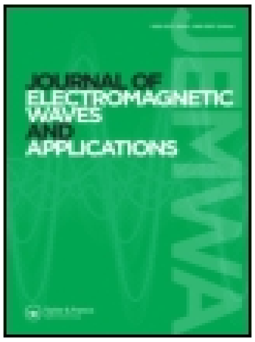

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ABSTRACT

Numerical computation of shielding effectiveness (SE) of electromagnetic shielding fabric (EMSF) is a research difficulty, making no a suitable model for it at present. This paper proposes a partition method based on the yarn diameter and fabric weave structure. The fabric is divided into overlapping region, lateral single yarn region, longitudinal single yarn region, and interstice region according to the weave feature. A fabric structure model for FDTD numerical computation of the SE is constructed. The electromagnetic parameters of each region are tested according to the transmission and reflection method. The Yee's grid discretization method of the structure model is given, and the absorption boundary and the excitation parameters are set to determine the physical model of the fabric. The numerical computation of the physical model is done by the East FDTD electromagnetic computation software. The computation data are compared with the actual testing data, and the results show that the computation results of the SE of the EMSF with the proposed model are satisfied. The research in this paper provides an important reference value for the design, production, evaluation, and theoretical study of the EMSF.

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Weave region; electromagnetic shielding fabric; shielding effectiveness; FDTD; numerical computation

1. Introduction

Electromagnetic shielding fabric (EMSF) is an important EMI product and has a wide range of application in the industrial, aerospace, medical, military, and civilian fields. Shielding effectiveness (SE) is an important indicator to measure the shielding performance of the EMSF and is an important basis for the design, production, and evaluation of the EMSF.

However, there has not been a mature and better computation model for the SE calculation of the EMSF up to now. Existing researches have focused on the shielding model [1], interstice influence [2], performance testing evaluation [3], influence analysis of the metal fiber content [4,5], influence analysis of the tightness [6], and product development [7,8]. Few studies have involved the SE calculation in above researches. In literature [9], they calculated the electromagnetic waves absorption of three-layer infinite-long elliptical-cylinder manikin under three different materials shielding using the FDTD method. They also proposed that the shielding effect of the dissipative material on the electromagnetic waves

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were better than that of the non-dissipative material, and the conductive materials were better than the non-conductive materials. Kurokawa [10] and Yoshimura [11] analyzed the SE performance of the EMS clothing and discussed the testing method for the EMS clothing using time-domain measurement and time-domain analysis method. They proposed different methods for different objects on the FDTD grid partition and the physical model construction from above three literatures, having important reference for our study. Liu et al. [12] proposed the influence of the fabric weave structure on the SE, and gave the quantitative indicators of the weave structure for the SE computation in a certain range. Wang et al. [13] considered the fabric as an ideal shield, studied the rapid computation of the SE of the EMSF using equivalent medium theory, and proposed a computation equation of the SE in a certain fabric density range. Researchers have done some work on the SE computation of the EMSF and clothing in above literatures. However, they only applied the FDTD in the clothing field, or calculated the SE of the fabric by general method. The SE calculation of the fabric using the FDTD has not reported at present. There have been researches about FDTD in other literatures [14–16], but they didn't study the EMSF. Only the FDTD physical model construction idea provides a certain reference for the study in this paper.

This paper studies the SE computation of the EMSF using the FDTD. Firstly, the fabric is divided into overlapping region, single yarn region, and interstice region according to the yarn diameter and the weave structure. A fabric structure model for FDTD numerical computation of the SE is established. Secondly, Yee's grid discretized partition of the structure model is done by introducing the partition coefficient. The electromagnetic parameters of each grid region are tested according to the transmission and reflection method. Thirdly, the physical model of the fabric is constructed by setting the absorption boundary and the excitation parameters. The numerical computation of the physical model is done by the East FDTD to obtain the SE value. Finally, the computation data are compared with the actual testing data and the results show that the proposed model can well calculate the SE of the EMSF.

