FDTD Numerical Calculation of Shielding Effectiveness of Electromagnetic Shielding Fabric Based on Warp and Weft Weave Points

Zhe Liu and Xiuchen Wang

Abstract—**In this article, the finite-difference time-domain (FDTD) method is used to study the scientific numerical calculation method of the shielding effectiveness (SE) of the electromagnetic shielding (EMS) fabrics. First, the fabric is divided into overlapping region, longitudinal single yarn region, transverse single yarn region, and interstice region of the warp (weft) weave points according to the yarn arrangement characteristics of the warp and weft weave points. Then, a structure model of the fabric is established based on the warp and weft weave points and the fabric weave. The partition coefficient and discrete method of Yee's grid is determined. The electromagnetic parameters of the grid are measured by the coaxial transmission/reflection method, and the appropriate absorption boundary conditions, excitation sources, and constraints are set to establish the physical model of the fabric. Finally, the physical model is numerically calculated to obtain the SE using EastFDTD electromagnetic calculation software. The contrastive analysis of the numerical simulation and the measured data is made combining the theory. The accuracy of the numerical simulation results, the correction method of the discrete factor, and the reason of the error are discussed. It is concluded that the model has been satisfied with the numerical calculation of the SE of the EMS fabric.**

Index Terms—**Electromagnetic shielding (EMS) fabric, finite difference time domain (FDTD), numerical calculation, shielding effectiveness (SE), warp and weft weave point.**

I. Introduction

ELECTROMAGNETIC shielding (EMS) fabric with the advantages of softness, variety, high strength, and low cost is a new type of artificial electromagnetic medium, which is widely applied in the fields of electromagnetic compatibility (EMC) and electromagnetic protection [1]. Shielding effectiveness (SE) is an important index to measure the shielding performance of the EMS fabric, and the SE value is mainly obtained by the experimental testing at present. Because of the softness of the fabric, the thickness and density of the fabric are often changed greatly during testing resulting in the instability of the testing results, which greatly interfere with the measurement of the shielding performance of the EMS fabric. In addition, the testing SE of the EMS fabric can only be obtained after the production of fabrics. In actual production, the SE of the fabric can be predicted during the fabric design in order to develop the EMS fabric with satisfied shielding requirements, high efficiency, and low cost. Therefore, it is an urgent problem to study scientific and effective numerical methods to predict and evaluate the SE of the EMS fabric. This research not only has important academic reference value for the theoretical research of the EMS fabric but also has important guiding significance for the design, production, testing, and evaluation of the EMS fabric.

It is difficult to effectively describe the structures and electromagnetic parameters of the EMS fabric because of the complex, flexible, and nonuniform spatial arrangement of the shielding fibers in the fabric. There is no numerical calculation method for the SE of the EMS fabric based on the arrangement of microfibers or yarns and there are also few related literatures at present. Literatures [1] and [2] studied the fast calculation of the SE of the EMS fabrics using equivalent medium theory. They gave a prediction method of the SE based on equivalent coefficient and analytical method to calculate the SE of the planar fabric and the fabric with holes. In literature [3], a grid model and two-dimensional (2-D) array were established according to the arrangement characteristics of metal yarns. A fast calculation method of the SE of the EMS fabric was established by analytic deduction method. The influencing factors were analyzed and a certain achievement had been obtained. Literature [4] introduced advanced 3-D time-domain tools for describing composite structures in EMC environment. They hoped to use reliable and accurate digital tools to characterize electromagnetic materials and lay a foundation for the calculation of the relevant electromagnetic parameters. In [5], the performances of the PP/stainless steel staple metal fiber blended EMS fabric were calculated using the aperture equation based on the concept of waveguide. They verified the validity of the numerical model for the SE prediction. In literature [6], the influence of the radiation frequency, metal content, metal mesh size, and geometric size on the SE of the composite fabrics was studied in the frequency range of 15–3000 MHz by coaxial transmission line method. The significance of these factors was tested by analysis of variance, and the accuracy and practicability of the model were verified. In addition to the above reports, most

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of the prediction of the SE focuses on other fields of the power, electricity, and electronic information, such as the calculation of the SE of various industrial cabinets [7]–[9], the SE calculation of different types of wire mesh [10], and the research of the microstructure of the conductive fibers for the establishment of the SE calculation model [11]–[13]. Although above studies have not directly studied the calculation methods of the SE of the EMS fabrics, the electromagnetic calculation methods and the microcharacterization methods of the fibers parameters provide useful references for this article. Other studies on the SE of the EMS fabrics focus on the structural characteristics [14], [15], the performance improvement [16], [17], the discussion of the influencing factors [18], [19], the performance evaluation [20]–[22], new product development [23]–[25], and new process research [26]–[28]. Although no specific calculation model is involved, the analysis of the SE provides a certain reference value for this research.

It can be seen that the theoretical calculation of the SE of the EMS fabric is less at present. The correlation calculation is only estimated from the surface arrangement of yarns according to the experimental values or rough analytic formulas, which lacks the scientific quantitative calculation research based on the essence of the electromagnetic characteristics. We consider that the numerical method suitable for the EMS fabric must meet the following three requirements:

1) the actual fabric structure is expressed with minimal errors;
2) the electromagnetic parameters of the division mesh are easy to obtain;
3) the solving process is stable.

