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Parameter Description of the Surface Metal Fiber Arrangement of Electromagnetic Shielding Fabric

DOI: 10.5604/12303666.1228174

Abstract
The influence of the surface metal fiber (SMF) arrangement on the shielding effectiveness (SE) of electromagnetic shielding fabric (EMSF) is important, but there is no reasonable description method for it at present, making the further exploration of the relationship between SMF and SE difficult. In order to scientifically describe the SMF arrangement of EMSF, this paper constructs a binary feature matrix of SMF based on a previous study of SMF region recognition. According to the feature matrix, three parameters of the exposure ratio, the discrete mean and disorder degree are proposed and the calculation equations for the three parameters given. Experiments were designed and testing samples determined to test the SE, and the exposure ratio, discrete mean and disorder degree of each sample are calculated. The relationship between the three parameters and the SE is analysed for effectiveness validation of the three parameters. Results show that the exposure ratio, discrete mean and disorder degree can describe three aspects of the SMF arrangement: the percentage content, porosity and orientation, which are positively correlated, negatively correlated and positively correlated to the SE, respectively. The research in this paper provides a basis for the study of the shielding mechanism, the transmission model, the shielding rule and the rapid non-destructive evaluation of the EMSF, and puts forward a new idea for the study of shielding theory and the application of the EMSF.

Key words: *electromagnetic shielding fabric, surface metal fiber blends, surface metal arrangement.*

Introduction

Electromagnetic shielding fabric (EMSF) is woven from blended yarn with metal and textile fiber. Its shielding function is obtained through the reflection, multiple reflections or the loss of electromagnetic waves by the metal fibers inside EMSF. Owing to fabric characteristics of flexible shape, high strength, soft feel and light weight, EMSF has become an important new material of electromagnetic protection. The fabrics are widely produced into clothing, tents, coverings and composite material matrix, and other products. EMSFs have a wide range of applications in the fields of military, defense, medicine, electricity and health [1].

The metal fibers are exposed on EMSF because of the yarn twist and yarn hairiness. These metal fibers are called ‘surface metal fibers’. The surface metal fiber (SMF) arrangement of EMSF can reflect the internal arrangement of the metal fibers and is also an important factor determining the surface resistance of the fabric [2]. Therefore the SMF arrangement is a key factor influencing the shielding effectiveness (SE) of EMSF.

Exploring the relationship between the arrangement of SMF and the SE has very important significance. We can study the shielding performance of EMSF by the easily identifiable SMF arrangement, and avoid complex arrangement analysis of the metal fiber inside EMSF. The workload and complexity of the research are greatly reduced. The research can provide a foundation for the future shielding mechanism analysis, transmission model construction, SE variation study, relevant electromagnetic computation and non-destructive testing of EMSF.

In order to study the relationship between the arrangement of SMF and the SE, the SMF region must firstly be identified and the characteristics of the regions described with some suitable parameters. We identified the SMF region of the EMSF using computer image analysis and microscope imaging technology in our previous research period [2-3]. In the previous researches，we established an objective description method of the SMF arrangement and verified the parameters’ effectiveness by analysing their influence on the SE.

Few researchers have studied the SMF arrangement of EMSF till now, and there is not a good method to accurately and reasonably describe the SMF arrangement. The reason for this is that the SMFs of SMSF are many and entangled, and the arrangement structure is complex. At present it is difficult to find an effective method for arrangement characteristic description as well as to construct an arrangement structure of the inner metal fiber. After preliminary researches, we found that the grey of SMF on the fabric image possessed obvious high graey and low grey characteristics. The SMF is the pixel point set with a certain gray value on the image. Therefore we considered analysing the arrangement characteristic of the pixel points in the grey regions by computer image analysis technology and constructing corresponding parameters to describe the complex arrangement of the metal fiber. The method which describes the macroscopic arrangement of the metal fiber by means of the microscopic gray arrangement is new for the arrangement of the SMF of EMSF research. Existing related researches focus on performance testing and evaluation [4-5], shielding model construction [6-7], structure influence [8-9], numerical calculation [10-11], influence analysis [12-13], production development [14-16] and testing research [17]. Nevertheless there have been related researches of the relationship between the SE and density [18], tightness [19] and metal fiber content [20]. However, most of these studies explored the influence of structural parameters on the SE at the macroscopic level. No detailed information about the relationship between the SMF arrangement and SE is available in current literature.