2. Physical grid discretization of EMSF

The idea of the FDTD is to divide the electromagnetic material into suitable YEE's grids and establish the Maxwell curl equations of each grid. The electric and magnetic field distributions are obtained by solving the equations, and the material parameters of the SE and reflection coefficient are calculated [17,18]. After the development for years, the FDTD curl equation, the boundary condition setting and the equation solution have been accomplished by the dedicated electromagnetic calculation or simulation software [19]. However, the YEE's grid discretized partition depends on the characteristic of the EMS materials. Different materials have different partition methods. Therefore, the key of the FDTD method application is how to construct the structure model of the EMSF and how to accurately use the YEE's grid partition method. This paper proposes a weave region partition method to divide the fabric and establish the structure model and physics model.

2.1. Physical model construction analysis of fabric

As shown in Figure 1, the EMSF is a complex and periodic structural material. Whatever the fabric weaves are, the yarns are interwoven and form three regions of the single yarn region,

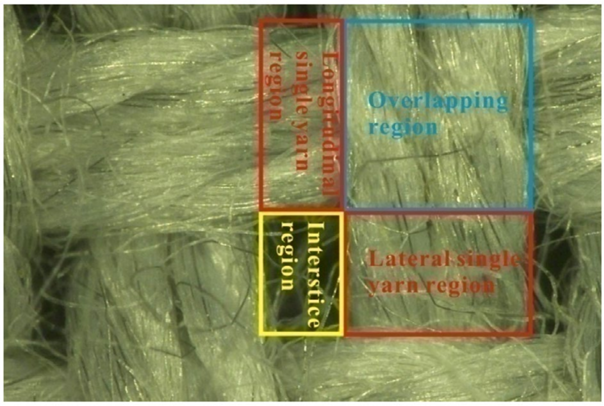

Figure 1. Weave region type of EMSF.

overlapping region, and interstice region. The single yarn region can be divided into lateral single yarn region and longitudinal single yarn region because of the different warp and weft densities. From the microscopic point of view, the shape and the arrangement of the internal conductive fibers in the regions possess irregular characteristic. The shielding fibers with different magnetic permeabilities and electrical conductivities have the stereo interleaving structure, resulting in various regions of the fibers possess different physical electromagnetic properties. The transmission, reflection, and absorption characteristics of the electromagnetic wave inside the fibers are very complex and are difficult to analyze. On the whole, the same type of the regions remains approximate composition and property, and the regular feature appear orderly. Therefore, each type region can be considered as the physical medium with the same dielectric constant, magnetic permeability, and electrical conductivity. The detail size of the medium is determined by the macroscopic parameters of the fabric, the recurring position of the EMSF is determined by the fabric weave type. A structure physical model of the EMSF for FDTD analysis is constructed.

2.2. Structure model construction

According to above analysis, we give a structure model of the EMSF based on the regions, as shown in Figure 2. In the model, the overlapping region is the center surrounded by the lateral single yarn region, the longitudinal single yarn region, and the interstice region. Each

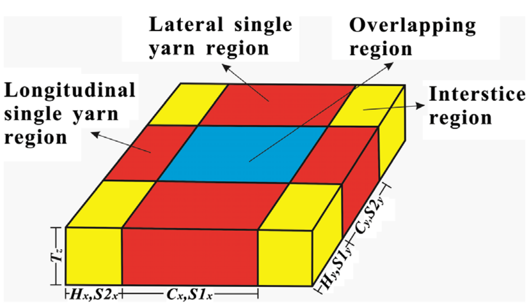

Figure 2. Schematic diagram of the weave region.

type of region is considered as an ideal homogeneous medium with regular size and the same electromagnetic parameters. The size is determined by the warp and weft densities. Let the sizes of the overlapping region, lateral single yarn region, longitudinal single yarn region, and the interstice region in the *x*, *y*, *z* directions are $C_x \times C_y \times T_z$, $S1_x \times S1_y \times T_z$, $S2_x \times S2_y \times T_z$, $H_x \times H_y \times T_z$, then the size relationships between each region are:

$$C_x = S1_x, C_y = S2_y, H_x = S2_x, H_y = S1_y \tag{1}$$

where T_z is the thickness of the fabric.

