Numerical and Experimental Study of the Shielding Effectiveness of Hybrid Fabrics

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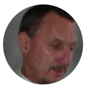

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NUMERICAL AND EXPERIMENTAL STUDY OF THE SHIELDING EFFECTIVENESS OF HYBRID FABRICS

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The electromagnetic interference shielding efficiency measurement needs to use special devices and in addition results are dramatically affected by applied measuring method. Measurements of surface or volume resistivity are simpler. It is known from theory that it is possible to measure characteristics of electrical part of electromagnetic field only at sufficiently high frequencies and therefore there should be mathematical relation between total shielding effectiveness SE [dB] and fabric resistivity or conductivity. One of modern application of materials with increased electromagnetic shielding efficiency is not only technical protection, but also protection of human being while operating specific electric equipments. The main aim of this work is investigation of the form of relation between electrical characteristics and total shielding effectiveness SE for special types of fabrics containing extremely thin metal fibers in its structure.

Key words: electromagnetic shielding efficiency, electric conductivity, correlation.

1. INTRODUCTION

According to World Health Organization [1], exposure to electromagnetic fields is not a new phenomenon. However, during the 20th century, environmental exposure to man-made electromagnetic fields has been steadily increasing as growing electricity demand, ever-advancing technologies and changes in social behavior.

Everyone is exposed to a complex mix of weak electric and magnetic fields, both at home and at work. Sources of such emissions could include generation and transmission of electricity, domestic appliances and industrial equipment, telecommunications and broadcasting. If the electromagnetic waves are not isolated effectively, they will cause interference with each other and result in technical errors. If somebody gets exposed under the electromagnetic, radiate environment, physical harms may occur on human body [2,3].

Metal is considered to be the best electromagnetic shielding material due its conductivity and permeability, but it is expensive, heavy, and may also have thermal expansion and metal oxidation, or corrosion problems associated with its use. In contrast, most synthetic fabrics are electrically insulating and transparent to electromagnetic radiation [4].

In recent years, conductive fabrics have obtained increased attention for electromagnetic shielding and anti-electrostatic purposes. This is mainly due to their desirable flexibility and lightweight [5]. One way how conductive fabrics can be created is by using minute electrically conductive fibers. They can be produced in filament or staple lengths and can be incorporate with traditional non-conductive fibers to create yarns that possess varying degrees of conductivity. Another way represents conductive coatings which can transform substrates into electrically conductive materials without significantly altering the existing substrate properties. They can be applied to the surface of fibers, yarns or fabrics. The most common are metal and conductive polymer coatings.

Direct measurement of fabrics electromagnetic shielding effectiveness is quite complicated especially because of need of special devices and time consuming preparation of samples. There are several methods available for shielding effectiveness (SE) measurement. However, for thin planar structures, there are no standards defining the evaluation of small samples of only a several tens of centimeters in size. Therefore, comparing presented research results is not easy.

Utilization of presumption that ‘electrical part of electromagnetic field dominates for sufficiently high frequencies’ seems to be simpler. Knowledge of the electrical characteristics which are easily measurable could be therefore used for establishment of electromagnetic shielding effectiveness of textile samples.

The main aim of this work is an investigation of the form of relation between electrical characteristics and total shielding effectiveness SE for special types of fabrics containing extremely thin metal fibers in its structure

2. THEOREY ON SHIELDING ELECTROMAGNETIC INTERFERENCE

An electromagnetic field is built up from various electric E and magnetic field H components. An electric field is created by a voltage difference and magnetic field is created by a moving charge, i.e. by a current. Every current is thus accompanied by both an electric and a magnetic field. Electromagnetic radiation consists of waves, see Fig. 1.

EMI shielding consists of two regions, the near field shielding region and far field shielding region. The amount of attenuation due to shield depends on the electromagnetic waves reflection from the shield surface, absorption of the waves into the shield and the multiple reflections of the waves at various surfaces or interfaces in the shield. The multiple reflections require the presence of large surface area (porous or foam) or interface area (composite material containing fillers with large surface area) in the shields. The loss connected with multiple reflections can be neglected when the distance between the reflecting surfaces or an interface is large compared to the skin depth δ [m] (the penetration depth) defined as:

$$\sigma = \frac{1}{\sqrt{\pi \varphi \mu K}} \qquad (1)$$

where *f* [Hz] is the frequency, *μ* is the magnetic permeability equal to $\mu_0.\mu_r$, μ_0 is the absolute permeability of free space (air = $4.\pi.10^{-7}$) and *K* [$S.m^{-1}$] is the electrical conductivity. An electric field at a high frequency penetrates only the near surface region of a conductor. The amplitude of the wave decreases exponentially as the wave penetrates the conductor. The depth at which the amplitude is decreased to 1/e of the value at the surface is called the "skin depth," and the phenomenon is known as the "skin effect" [6].

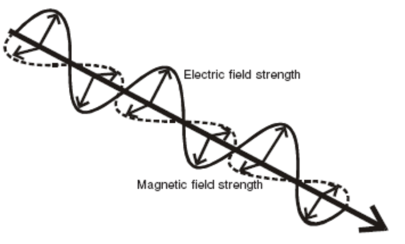


Fig. 1 Electromagnetic wave.

