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Modeling Protective Properties of Textile Shielding Grids Against Electromagnetic Radiation

Abstract
The shielding properties of conductive grids are mainly due to the reflection of electromagnetic waves from their surface. The shielding effectiveness depends on the grid mesh size and the thickness and resistivity of the grid material. This paper presents the results of model studies of equivalent circuits of new grids made of woven fabrics containing various types of conductive threads in their structures. The results obtained in the simulation software Matlab/Simulink were compared with measurement results of the transmission and reflection losses (coefficients) of the electromagnetic radiation (EMR) obtained by the wave-guide applicator method within the frequency range of 2.5 - 18 GHz, showing their great similarity. The modelling method developed makes it possible to optimise the design processes of the structure and raw material composition of shielding fabrics with the EMR suppression expected for the practical applications specified.

Key words: *textile shields, electromagnetic radiation, equivalent circuit, modeling.*

Introduction

EMR shielding grids made of metal wires or conductors are one of the most frequently used protective measures against electromagnetic radiation. Their great popularity results from the high effectiveness of electromagnetic shielding and physical properties desired. They are definitely lighter than corresponding metal sheets, their production uses less materials, and their natural holes provide ventilation and light access, which is often of great practical importance. These also enable definitely easier mechanical working to shape various shielding systems. However, recent innovative trends have been going towards searching for EMR shielding materials with still better shielding effectiveness and physical properties. One such proposal is presented in this paper, concerning electromagnetic shields made of textile shielding grids. Such materials, made by the weaving technique with the use of electro-conductive threads or fibres incorporated into the fabric structure, are characterised by very good shielding effectiveness, comparable with that of metal grids. In comparison to metal grids, they have definitely better functional values, are much lighter and more elastic , much less conductive material is required for their making, and are easy to transport and apply, being suitable as e.g. wall-covering elements for light room shielding. One can also easily stick them together or construct effective nonreflecting shielding systems from them [1]. Then, taking into account the fact that in shielding grids the process of EMR suppression consists mainly of reflecting this radiation, in multi-layer composite systems they are used as the last layer in relation to the incident electromagnetic wave [2].

Currently a trend is beginning to become established that the designing of physical shielding materials is preceded by or simultaneously performed with simulation studies. Then such an approach allows one to obtain a mathematical model that can be later used in the initial phase of designing a new material for the creation of a prototype. Simulation studies are definitely less expensive and faster than those with a real object. They require one to use a computing unit (PC) with appropriate software and mathematical model of the phenomenon or process to be simulated. In this paper, we undertook the creation of a general model of a woven shielding grid followed by its identification to determine unknown parameters of the description.

Woven shielding grids

Searching for innovative materials with a high EMR shielding effectiveness, a woven grid made of continuous polyester fibres with electro-conductive filaments incorporated into its structure at uniform intervals was proposed. The fabric was made with the use of a plain weave, the structural assumptions of which are shown in ***Figure 1***. The basic assumption was that the grid, formed of conductive filaments, would have a side length of about 3 mm and a shape as close to a square as possible. Considerable attention was paid to the workmanship quality of the grid of conductive filaments, providing a uniform mesh shape and close contact at filament crossings, since, taking into account electromagnetic properties, it is the conductive structure that is of importance for the shielding effectiveness. The remaining portion of the fabric structure of polyester fibres only constitutes a mechanical support for electro-conductive filaments. Considering the negligible thickness of conductive filaments compared with the grid dimensions, such a structure may be treated as a flat shielding system. The length of the electromagnetic wave, comparable with that of the conductive grid size, corresponds to a frequency of about 10 GHz. Hence it was decided to carry out tests within the range of 2.5 – 18 GHz, which makes it possible to test the shield properties for lower and higher frequencies than 10 GHz.

Implementing the design assumptions, the following woven fabric samples were made:

- ***Sample P1*** – a flat harness woven fabric with a plain weave, made of continuous polyester fibres, type DTTW 167 dtex f32, with electro-conductive composite threads distributed in the

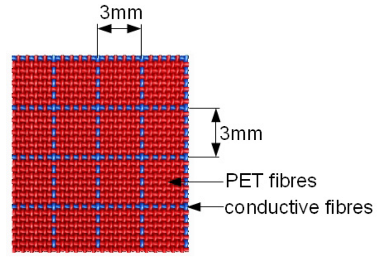

Figure 1. *Structural assumptions of the shield made of woven fabric with a plain weave.*

form of a square grid with a side of about 3 mm. The composite conductive thread was made of a silver-plated copper filament with a diameter of 0.079 mm, twisted together with a multifilament polyester yarn (copper 0.079 mm + PET 167 dtex) + PET 330 dtex. The resulting linear density of the conductive composite yarn was 840 dtex.