Let the warp density and weft density are D_v and D_w, the yarn densities of the warp yarn and the weft yarn are V_{tex} and W_{tex}, then the warp yarn diameter d_v, and weft yarn diameter d_w are calculated as [5]:

$$d_v = C_v\sqrt{N_{tex\_v}}, \quad d_w = C_w\sqrt{N_{tex\_w}} \tag{2}$$

where, C_v and C_w are the coefficients of the warp yarn and the weft yarn, $N_{tex\backslash v}$ and $N_{tex\backslash w}$ are the yarn densities of the warp yarn and the weft yarn.

Therefore, the size of each region can be obtained as:

$$C_x = S1_x, \quad S1 = d_v \tag{3}$$

$$C_y = S2_y, \quad S2 = d_w \tag{4}$$

$$H_x = S2_x, \quad S2_x = \frac{\frac{10}{D_v} - C_x}{2} \tag{5}$$

$$H_y = S1_y, \quad S1_y = \frac{\frac{10}{D_w} - C_y}{2} \tag{6}$$

According to above model parameters, the whole structure model of the EMSF can be established as:

$$F(x, y, z) = \sum_{i=1}^{D_w}\sum_{j=1}^{D_v}\delta(x - jC_x - 2jH_x, y - iC_y - 2iH_y, T_z) \tag{7}$$

Equation (7) shows the region partition structure of the structure model and gives the calculation method of any point (*x, y, z*), providing the basis for the further YEE's grid partition.

2.3. Physical grid partition

In order to build the differential equation, the continuous variables are discretized in the space. Yee proposed a spatial arrangement method of the electric and magnetic fields for the iterative Maxwell's equations in 1966 [17]. Continuum was divided into a number of Yee's grids. Each electric or magnetic field component in the grid was surrounded by four magnetic or electric field components. The electric and the magnetic fields were alternately sampling in the time domain. The sampling interval time was a half time step, and the spatial position was a half grid. The iterative solution of the explicit difference equations which were constructed by the discretized Maxwell's equations was done. The electromagnetic field distribution of each time was obtained to solve the initial value and absorbing boundary conditions of the electromagnetic field problem by the FDTD difference equations. Suppose Δx, Δy, and Δz are the spatial step of the *x*-axis, *y*-axis, and *z*-axis, and Δt is the time step, $f(x, y, z, t)$ represents a component of E or H in the Cartesian coordinate system. The discretization of $f(x, y, z, t)$ on entire time and spatial domain can be expressed as:

$$f(x,y,z,t) = f(i\Delta x, j\Delta y, k\Delta z, n\Delta t) \tag{8}$$

$$f(i\Delta x, j\Delta y, k\Delta z, n\Delta t) = f^n(i,j,k) \tag{9}$$

According to the principle of Equation (8)–(9), the structure model of the EMSF shown in Equation (7) is divided and the YEE's grid for the Maxwell equations curl establishment is formed. Here, we introduce a partition factor φ to divide the weave region grid into uniform square grids in the three-dimensional space range. Let ε is the partition accuracy of the grid, then φ is satisfied with the following equation:

$$\begin{aligned}&\left(\left|\mathrm{int}\left(\tfrac{C_x}{\varphi}\right) - \tfrac{C_x}{\varphi}\right| \le \varepsilon\right) \bullet \left(\left|\mathrm{int}\left(\tfrac{C_y}{\varphi}\right) - \tfrac{C_y}{\varphi}\right| \le \varepsilon\right) \bullet \left(\left|\mathrm{int}\left(\tfrac{H_x}{\varphi}\right) - \tfrac{H_x}{\varphi}\right| \le \varepsilon\right)\\ &\bullet \left(\left|\mathrm{int}\left(\tfrac{H_y}{\varphi}\right) - \tfrac{H_y}{\varphi}\right| \le \varepsilon\right) \bullet \left(\left|\mathrm{int}\left(\tfrac{T_z}{\varphi}\right) - \tfrac{T_z}{\varphi}\right| \le \varepsilon\right) = 1\end{aligned} \tag{10}$$

The general value of ε is $\frac{1}{10^n}$, the larger value of n denotes higher accuracy.

