WEB APPLICATION FOR PREDICTING THE SHIELDING EFFECTIVENESS OF WOVEN FABRICS WITH CONDUCTIVE YARNS

Ion Razvan RADULESCU[1], Lilioara SURDU[2], Emilia VISILEANU[3], Marian COSTEA[4], Ion PATRU[5], Viorica VOICU[6]

The shielding of electromagnetic smog is nowadays a necessity in many applications and the use of textile shields brings multiple advantages. This paper aims to find a simple relation, in a given frequency range, for shielding effectiveness of woven fabrics with conductive yarns. The proposed relation resulting after a thoroughly analyze of components of the general equation, was satisfactory validated by conducting experimental tests with various types of conductive fabrics. A web application was performed to support the design process of woven fabrics, based on the validated model. The web application is destined for stakeholders in textiles online at www.certex.ro/victtex/.

Keywords: technical textiles, electromagnetic shielding, modelling, experimental study, validation, software

1. Introduction

Main aim of this paper is to adequately model electromagnetic shields made of woven fabrics with conductive yarns in order to obtain a simplest analytical relation for its shielding effectiveness (SE), in a given range of frequency. Conventional electromagnetic shields are built from metallic plates with a good electrical conductivity and/or high magnetic permeability, which are however stiff and heavy weighted. Woven fabrics with conductive yarns are flexible, light weighted, mechanical resistant and shapeable for any object's geometry [1]. Thus, woven shields have numerous advantages and applications as technical textiles, such as: outdoor tents for protection of electronic equipment, shielded rooms against wireless communication (GSM, WiFi), tarpaulins and curtains against electromagnetic smog for protection of homes, schools and kindergartens etc.

Moreover, textile processing technology enables adaptation of a woven shield to the requirements of a specific application. It is possible to manufacture

[1] INCDTP – Bucharest, Romania, e-mail: razvan.radulescu@certex.ro
[2] INCDTP – Bucharest, Romania
[3] INCDTP – Bucharest, Romania
[4] Faculty of Power Engineering, University POLITEHNICA of Bucharest, Romania
[5] ICMET – Craiova, Romania
[6] ICMET – Craiova, Romania, e-mail: programe@icmet.ro

customized and cost effective electromagnetic woven shields with an adequate design. Modelling supports design, by providing a link between fabric's parameters and shielding effectiveness. Costs, time and resources are thus reduced in the attempt to manufacture customized woven shields [2].

The shielding of electromagnetic (EM) radiation is a solution belonging to electromagnetic compatibility field [3]. Modelling of shielding may be performed either with impedance method or circuit method [4]. The impedance method performs an analogy with the propagation of TEM waves in long bifilar transmission lines. The method uses electric and geometric parameters of the shield to estimate shielding effectiveness [5]. The circuit method analyses the change of electric parameters of the shield with increasing frequency of the incident field [6]. The circuit method estimates the shielding effectiveness based on electric and geometric parameters of various shapes, such as: sphere, cylinder, parallel plates, parallel grids etc.

Several, dedicated attempts to model the shielding effectiveness of electro-conductive textile materials have been already performed in the scientific literature. One proposed mathematical model uses the gain of small apertures materials and their analogy with small antennas [7]. This model was validated by means of experimental measurements on various types of fabrics [8]. The literature reports shielding effectiveness models for fabrics with conductive coatings [9] as well as fabrics with magnetron plasma thin deposited metallic layers [10]. Research was directed towards modelling of other electric properties of fabrics, such as dielectric properties as function of surface and volume resistivity [11] or towards the study of electric conductivity of hybrid yarns [12]. Electro-conductive textiles are used nowadays in various applications, such as smart materials which react at stimuli from the environment [13].

This research paper proposes a method to estimate the shielding effectiveness of woven fabrics with conductive yarns based on the circuit method for grid structures [6]. Main contribution is adaptation of an analytic relation from the specialty literature for practical use. This adaptation was performed taking into account the specific properties of conductive yarns, namely a yarn radius smaller than skin depth on the studied frequency domain. A software web application based on the simplified analytic relation was programmed in PHP/MySQL. This application is destined to the stakeholders in the textile industry (SMEs) and supports the design process of woven shields.

2. Description of the analytic relation for the shielding of an enclosure

The physical phenomenon of shielding produced by an enclosure covered with woven fabrics is based on the following considerations [6]:

- The wave length of the incident field is much greater than the dimensions of the shielding enclosure;

- The incident field with magnetic component amplitude H_a is homogenous on both walls of the shielding enclosure and parallel with the *Oy* axis;
- The incident field is a low-impedance near electromagnetic field, its effect being a much greater induction current than displacement current, which may be neglected;
- The parallel conductive yarns are connected at their ends, enabling the circulation of eddy currents (*I*) induced by the incident field (Fig. 1).