In order to scientifically describe the SMF arrangement of EMSF, three parameters i.e. the exposure ratio, discrete mean and disorder degree, which are related to the SMF arrangement, are proposed based on the binary feature matrix of the SMF constructed in the previous study. The relationship between the three parameters and the SE of the EMSF is explored to determine the parameters' effectiveness. Finally we also highlight the research trend for the SMF arrangement and point out the research value.

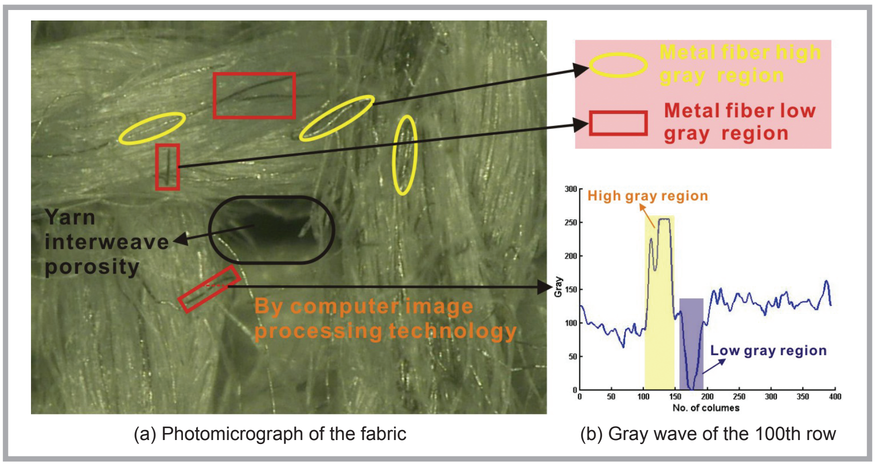

Figure 1. Surface metal fiber of EMSF.

SMF description of EMSF

SMF matrix

When observing a number of enlarged images surface of EMSF, we find that the grey of the metal fiber region possesses long and narrow features with low greyness (see the metal fiber in the rectangular box in ***Figure 1***) and long and narrow features with high greyness (see the metal fiber in the oval box shown in ***Figure 1***). Therefore we build a grey identification metal fiber region (see the metal fiber in the oval box shown in ***Figure 1.b***) according to the three features above (edge condition, width condition, and grey condition) and make a logic operation [2].

After the SMF region of the EMSF is identified, let the grey of the pixel points in the SMF region be g_m, and the gray of the pixel points in other regions be g_f, then the image of the EMSF is converted into a binary feature matrix composed of g_m and g_f. There are $N \times M$ elements in the matrix, and then the matrix F_B is expressed as:

$$F_B = \begin{vmatrix} g_x & g_f & \cdots & g_f \\ g_f & g_x & \cdots & g_x \\ \cdots & \cdots & \cdots & \cdots \\ g_f & g_x & \cdots & g_f \end{vmatrix}_{N \times M} \quad (1)$$

From above matrix, the pixel points in the metal fiber region are denoted by the same gray value, and the pixel points in other regions are denoted by another grey value. We can easily determine the positions of all pixel points in the metal fiber region. Therefore the parameters describing the SMF arrangement feature are constructed combined with the whole condition of the surface pixels. According to electromagnetic wave theory [21], the SE of EMSF is closely related to the content, porosity and direction consistency of the metal fiber. We propose three related parameters i.e. the exposure ratio, discrete mean and disorder degree according to parameters describing the SMF arrangement feature from ***Equation (1)***.

Exposure ratio of SMF

The exposure ratio, denoted by cov_m, refers to the ratio of the metal fiber area to the total area, and reflects the percentage content of metal fiber in the fabric surface. The method is simple, and we only calculate the ratio of the number of pixel points in the metal fiber area to the total number of pixel points. If the number of pixels points with a g_m gray value in matrix F_b is N_{metal}, then the exposure ratio is calculated as:

$$\mathrm{cov}_m = \frac{N_{metal}}{N \times M} \quad (2)$$

Discrete mean of SMF

The discrete mean, denoted by dis_m, represents the average value of the distance between the metal fibers, and reflects the degree of overall dispersion among them. We can use vertical and horizontal scanning methods.