2.4. Constraint condition

When the finite difference time domain is calculated, the stability and convergence assurance of field distribution of the EMSF is the constraint condition. The Maxwell's equations considering the time-harmonic field is computed by the differential solving and difference approximation replacing. The numerical growth factor q is obtained as:

$$q = \frac{f^{n+1/2}}{f^n}, \frac{f^{n+1/2}}{f^n} = \exp\left(\frac{1}{2} j\omega\Delta t\right) \tag{11}$$

From Equation (11), the constraint condition of the numerical stability is: the time step $n \to \infty$ and Δt is small enough, the growth factor meets $|q| \le 1$that is:

$$\Delta t \le \frac{T}{\pi} \tag{12}$$

According to the dispersion mechanism, the influence of the numerical dispersion decrease with the decrease in the time and spatial steps. However, the decrease in the time and spatial steps results in the increase in the computing times and the storage space. In order to suppress the numerical dispersion, the constraint condition of the spatial step is expressed as:

$$\Delta x \le \frac{\lambda}{12} \tag{13}$$

where, λ is the wavelength in the medium. The minimum value of the computing spatial step is calculated by Equation (13) according to the frequency range of the clothing region research.

3. Experiment and verification

3.1. Sample preparation

In order to verify the proposed model, we select a number of samples with different types and specifications. Table 1 lists the specifications of three representative samples.

The fabric densities are tested using the density testing system (Y511B), the warp yarn diameter and weft yarn diameter are calculated according to the yarn density from the Equation (2), the structure model is constructed by the Equation (7). The partition factors φ of the structure model in the three directions are obtained by the Equation (8)–(9). The YEE's grid partition of the structure model is accomplished.

3.2 Grid partition

The structural models of the Sample 1, Sample 2, and Sample 3 are built according to the Equation (7). The volume weights of the yarns are tested using the experimental method [5], and the diameter coefficient C_v of the warp yarn and the diameter coefficient C_w of the weft yarn are calculated. Both coefficient values are 0.038. According to the Equations (1)–(6), the values of the parameters of each region in the model are calculated, as shown in Table 2. The spatial step is determined according to the principle and the numerical stability conditions of the periodic structure from Equation (10). The spatial step is obtained as: $\Delta x = \Delta y = \Delta z = 0.01$mm. The number of the grids of the computation model is obtained (see Table 2). The space interval is satisfied $c\Delta t = \delta/2$. Where, c is the speed of the light, and the value is $\Delta t = 0.1$ ps in computation. The observation point is set at +6 grid in the Z-axis direction. The SE is obtained by computing the field strength changes of the observation point between the model with the fabric and the model without the fabric.

Table 1. Sample specification.

	Metal fiber content (%)	Yarn density	Fabric weave	Warp and weft density (ends/10 cm)	Thickness (cm)
Sample 1	50% Silver fiber/ 50%cotton	32 tex	Plain weave	115 × 82	0.26
Sample 2			Twill weave	98 × 86	0.25
Sample 3			Plain weave	80 × 72	0.24

Table 2. Parameters values of each region of the sample structural model and the number of the grids of the computation model.