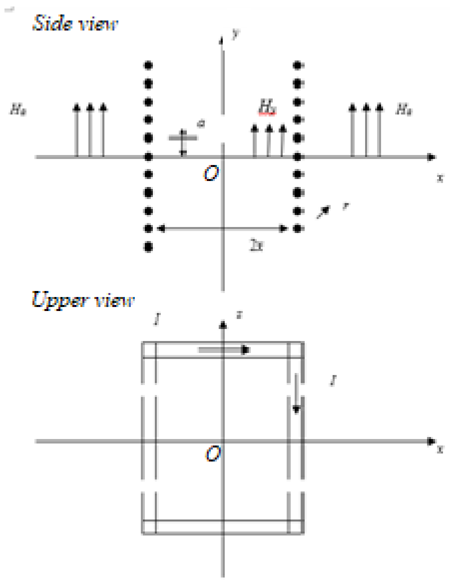

Fig. 1 – Side and upper view of enclosure covered with woven fabrics.

Fig. 1 presents the side and upper view of the shielding enclosure covered with woven fabrics. Eddy currents close (along Oz axis) at a certain length and produce an opposing field to the incident one, reducing the intensity of magnetic field in the inner of the enclosure to H_y.

The following geometric and electric parameters apply for the enclosure covered with woven fabric:

r – conductive yarn radius of the fabric
a – distance between the conductive weft yarns
2*x* – distance between the two walls of the enclosure
σ – electric conductivity of the yarn
μ - magnetic permeability of the yarn
δ – the skin depth (related to the frequency)
ρ_i – resistance function
λ_i – induction function (expressed as ratio between *r* and δ)
W – reflection factor

The analytic relation for shielding effectiveness is based on computing the shielding factor Q. The shielding factor includes some electric parameters, such as the ratio between yarn radius and skin depth [6]:

$$\left(\frac{r}{\delta}\right) = \frac{r}{\sqrt{\frac{2}{\omega\sigma\mu}}}. \tag{1}$$

with $\omega = 2\pi f$ the angular frequency of the incident near EM field.

The resistance function is a physical-electrical parameter describing the increase of electrical resistance in a conductive yarn, with increase of frequency. The phenomenon is explained by decreasing of skin depth and smaller cross-section for circulation of electrical eddy currents. Resistance increases according to resistivity relation. The resistance function has the following expression [6]:

$$\rho_i\left(\frac{r}{\delta}\right) \approx \begin{cases} 1 + \frac{1}{48}\left(\frac{r}{\delta}\right)^4 & \text{for } r \leq 1.5\delta \\ \frac{r}{2\delta} + \frac{1}{4} + \frac{3}{32}\frac{\delta}{r} & \text{for } r \geq 1.5\delta \end{cases} \tag{2}$$

The induction function describes the behavior of the inductivity with increase of frequency. It has an opposite behavior when compared to resistance function, decreasing with the increase of the frequency. The induction function has the following expression:

$$\lambda_i\left(\frac{r}{\delta}\right) \approx \begin{cases} \frac{1}{4} & \text{for } r \leq 2\delta \\ \frac{\delta}{2r}\left(1 - \frac{3}{16}\left(\frac{\delta}{r}\right)^2 + \cdots\right) & \text{for } r \geq 2\delta \end{cases} \tag{3}$$

The effective magnetic permeability considers the decrease of magnetic permeability with increase of frequency for ferromagnetic yarns. It has according to [6] the following expression computed in complex representation:

$$\mathrm{Re}\frac{\mu_w}{\mu} \approx \begin{cases} 1 & \text{for } r \leq \delta \\ \frac{\delta}{r} & \text{for } r \geq \delta \end{cases}$$
$$\mathrm{Im}\frac{\mu_w}{\mu} \approx \begin{cases} -\frac{1}{4}\left(\frac{r}{\delta}\right)^2 & \text{for } r \leq \delta \\ -\frac{\delta}{r}\left(1 - \frac{1}{2}\frac{\delta}{r}\right) & \text{for } r \geq 2\delta \end{cases} \tag{4}$$

The reflection factor W is an electrical parameter describing the effect of magnetic field produced by eddy currents to the incident magnetic field. It is defined in relation to the magnetic properties of the yarns, thus having two different expressions for ferromagnetic and diamagnetic yarns:

