

**Figure 5.** CCI sampling loom and the weaving experiment.

## Experimental details

In the experiment, yarn C is 100% cotton yarn with yarn count of 20/2 Ne S ply. Yarn A is 22/1 dtex single filament silver-coated conductive yarn and yarn B is another silver-coated conductive yarn of 235/34 dtex 2-ply. The electrical resistances of each conductive yarn are 72.6 and 1.1 Ω per cm, while the diameters are 0.005 and 0.290 mm, respectively. The inner fiber of yarn A and yarn B is nylon 6 and nylon 66, respectively. Each kind of sample has three pieces manufactured by a CCI tech automatic dobby sampling loom (Figure 5) in three weaves: plain weave, twill weave, and satin weave. The head type is a gripper head with a speed of around 25 r/min.

As displayed in Table 5, the experiment selects three kinds of fabric with specific weft density and arrangement, which are 30S1, 30S2, and 35S5 with cover factors of 30, 15, and 7, respectively. 30S1 means the fabric has yarn A in every pick with a weft density of 30 picks/inch. 30S2 means the fabric has yarn A in every other pick with a weft density of 30 picks/inch. 35S5 means the fabric has yarn A in five picks with a weft density of 35 picks/inch. The warp density is maintained at 40 ends/inch.

The design and fabrication of the samples are displayed in Figure 6. All samples are 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 are placed inside the control room for 24 h before testing and none of them are treated with washing or ironing before testing. The samples are aligned on an insulated hard board, the electrical resistance of which was measured by the four-probe method with a Keithley 2010 multimeter.


**Figure 6.** Sample design and fabrication.

## Result and discussion

### Comparison between simulated and measured results

Table 6 lists the simulated result calculated by the fast estimated model. Figure 4 illustrates the comparison between the simulated values and the measured values. The error bar represents the standard deviation. The variations of the 30S1(K30) sample are 12.36% for plain, 1.93% for twill, and 5.43% for satin. The variations of the 30S2(K15) sample are 13.99% for plain, 10.05% for twill, and 3.27% for satin. The variations of the 35S5(K7) sample are 20.72.11% for plain, 12.78% for twill, and 13.95% for satin. The error percentage decreased in the K31 and K15 samples, but increased in the K7 sample when the structure changed. In addition, as the cover factor decreased, the error percentage apparently increased.

| Sample | $K_P$ | $RK_P$ (Ω) | $RM_P$ (Ω) | $K_T$ | $RK_T$ (Ω) | $RM_T$ (Ω) | $K_S$ | $RK_S$ (Ω) | $RM_S$ (Ω) |
|---|---|---|---|---|---|---|---|---|---|
| **30S1 (K30)** | 0.4459 | **4.461** | 5.090 | 0.4582 | **4.292** | 4.990 | 0.4646 | **4.178** | 5.270 |
| **30S2 (K15)** | 0.2217 | **8.954** | 9.130 | 0.2278 | **8.626** | 9.590 | 0.2310 | **8.391** | 9.620 |
| **35S5 (K7)** | 0.1021 | **19.397** | 20.510 | 0.1054 | **18.630** | 19.260 | 0.1072 | **18.054** | 20.980 |

**Table 6.** Comparison of simulated value and measured value

Suppose that $R_M = A + B * R_S$ (20), where intercept A represents the deviation of the simulated value while coefficient B represents the degree of linear fit. In Figure 7, the linear regression analysis indicates that all the coefficients $B$ are close to 1, which means the models are quite fit to the measurement.

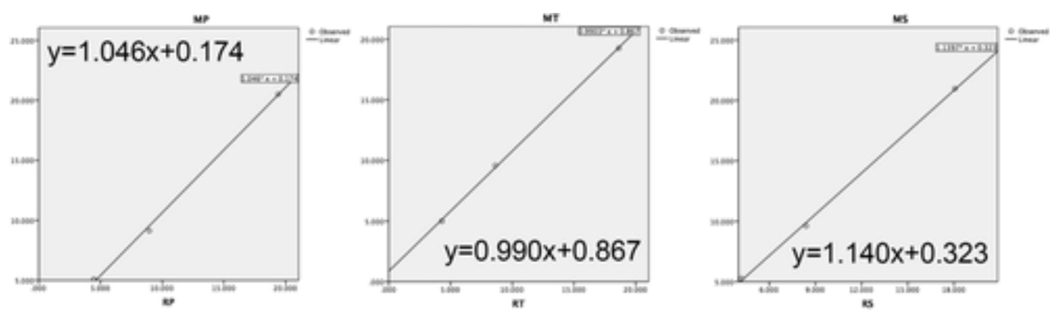


**Figure 7.** Linear regression analyses of the simulated and measured values.

The ANOVA table (Table 7) indicates that all the $P$-values are less than 0.05, which means the results are considered statistically significant and the models are well fitted. In addition, the values of $R^2$ are 1.000, 0.996, and 1.000. The closer to 1 the figure is, the better the fit is.