Therefore, finite-difference time-domain (FDTD) method is chosen to calculate the EMS fabric in this article.

However, the application of the FDTD in the EMS fabrics has rarely been reported up to now. We have tried to apply the FDTD to the calculation of electromagnetic parameters of the fabrics for the first time, and have proposed the model based on the warp and weft density [29] and a calculation model based on overlapping region, single yarn region, and interstice region [30]. The numerical simulation calculation of the plain weave, twill weave fabrics was carried out using above two structural models and a certain achievement was obtained. However, the two methods are relatively simple and achieve ideal results for simpler fabrics. The complex feature regions of the fabric and the changes of the fabric weave are not taken into account, the fabric with complex weaves cannot be calculated ideally, resulting in the application of these two methods is greatly limited.

In summary, there is no mature method for the SE calculation of the EMS fabric. This article proposes an FDTD method based on the warp and weft weave points to calculate the SE of the EMS fabric on the basis of previous studies. First, the fabric is divided into overlapping region of the warp (weft) weave point, longitudinal single yarn region of the warp (weft) weave point, transverse single yarn region of the warp (weft) weave point, and interstice region according to the yarn arrangement characteristics of the warp and weft weave points. The structural models of the fabric are established according to the warp and weft weave points and weave characteristics. The partition coefficient and discrete method of Yee's grid is determined according to the structural parameters of the model. The coaxial transmission/reflection method is used to measure the electromagnetic parameters of the grid, and the appropriate absorption boundary conditions, excitation sources, and constraints are set to establish the physical model of the fabric. The actual testing is used to verify the above model, and it is concluded that the method can calculate the SE of the EMS fabric well.

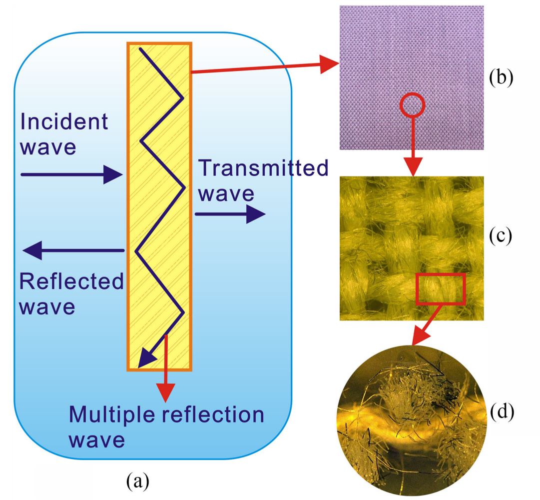

Fig. 1. Shielding principle and characteristic of electromagnetic wave by EMS fabric. (a) Shielding principle diagram of fabric. (b) Fabric. (c) Enlargement diagram of fabric. (d) Local cross section.

II. Structural Model of EMS Fabric

A. Shielding Principle and Characteristics of EMS Fabric

As shown in Fig. 1, the shielding effect of the EMS fabric is mainly caused by adding the shielding fibers such as stainless steel fibers, silver-plated fibers, and copper–nickel-plated fibers. As shown in Fig. 1(a), after the incident of electromagnetic wave, only a small amount of electromagnetic wave penetrates through the fabric due to the reflection and multiple reflection of a large number of shielding fibers, forming the shielding of the electromagnetic wave. Inevitably, there will be tiny interstices in fabrics because of the interwoven by yarns and the regularity of the fabric, as shown in Fig. 1(c). In addition, the shielding fibers show complex arrangement at the microlevel because the yarn is blended by fibers. As shown in Fig. 1(d), the black fibers are the shielding fibers. Therefore, it is necessary to find an appropriate and effective method for theoretical accurate numerical calculation of the EMS fabrics with the characteristics of soft and changeable, a large number of microvoids, regular macroyarn arrangement, and complex microshielding fiber arrangement.

FDTD algorithm is a direct time-domain method for solving Maxwell differential equation. The algorithm possesses many advantages of the accuracy, the analysis speed, and the application scope. Especially, the FDTD is suitable for the analysis of electromagnetic problems of the arbitrary 3-D materials. So, it has become a new hotspot method in the field of electromagnetic engineering and academia, and has many applications in many

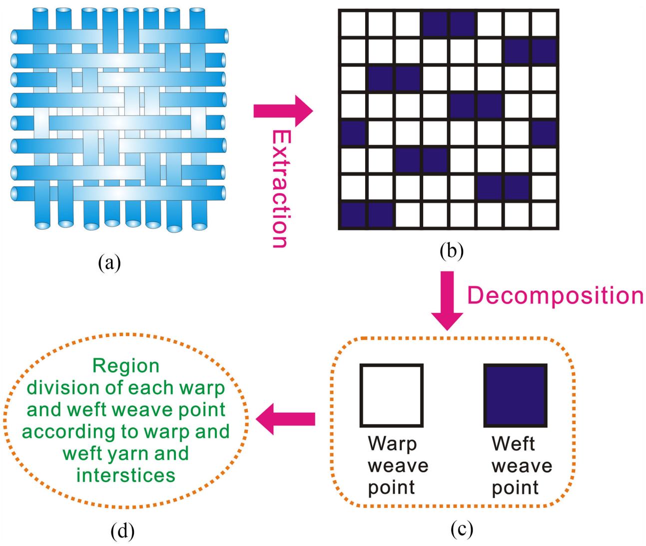

Fig. 2. Region division method for any EMS fabric based on warp and weft fabric weave. (a) Any fabric weaves. (b) Minimum weave. (c) Warp and weft weave points. (d) Region division of FDTD.