Figure 2 shows some metal fibers of the binary feature image of the fabric surface. ***Figure 2*** is only a schematic diagram for explaining the method of parameter calculation, and does not represent s diagram of the SMF of a specific fabric. The SMF matrix built by the gray identification method proposed only possesses two values, the high gray value and low gray value. Therefore the following method in this paper is applied for the SMF analysis of any fabric.

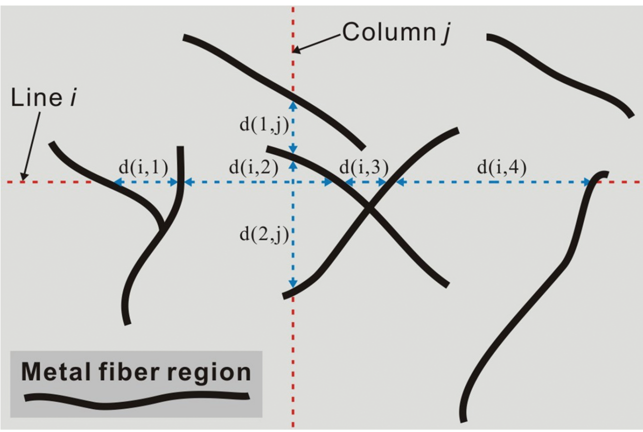

Figure 2. Schematic diagram of discrete mean.

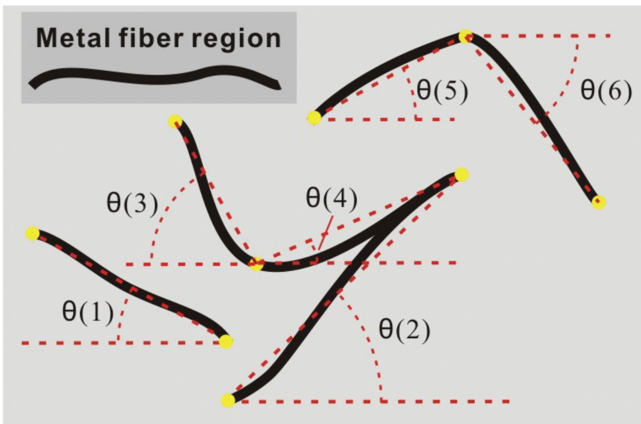

Figure 3. Schematic diagram of disorder degree.

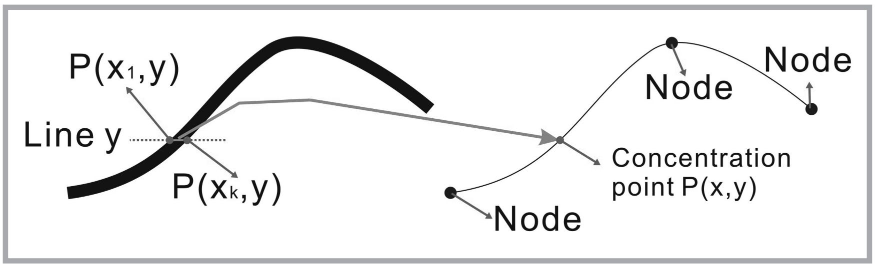

Figure 4. *Fiber region normalization, a) metal fibre region origin, (b) concentrate line of metal fibre region.*

However, *Line i* is a scanning line of any horizontal direction. We can easily calculate the distance between all adjacent metal fibers on the scanning line according to the position of the feature value of the metal fiber, such as $d(i,1)$, $d(i,2)$, $d(i,3)$ and $d(i,4)$. Similarly *Column j* is a scanning line of any vertical direction. We can calculate the distance between all adjacent metal fibers on the scanning line according to the feature value of the metal fiber, such as $d(1,j)$ & $d(1,j)$. From ***Equation (1)***, the number of the horizontal scanning line is N, the number of the vertical scanning line M, let the number of the distance between adjacent metal fibers of the i scanning line be $k(i)$, and the number of the distance between adjacent metal fiber of the j scanning line be k'(j), then the dispersion can be calculated as:

$$dis_m = \frac{\sum_{i=1}^{N}\sum_{j=1}^{k(i)} d(i,j) + \sum_{i=1}^{M}\sum_{j=1}^{k'(i)} d(j,i)}{\sum_{i=1}^{N} k(i) + \sum_{j=1}^{M} k'(j)} \quad (3)$$

Disorder degree of SMF

The disorder degree, denoted by ori_m, reflects the consistency of the fiber arrangement, and represents the consistency of overall arrangement angles of the metal fibers. We use the variance of the 'fiber segment' angle in the binary feature image to denote the parameter.