- ***Sample P2*** – a flat harness woven fabric with a plain weave made of continuous polyester fibres, type DTTW 167 dtex f32, with electro-conductive threads distributed in the form of a square grid with a side of about 3 mm. The conductive thread was made of silver plated polyamide filaments, 110 dtex, twisted with a multi-filament polyester yarn: (Shildex 110 dtex + PET 190 dtex). The resulting linear density of the conductive composite yarn was 300 dtex.
- ***Sample P3*** – a flat harness woven fabric with a plain weave, made of continuous polyester yarns, type DTTW 167 dtex f32, with conductive threads distributed in the form of a square grid with a side of 3 mm. The composite conductive thread was made of a steel filament with a diameter of 0.035 mm, twisted with multifilament polyester yarn: (steel 0.035 mm + PET 167 dtex) + PET 330 dtex. The resulting linear density of the conductive composite yarn was 580 dtex.

Figure 2 shows photos of the fabric samples with visible various conductive threads weaved into the fabric structure. As is seen, such shields may be treated as recurrent structures, in which the same shape of the conductive check is repeated in all directions on the plane.

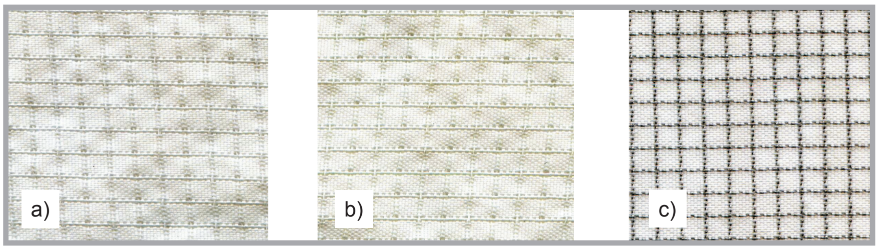

Figure 2. *Photos of fabric samples with visible various types of conductive threads incorporated into the fabric structure; a) sample 1, b) sample 2, c) sample 3.*

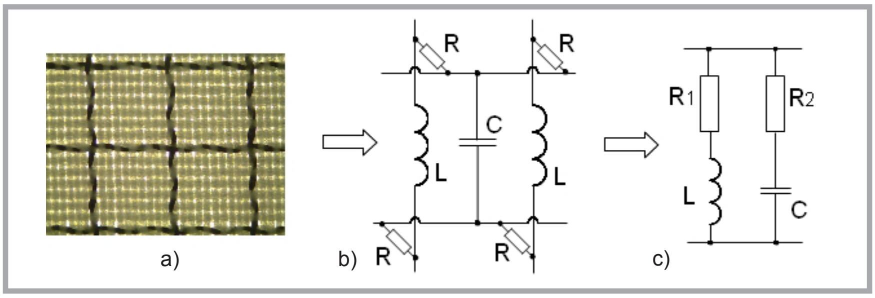

Figure 3. *Stages of the formation of an equivalent model for a shield made of woven fabric; a) photo of a woven shielding grid in transmitted light, b) circuital equivalent scheme of shielding grid, c) final form of the electric model of the shielding grid.*

Modeling by means of equivalent circuits

The method of modelling with the use of equivalent circuits for recurrent structures was first proposed by Anderson [3]. This technique uses the interaction that occurs between the incident electromagnetic wave, with a specified frequency and polarization, and elements of the infinite shielding recurrent structure. Assuming that this structure consists of infinite, thin, continuous and ideally conductive stripes, it is possible to determine the equivalent impedance that, depending on the parallel or perpendicular polarisation of the incident electromagnetic wave, shows either an inductive or capacitive character [4]. In many solutions of practical recurrent structures, inductive and capacitive elements occur at the same time and their combination creates the equivalent impedance of the structure. Combinations of this type may be treated as an equivalent filtration system composed of RLC elements that can be analysed by known methods of dealing with electric circuits of alternating current, e.g. the operational method. Such an approach allows to directly obtain Bode's diagrams, i.e. the amplification modulus and phase of an equivalent electric circuit as a function of the electromagnetic wave.