	H_x, $S2_x$	H_y, $S1_y$	C_x, $S1_x$	The number of grids of computation model
Sample 1	0.33	0.50	0.21	87 × 121 × 26
Sample 2	0.40	0.47	0.21	101 × 115 × 25
Sample 3	0.52	0.59	0.21	125 × 139 × 24

3.3. Electromagnetic parameter determinations

The region samples are tested by the transmission/reflection method using the vector network analyzer. The electromagnetic parameters of each region are obtained by the S sequence parameters. The method has the characteristics of easy operation, high precision and wide frequency band. Therefore, it is an accurate testing method to measure the electromagnetic parameters of the fabric at present. In existing transmission/reflection methods, the NRW method proposed by Nicolson, Ross, and Weir et al. is a common method. The characteristic of the method are the following: iterative solution process is not necessary, the method is suitable for coaxial and waveguide systems, there are many ways to improve the method. Therefore, the method is used widely on the electromagnetic parameters testing of different loss, magnetic and non-magnetic materials [20,21].

We test the electromagnetic parameters of the weave region by the coaxial transmission/reflection method. The continuous single yarn region and the overlapping region of the sample are hardened by the collodion. Then the size of samples is made with 0.75 cm × 1 cm according to the experimental demand. The SE is tested by the vector network analyzer, coaxial air line, and fixture. The electromagnetic parameters of each region are calculated according to the S sequence parameters. The electromagnetic parameters in the interstice region are regarded as vacuum electromagnetic parameters. The testing electromagnetic parameters are listed as shown in Table 3.

3.4. Other parameter determination

(1) Boundary condition setting: the periodic array structure of the EMSF results in the same periodic of the field distribution near the EMSF. However, the phase has a regular phase difference owing to linear distribution of the feeding phase or the obliquely incident of the plane wave, shows regular phase retardation in the time domain, and forms a quasi-periodic conditions. Therefore, we intercept a grid unit of the structure model of the EMSF, the center point of the overlapping region is the center of the whole cycle unit, the periodic absorption boundary is set in the directions of the *x*-axis and *y*-axis, the PML absorption boundary is set in the direction of the *z*-axis, the thickness of the PML boundary layer is 8 grids.

Table 3. Electromagnetic parameter of weave region with different yarn densities.

Parameters	Frequency	50% Silver fiber Cover region 32 tex	50% Silver fiber Single region 32 tex
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 permeability μr	All frequencies	1	1

(2) Excitation source setting: there are several types of excitation source. The broadband properties of the fabric can be obtained by one computation using Gaussian pulse excitation. The relative computing time can be shortened. There is no analytical expression in the field distribution and the radiation field must be obtained by the differential iteration because the transmission signal is a broadband time domain signal in the fabric. Therefore, we select the Gaussian pulse wave as the excitation source, and the frequency range is 2250–2650 MHz. This is consistent with the actual situation, and effectively simulated results can be obtained.

(3) SE value obtaining: we use the East FDTD software to calculate the electromagnetic field strength according to the computation model, the computation data are analyzed using the MATLAB and Origin data processing tools. The SE of the fabric can be denoted by the decibel value of the center point [6]:

$$SE = 20\log\frac{E_0}{E_1} \tag{14}$$

where E_0 is the electric field strength under the condition of no shield fabric, and $E1$is the electric field strength under the condition of shield fabric.

3.5. SE testing of sample

The fabrics listed in Table 1 are made as testing samples with the size of 65 mm × 110 mm. the SE of the samples are tested using the waveguide system. The waveguide system is developed by Xi'an Technology University and the experimental method is referred by the China entry–exit inspection and quarantine industry standard "SN/T2161-2008 Textile anti-microwave performance test methods - waveguide method." The method more objective evaluates the changes of the SE and has higher accuracy than the coaxial planar system. The signal transmitting distance and the signal reception distance can well simulate the actual environment status of the electromagnetic transmission and reception. The experimental results are close to the actual results. In addition, the testing results are sensitive to the interstice of the fabric. This is not achieved by other methods such as the coaxial planar system. Therefore, the method is suitable for the testing of the EMSF. The testing frequency range is narrow because of less number of the waveguide and special shape of the testing equipment. The type of the waveguide is BJ22. The frequency range of the waveguide is 2200–2650 MHz, the testing size is 110 mm × 65 mm. The power parameter of the universal vector analyzer with printing function is 50 Hz AC, the rated voltage is 220 V and the current is 0.1 A. The waveguide system is shown in Figure 3.