The 'fiber segment' refers to the positive growth segment and negative growth segment in the fibers. For many metal fibers, there is only a segment in the total fibers, such as the two corresponding fibers of the two angles $\theta(1)$ & $\theta(2)$ in ***Figure 3***. For several fibers, there are several segments in the total fibers, such as the corresponding fibers of angles $\theta(3)$ & $\theta(4)$ and angles $\theta(1)$ & $\theta(2)$.

In order to segment the fibers, the fibers undergo normalisation, in which the fiber region with a several point width is abstracted into a segment with only a pixel point width. As shown in ***Figure 4***, the left diagram is the original image of the metal fiber region, and the right is the normalisation image. *Line y* refers to the y line in the metal fiber region, and the pixel points on the line of the metal fiber region are $P(x_1, y)$, $P(x_2, y)$,..., $P(x_{k-1}, y)$ & $P(x_k, y)$, where k is the total number of metal fiber points on the line. Then the corresponding point $P(x, y)$ after normalization can be expressed as:

$$P(x,y) = \frac{\sum_{i=1}^{k} P(x_i, y)}{k} \quad (4)$$

Let us suppose a point on the metal fiber curve after normalisation is $P_N(x_n, y_n)$, y_{n-i} the left adjacent point of point y_n, and y_{n+i} is the right adjacent point of point y_n, then:

$$\sum_{i=1}^{h}(\text{sign}(y_n - y_{n-i}) \times \text{sign}(y_n - y_{n+i})) = h \quad (5)$$

Where, $\text{sign}(y_n - y_{n-i})$, i = 1,2,...$h$ has the same sign, and $\text{sign}(y_n - y_{n+i})$, also has the same sign. The reason to set parameter h in ***Equation (5)*** is to expand the scope of the decision points and avoid a short fiber segment. Experiments proved that the value of parameter h could be adjusted from 3 to 10.

Supposing the number of metal fiber segments of the total image is N_{sec} after analysis according to the methods above, the start node of any segment is $P_{N\_i}(x_s, y_s)$, and the end node is $P_{N\_i}(x_e, y_e)$, then the horizontal angle $\theta(i)$ of any segment can be obtained as:

$$\theta(i) = arctg\left(\left|\frac{y_e - y_s}{x_e - x_s}\right|\right) \quad (6)$$

Therefore the disorder degree of the metal fiber is:

$$ori_m = \sqrt{\frac{\sum_{i=1}^{N_{\text{sec}}}(\theta(i) - \bar{\theta})^2}{N_{\text{sec}}}} \quad (7)$$

Where,

$$\bar{\theta} = \frac{\sum_{i=1}^{N_{\text{sec}}} \theta(\text{i})}{N_{\text{sec}}} \quad (8)$$

Table 1. *Specifications and calculation results of parameters of SMF of samples.*

Number	Fabric weave	Yarn density	Metal fiber content of single yarn, %	Fabric density, ends/10 cm	Exposure ratio	Discrete mean	Disorder degree
1#	Plain	23.5 tex	25%	140×156	0.039	239.4	0.415
2#			25%	189×136	0.043	219.8	0.416
3#			25%	262×102	0.048	184.4	0.417
4#			30%	307×96	0.064	131.7	0.420
5#			30%	208×200	0.077	130.1	0.422
6#	Twill		25%	190×114	0.053	351.2	0.416
7#			25%	145×244	0.061	293.3	0.417
8#			25%	250×181	0.068	286.6	0.418
9#			30%	192×171	0.069	250.4	0.419
10#			30%	306×105	0.078	217.2	0.420
11#	Satin		25%	137×150	0.043	256.8	0.416
12#			30%	188×84	0.049	216.2	0.417
13#			25%	194×190	0.058	210.1	0.418
14#			25%	196×208	0.061	199.1	0.418
15#			30%	320×144	0.084	63.6	0.421

Validation experiments

Experimental methods

Five high power surface images of each of the samples with plain, twill and satin weaves are obtained by a VHX-600 high power microscope (KEYENCE Company, Japan). The images are identified and binary feature matrixes obtained by the MATLAB 7.5 program according to the algorithm proposed. The exposure ratio, discrete mean and disorder degree of SMF of the samples are calculated according to ***Equations (1)-(8)***. The SE values of the samples are tested using a DR-S02 shielding effectiveness instru-