Figure 3 shows particular stages of the formation of an equivalent circuit of a shield made of woven fabric containing conductive threads. The starting point is a photo of the fabric in transmitted light, taken by means of a stereoscopic microscope from Olympus (***Figure 3.a***). It presents the shielding grid surface, on which conductive filaments are visible, distributed at approx. 3 mm intervals. For an electromagnetic wave with vertical polarisation, such a surface may be treated as one built of wires with an infinite length corresponding to vertical inductances (L) in the equivalent circuit (***Figure 3.b***). In turn, the horizontal conductive elements correspond to capacities (C) that in the equivalent scheme are combined in parallel with inductances. Thus the circuital equivalent scheme of the shielding grid, shown in ***Figure 3.b***, is a parallel combination of equivalent elements L and C. However, considering the fact that the connection of conductive filaments crossing in the fabric (***Figure 3.a***) is not ideally conductive, one should take into account additional resistance R in the equivalent scheme (***Figure 3.b***). Passing from the equivalent periodical structure (distributed parameters) – ***Figure 3.b*** to the model in the form of a transmission line (concentrated parameters), one may propose an equivalent electrical model, as shown in ***Figure 3.c***. Resistances R1 and R2 proposed in the model take into account the crossing of conductive filaments in the shielding fabric and the resistances of the conductive filaments themselves, which leads to the presence of real equivalent inductive and capacitive elements (with serial resistance) of the model. Taking into account theoretical considerations [5], the connection of the equivalent model shown in ***Figure 3.c***, depending on the parameters of RLC elements and frequency, can be in a parallel resonance that, in the case of the relation to electromagnetic phenomena, corresponds to an ideal transmission of the electromagnetic wave through a shielding grid of this type. However, in the real case of the shielding grid, as a result of a relatively great distance between horizontal elements of the grid, the equivalent capacity C is too low to cause real resonance. Such a situation is illustrated

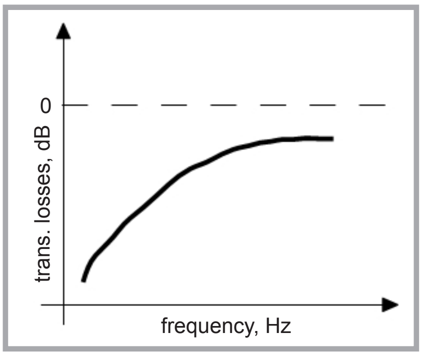

Figure 4. *Changes in the transmission losses as a function of the frequency of the electromagnetic wave for the equivalent model of the shielding grid.*

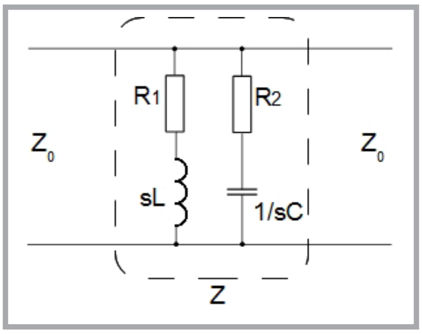

Figure 5. *Equivalent model of the textile fabric shield with the use of a transmission line.*

in ***Figure 4***, showing a pictorial graph of the change in the transmission losses (coefficient) of the electromagnetic wave by the shielding grid as a function of the frequency. The structure of the shielding grid, leading to great disproportions between values of the equivalent capacity and inductance, results in the situation shown in the graph where the transmission losses increases with an increase in the frequency; however, in spite of this it never reaches a value equal to '0 dB' or the ideal transmission [6].

Using the operational method (Laplace transform) of solving RLC electrical systems, the equivalent scheme in ***Figure 3.c*** can be presented in a form enabling the determination of frequency characteristics of the transmission and reflection losses of the electromagnetic wave (***Figure 5***).

Hence the equivalent impedance of connection, according to the equivalent model shown in ***Figure 5***, can be expressed by ***Equation 1***, where: L – equivalent induction of the model, in H, C- equivalent capacity of the model, in F, R_1, R_2 – serial resistances of the model, in Ω.