In the actual testing, the shielding effectiveness (SE, dB) of the fabric is calculated as in Equation (14). Where, E_0 is the electric field intensity of one frequency point without shield, E_1 is the electric field intensity of one frequency point with shield.

4. Results and analysis

4.1. SE comparison between the numerical calculations and testing results

Figures 4–6 give the SE comparison between the numerical calculation results and the actual testing results of the samples1#, 2#, 3#. From Figures 4–6, it is noticed that the numerical

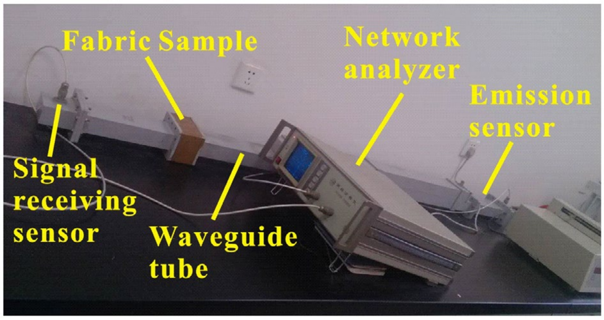

Figure 3. Waveguide system.

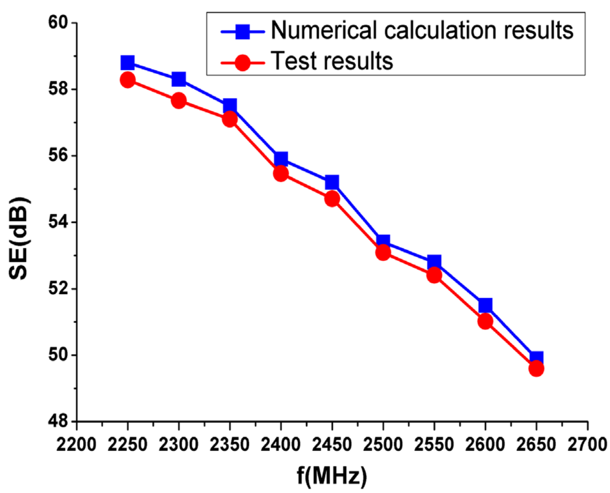

Figure 4. Comparison between numerical calculation results and the actual testing results of samples 1#.

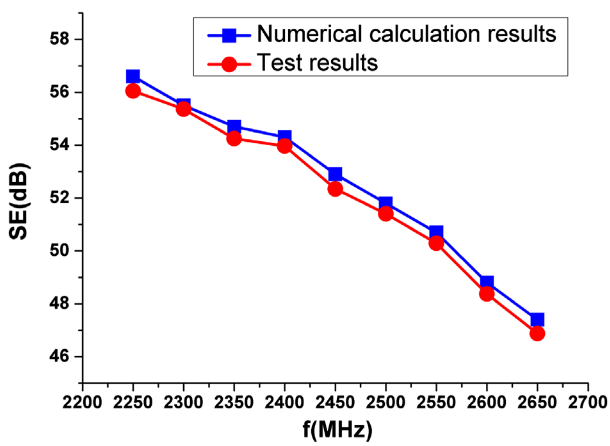

Figure 5. Comparison between numerical calculation results and the actual testing results of samples 2#.