| | Sum of squares | *df* | Mean square | *F* | Sig. |
|---|---|---|---|---|---|
| Plain weave | | | | | |
| Regression | 127.641 | 1 | 127.641 | 563.150 | .027 |
| Residual | .227 | 1 | .227 | | |
| Total | 127.867 | 2 | | | |
| Twill weave | | | | | |
| Regression | 106.049 | 1 | 106.049 | 2047.686 | .014 |
| Residual | .052 | 1 | .052 | | |
| Total | 106.101 | 2 | | | |
| Satin weave | | | | | |
| Regression | 131.480 | 1 | 131.480 | 1174.586 | .019 |
| Residual | .112 | 1 | .112 | | |
| Total | 131.592 | 2 | | | |

**Table 7.** Analysis of variance table of linear regression

A comparison of the previous model and the fast estimated model is given in Figure 8. RK represents the result using the fast estimated model; RS represents the simulated value using the previous model; RM represents the measured value. The accuracy of the fast estimated model is literally the same as that of the previous model. However, both models have deviation compared to their measured values. There may be two reasons for this. The first one is that the predicted models have their limitations in precision due to the calculation method, no matter the length or cover factor, only considering ideal circumstances. The second reason may be the deviation that is brought from the measurement of the electrical resistance.

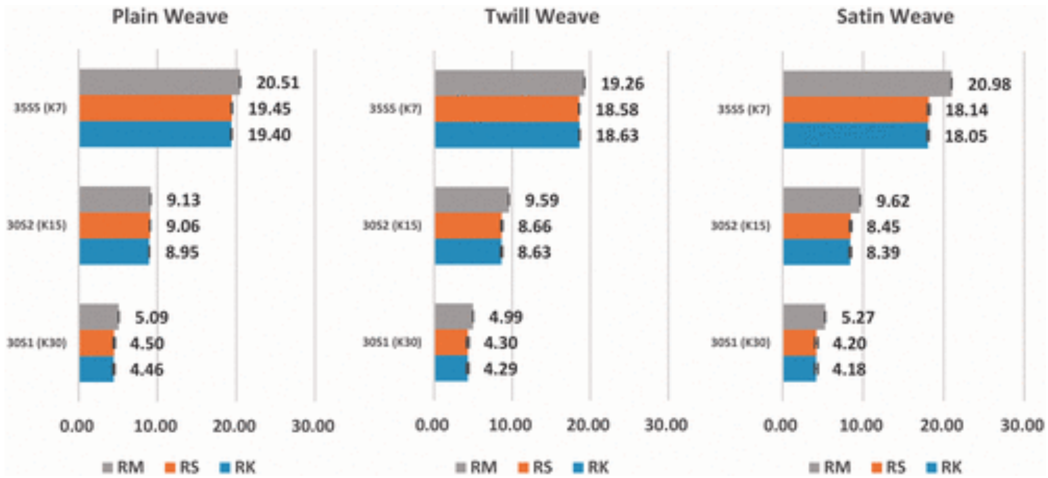


**Figure 8.** Comparison of the previous model and the fast estimated model.

## Equivalent fabric with similar electrical resistance

According to the testing results both in the previous and current experiment, equivalent samples have been noticed due to their similar electrical resistance. The same structures with different weft density or different parameters in both are the target data. Take P25, T25, and S25, for example, shown below, where most of the samples find very similar substitutes while others may be affected by the arrangement limitation of yarn A for unmatched data. In Table 8, the selected samples are listed to support the concept of equivalent fabric, which means that through parameter adjustment, the designer can substitute one design sample with another. The design option, fabric quality, and production cost may meet the needs of different requirements.