One of the basic test methods concerning shielding material is the procedure for the determination of the losses of transmission and reflection of an electromagnetic wave through a sample and from the surface thereof, respectively, within a wide range frequency. In co-operation with the Military Institute of Armament (Zielonka, near Warsaw) such tests were carried out by means of a wave-guide applicator, using procedure LR.PB.18: Measurement of frequency characteristics of the losses of transmission and reflection was performed using the system presented in [7, 11]. To enable comparison of the values of transmission and reflection losses obtained by means of the measurements, calculated according to simulation with the model presented in ***Figure 5***, it is necessary to determine the analytic forms of the transmission and reflection losses.

$$Z=\left(\frac{1}{R_1+sL}+\frac{1}{R_2+\frac{1}{sC}}\right)^{-1}=\frac{s^2LCR_2+s\left(L+R_1R_2C\right)+R_1}{s^2LC+sC\left(R_1+R_2\right)+1}\quad\text{, in }\Omega \tag{1}$$

$$T=\left|\frac{2\left(s^2R_2LC+s\left(R_1R_2C+L\right)+R_1\right)}{s^2\left(2R_2LC+Z_0LC\right)+s\left(2\left(R_1R_2C+L\right)+\left(R_1+R_2\right)Z_0C\right)+2R_1+Z_0}\right| \tag{3}$$

$$\Gamma=\left|\frac{Z_0\left(s^2LC+s\left(R_1+R_2\right)C+1\right)}{s^2\left(2R_2LC+Z_0LC\right)+s\left(2\left(R_1R_2C+L\right)+\left(R_1+R_2\right)Z_0C\right)+2R_1+Z_0}\right| \tag{5}$$

$$T=\left|\frac{2\left(-\omega^2R_2LC+j\omega\left(R_1R_2C+L\right)+R_1\right)}{-\omega^2\left(2R_2LC+Z_0LC\right)+j\omega\left(2\left(R_1R_2C+L\right)+\left(R_1+R_2\right)Z_0C\right)+2R_1+Z_0}\right| \tag{6}$$

$$\Gamma=\left|\frac{Z_0\left(-\omega^2LC+s\left(R_1+R_2\right)C+1\right)}{-\omega^2\left(2R_2LC+Z_0LC\right)+j\omega\left(2\left(R_1R_2C+L\right)+\left(R_1+R_2\right)Z_0C\right)+2R_1+Z_0}\right| \tag{7}$$

Equations 1, 3, 5, 6 and 7.

Based on transmission line theory, the transmission loss is expressed by the following formula [8 - 10]:

$$T=\left|\frac{2Z}{2Z+Z_0}\right| \tag{2}$$

Where Z_0 – wave impedance equal to 377 *Ω*.

After substituting formula (1) into (2), we obtained formula (3).

Another characteristic coefficient determined in considerations connected with the transmission line is the reflection losses, defined according to the formula:

$$\Gamma=\left|\frac{Z_0}{2Z+Z_0}\right| \tag{4}$$

After substitututing formula (1) into (3), we obtained formula (5).

The substitution of $s=j\omega$ into (3) and (5), where $\omega = 2\pi f$, enables the determination of analytical formulas for frequency characteristics of the losses of transmission and reflection based on model (1) - ***Equations 6*** and ***7***, where: T – transmission losses (coefficient), Γ – reflection losses (coefficient), R_1, R_2 – serial resistances, Z_0 – wave impedance of vacuum, Z_0=*377* Ω, ω – angular velocity in rad/s, $\omega = 2\pi f$, f – frequency in Hz.

Parameterisation of the model

The shielding effectiveness of three fabric structures containing conductive threads was assessed. Independently the courses of transmission and reflection losses were determined as these explicitly verify the shielding effectiveness of the materials tested [7]. The transmission loss informs how much energy passes through the sample tested, and its inverse testifies to the effectiveness of shielding. In turn, the reflection loss informs about the suppression of radiation reflected from the sample, indicating what happens with the incident electromagnetic radiation on the sample – whether it is reflected or changed into heat inside the sample, which means suppressed. The losses of transmission and reflection were determined within the following ranges of frequency:

- from 2.5 to 3.5 GHz
- from 3.5 to 5 GHz
- from 5 to 8 GHz
- from 8 to 13 GHz
- from 13 to 18 GHz.