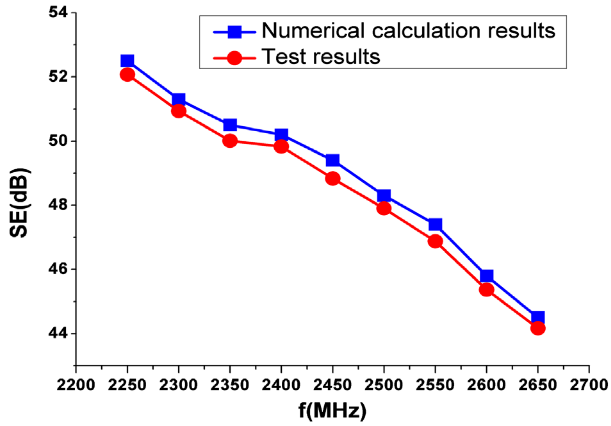

Figure 6. Comparison between numerical calculation results and the actual testing results of samples 3#.

calculation results are agree with the actual testing results. It is proved that the proposed model had reached the desired effect. It is also observed that The SE values of testing results are smaller than the values of numerical calculation. The reason is that the tiny leak of the electromagnetic wave occurs in actual testing.

4.2. Influence of conductive fiber in the interstice region

The hairiness of the conductive fiber existing in the yarn pores has important influence on the results of the numerical calculation. The electromagnetic parameters in the interstice region are treated as vacuum electromagnetic parameters when the SE of the EMSF is calculated. In fact, the conductive fibers exist in the interstice region and the region is not a pure vacuum media because of the softness and tightness of the fabric, as shown in Figure 1. In order to solve the problem, we introduce a correction coefficient κ to add the yarn diameter and reduce the size of the interstice. The yarn diameter can be calculated as:

$$d_v = \kappa C_v \sqrt{N_{tex\_v}}, \; d_w = \kappa C_w \sqrt{N_{tex\_w}} \tag{15}$$

The correction coefficient κ is related to the yarn quality, conductive fiber content, the type of the conductive fiber and the fabric weave structure. After experiments, the correction coefficient is 1.03 for sample 1#, the correction coefficient is 1.05 for the samples 2# and 3#. Figure 7 shows the numerical calculation results of samples 1# when the correction coefficient is 1.03. The length and the arrangement characteristic of the yarn hairiness are different because of the different types of the yarn and the interweave manners between the yarns. Therefore, the correction coefficients of the fabrics are different. According to the experiments, the correction coefficient is in the range of [1.011.08].

4.3. Error analysis

The errors of the numerical calculation results are mainly from the accuracy of the obtained electromagnetic parameter, the rationality of the size of the grid, and the yarns overlap.

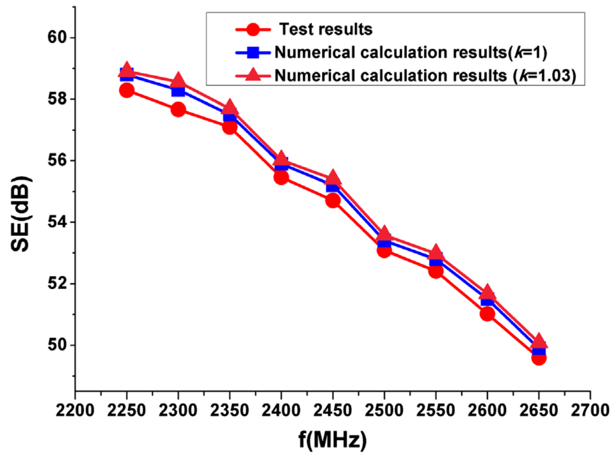

Figure 7. Numerical calculation results of samples 1# when $\kappa = 1.03$

The electromagnetic parameters are the specific conditions before the numerical calculation of the SE of the electromagnetic shielding fabric are done using the FDTD. Its accuracy directly affects the results of numerical calculation. The errors mainly from the sample manufacture. The samples are not tested in a planar natural state because of the flexibility of the textile fabric. The testing results error causes the calculation results error. Therefore, the shape stability of the testing samples must be treated by hardener to obtain the accurate results of electromagnetic parameters.

The grid partition is an important factor that leads to errors in calculation results of the SE of the electromagnetic shielding fabric. If the grid size is large, the calculation time is saved, but any single electromagnetic parameter can not accurately reflect the actual physical situation of the grid because there are different regions in a grid. The calculation results produce errors. If the grid size is too small, the calculation amount is too large, which affect the efficiency of numerical calculation and increase the instability of numerical calculation. Therefore, it is necessary to ensure that the corresponding region of the grid is a single physical region in order to reduce the error and get accurate numerical results.