| Basic sample | Equivalent sample | Basic sample | Equivalent sample | Basic sample | Equivalent sample |
|---|---|---|---|---|---|
| P25-S2 (10.92Ω) | S35-S3 (10.94Ω) | T25-S2 (10.43Ω) | S35-S3 (10.94Ω) | S25-S2 (10.19Ω) | S35-S3 (10.94Ω) |
| P25-S3 (16.27Ω) | S30-S4 (16.91Ω) | T25-S3 (15.54Ω) | P35-S4 (15.63Ω) | S25-S3 (15.18Ω) | T35-S4 (14.93Ω) |
| P25-S4 (22.15Ω) | T35-S6 (22.40Ω) | T25-S4 (21.16Ω) | S30-S5 (21.88Ω) | S25-S4 (20.66Ω) | P35-S5 (19.45Ω) |
| P25-S5 (27.49Ω) | P30-S6 (27.49Ω) | T25-S5 (26.26Ω) | T30-S6 (26.26Ω) | S25-S5 (25.65Ω) | S30-S6 (25.65Ω) |
| P25-S7 (61.33Ω) | S35-S8 (61.99Ω) | T25-S7 (58.59Ω) | S35-S8 (61.99Ω) | S25-S7 (57.22Ω) | S35-S8 (61.99Ω) |
| P25-S8 (88.59Ω) | P35-S9 (88.59Ω) | T25-S8 (84.63Ω) | T35-S9 (84.63Ω) | S25-S8 (82.65Ω) | S35-S9 (82.65Ω) |

**Table 8.** Selected equivalent samples with weft density of 25 picks/inch (color online only)

Equivalent samples make the concept of customized design realizable, as shown in Figure 9. At the same size with the same electrical resistance, it is possible to choose woven fabric with a different structure and weft density. If the structure maintains constant, design A can be substituted by arranging less yarn A in the fabric and increasing the weft density. For example, with the same structure in the satin weave, S25-S5 has the same electrical resistance as S30-S6. S6 has less yarn A, which can reduce the usage of silver-coated yarn, thus reducing the cost only by revising a larger weft density. If the structure needs to be replaced by another one, the arrangement of yarn A will be raised while the weft density decreases, such as a loose (25/picks/inch) twill with yarn A embedded in every three picks or a tight (30/picks/inch) satin with yarn A in every four picks. If the density is fixed, a substitute design can also be obtained by arranging more yarn A to reduce the deviation caused by the structure alternating. As shown in Table 8, the red colored values are very similar, which can be adopted as substitute samples. The blue colored ones have the exact same values, which can be perfectly switched as equivalent samples.

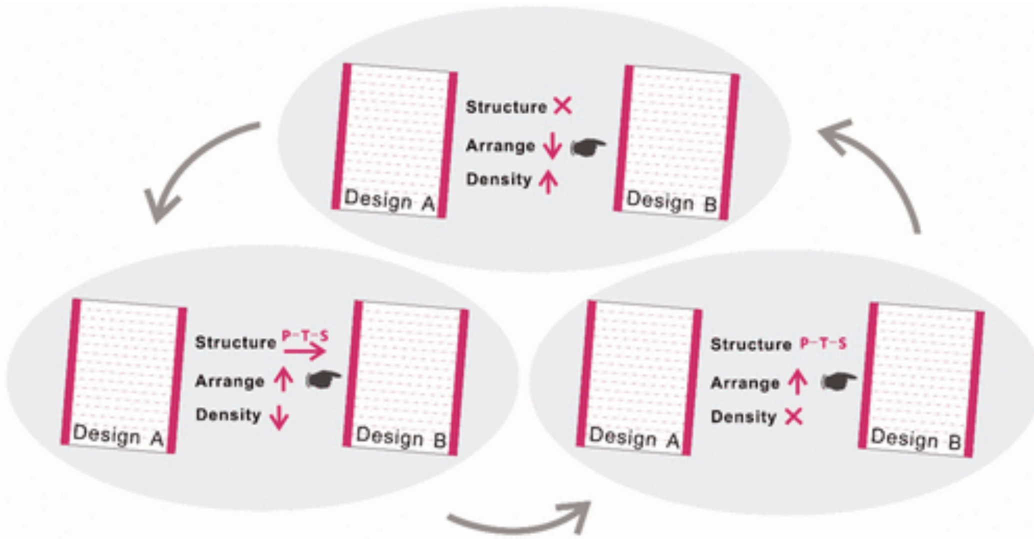


**Figure 9.** Concept of customized design of conductive thermal woven fabric.

After calculating all the cover factors of yarn A, some interesting phenomena occurred. As highlighted in blue, Table 9 shows that the cover factor of 25 picks/inch is almost the same as that with 30 picks/inch. Referred to Table 8, all samples S5 with a weft density of 25 picks/inch have similar electrical resistance of samples S6 of 30 picks/inch, despite their different structures. In addition, as colored in blue in Table 9, the values of the cover factor are almost the same, which means that the electrical resistance of those samples can be switched to equivalent samples with some adjustment in structure. In summary, samples with lower density in certain numbers of yarn A can be replaced by samples with higher density in lower numbers of yarn A combining with structure adjustment, which makes it controllable to the electrical resistance of the thermal woven fabric within the same size, thus reducing the usage of silver-coated yarn and thereby reducing the cost.