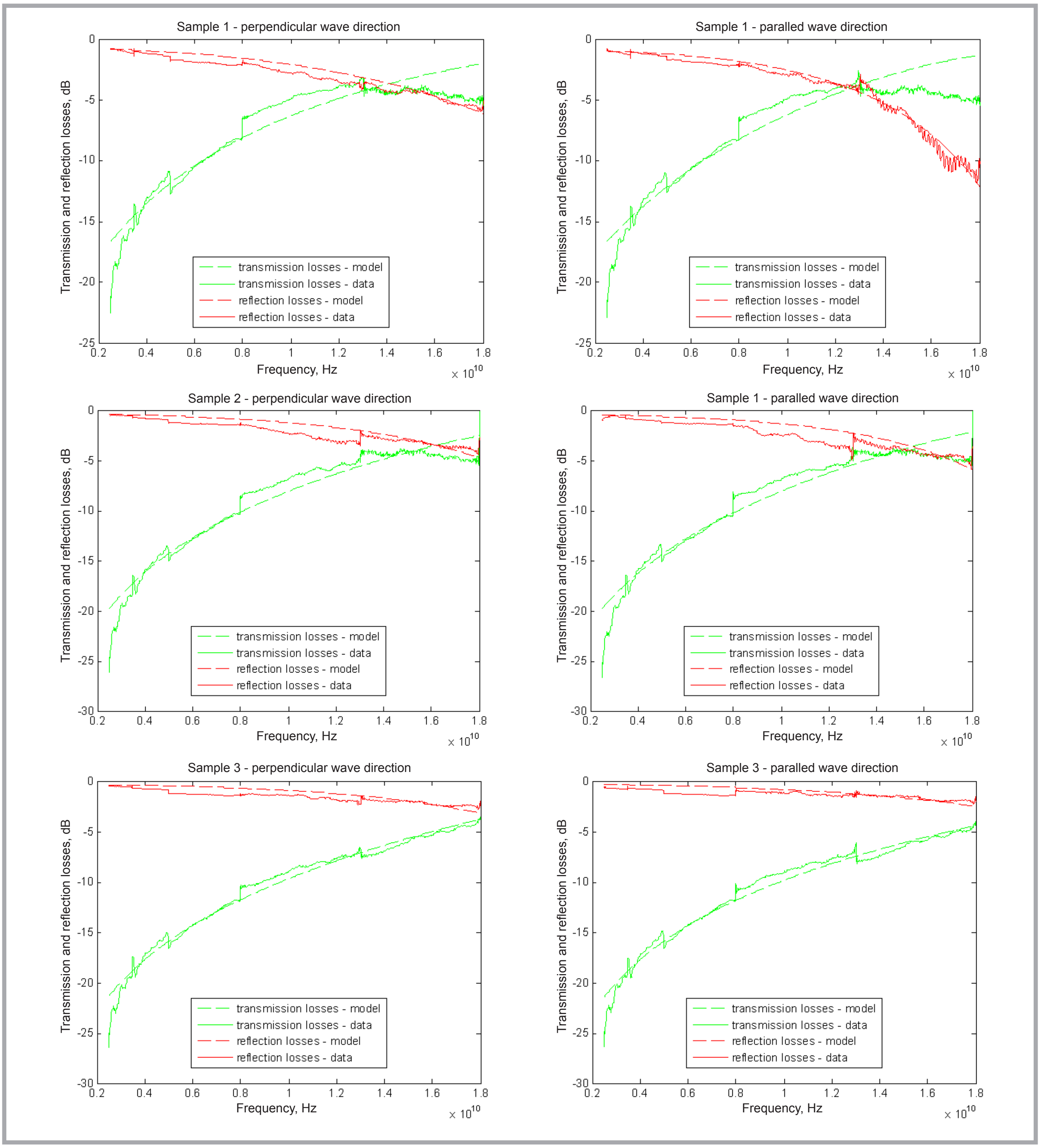

Figure 6. *Changes in the frequency characteristics of transmission and reflection losses for three samples tested (sample 1, 2 & 3) and two wave propagation directions compared with the theoretical model.*

Each sample of textile shield was tested twice, determining the losses of transmission and reflection in two directions of the electromagnetic wave propagation: perpendicular and parallel. It was also confirmed that the fabric side (back or face) on which the EMR incidence occurs has no effect on the results of the transmission and reflection coefficient obtained. Therefore only one side of each fabric structure was tested for two directions of wave propagation. The measurement results obtained were used to determine the values of parameters R_1, R_2, L and C of the equivalent model, shown in ***Figure 5***. To that end, the optimisation numerical procedure of Matlab/Simulink software was used, appropriately adapted to the needs of this task, minimising the error between the values of transmission and reflection losses measured and the courses of their characteristics calculated from ***Equations 6*** and *7*. We also made use of the possibility of the modification of sample validity, based on the weighting function, to reduce the influence of less probable measurements on the model parameters, taking the crossing point of measured and modelled characteristics as reference. Dependences showing the courses of the frequency characteristics of transmission and reflection losses for the real and model cases are illustrated in ***Figure 6***.