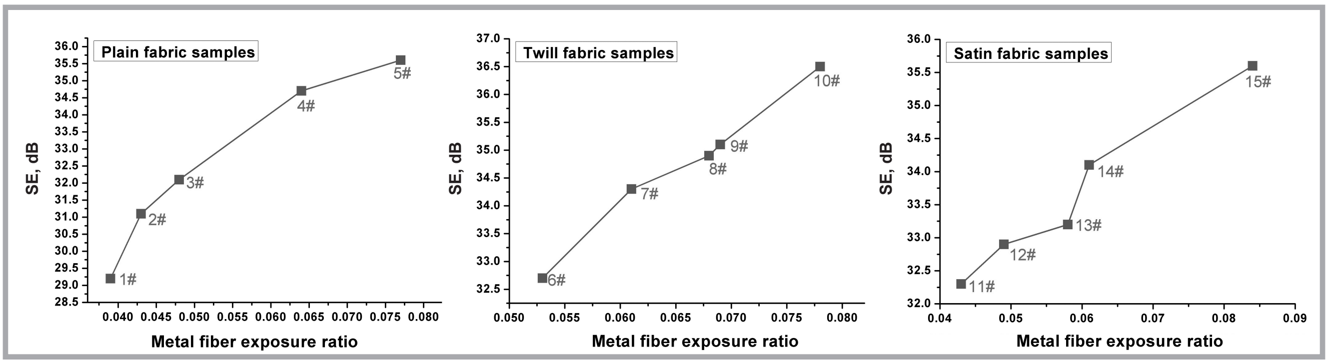

Figure 5. *Relationship between exposure ratio of SMF and SE (f = 1 GHz).*

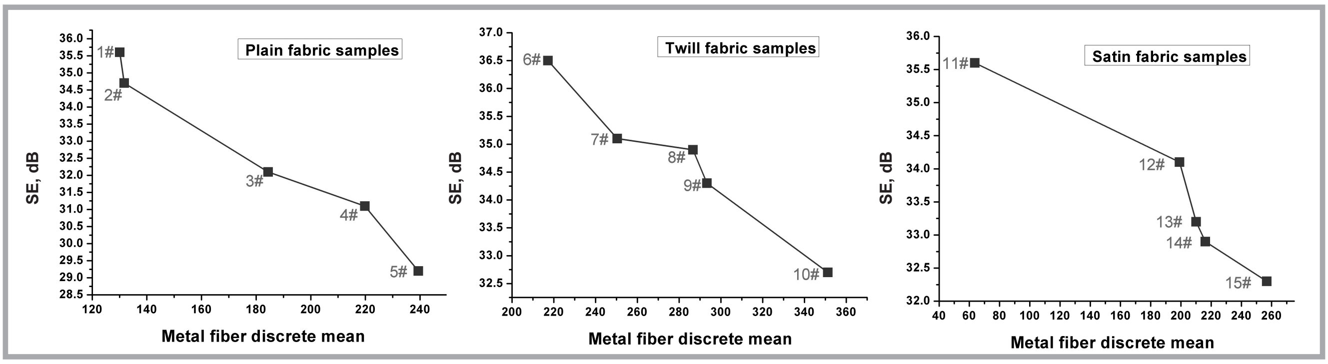

Figure 6. *Relationship between the discrete mean and SE (f = 1 GHz).*

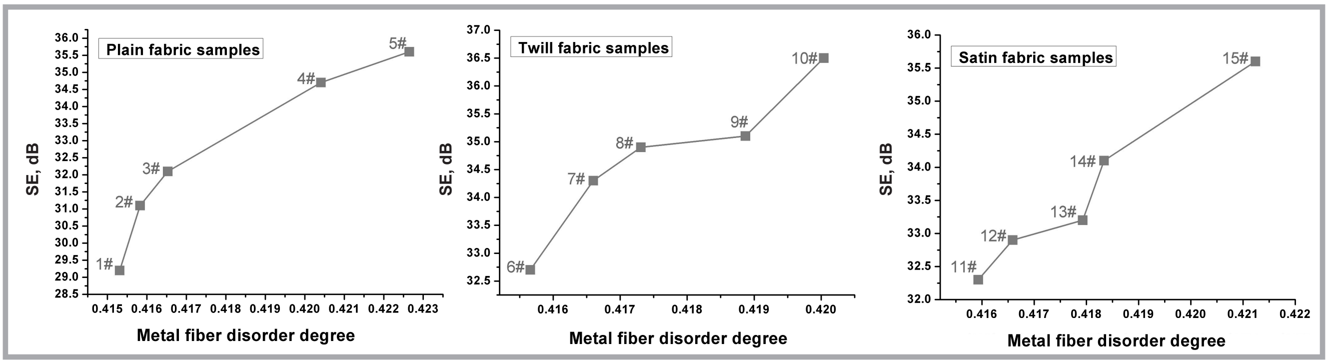

Figure 7. *Relationship between disorder degree and SE (f = 1 GHz).*

ment (Beijing Dingrong Co. Ltd, China), and the frequency range is selected from 30 MHz to 1.5 GHz. A DR-S02 shielding effectiveness instrument is made according to the coaxial planar shielding method (ASTM4935 standard), as recommended by the American National Bureau of Standards (NBS). The coaxial planar method is a popular test method for the SE of electromagnetic shielding material. Characteristics of the method are a wide testing range, small size of the testing sample, good testing reproducibility and low testing cost. The method is widely applied for the SE test of t shielding fabric, sheet metal, metal mesh, conductive glass, conductive medium flat panels and other electromagnetic shielding materials. According to the experiments above, we explore the relationship between the SE and the exposure ratio, discrete mean and disorder degree of SMF of the samples and determine the effectiveness of the parameters.

Experimental materials

We select blended yarn and weave samples on an SGA598 sample loom (Jiangyin Tongyuan Textile Machinery Co. Ltd., China). The blended materials are stainless steel fibers, polyester fibers and cotton fibers, and the blending proportions of the blended yarns are two kinds: 25%/45%/30% and 30%/40%/30%. The yarn linear density is 23.5 *tex*×2. Details of the densities of the samples and the parameters of the SMF are listed in ***Table 1***.

Measured data

The specific density and parameters of SMF of the samples are tested using a Y511B density tester (Changzhou First Textile Equipment Co. Ltd, China). The SMF regions of the EMSF are analysed and the parameters of the exposure ratio: the discrete mean and disorder degree are calculated using MATLAB7.5 according to the algorithm proposed. The results are listed in ***Table 1***, and the SE testing results of the samples are shown in ***Figures 5-7***.

Analysis and discussion

Influence of SMF exposure ratio on SE