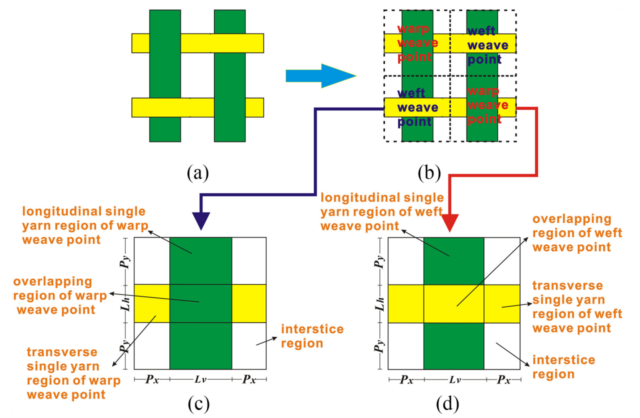

Fig. 3. Region division based on warp and weft weave point. (a) Minimum weave. (b) Weave diagram. (c) Division schematic diagram of the warp weave point. (d) Division schematic diagram of the weft weave point.

fields [31], [32]. The electromagnetic numerical calculation of the fabrics should possess the requirements that it can express the actual structure of the fabrics, can easily obtain grid electromagnetic parameters, and possesses less computational resources and stable solution process. The FDTD better possesses above characteristics than other methods such as moment method, finite-element method, transmission line method, and analytical method, and is suitable for soft and changeable fabrics with small size and regular shape characteristics. The method is also suitable for the problem of the EMS analysis. Therefore, FDTD is used to analyze and calculate the fabrics in this article.

B. Structural Characteristics Analysis of Fabric

One of the key problems to the SE calculation of the EMS fabric by the FDTD is the construction of the structural model. The EMS fabric is soft and deformable, and the arrangement of the shielding fibers presents a complex spatial structure, but follows a certain rule at the same time. In this article, considering the different characteristics of the electromagnetic parameters of the weft and warp weave points, the weave points are regarded as different physical regions to establish the structural model and physical model of the fabric. Fig. 2 shows a method of the regions division for any EMS fabrics based on the warp and weft fabric weave point. Fig. 2(a) shows the type of any fabric weaves. Fig. 2(b) shows the minimum weave extracted by the weave of Fig. 2(a), and the fabric is formed by many minimum weaves. Fig. 2(c) shows the warp and weft weave points extracted from the minimum weave.

Fig. 3 shows a region division method of the structural model of the plain weave established according to the method in Fig. 2. Fig. 3(a) shows the structural diagram of the minimum weave of the fabric, Fig. 3(b) shows the weave diagram of the fabric, Fig. 3(c) shows the schematic diagram of the warp weave point, and Fig. 3(d) shows the schematic diagram of the weft weave point. It can be observed from Fig. 3 that the type of the partition region has the following characteristics according to the warp and weft weave points: 1) Because of difference of the density of the warp and weft yarns, the arrangement structure and the order of upper and lower coverage of the weft weave point and warp weave point are different. The electromagnetic parameters of the weave points are different, which can well reflect the actual fabric structure. 2) The sizes of the warp and weft weave points are the same. The transverse region of the warp and weft weave points belongs to the same type of the region, and the longitudinal region of the warp and weft weave points belongs to the same type of the region. Therefore, any part of the fabric can be expressed by five types of the region: overlapping region of the warp weave point, overlapping region of the weft weave point, transverse single yarn region, longitudinal single yarn region, and interstice region.

C. Establishment of Structural Model

As shown in Fig. 3, a 3-D rectangular coordinate system is established in the weft direction of the fabric as the X-axis, the warp direction as the Y-axis, and the vertical direction of the fabric as the Z-axis. The widths of different regions of the warp weave point and the weft weave point along the X-axis are P_x, L_v, and P_y, the widths of different regions along the Y-axis are P_y, L_h, and P_y, the thickness of all the regions in the Z-direction is the same, and the values are uniformly expressed as T_z. The 3-D size of the overlapping region of the warp weave point and the weft weave point can be expressed as $L_v \times L_h \times T_z$, the horizontal single yarn region can be expressed as $P_x \times L_h \times T_z$, the longitudinal single yarn region can be expressed as $L_v \times P_y \times T_z$, and the interstice region can be expressed as $P_x \times P_y \times T_z$. Let the warp density and weft density of the fabric are D_v and D_w, the diameters of the weft and warp yarn are d_v and d_w; they can be calculated as [33]