Warp and weft yarn overlap is determined by the flexural properties of textiles, which can cause the structural model of numerical simulation is deviate from the actual fabric structure. The solution method is the fabric is fixed to be a good natural state when the fabric density is tested. The distortion in any direction is reduced and the overlap is avoided to obtain the correct density and weft density. For the fabric with large tightness, the overlap is unavoidable, resulting in the yarn being crushed. Therefore, the diameter coefficient of the yarn needs to be corrected to ensure that the physical model of the numerical calculation is in good agreement with the physical model. The error of the calculation results is reduced.

4.4. Comparison of numerical methods and experimental methods

According to multiple comparison results, the fabric is divided into weave regions with different relative magnetic permeability μ_r and relative electrical conductivity σ_r, can express the physical model of the fabric. The numeral calculations using the FDTD method can be obtained satisfied results. We consider that the SE result obtained by the field simulation of the FDTD is more accurate than the experimental results. The error is great when the SE of the fabric is tested. The main reasons are the following: (1) the thickness of the fabric changes with the difference of the clamp pressure results in the transmission coefficients of the electromagnetic waves change. The SE results are changed. (2) The fabric has the softness characteristic. The spatial position and the three-dimensional shape of the internal conductive fibers change when the samples are clamped, causing the relative magnetic permeability μ_r and relative electrical conductivity σ_r change. The SE results are affected. (3) The yarn entanglement and hairiness characteristics lead to uneven of the porosity and yarn overlap. These phenomena randomly appear with the placement of the fabric and the degree of pressure. Therefore, the uncertainty of the test results increases. (4) The testing device itself reason. Such as the leak of the electromagnetic waves, the surface impedance of the fixture and the emission source all influence the SE results. For the FDTE method, the absorbing boundary, the excitation source, the constraint conditions and solving are scientific and precise. The accuracy of each calculation can be ensured. By comparison, the determination of the electromagnetic parameters of the weave region for the numerical calculation is crucial. Though the testing method also influences the parameters accuracy, the influence has reduced to a minimum. We use the coaxial transmission/reflection method, the fabric sample is relatively fixed and has not changed by the external factors, so that the testing results can reflect the actual electromagnetic parameters of the fabric.

In addition, according to the results deduction in this paper, the spacial arrangement formations of the shielding fibers in the overlapping regions, the lateral single yarn regions and the longitudinal single yarn regions are completely different, resulting in the electromagnetic parameters of the three regions are different. Therefore, the three regions must be precisely defined according to the fabric weave type. The numerical calculation method in this paper can well meet this requirement. The definition method of the regions is the computation of the fabric structure parameters of the yarn density, fabric weave type. Compared to the experimental method, the numerical calculation method can reduce the error and get good results.

5. Conclusions

(1) The fabric is divided into overlapping region, lateral single yarn region, longitudinal single yarn region, and interstice region according to the fabric weave feature, describing the fabric characteristic well and providing the basis for the FDTD physical model construction.
(2) The partition coefficient determination can discrete the structure model into suitable YEE's grid, providing protection for the further computation of the FDTD.
(3) The electromagnetic parameters of each weave region are tested using the coaxial transmission/reflection method, and the testing results are applied in the FDTD computation. The results are accurate.
(4) The conductive fibers in the interstice region affect the electromagnetic parameters of the weave region. The diameter correction coefficient can be correct the model considering the factor, making the FDTD computation results accurate.

(5) The proposed physical model is suitable for the numerical computation of the SE of the EMSF. The computation results are satisfied and possess obvious value and research meaning.
(6) The overlapping regions, the lateral single yarn regions and the longitudinal single yarn regions are precisely defined according to the fabric. The influence of the numerical computation results by the error definition is significant. The construction method of the fabric structure model proposed in this paper can ensure the precise definition of each region.

Disclosure statement

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