Figure 5 shows a graph of the relationship between the SE and exposure ratio of the samples. We only illustrate the graph at 1 GHz frequency because the relationships between the SE and parameters of the SMF are consistent from 30 MHz frequency to 1.5GHz frequency. ***Figures 6-7*** also are also shown based on this. From ***Figure 5***, it is observed that the exposure ratio of the SMF is positively correlated to the SE. Although details of the mathematical expressions remain to be studied, it can be sufficiently explained that the exposure ratio is the parameter of the SMF arrangement describing the SE of EMSF.

We can also explain the effectiveness of the exposure ratio parameter from the definition. The exposure ratio is obtained by calculating the number of pixel points of the SMF of the EMSF, representing the percentage content of the SMF. A higher exposure ratio results in a higher content of the SMF per unit area and a greater metal fiber content of the entire fabric per unit area. Therefore more shielding fibers bring about a greater shielding effect of the fabric.

The phenomenon from ***Figure 5*** can also be analysed from the electrical communication of the fabric. The contact points among the metal fibers increase with an increase in the exposure ratio, forming a good effect of electrical communication among metal fibers and significantly improving the conductivity of the fabric. According to electromagnetic theory [21], the electromagnetic shielding material will produce induced current by way of an incident electromagnetic wave. The electric and magnetic fields produced by the induced current are quite the opposite to the electric and magnetic fields of the incident electromagnetic wave, playing a consumption role in the incident electromagnetic wave. When the electrical conductivity increases, the induced current will also rise, and the electrical and magnetic fields opposite the incident electromagnetic wave also increase; hence, the fabric can consume more electromagnetic waves and the fabric achieves a higher SE. Therefore the exposure ratio reflects the electrical communication of the fabric. A higher exposure ratio means a better conductivity performance, higher induced current and better SE of the fabric.