$$L_v = d_v \tag{1}$$

$$L_w = d_w \tag{2}$$

$$P_x = \frac{\frac{10}{D_v} - L_v}{2} \tag{3}$$

$$P_y = \frac{\frac{10}{D_w} - L_y}{2}. \quad (4)$$

The warp and weft yarn densities are set by T_v and T_w, respectively, C_v and C_w be the diameter coefficient of the warp and weft yarns, then

$$L_v = d_v = C_v\sqrt{T_v} \quad (5)$$

$$L_w = d_w = C_w\sqrt{T_w}. \quad (6)$$

Substituting (5) and (6) into (3) and (4), the following results are obtained:

$$P_x = \frac{\frac{10}{D_v} - C_v\sqrt{T_v}}{2} \quad (7)$$

$$P_y = \frac{\frac{10}{D_w} - C_w\sqrt{T_w}}{2}. \quad (8)$$

Suppose the numbers of the warp and weft weave points are N_v and N_w in a fabric weave. For different weaves, a matrix is consisted of R_v warp weave points and R_w weft points as elements. The value of the row number M and column number N is determined by the type of the fabric weave, which is satisfied as

$$N_v + N_w = N \times M. \quad (9)$$

For further Yee's grid, it is necessary to determine the relative positions in different regions of each point (x, y, z) within each weave point to obtain the specific width, length, and height of the grid in three directions, which can be calculated as

$$\begin{aligned} &F(x, y, z) \\ &= \sum_{i=1}^{N}\sum_{j=1}^{M} \delta(x - (j-1)P_x - 2(j-1)L_v, \\ &\quad y - (i-1)P_y - 2(i-1)L_h, z). \end{aligned} \quad (10)$$

The specific locations of the warp and weft weave points are obtained according to the type of the weaves to determine the corresponding electromagnetic parameters of each point (x, y, z) in (10).

III. Construction of Physical Model

A. Yee's Grid Partition

The continuum must be divided into several Yee's grids in space in order to establish the difference equation. Let Δx, Δy, and Δz are the space steps of three coordinate axes of x, y, and z, respectively. Δt is the time step. $f(x, y, z, t)$ represents a component of *E* or *H* in a rectangular coordinate system. The discreteness in time and space domain can be expressed as [30]

$$f(x, y, z, t) = f(i\Delta x, j\Delta y, k\Delta z, n\Delta t) = f^n(i, j, k). \quad (11)$$

In order to divide the structure model of the EMS fabric shown in (10) into Yee's grids that can establish curl Maxwell equation, a discrete factor γ is introduced to divide the grids of the weave region into uniform square grids in 3-D space. Let ε be the division accuracy of the grid, and then λ be satisfied as

$$\begin{aligned} &\left|\text{int}\left(\frac{P_x}{\gamma}\right) - \frac{P_x}{\gamma}\right| \approx \left|\text{int}\left(\frac{P_y}{\gamma}\right) - \frac{P_y}{\gamma}\right| \approx \left|\text{int}\left(\frac{L_v}{\gamma}\right) - \frac{L_v}{\gamma}\right| \\ &\approx \left|\text{int}\left(\frac{L_h}{\gamma}\right) - \frac{L_h}{\gamma}\right| \approx \left|\text{int}\left(\frac{T_z}{\gamma}\right) - \frac{T_z}{\gamma}\right| \leq \varepsilon. \end{aligned} \quad (12)$$

The value of ε is generally taken as $\frac{1}{10^n}$. The greater the value of n is, the higher the accuracy will be. The solution of the discrete factor γ is the key process. The value of the discrete factor is in a range that can be selected according to the calculation speed requirement under the condition of the conformity equation (12). The smaller the value of γ is, the more accurate the calculation will be, but the amount of calculation will also increase substantially.

B. Boundary Conditions Setting

The distribution of the field amplitude near the fabric has the same periodicity because of the periodic array structure of the EMS fabric. A cyclic element of the structure model of the EMS fabric is intercepted. Periodic absorption boundary is set in the x-axis direction and the y-axis direction, and the PML absorption boundary is set in the z-axis direction.

The recursive formula of the field components suitable for the periodic boundary conditions of the EMS fabric can be obtained according to Floquet's theory. Let the plane wave incident vertically on the surface of the EMS fabrics, the incident direction is the negative direction along the z-axis direction, the direction of the electric field is parallel to the x-axis, and the direction of the magnetic field is parallel to the y-axis direction. According to the grid discrete of (11), (12), and Maxwell's equations, the electric field components E_x, E_y, and E_z on the periodic boundary under the 2-D periodic structure can be calculated by the transformation of the electric field intensity on the periodic boundary under the 2-D periodic structure. Fig. 4 shows the diagram of the periodic structure of fabrics. Suppose the distance between the points *A* and *B* along the x-axis direction is T_x, and the distance between points *C* and *D* along the y-axis direction is T_y, that is $x^B = x^A + Tx$, $y^D = y^C + T^y$, then the field intensity is conversed as

$$\varphi(x^B, y, t) = \varphi\left(x^A, y, t - \frac{T^x}{\nu\phi x}\right) \quad (13)$$

$$\varphi(x, y^D, t) = \varphi\left(x, y^C, t - \frac{T^y}{\nu\phi y}\right) \quad (14)$$

where $\nu\phi x = c/(\sin\theta\cos\phi)$ and $\nu\phi\text{y} = c/(\sin\theta\sin\phi)$ be the phase velocity of the plane electromagnetic wave along the x- and y-axis directions, and ν be the phase velocity of the incident wave propagating along the k direction.