Efficiency of electromagnetic shields is commonly expressed by the total shielding effectiveness *SE* [dB], which represents the ratio between power P_2 [W] received with the shield is present and power P_1 received without the shield is present:

$$SE = -10 \log\left(\frac{P_2}{P_1}\right) \qquad (2)$$

where log(x) is decimal logarithm.

The electromagnetic shielding efficiency of element is characterized by its electric conductivity, permittivity, and permeability, parameters of source and properties of ambient surrounding. Basic proposed numerical models of fabrics SE are based either on electrical properties (especially volume conductivity) of element or on analysis of leakage through of opening in textile.

Shielding effectiveness *SE* of the conductive materials can be explained by the following expression [7, 8]

$$SE = 50 - 10 \log\left(\frac{f}{K}\right) + 1.7t\sqrt{f\,K} \qquad (3)$$

where *K* [$S\ cm^{-1}$] is the volume conductivity of the conductive material and *f* [MHz] is the frequency.

The usefulness of this model can be ascertained by comparison with the model of White [6], which is usually used to predict the shielding effectiveness of a conductive sample of thickness *t* [cm] to an electromagnetic wave of frequency *f* (Hz), given as

$$SE = 168 - 10 \log\left(\frac{K_C f}{K}\right) + 1.315\,t\sqrt{f\,\frac{K}{K_C}} \qquad (4)$$

where *K* [$S\ cm^{-1}$] is the volume conductivity and K_c is copper conductivity ($5.82\ 10^5\ S\ cm^{-1}$).

The analysis of leakage through openings in conductive yarn fabric shields is based on transmission line theory [9]. The shielding effectiveness is given by the equation

$$SE = A_a + R_a + B_a + K_1 + K_2 + K_3 \qquad (5)$$

where A_a [dB] is attenuation introduced by a particular discontinuity, R_a [dB] is a fabric aperture with single reflection loss, B_a [dB] is a multiple reflection correction term, K_1, K_2, K_3 are correction terms. The empiric relations for these attenuation are published e.g. in the work of Perumalraja [9]. In order to approximate the mesh nature of the fabrics, the following assumptions are used:

1) The conductive fibers are wound together in a bundle in the center of the bundle of nonmetallic fibers. These two bundles together form the fabric strands.

2) The only influence of the nonmetallic fibers is to space the bundles of metallic fibers apart.

3) The pores in the fabric are square.

The fabric should contain as few portions of pores as possible for the most effective shielding.

The shield effectiveness *SE* of materials with (carbon) filler depends on the volume percent of the filler material *V* [%] [10]

$$SE = 2.46V \qquad (6)$$

For a single conductive layer, the theoretical value *SE* can be written as [11]

$$SE = 20 \log\left(1 + \frac{K\,t\,Z_0}{2}\right) \qquad (7)$$

where *K* is conductivity; *t*, the thickness of the sample; and Z_0, the free-space wave impedance, 377Ω. For low electrically conductive materials are these models in original form not useful [11].

3. EXPERIMENTAL

3.1 Hybrid Yarns

Hybrid yarns were composed of polypropylene and different content of staple stainless steel metal fiber (1 – 75 %). The aspect ratio (length/diameter ratio, l/d) of the SS is 6250 used in this study, since the diameter of the SS is 8 μm and the fiber length of the SS is 50 mm. See Fig. 2 for microscopic image of hybrid yarn.

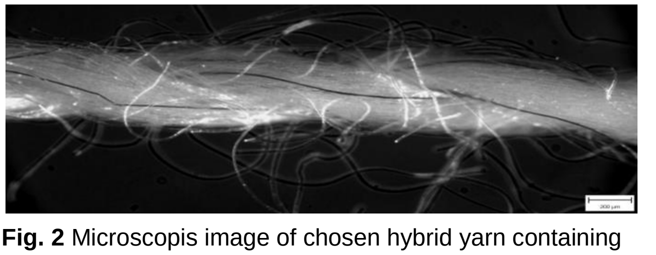


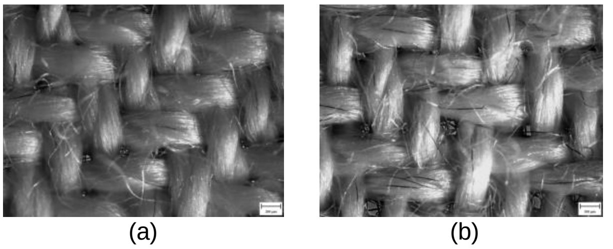
Fig. 2 Microscopis image of chosen hybrid yarn containing 5% of stainless steel fibre (diameter of fibre is around 8 μm).

3.2 Hybrid Fabrics

The nine fabrics with the same structure were used. Samples were twill weaves with weft and warp fineness 51 tex - warp sett 20 1/cm, weft sett 19 1/cm made of the hybrid yarn containing different portion of conductive phase. Weight per unit area of woven samples was 220 g.m^{-2}. More details about fabrics are given in the Table 1. Microscopic figures of chosen studied samples are at Fig. 3.

