Comparison among Models to Estimate the Shielding Effectiveness Applied to Conductive Textiles

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Abstract. *The purpose of this paper is to present a comparison among two models and its measurement to calculate the shielding effectiveness of electromagnetic barriers, applying it to conductive textiles. Each one, models a conductive textile as either a (1) wire mesh screen or (2) compact material. Therefore, the objective is to perform an analysis of the models in order to determine which one is a better approximation for electromagnetic shielding fabrics. In order to provide results for the comparison, the shielding effectiveness of the sample has been measured by means of the standard ASTM D4935-99.*

Keywords

Compact barriers, conductive textiles, modelling, shielding effectiveness, wire mesh barriers.

1. Introduction

Textile-based shields are useful in areas such as in designing of EM barriers to shield devices' joints against external interferences [1], protective clothes for workers or patients in radiotherapy rooms or military applications.

The manufacture of conductive textiles has a significant cost, besides a waste of materials such as copper, nickel, iron or silver. The modelling of conductive textiles before their production in the industry [2] allows manufacturers to save money.

This paper presents two models to estimate the shielding effectiveness (SE) of different types of electromagnetic barriers: wire mesh screens and compact material. The models have been programmed in a Matlab environment performing an estimation of the shielding effectiveness between 30 MHz and 1,5 GHz of a real sample with characteristics as follows: $l = 220$ µm, $s = 120$ µm, $\sigma = 2040$ S·m^{-1}, $t = 360$ µm and $d = 270$ µm, where l stands for length of apertures, width of apertures is defined by s, σ is the conductivity of the sample, t stands for thickness and d is the diameter of threads. The thickness of the sample was measured by using a micrometre, which is not an exact measurement method and can lead to errors. More exact techniques are used by the industry such as microscopic examination, resonance methods or laser diffraction [3]. The conductivity of the textile was obtained by placing two electrodes between the opposite boundaries of a square textile sample and bulk resistance was measured with an RLCG bridge ESCORT ELC-3133A.

The actual SE of the sample was measured with a network analyzer ZVRE Rohde&Schwarz by following the standard ASTM D4935-99 [4] in order to provide a point of reference to compare results. Although there is a new version of the standard and it is no longer supported, it is still used in many technical papers.

The rest of the paper is organized as follows: Section 2 describes modelling of wire mesh barriers. Section 3 presents modelling of compact material. Section 4 introduces measuring workplace and results are discussed in section 5. Finally, conclusions are presented in section 5.

2. Modelling of Wire Mesh Barriers

This section describes the method used to model the electromagnetic shielding behaviour of wire-mesh screens [5]. The main goal is to find out if a conductive textile can be modelled as a wire-mesh screen without a major error in the calculation.

Wire-mesh screens can be properly used in applications such as the screening of rooms or big scenarios because of saving material, compared to compact sheet screens. The advantage is lower cost and reduced weight per unit area. This method considers that the mesh dimensions are small compared to wavelength, the wire is circular and the mesh holes are square as Fig. 1 shows.

Wire mesh screens with bonded junctions can be described by their equivalent sheet impedance for a screen with square meshes of dimensions $a_s \times a_s$. Using Cartesian coordinates to represent its equivalent sheet impedance it is possible to obtain the parameters Z_{s1} and Z_{s2} [5]. Z_{s1} corresponds to the sheet impedance for perpendicularly polarized plane waves Eq. (1), while Z_{s2} corresponds to the effective sheet impedance for the parallel-polarized plane waves Eq. (2):

$$Z_{s1} = Z_w^{'} a_s + j\omega L_s, \tag{1}$$

$$Z_{s2} = Z_{s1} - \frac{j\omega L_s}{2} \sin^2\theta, \tag{2}$$

where θ is the angle of incidence with respect to the normal direction to the mesh, L_s is the sheet inductance given by Eq. (3), r_w is the radius of the mesh wires and as the mesh aperture size. $Z_w^{'}$ is the internal impedance per unit length expressed as Eq. (4):

$$L_s = \frac{\mu_0 a_s}{2\pi} \ln\left(1 - e^{-2\pi r_w/a_s}\right)^{-1}, \tag{3}$$

$$Z_w^{'} = R_w^{'} \frac{\sqrt{j\omega\tau_w} I_0\left(\sqrt{j\omega\tau_w}\right)}{2 I_1 \sqrt{j\omega\tau_w}}, \tag{4}$$

where $k_0 = \omega\sqrt{\mu_0\epsilon_0}$ is the free-space wavenumber, $\tau_w = (\mu\sigma r_w^2)$ is the diffusion time constant, $R_w^{'} = (\pi r_w^2 \sigma)^{-1}$ is the dc resistance per unit length of the mesh wires and I_n denotes the modified Bessel function of the first kind of order n.