C. Constraint Condition

It is necessary to consider the constraints to ensure the stability and convergence of the field distribution of the EMS fabric when the calculation of the FDTD is carried out. The effect of numerical dispersion can be reduced by reducing the step size of time and space according to the dispersion mechanism, but the

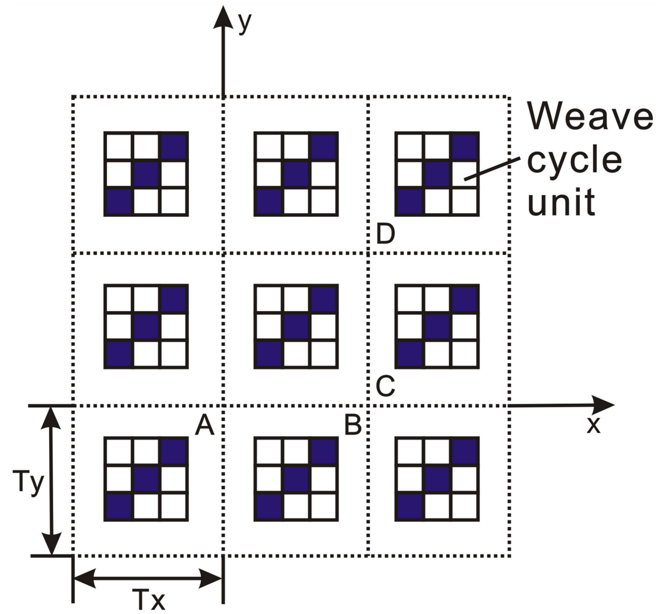

Fig. 4. Diagram of the periodic structure of fabrics.

computing time and storage space increase. Therefore, in order to suppress numerical dispersion, the space step size is usually constrained by [29]

$$\Delta x \leq \frac{\lambda}{12} \tag{15}$$

where λ be the wavelength in medium.

D. Excitation Source Setting

There are many kinds of excitation sources. The broadband characteristics of the fabric can be obtained by one calculation of the excitation of the Gaussian pulse, and the corresponding calculation time can be shortened. There is no analytic expression for the field distribution because the transmission in the fabric is wideband time-domain signal. The incident field must be iterated by the difference scheme. Therefore, this article chooses the Gaussian pulse wave as the excitation source, which is consistent with the actual situation and can obtain effective simulation results. Let $t_0 = 0.8\tau$, it can be calculated as

$$E_i(f) = -\frac{\tau}{2} \exp\left(-j2\pi ft - \frac{\pi f^2 \tau^2}{4}\right) \tag{16}$$

where τ be the constant, which determines the width of the Gaussian pulse.

E. Determination of Electromagnetic Parameters

The region samples are tested with the transmission/reflection method using the vector network analyzer. The electromagnetic parameters of each region are calculated according to the sequence parameters. The transmission/reflection method with the characteristics of easy operation, high precision, and wide bandwidth is an accurate method to obtain electromagnetic parameters of the fabric at present. The Nicolson–Ross–Weir (NRW) method is the most commonly used one [34], and its characteristics are that the solution process does not need iteration and it is applicable to coaxial system and waveguide system. The method has been widely applied in measuring the electromagnetic parameters of different loss, magnetic and nonmagnetic materials [30].

In order to make good use of the NRW method, this article presents the method of the slicing of the single yarn region and overlapping region of the warp and weft weave points. The samples of continuous single yarn region and covering region are hardened by collodion. The sample with the size of 0.75 cm × 1 cm is made according to the requirement. The vector network analyzer, coaxial air line, and the fixture are used to test the samples and the electromagnetic parameters of each region are calculated according to the S sequence parameters. The interstice region is treated as vacuum electromagnetic parameters.

TABLE I
SPECIFICATION OF THE SAMPLE

	Metal Fiber Content	Yarn thickness	Fabric weave	Fabric density	Thickness
Sample 1	50%	32tex	plain	120 × 90	0.26 mm
Sample 2	Silver	32tex	twill	196 × 123	0.27 mm
Sample 3	fiber	25tex	plain	256 × 187	0.24 mm
Sample 4		25tex	twill	287 × 192	0.25 mm

IV. EXPERIMENTAL VERIFICATION

A. Sample Preparation

In order to validate the model proposed in this article, we choose different kinds of samples with different specifications for experiments. Table I lists the specifications of four representative samples.