Influence of SMF discrete mean on SE

Figure 6 is the graph between the discrete mean and SE of the samples. From ***Figure 6***, it is noticed that the discrete mean is negatively correlated to the SE. Although the negative correlation needs continued study, ***Figure 6*** illustrates the relation between the discrete mean and EMSF and can prove the effectiveness of the parameter for the SMF arrangement feature.

In fact, according to the given definition, the discrete mean refers to the interstice size of the SMF arrangement. The higher the discrete mean value, the larger the distance between the metal fibers. Furthermore the larger interstice size between metal fibers of the EMSF results in more leakage of the electromagnetic wave [1, 7] and a lower SE value of the fabric. Therefore the discrete mean is a reasonable parameter describing the SMF arrangement of EMSF from a theoretical viewpoint. The reason for this phenomenon can also be explained from the interstice change in the fabric. An increase in the discrete mean produces an increase in the average distance of metal fibers, making the interstice among the metal fibers increase. According to electromagnetic theory [21], the materials will lose the shielding effect because of the full transmission when the incident electromagnetic wave enters into the medium porosity and the wavelength is smaller than the diameter of the pores. The electromagnetic wave will cause a coupling effect when the wavelength is larger than the diameter of the pores, leading to a lot of electromagnetic energy leakage and a decrease in the shielding effect of the fabric. Therefore a higher discrete mean results in a larger interstice among the metal fibers, leading to an increase in the transmission coefficient of the fabric and decrease in the overall SE of the fabric.

Influence of SMF disorder degree on SE

Figure 7 illustrates the graph between the disorder degree of the SMF and SE. From ***Figure 7***, it is observed that the relationship between the disorder degree of the SMF and the SE is close. Under normal conditions, the SE of the fabric increases with an increase in the disorder degree of the SMF. The results can also be explained from a theoretical angle. According to the definition of the disorder degree, it is the variance of the direction consistency of the SMF, and a higher disorder degree means more dispersion of the angle between the radial direction and the horizontal or vertical direction of the metal fiber. The direction consistency of the metal fiber is bad as the metal fibers are distributed in different directions and they lack a major, centralised distribution angle, and thus the arrangement structure of the metal fibers is messy: they are interlaced, connection points among them increase and the conductivity of the EMSF increases, making the SE of the EMSF rise. According to electromagnetic theory, the shielding effect is determined by the two electromagnetic parameters of electrical conductivity and magnetic permeability [22]. The shielding effect of EMSF, whose main shielding function is reflection, is determined by the electrical conductivity. The electrical conductivity and SE of the fabric increase when the disorder degree increases. Therefore it is proved that the disorder degree parameter is a scientific parameter to describe the SMF arrangement of EMSF from experimental and theoretical viewpoints.

Summary and conclusions

This study comprises a new research field for the theory and application of EMSF. The existing shielding mechanism of EMSF is not clear. The research provides new ideas for the description of the SMF arrangement and provides a basis for the study of the shielding and absorption mechanism. The electromagnetic parameters of EMSF need to be known whenever we use the finite element method, transmission line method, FDTD method or method of moments. The research provides a basis for the construction of electromagnetic parameters and a transmission model. The SMF arrangement determines the shielding and absorption rule of EMSF, and they influence the transmission coefficient, reflection coefficient and reflection angle. The research of the SMF arrangement also provides an important basis for the study of the shielding and absorption rule. The research reveals the relationship between the SMF arrangement and SE and constructs a related electromagnetic computation method, providing the basis for the study of nondestructive evaluation of EMSF. The main conclusions are summarised as follows:

1) The exposure ratio cov_m of SMF proposed can describe the percentage content of the SMF of EMSF, and is positively correlated to the SE of the EMSF.
2) The discrete mean dis_m of SMF proposed can represent the porosity of the SMF of EMSF, and negatively relates to the SE of the EMSF.

3) The disorder degree ori_m of the SMF proposed can present the orientation of the SMF of EMSF, and the SE of the EMSF increases with an increase in the disorder degree.
4) The effectiveness of the exposure ratio, discrete mean and disorder degree parameters, which describe the SMF arrangement of the EMSF, is satisfactory. The research is valuable and provides a basis for the study of the theory and application of EMSF.

Acknowledgement

This research was supported by the National Natural Science Foundation of China (Grant No.61671489, Grant No.61471404) and was supported by the University Key Scientific Research Project Plan of Henan Province (No.16A540002)

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Received 24.02.2015 Reviewed 28.04.2016