On the one hand, reflection and transmission coefficients for perpendicularly polarized plane waves are Eq. (5) and Eq. (6) respectively.

$$R_1 = \frac{-Z_0}{Z_0 + 2Z_{s1}\cos\theta} \sin^2\theta, \tag{5}$$

$$T_1 = \frac{2Z_{s1}\cos\theta}{Z_0 + 2Z_{s1}\cos\theta}. \tag{6}$$

On the other hand, reflection and transmission coefficients for parallel-polarized plane waves are Eq. (7) and Eq. (8) respectively. Figure 2 shows the difference between the incidence of parallel-polarized plane waves and perpendicularly polarized plane waves to a shield.

$$R_2 = \frac{Z_0\cos\theta}{2Z_{s2} + Z_0\cos\theta}, \tag{7}$$

$$T_2 = \frac{2Z_{s2}}{2Z_{s2} + Z_0\cos\theta}. \tag{8}$$

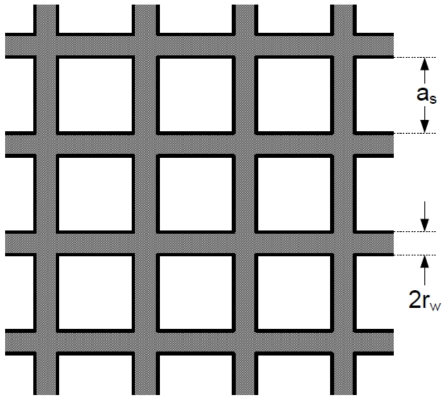

Fig. 1: Wire mesh with square apertures and bonded junctions.

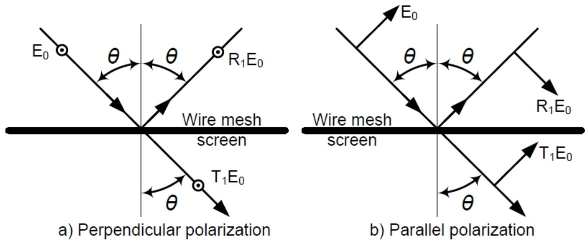

Fig. 2: Angle of incidence with respect to the normal incidence to a shielding barrier [5].

The shielding effectiveness for plane waves is defined as:

$$SE_{1,2}(\theta) = -20\log|T_{1,2}(\theta)|, \tag{9}$$

where in the case that the mesh wires are perfectly conducting, it is defined as Eq. (10) for perpendicularly polarized plane waves and as Eq. (11) for parallel-polarized plane waves:

$$SE_1(\theta) = -20\log\left|\frac{(2\omega L_s/Z_0)\cos\theta}{1 + (\omega L_s/Z_0)^2\cos\theta}\right|, \tag{10}$$

$$SE_2(\theta) = -20\log\left|\frac{(2\omega L_s/Z_0)\left(1 - \frac{1}{2}\sin^2\theta\right)}{(\omega L_s/Z_0)\left(1 - \frac{1}{2}\sin^2\theta\right)\cos^2\theta}\right|. \tag{11}$$

However, the polarization direction is likely unknown. Therefore, it must come into consideration a polarization-independent shielding effectiveness SE_0 given by:

$$SE_0(\theta) = -10\log\left\{\frac{1}{2}|T_1(\theta)|^2 + \frac{1}{2}|T_2(\theta)|^2\right\}. \tag{12}$$

3. Modelling of Compact Materials

This section describes the method used to model the electromagnetic shielding behaviour of compact sheet screens [6]. The main goal is to find out if a conductive textile can be modelled as a compact screen without a major error in the calculation. It can be possible since a mesh screen can be viewed as a compact screen for a range of frequencies.

This section presents a theoretical model for multi-layered structures to calculate its shielding effectiveness, which is based on the transmitted wave matrix in the far field area [6]. Figure 3 shows the transmission and reflection scheme of an N-layers structure.