B. Measurement of Electromagnetic Parameters

Using the method proposed in Section III-E, the electromagnetic parameters of the overlapping region and the single yarn region of the weave points of 32tex and 25tex 50% silver fiber fabric are tested at different frequencies. The testing results are listed in Table II [30]. Results show that the electromagnetic parameters in the same regions of 32tex 50% silver fiber fabric are same with that of 25tex 50% silver fiber fabric from the same production lines.

C. Determination of Grid and Other Parameters

The structural models of samples 1–4 are established according to (10) in Fig. 3. The volume weight of the yarn of 32tex 50% silver fiber fabrics and 25tex 50% silver fiber fabrics using the experimental method [33] is measured and the yarn diameter coefficients are calculated as $C_v = C_w = 0.038$. Combining (11) and (12) and the characteristics of the warp and weft weave points of fabric weave, the space step is determined as

TABLE II
ELECTROMAGNETIC PARAMETERS OF THE WARP AND WEFT WEAVE POINTS IN DIFFERENT REGIONS

Parameter	Frequency	50% silver fiber overlapping region of weave point	50% silver fiber single yarn region of weave point
Relative electrical conductivity σ_r (10^{-3})	2250	2.589	0.303
	2300	2.139	0.247
	2350	1.545	0.181
	2400	0.791	0.087
	2450	0.592	0.064
	2500	0.276	0.029
	2550	0.211	0.022
	2600	0.121	0.013
	2650	0.059	0.006
Relative magnetic conductivity μ_r	All frequencies	1	1

TABLE III
NUMBER OF GRIDS OF MINIMUM WEAVE AND PARAMETERS OF EACH REGION OF THE SAMPLE STRUCTURAL MODEL (mm)

	P_x	L_v	P_y	L_h	The number of grids of minimum weave
Sample 1	0.32	0.21	0.46	0.26	170 × 226 × 26
Sample 2	0.16	0.21	0.31	0.27	159 × 249 × 27
Sample 3	0.08	0.19	0.16	0.24	70 × 102 × 24
Sample 4	0.07	0.19	0.15	0.25	99 × 147 × 25

$\Delta x = \Delta y = \Delta z = 0.01$ mm. The number of the grids and the parameter values of the computational model are obtained, as shown in Table III. Here, the spatial interval is satisfied with $c\Delta t = \delta/2$, where c is light speed, and $\Delta t = 0.1$ ps.

According to Section III, the periodic absorption boundaries are set in the x-axis and y-axis directions by intercepting a weave cycle of the fabric, and the PML absorption boundaries are set in the z-axis direction. Gaussian pulse wave is chosen as excitation source. The range of the frequency is selected from 2250 to 2650 MHz, and constraint conditions are set according to wavelength λ from (15).

D. Numerical Simulation of SE

The numerical simulation of the electromagnetic intensity of the EMS fabric is carried out using EastFDTD software based on the above models and formulas. The FDTD calculation results are analyzed using MATLAB and origin data processing tools. The observation point is set at $+ 6$ grids in the z-axis direction. The SE is obtained by calculating the changes of field strength of the observation points before and after placing the fabric model.

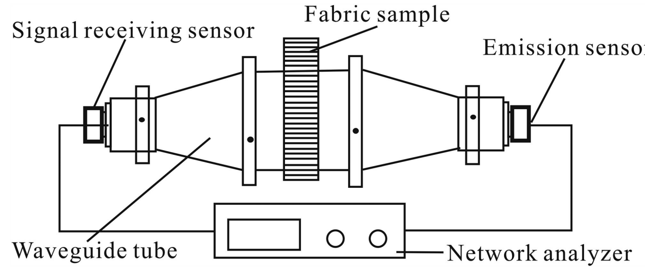

Fig. 5. Waveguide system.

The SE of the fabric can be expressed in decibels of the center point [35]

$$\mathrm{SE} = 20 \lg \frac{E_0}{E_1} \tag{17}$$

where E_0 is the electric field strength and magnetic field strength with unshielded fabrics, and E_1 is the electric field strength and magnetic field strength with shielded fabrics.

E. SE Test of Sample

The fabrics listed in Table I are made as testing samples with the size of 65 mm × 110 mm to test the SE using the waveguide system. The waveguide system is developed by Xi'an Technological University. The testing results of the waveguide system are more accurate than the coaxial planar system, and the testing method of the waveguide system is in keeping with the actual use state of the fabric. Because the number of the waveguides is few and the shape of the waveguides is special, the test coverage frequency of the device is narrow and the size of the test sample is strict. The test frequency range is 2250–2650 MHz, and the test sample size is 110 mm × 65 mm. The waveguide system is shown in Fig. 5 [11].

In the actual testing, the SE of the fabric is calculated as in (17).

V. RESULTS AND ANALYSIS

A. Comparisons Between Numerical Calculation and SE

Figs. 6 and 7 show the comparison diagrams between the SE of the numerical calculation proposed in this article and the measured SE of samples 1–4, respectively, where the grids are divided into $0.1d$. It can be seen that the numerical results are in good agreement with the measured values, which proves that the model in this article has achieved ideal results. In addition, it is also found that the test results of all samples are generally lower than those of numerical simulation. We consider that the reason is the actual test will produce a certain degree of microleakage of the electromagnetic wave.