**Table 9.** Cover factor of yarn A of all samples (color online only)

| | Sample | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 | S11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Interval Picks | +0 | +1 | +2 | +3 | +4 | +5 | +10 | +15 | +20 | +25 | +50 |
| $D_w$ | $\rho$ | 1 | 2 | 3 | 4 | 5 | 6 | 11 | 16 | 21 | 26 | 51 |
| 25 | | **147** | **73** | **49** | **36** | **29** | **24** | **13** | **9** | **7** | **5** | **2** |
| 30 | $N_{WE}$ | **177** | **88** | **59** | **44** | **35** | **29** | **16** | **11** | **8** | **6** | **3** |
| 35 | | **206** | **103** | **68** | **51** | **41** | **34** | **18** | **12** | **9** | **7** | **4** |

| | 25 picks/inch | | | | | | 30 picks/inch | | | | | | 35 picks/inch | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **KweA** | RKp | **KweA** | RKt | **KweA** | RKs | **KweA** | RKp | **KweA** | RKt | **KweA** | RKs | **KweA** | RKp | **KweA** | RKt | **KweA** | RKs |
| **S1** | **0.373** | 5.328 | **0.383** | 5.140 | **0.387** | 5.014 | **0.446** | 4.461 | **0.458** | 4.292 | **0.465** | 4.178 | **0.513** | 3.879 | **0.530** | 3.713 | **0.538** | 3.606 |
| **S2** | **0.185** | 10.707 | **0.190** | 10.342 | **0.192** | 10.083 | **0.222** | 8.955 | **0.228** | 8.627 | **0.231** | 8.392 | **0.257** | 7.741 | **0.265** | 7.421 | **0.269** | 7.202 |
| **S3** | **0.124** | 15.932 | **0.128** | 15.402 | **0.129** | 15.009 | **0.149** | 13.340 | **0.153** | 12.862 | **0.155** | 12.506 | **0.169** | 11.711 | **0.175** | 11.236 | **0.178** | 10.900 |
| **S4** | **0.091** | 21.665 | **0.094** | 20.957 | **0.095** | 20.416 | **0.111** | 17.873 | **0.114** | 17.241 | **0.115** | 16.760 | **0.127** | 15.602 | **0.131** | 14.977 | **0.133** | 14.525 |
| **S5** | **0.074** | 26.877 | **0.075** | 26.010 | **0.076** | 25.333 | **0.088** | 22.453 | **0.091** | 21.670 | **0.092** | 21.060 | **0.102** | 19.394 | **0.105** | 18.625 | **0.107** | 18.060 |
| **S6** | **0.061** | 32.457 | **0.062** | 31.423 | **0.063** | 30.600 | **0.073** | 27.083 | **0.075** | 26.149 | **0.076** | 25.408 | **0.085** | 23.374 | **0.087** | 22.456 | **0.089** | 21.770 |
| **S7** | **0.033** | 59.811 | **0.034** | 57.977 | **0.034** | 56.422 | **0.040** | 49.000 | **0.041** | 47.366 | **0.042** | 45.997 | **0.045** | 44.067 | **0.046** | 42.389 | **0.047** | 41.068 |
| **S8** | **0.023** | 86.299 | **0.023** | 83.713 | **0.024** | 81.439 | **0.028** | 71.193 | **0.028** | 68.870 | **0.029** | 66.854 | **0.030** | 66.019 | **0.031** | 63.558 | **0.031** | 61.552 |
| **S9** | **0.018** | 110.872 | **0.018** | 107.604 | **0.018** | 104.655 | **0.020** | 97.797 | **0.021** | 94.667 | **0.021** | 91.866 | **0.022** | 87.950 | **0.023** | 84.720 | **0.024** | 82.023 |
| **S10** | **0.013** | 155.064 | **0.013** | 150.595 | **0.013** | 146.418 | **0.015** | 130.284 | **0.016** | 126.186 | **0.016** | 122.418 | **0.017** | 112.993 | **0.018** | 108.898 | **0.018** | 105.405 |
| **S11** | **0.005** | 386.595 | **0.005** | 376.143 | **0.005** | 365.374 | **0.008** | 260.027 | **0.008** | 252.197 | **0.008** | 244.497 | **0.010** | 197.407 | **0.010** | 190.465 | **0.010** | 184.252 |