Considering that all layers are isotropic and homogeneous, the intrinsic impedance of the i^{th} layer Z_i is given by:

$$Z_i = \left[\frac{\mu_r}{\epsilon_i + \sigma_i/j\omega}\right]^2 \quad i = 1, 2, \ldots, N. \tag{13}$$

The characteristic matrix of the i^{th} layer is given by:

$$\mathbf{M_1} = \begin{bmatrix} \cos(k_i d_i) & -jZ_i \sin(k_i d_i) \\ -j/Z_i \sin(k_i d_i) & \cos(k_i d_i) \end{bmatrix}, \tag{14}$$

where $\epsilon_i^{'}$ is the real part of the complex permittivity of the i^{th} layer given by $\epsilon_i^* = \epsilon_i^{'} - \epsilon_i^{''}$ and k_i is the wavenumber, defined by:

$$k_i = \frac{2\pi}{\lambda_0}\left[\left(\epsilon_i^{'} + \sigma_i/(j\epsilon_0\omega)\right)\right]^2. \tag{15}$$

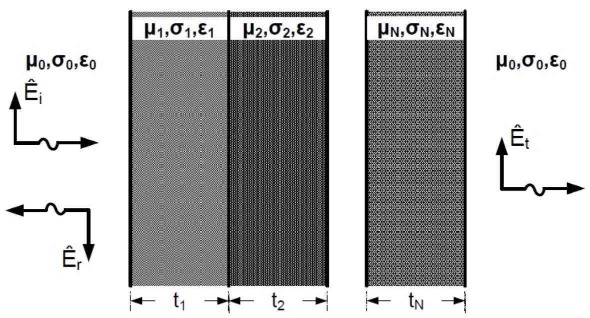

Fig. 3: Transmission and reflection of an EM wave with normal incidence [6].

The characteristic matrix of the whole structure is

$$[\mathbf{M}] = [\mathbf{M_1}] \cdot [\mathbf{M_2}] \ldots [\mathbf{M_N}] = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}, \tag{16}$$

and both reflection and transmission coefficient of the whole N-layered structure is given by Eq. (17) and Eq. (18) respectively:

$$R = \frac{(M_{11}Z_0 - M_{12}) - Z_1(M_{22} - M_{21}Z_0)}{(M_{11}Z_0 - M_{12}) + Z_1(M_{22} - M_{21}Z_0)}. \tag{17}$$

$$T = \frac{2\left[M_{22}(M_{11}Z_0 - M_{12}) + M_{12}(M_{22} - M_{21}Z_0)\right]}{(M_{11}Z_0 - M_{12}) + Z_1(M_{22} - M_{21}Z_0)}. \tag{18}$$

The shielding effectiveness takes into account the transmission parameter Eq. (18), which is therefore given by:

$$SE = -20\log|T|. \tag{19}$$

4. Measuring Workplace

This section describes measuring principle and apparatus for shielding effectiveness measurement according to standard ASTM D4935-99 [4]. It was published in 1999 and in 2005 was removed from ASTM standards. However, it still remains the method used by professionals for measurement.

Measuring apparatus consists of a network analyser, we used ZVRE Rohde&Schwarz, RF connecting cables, measuring adapter, attenuators that prevent from unwanted reflections or signal interference and computer for data evaluation. Measuring adapter is formed by two symmetrical parts axially split coaxial line, Fig. 4.

The random error of this measurement method and used specimen is ±5 dB [4].

Measurement is the type of comparison measurement. At first, two circular calibration samples are inserted between two symmetrical parts of measuring adapter, i.e. not hatched part of the sample as shown in Fig. 4. Network analyzer is then calibrated, calibration samples are replaced by measuring samples (circular sample without any cut in Fig. 4 and the resulting values are stored in a computer.

The sample is conductive textile material which consists of 30 % SilveR.STAT®, 30 % SHIELDEX®and 40 % PES with 35,5 tex.

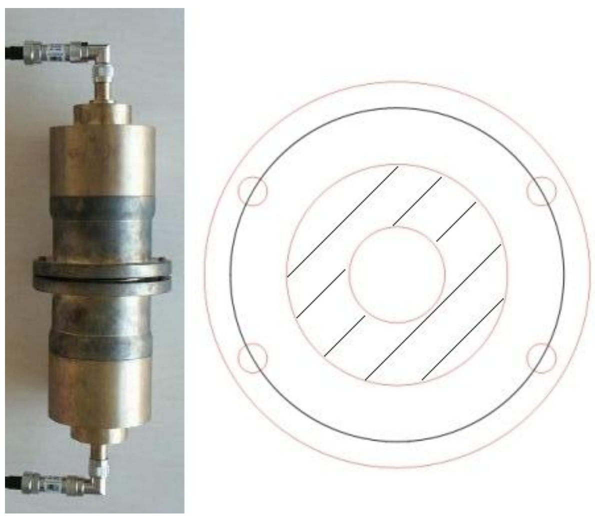

Fig. 4: Measuring adapter (left) and basis for sample preparation (right) according to standard ASTM D4935-99.

5. Obtained Results

This section describes comparison of results obtained from modelling and measurement.