The reasons why the above-mentioned good numerical simulation results can be achieved are as follows: first, it is related to the characteristics of silver fibers of the fabric. The yarns are smooth, the grids are accurate in calculation, and there are few cases of multiple media in the same grids. Second, the partition method of the warp and weft weave points presented in this

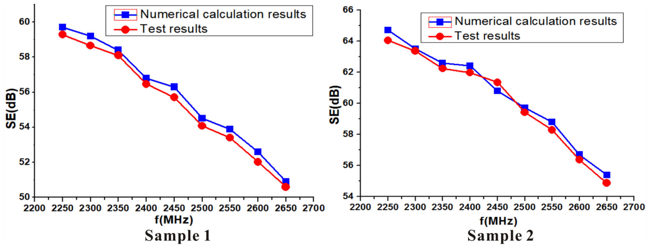

Fig. 6. Comparisons between numerical calculation and experimental results of samples 1 and 2.

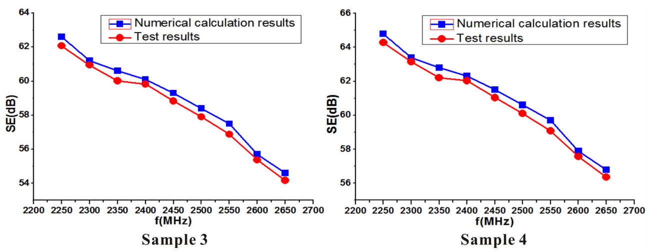

Fig. 7. Comparisons between numerical calculation and experimental results of samples 3 and 4.

article can take into account the characteristics of all overlapping yarn region, single yarn region, and interstice region, so that the grid partition can well express the real state of the fabric. Third, because of the characteristics of silver fibers, the electromagnetic parameters are obtained accurately, so that the calculation results are in good agreement. Finally, the test method is consistent with the actual situation. The waveguide method can well reflect the actual shielding form of the fabric, so it can be in good agreement with the FDTD numerical analysis results.

B. Modification of Discrete Factor γ

Discrete factor γ determines whether grid partition can clearly disperse each region of the weave point effectively or not, and determines the accuracy of the numerical calculation. Usually, the reason causing the error is to divide the regions of the single yarn region, the interstice region, and the overlapping region of the weave points into other regions. Therefore, we further limit the range of the discrete factor γ, which is based on the diameters of the warp and weft yarns d_v, d_w, T_z, and the minimum diameters d_f of the involved shielding fibers. The range can be represented as

$$\gamma \in [d_f, \min(d_v, d_w, T_z)]. \tag{18}$$

The discrete factor γ is determined in the range of (18). After the analysis of the numerical results of many samples, it is found that small value of the discrete factor γ will lead to fine partition of the conductive fibers, which will lead to many Maxwell equations and affect the calculation speed. If the grid size is too large, the fabric structure will be inaccurate and the numerical results will be too rough. Fig. 8 shows a comparison of the numerical results of sample 1 with different grid discrete factors γ, where

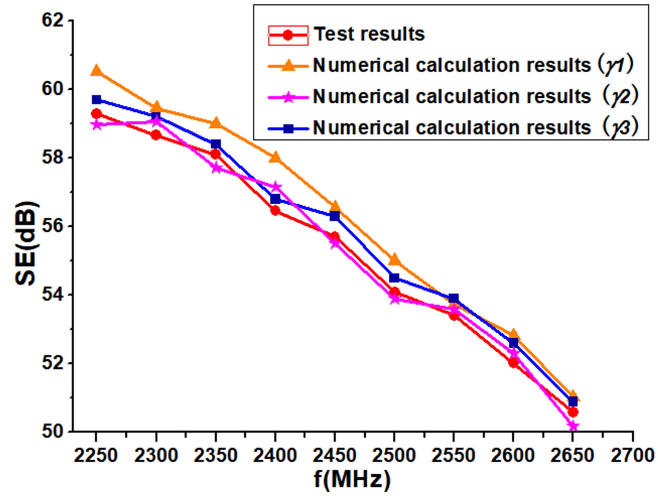

Fig. 8. Comparison of the numerical results of sample 1 with different discrete factors γ.

$$\gamma_1 = d_f \tag{19}$$

$$\gamma_2 = \frac{d_f + \min(d_v, d_w, T_z)}{2} \tag{20}$$

$$\gamma_3 = \min(d_v, d_w, T_z). \tag{21}$$

It can be seen from Fig. 8 that the numerical results deviate from the measured values when the discrete coefficients are chosen as d_f and $\min(d_v, d_w, T_z)$ is larger than that when the discrete coefficients are chosen as $(d_f + \min(d_v, d_w, T_z))/2$. Therefore, the discrete coefficients are further revised. Generally, it is better to choose the values in the range as

$$\gamma \in [\gamma_1, \gamma_2] \tag{22}$$

where

$$\gamma_1 = d_f + \frac{\min(d_v, d_w, T_z) - d_f}{4} \tag{23}$$

$$\gamma_2 = d_f + \frac{3(\min(d_v, d_w, T_z) - d_f)}{4}. \tag{24}$$

C. Error Analysis

There are many error factors that will affect the numerical results because of the softness and variability of the fabric. The error factors mainly come from the determination of the electromagnetic parameters, the yarn deformation, the fabric structure distortion, the fabric thickness change, and various conditions setting of the numerical calculation, and so on. For example, when the fabric density is high, yarns are often flattened due to the overlap. If the yarn diameter is represented by the diameters d_v, d_w of the ideal circle, errors occur. It is necessary to further study the diameter coefficients C_v, C_w and the correction method to reduce the errors. For the fabrics in the actual state, the warp and weft yarns tend to show a slightly inclined shape. Therefore, the warp density D_v and weft density D_w vary in different regions, which will inevitably