## Significance of the fast estimated model

Both the simulated model and the fast estimated model can satisfy the predicted the target electrical resistance. The comparison of the data is listed in Table 10. It is notable that the accuracy of the predication is similar.

| Sample | $RK_P$ (Ω) | $RS_P$ (Ω) | Error percentage (%) | $RK_T$ (Ω) | $RS_T$ (Ω) | Error percentage (%) | $RK_S$ (Ω) | $Rs_S$ (Ω) | Error percentage (%) |
|---|---|---|---|---|---|---|---|---|---|
| **30S1 (K30)** | 4.461 | 4.500 | 0.9 | 4.292 | 4.300 | 0.2 | 4.178 | 4.200 | 0.5 |
| **30S2 (K15)** | 8.954 | 9.060 | 1.2 | 8.626 | 8.660 | 0.4 | 8.391 | 8.450 | 0.7 |
| **35S5 (K7)** | 19.397 | 19.450 | 0.3 | 18.630 | 18.580 | −0.3 | 18.054 | 18.140 | 0.5 |

**Table 10.** Comparison of simulated value and measured value

| Fast estimated model – **design oriented** | |
|---|---|
| Designer | ⇒ only cover factor matters |
| | ⇒ comprehensible, manageable |
| | ⇒ easy math |
| | ⇒ customized design |
| | ⇒ substitute design |
| | ⇒ reduce sampling |
| | ⇒ energy conservation |
| | ⇒ cost reduction |
| **Simulation model – production oriented** | |
| Technician | ⇒ length of conductive yarn |
| | ⇒ usage of conductive materials |
| | ⇒ cost of conductive materials |
| | ⇒ guide design and production |
| | ⇒ cost reduction |
| | ⇒ energy conservation |

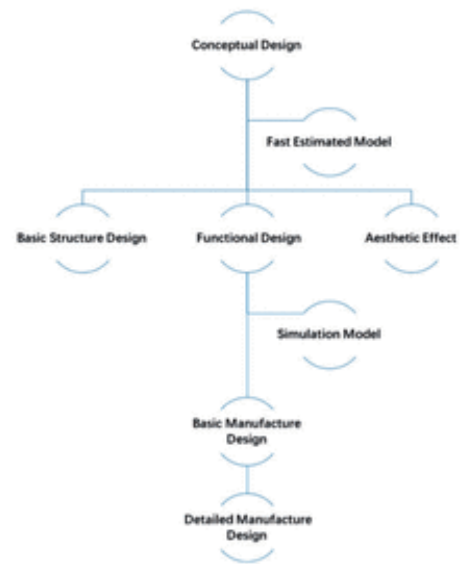


**Table 11.** Difference between the fast estimated model and the previous simulated model

The main difference between these two models is their different purposes as listed in Table 11. The proposed fast estimated model is design oriented and is suitable for the designer to adopt, since a number of fashion and textile designers have trouble understanding the mechanism and complex math during the design and development of new textile products, not to mention the thermal textile, which requires a multi-disciplinary background. It is impractical and a waste of energy and time to make them master the technology and knowledge in a short training time. Thus, a more comprehensible and manageable method is keenly required. With the fast estimated model and concepts similar to that, the designer mainly needs to focus on the textile and product rather than the complex calculation of electrical resistance or others, which can reduce the sampling, thus saving energy and money. The experience and cover factor can meet most of their needs in designing thermal products.

On the other hand, the previous simulated model is production oriented and is suitable for technicians in industry. It can predict the length of conductive yarn that will be used in production, which can help technicians during weaving preparation. It can also estimate the cost of conductive yarn, which is fairly expensive, in order to reduce waste in the weaving phase. It can adjust the design and production in advance according to the calculation as well, which can save energy and reduce emissions.

## Conclusion

This paper proposed a design-oriented fast estimated method to obtain the electrical resistance of CTWFs based on the previous production-oriented model. The cover factor was a major factor in this model. The results revealed that the proposed fast estimated model was well fitted and could well simulate the electrical resistance of CTWFs within a certain error variation. Compared to the previous model, this new model has similar accuracy. Based on this model, conductive woven fabric and equivalent fabric can be used as a substitute for different applications at optimum conditions. Designers can estimate the electrical resistance; thus, the customized design of CTWFs can be produced effectively with minimum waste.

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