1) For diamagnetic yarns with content of e.g. copper, aluminum, silver:

$$W = \begin{cases} \frac{j}{4}\left(\frac{r}{\delta}\right)^2 & \text{for } r \le \delta \\ 1 - \frac{(1-j)\delta}{r} - \frac{j}{2}\left(\frac{\delta}{r}\right)^2 & \text{for } r \ge 2\delta \end{cases} \quad (5)$$

2) For the ferromagnetic yarn (e.g. stainless steel), the reflection factor is expressed in relation to the effective magnetic permeability μ_W and the constant factor k. The effective magnetic permeability describes the behavior of the magnetic permeability of the yarns in relation to the frequency. It has the following expression:

$$\frac{\mu_w}{\mu} = \frac{2\,J_1(\mathrm{jkr})}{\mathrm{jkr}\,J_0(\mathrm{jkr})}, \quad (6)$$

J_1 and J_0 are the Bessel functions of the degree 1 and 0, and W has the expression:

$$W = -\frac{\frac{\mu_w}{\mu}\left(1+\frac{\mu_0}{\mu}\right) - 2\frac{\mu_0}{\mu}}{\frac{\mu_w}{\mu}\left(1-\frac{\mu_0}{\mu}\right) + 2\frac{\mu_0}{\mu}} \quad (7)$$

while k is a constant factor (complex propagation factor), computed according to the expression:

$$\mathrm{k}^2 = \mathrm{j}\omega\mu\sigma\,. \quad (8)$$

The definition of shielding factor Q is expressed as ratio between the intensity of the magnetic field inside the enclosure (H_y) and the intensity of the magnetic field outside the enclosure (H_a) [6]:

$$Q \equiv \frac{H_y}{H_a} = \frac{\rho_i + \mathrm{j}\left(\frac{r}{\delta}\right)^2\left[\lambda_i + \left(\frac{\pi r}{a}\right)^2 W - \ln\left(2\sinh\frac{\pi r}{a}\right)\right]}{\rho_i + \mathrm{j}\left(\frac{r}{\delta}\right)^2\left[2\pi\frac{x}{a} + \lambda_i - \ln\left(2\sinh\frac{\pi r}{a}\right) - \left(\frac{\pi r}{a}\right)^2 W\right]} \quad (9)$$

The shielding effectiveness is resulting from the relation of the shielding factor Q, either in Neper (Np) or in Decibel (dB):

$$\mathrm{SE} = \ln\left(\frac{1}{|Q|}\right)\ [\mathrm{Np}] \quad (10)$$

$$\mathrm{SE} = 20\log_{10}\left(\frac{1}{|Q|}\right)\ [\mathrm{dB}] \quad (11)$$

This study aims to adapt these analytical relations for practical use.

3. Experimental study

In order to validate the proposed analytic relation, an experimental study was conducted, including the manufacturing of two types of woven fabrics with conductive yarns as well as an experimental setup for the measurement of the shielding effectiveness of an enclosure, covered with these two types of fabrics.

3.1 Materials - the woven fabrics with conductive yarns

Two woven fabric were designed and manufactured to cover the shielding enclosure. The woven fabrics used stainless steel (RAZ-1) and silver yarns (RAZ-5) in weft or warp/weft direction. The diameter of conductive yarn was around 280 µm and the distance between the conductive yarns was of 4 mm. The electrical conductivity of the stainless-steel yarns was 7700 S/m while the electrical conductivity of silver yarns was 111000 S/m. The relative magnetic permeability of the stainless-steel yarns was 7.36. The physical-mechanical and electric properties of textile materials were tested in INCDTP – Bucharest accredited laboratories.

3.2 Methods - the electric measurement system

The shielding enclosure was built from wooden bars with the cross-section of 2x3 cm and the length of 1 m. As known, dry wood has similar magnetic permeability as air and hence it does not influence the measurements. Covers from woven fabrics RAZ-1 and RAZ-5 were tailored to meet dimensions of the shielding enclosure. Fig. 2 and 3 show the experimental setup, composed of the enclosure with textile covers and the electric measurement system.

Fig. 2 – The experimental setup.