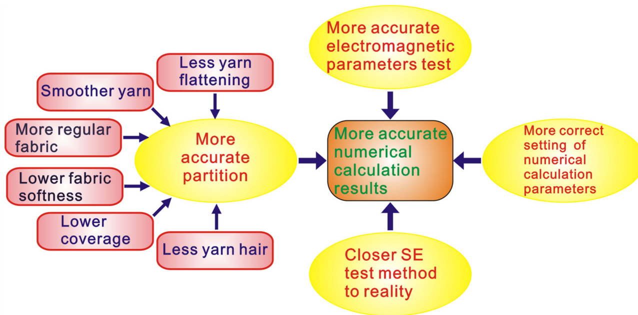

Fig. 9. Main factors and the ways affecting the errors.

lead to errors in the numerical results. In addition, in the field of electromagnetic theory, there are many methods to measure the electromagnetic parameters, and the results measured by different methods are different. Especially, the softness of fabrics makes the determination of the electromagnetic parameters more difficult, which will cause errors in numerical values. Similarly, the number of the grids, the size of the grids and the setting of boundary conditions, the constraints, and the excitation sources all cause errors in the numerical results.

However, the influence of the above factors leading to errors on the numerical results has not been clear up to now. The reason is that the influence of these factors on the numerical results cannot be expressed mathematically or the error scope cannot be clearly given. The change of the error may be large or small, positive or negative. The specific precise error control methods still need to be explored in the follow-up study, but the overall error control is clear. Fig. 9 shows the main factors and the ways affecting the errors.

D. Comparisons With Existing Methods and Application Prospects

Although electromagnetic numerical methods have been applied in many fields such as EMC and electromagnetic protection, their applications in the EMS fabrics have rarely been reported up to now. Table IV presents the comparison of the only relevant literatures available at present.

This article provides a new way to theoretically calculate the SE of the EMS fabric, and solves the problem that the large errors of the SE are produced easily only depending on equipment testing. This article has important application prospects. First, for scientific research, it can be applied in FDTD numerical calculation of the EMS fabrics. The factors, rules, and mechanisms affecting the SE of the fabrics are explored theoretically, which provides a basis for defining many unknown problems in the field of the EMS fabrics. Second, the SE can be predicted accurately by the FDTD numerical calculation of the SE of the EMS fabrics. It not only saves time but also avoids the cost of the test weaving, which can develop the EMS fabric with high efficiency, low cost, high quality, and satisfied SE. Third, this article lays a foundation for further frontier research of the EMS fabrics, such as the establishment of the genome of the EMS fabrics and the development of new high-performance EMS fabrics, and provides an effective means to solve related scientific problems. Finally, this article also has important applications in evaluating the quality and performance of the EMS fabrics. It can scientifically evaluate the shielding performance of the EMS fabrics. Therefore, this article not only has important academic reference value but also has important guiding significance for the actual production of the EMS fabric.

TABLE IV
LITERATURE COMPARISON OF FDTD APPLICATION IN FABRICS

Literature	Research characteristics	Comparison with this article
[29]	SE of fabric is simulated by FDTD, an ideal simple structure model based on the density of the warp and weft yarn is established	Without considering the actual fabric structure and yarn characteristics, the accuracy is not high and the suitable fabric types are not wide
[30]	SE of fabric is simulated by FDTD, the method of dividing yarn diameter and structure is established	Without considering the key factors such as the warp and weft weave point, weave cycle, the accuracy is general and the weave scope of the fabric is not wide
[36], [37]	SE testing of clothing by FDTD	SE calculation of fabric is not involved
[38]	infrared and thermal shielding properties of steel textile by FDTD	SE calculation of fabric is not involved
[39]	Transmissivity of thin films in ultraviolet region	SE calculation of fabric is not involved

VI. CONCLUSION

1) The warp weave point and the weft weave point can describe the fabric characteristics well. The structure model of the EMS fabric based on the warp and weft weave points can well express the fabric structure, which is the basis of the FDTD numerical calculation.
2) The parameters of the grid partition method, the boundary condition, and the excitation source are set up according to the fabric structure model based on the weave points. The established physical model of the EMS fabric is suitable for the FDTD numerical calculation. The numerical calculation values are in good agreement with the measured values, which has obvious theoretical value and application significance.
3) The influence of the discrete coefficient γ on the FDTD numerical results is great. The FDTD numerical results modified by (19)–(24) are consistent with the measured values well.

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