Table 1. Calculated parameters of the equivalent models for all cases of real tests.

Model parameter	Sample 1		Sample 2		Sample 3	
	perpendicular	in parallel	perpendicular	in parallel	perpendicular	in parallel
L, in nH	1.59	1.47	1.16	1.13	0.96	0.97
C, in pF	0.02	0.04	0.03	0.04	0.03	0.02
R_1, in Ω	16.69	19.82	8.24	9.47	7.26	6.40
R_2, in mΩ	0.13	0.14	0.17	0.14	0.27	0.33

Analysing the real and simulated courses of transmission and reflection losses shown in ***Figure 6***, one can observe that the circuital equivalent model of textile shields proposed and presented in ***Figure 5*** reflects very well the behaviour of all the three samples of woven structures – the real shield proposed. It should be emphasised that the model was verified by the very high compatibility of the two theoretical waveforms obtained from ***Equation 6*** and ***7*** by the two independent measurements of transmission and reflection. The only divergences between the model and real characteristics can be observed in the case of samples 1 and 2 for a transmission loss within the highest frequency range tested, i.e. from 13 GHz to 18 GHz. In these cases, the divergences definitely testify to the benefit of the simulation model since the course of the simulation result of the transmission loss is more probable than that obtained in real tests. Within the range of 13 – 18 GHz, especially in the case of sample 1, a decisive change in the transmission loss course is visible (the curve begins to decrease, while in the previous range it had an upward trend), which most probably indicates an error in the coefficient value measured in this range. It is also seen that the model approach proposed fails to reflect the jumps (several dB at a time) in transmission and reflection loss characteristics occurring after changing the measurement range. In fact, such jumps do not occur; they are connected with modification of the measurement stand consisting in replacing wave-guide elements. By repeating the measurements and remounting the textile shield sample tested on the apparatus frame, it is impossible to maintain its identical arrangement and stress (tension), which is reflected in the occurring jumps in coefficient characteristics.

The characteristics presented in ***Figure 6*** also confirm the observation that in a shielding system of this type, the equivalent capacity value in the model is relatively low, and within the frequency ranges considered, it is impossible to obtain a resonance phenomenon that would result in an ideal transmission of EMR through the sample tested. However, in physical reality it is difficult to expect an ideal transmission due to the occurrence of dissipating elements (e.g. non-zero resistances of conductive filaments and spots of their contact).

Table 1 shows the absolute values of particular model parameters for all the samples of fabric structures and two EMR propagation directions. The results obtained allow to figure out the values of particular passive RLC elements, which is of paramount importance for designers of filters using analog systems. A practical system for building analog filters with the use of the values of elements from ***Table 1*** and according to the scheme shown in ***Figure 5*** would show identical frequency properties as the proposed shields within the frequency range considered. The characteristics shown in ***Figure 6*** and the parameters of values of the circuital model parameters listed in ***Table 1*** reveal a slight asymmetry of the woven shielding structures due to the EMR propagation direction. This asymmetry results from the sole fabric structure, in which one can distinguish the warp and weft – elements that are not geometrically identical in respect of the incident electromagnetic wave direction.

The resistance resulting from the crossing of conductive threads and their finite conductivity is revealed in the model mainly in the form of resistance R1, that is at a level of several to a dozen or so ohms.

Conclusion

The simulation model using equivalent electric circuits proposed constitutes a relatively accurate reflection of the shielding effectiveness of the woven shields against EMR. This fact is confirmed by the very good simultaneous representation of the courses of transmission and reflection losses obtained, on the one hand, on the basis of the same theoretical model and, on the other, based on independent measurements for all the sets of measurement data (***Figure 6***) and parameters consistent with ***Table 1***.

The use of the model makes it possible to control and verify measurement results occurring with changes in the measurement range, which can be burdened with some error due to the difficulty of maintaining constant values of the tension and geometric dimensions of the fabric samples remounted on the apparatus frame. Therefore the model can be used to design shielding structures with assumed EMR shielding capabilities, significantly shortening and facilitating this laborious process.

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