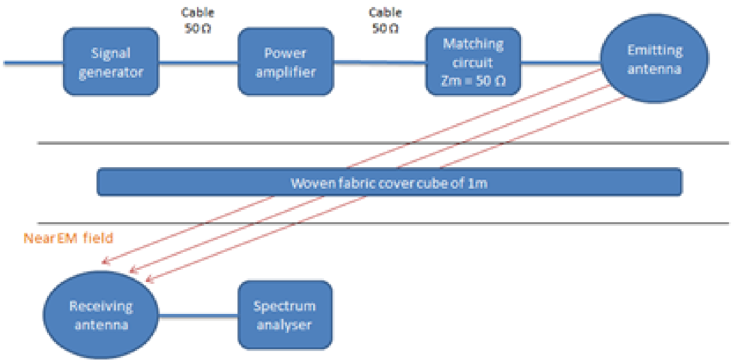

Fig. 3 – Block diagram of the experimental setup.

The experimental study was performed in EMC Laboratory of Faculty of Power Engineering at University Polytechnica Bucharest.

4. Results

The specific properties of woven shields, having conductive yarns with a skin depth greater than the radius, as well as the reduced variation of some electric parameters (ρ_i, λ_i) on the studied frequency domain were main premises for mathematical simplification of equation (9). The simplified analytic relation for the shielding factor (12) was computed by means of mathematical operations from (9) and is valid for a certain frequency domain (13):

$$|Q| = \frac{1}{2\pi}\frac{a}{x}\left(\frac{\delta}{r}\right)^2 \tag{12}$$

$$f_{min} \geq \frac{1}{2\pi^2\sigma\mu\frac{x}{a}r^2} \tag{13}$$

The upper frequency f_{max} is limited by the resonance frequency of 20 MHz, accordingly to the standard IEEE 299.1 [14]. Standard IEEE 299.1 describes a shielding effectiveness testing method for shielding enclosures with sides between 0.1-2.0 m, based on an receiving-emitting antenna system. Depending on the frequency range, various types of antennas are used: loop, dipole or horn antennas. Loop antennas are used for the frequency range of 9 kHz-20 MHz, while the frequency range 20-300 MHz is considered to be resonant with the shielding enclosures. Fig. 4 shows the shielding effectiveness for the simplified and initial analytic relation.

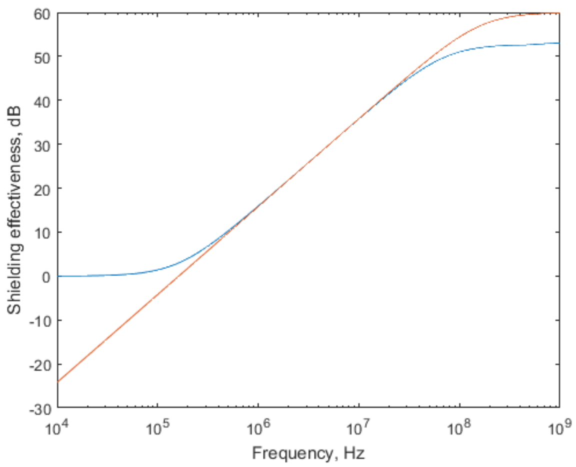

Fig. 4 - Shielding effectiveness for simplified relation (red curve) and analytic original relation (blue curve) for parameters of woven fabric RAZ-1

Shielding effectiveness of the fabrics RAZ-1 (stainless steel) and RAZ-5 (silver) was measured in the frequency range 1-30 MHz. The silver fabric presents values in the noise (incertitude measuring) zone and is it supposed to yield better results at higher frequencies. The stainless-steel fabric reaches a shielding effectiveness of 10 dB at 20 MHz, due to its ferromagnetic nature. The deviation between calculated and experimental data could be explained first of all by the difference of experimental setup to the ideal one and the weak electrical connection between conductive yarns at the edges of the enclosure.

5. Discussion – the software program destined for textile companies

The simplified analytic relation for estimation of shielding effectiveness (12) was the basic idea in programming a web application, destined for the textile specialists. The web application was programmed in PHP / MySQL by the authors of the study. It is hosted at the URL http://www.certex.ro/victtex/login.php and uses authentication for access. The web application addresses a relational data basis, conceived for the specificity of woven fabrics with conductive yarns. The application uses PHP forms for introducing the parameters of the fabrics into the data basis. A PHP form for the test of shielding effectiveness is used to introduce the geometric and electric parameters of the shielding enclosure and to select the conductive yarn of the woven cover (Fig. 5).