5.1. Wire Mesh Barriers

In this section, the textile sample has been modelled as a wire mesh screen. Although, the real dimensions of apertures is 220 μm×120 μm, the equations described above requires of square apertures. Therefore, square apertures of dimensions 220 μm×220 μm were considered because the shielding effectiveness is mainly affected by the highest dimension of an aperture.

Figure 5 shows the calculation of the shielding effectiveness of the sample, modelled as an electromagnetic wire mesh barrier that is compared to its measured shielding effectiveness in the frequency range 30 MHz–1,5 GHz. Although both curves are flat and proportional, there is an offset about 3 dB between them at whole frequency range (3,2 dB at 1 GHz), which is less than ±5 dB (maximal random error of used measurement method).

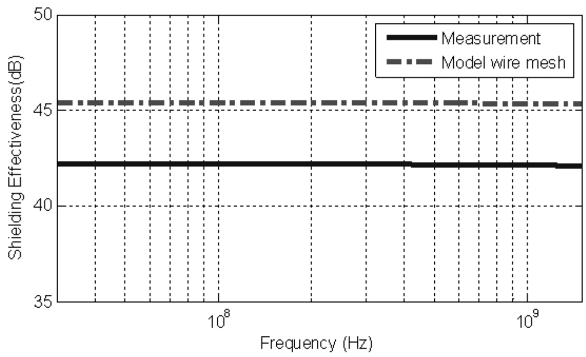

Fig. 5: Modelling of the sample as wire mesh.

5.2. Compact Materials

This section shows the results obtained from modelling the textile sample as a compact electromagnetic barrier. A good approximation is expected because the higher dimension of apertures in the textile, 220 μm, is much lower than the wavelength at 1,5 GHz, $\lambda_{|f=1,5\ GHz} = 0,2$ m, so the textile barrier's behaviour as an EM shield is expected to follow the one of a compact electromagnetic barrier.

Figure 6 shows the calculation of the shielding effectiveness of the given sample, modelled as an electromagnetic compact barrier and compared to its measured shielding effectiveness also in the frequency range 30 MHz–1,5 GHz. The figure shows a good approximation to the actual values of shielding effectiveness. At an example frequency of 1 GHz, the measured shielding efficiency is equal to $42,1 \pm 5$ dB, while the modelling of Sample A as a compact electromagnetic barrier gives shielding effectiveness of 43,5 dB. Therefore, it is inside the uncertainty margin of error given by the measurement method.

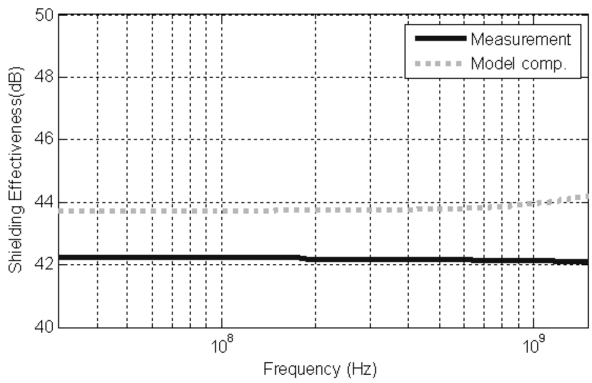

Fig. 6: Modelling of the sample as compact material.

6. Conclusion

Two methods have been shown in order to model the shielding effectiveness of different type of materials and the results were compared to measurement of real sample. The first method is focused on modelling of wire mesh screens, and the second one on modelling of the shielding effectiveness of electromagnetic compact barriers.

In the case of the wire mesh model, an error of 3 dB at 1 GHz (and in the almost whole frequency range 30 MHz–1,5 GHz) with respect to measurements has been detected, i.e. about 45 dB for model and 42 dB for measurement. It is inside the uncertainty margin of ±5 dB due to the measurement method and it represents a good approximation.

Modelling of conductive textile as an electromagnetic compact barrier has achieved better results compared to measurements in the frequency band 30 MHz–1,5 GHz. Shielding effectiveness of about 44 dB has been achieved for the model in the frequency range 30 MHz–1,5 GHz (43,5 dB at 1 GHz) in comparison with measurement results, i.e. about 42 dB in the frequency range 30 MHz–1,5 GHz (42,1 dB at 1 GHz). Obtained values have been shown to be inside the uncertainty margin of the measurement method.

When comparing the results of modelling it is obvious there is a contradiction with theory. The shielding effectiveness of compact electromagnetic barrier must be in principle higher than the shielding effectiveness of wire mesh. This error is again smaller than the random error measurement method.

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