Fig. 5 – PHP form for introducing the parameters of the fabric

The relational data basis includes a set of physic-mechanic and electric properties of the conductive textile materials, however the following geometrical and electrical parameters are used to estimate the shielding effectiveness according to relation (12):

- Yarn radius (r)

- Distance between conductive yarns in warp or weft direction (*a*)
- Distance between the walls of the enclosure (2*x*)
- Electrical conductivity of the yarn (σ)
- Relative magnetic permeability (μ_r)
- Frequency of the incident magnetic field (*f*)

By submitting these data into the PHP form, the software program displays the estimated value of the shielding enclosure (Fig. 6).

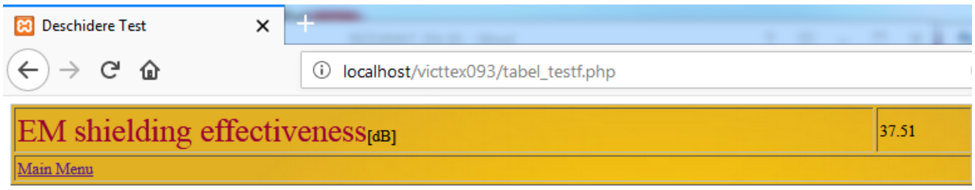

Fig. 6 – Predicted shielding effectiveness

Thus, the software web application may be used for support in the design process of woven shields. If raw material and distance between of conductive yarns of a woven shield are known parameters, the user of the software is able to find out the shielding effectiveness. This is useful in applications with given target shielding effectiveness (e.g. 35 dB). The woven shield may to be customized cost-effectively to the required application.

6. Conclusions

This paper approaches the modern topic of electromagnetic shielding by means of woven fabrics with conductive yarns. Main result is a simplified analytic relation, allowing the prediction of the shielding effectiveness based on the geometrical and electrical parameters of the fabric. The simplified relation was validated by experimental tests, based on two woven fabrics with conductive yarns having stainless steel and silver content. An experimental setup was built, composed of an enclosure covered with the fabrics and an electrical measurement system. Validation presented good results for the stainless-steel fabric in the frequency range 1-20 MHz. Based on this simplified analytic relation, a web application was programmed, destined for use by textile companies in the design of woven shields. The web application is available online at www.certex.ro/victtex/.

R E F E R E N C E S

[1] *A. Dodu*, The Textile Engineering Handbook (Manualul Inginerului Textilist), Bucharest: AGIR, 2005.
[2] *K. Velten*, Mathematical modelling and simulation, Germany: WILEY-VCF Verlag, 2009.
[3] *M. Costea*, Methods and means used to ensure electromagnetic immunity (Metode și

mijloace de asigurare a imunității electromagnetice), Bucharest: AGIR, 2006.
[4] *A. Schwab*, Electromagnetic compatibility, Bucharest: AGIR, 2013.
[5] *C. Paul*, Electromagnetic compatibility (Compatibilitate electromagnetică), WILEY-Inter Science, 2006.
[6] *H. Kaden*, Wirbelstroeme und Schirmung in der Nachrichtentechnik, Munich: Springer-Verlag, 1959.
[7] *J. Hajek and J. Svoboda*, "PhD Thesis: Modelling the shielding effectiveness of flat textiles," TU Prague, 2010.
[8] *A. Caro and L. Vojtech*, "Master Thesis: Modelling of textile reinforced composite barriers against electromagnetic radiations," TU Prague, 2011.
[9] *J. Ziaja, M. Ozimek and J. Koprowska*, "Metallic and oxide Zn and Ti layers on textiles as shields for electromagnetic fields," in EMC Europe Workshop, Athens, 2009.
[10] *J. Ziaja, M. Ozimek and J. Janukiewicz*, "Application of thin films prepared by impulse magnetron sputtering for shielding of electromagnetic fields," Electroteh. Rev., vol. R. 86, no. nr. 5, pp. 222-224, 2010.
[11] *J. Pospieszna, M. Jaroszewski and W. Bretuj*, "Influence of surface and volume resistivity on dielectric properties of carbon-polypropilene fabric composite obtain by plasma deposition," Electrotech. Rev., vol. R.86, no. nr. 5, pp. 275-278, 2010.
[12] *V. Safarova and J. Militky*, "A study of electrical conductivity of hybrid yarns containing metal fibers," Journal of Materials Science and Engineering, vol. B2, no. 2, pp. 197-202, 2012.
[13] *L. van Langenhove*, "An overview," in Smart textiles for protection, Cambridge, Woodhead Publishing Limited, 2013, pp. 3-30.
[14] IEEE Standard Method for Measuring the Shielding Effectiveness of Enclosures and Boxes Having all Dimensions between 0.1 m and 2 m, IEEE 299.1-2013, std.