Table 1 Studied fabrics details.

Sample	Composition	Thickness [mm]
1	99% POP/ 1% SS	0.78
2	97% POP/ 3% SS	0.75
3	95% POP/ 5% SS	0.77
4	90% POP/ 10% SS	0.75
5	85% POP/ 15% SS	0.73
6	80% POP/ 20% SS	0.71
7	60% POP/ 40% SS	0.70
8	40% POP/ 60% SS	0.63
9	25% POP/ 75% SS	0.57



(a) (b)

Fig. 3 Microscopic images of chosen studied fabrics: a) sample 1, b) sample 4.

3.3 Characterization

Electric resistivity

Volume resistivity was measured according to the standard ČSN 34 1382, at the temperature T = 22,3 °C and relative humidity RH = 40,7 %. Volume resistivity is measured by applying a voltage potential between two electrodes of specified configuration that are in contact with the opposite side of a material under test. Volume resistivity ρ_V [Ω.cm] was calculated from relation:

$$\rho_V = R_V \frac{\pi R_1^2}{4t} \quad (8)$$

where R_V [Ω] is volume resistance reading, R_1 outer radius of electrode [cm], t thickness of sample [cm]. The mean values of ρ_V are listed in Table 2.

Table 2 Mean values of ρ_V *and SE*

Sample	ρ_V [Ω.cm]	SE [dB]
1	1.51E+03	19.26
2	1.56E+03	26.69
3	5.47E+03	29.16
4	1.789E+04	31.83
5	3.642E+04	33.54
6	7.749E+04	36.02
7	2.840E+05	36.10
8	7.339E+06	37.55
9	1.424E+07	38.30

Electromagnetic shielding efficiency

Electromagnetic shielding for higher frequencies was characterized by the attenuation of electromagnetic field power density by using simple device (see Fig. 4).

Basic parts of device are two waveguides. One waveguide is connected with receiving wire (antenna). Textile sample is placed on the entrance of second waveguide. The end of this waveguide is filled by foam saturated by carbon absorbing the electromagnetic field passed through sample. Sample is oriented perpendicularly to the electromagnetic waves. Transmitting antenna is placed in front of first the waveguide input. As a source of electromagnetic field the ZigBee module working at frequency 2.4 GHz is used. The total shielding effectiveness S_T [dB], is calculated from (2) where P_1 [W.m^{-2}] is input power density and power P_2 is power density after passing through sample. The mean values of *SE* are given in the last column of Table 2.

Standard ASTM D4935-99 was used for reference measurement in a frequency range of 30 MHz to 1.5 GHz.

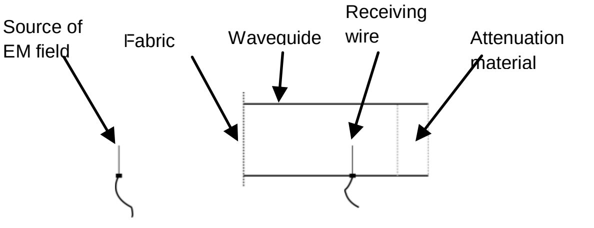


Fig. 4 Scheme of device for measurement of electromagnetic shielding efficiency.

3.4 Results and discussion

Electromagnetic shielding efficiency

The dependence of total shielding effectiveness *SE* on the percentage of conductive component *P* is shown in Fig. 5.

The solid line in this graph corresponds with the logarithm model with parameters obtained by the minimizing sum of squared differences. A relatively good fit is visible. This model can be used for prediction of the value of *P* for sufficient shielding:

$$P = e^{\frac{SE-21.45}{4.18}} \quad (9)$$

For example the *SE* = 35 can be obtained at conductive component concentration *P* = 33.1 %.

The percolation threshold can be observed. It is about 3% of conductive component.

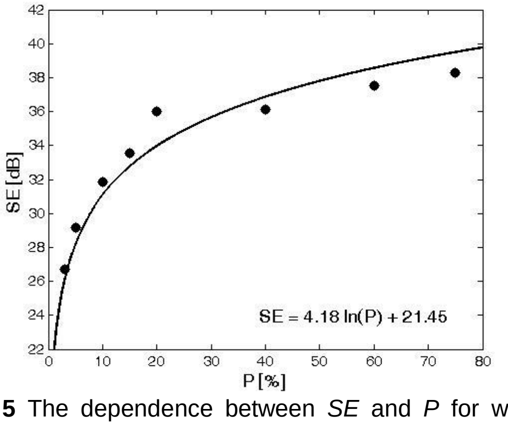


Fig. 5 The dependence between *SE* and *P* for woven samples.

Correlation between electric resistance and electromagnetic shielding

The dependence of total shielding effectiveness *SE* on logarithms of volume resistivity ln (R_V) above percolation threshold is shown in Fig. 6.

The approximate linearity is visible. The solid lines in this graph correspond to the linear model with parameters obtained by the minimizing sum of squared differences. This graph clearly indicates that it is sufficient to measure only the electric field characteristics for sufficiently high frequencies.

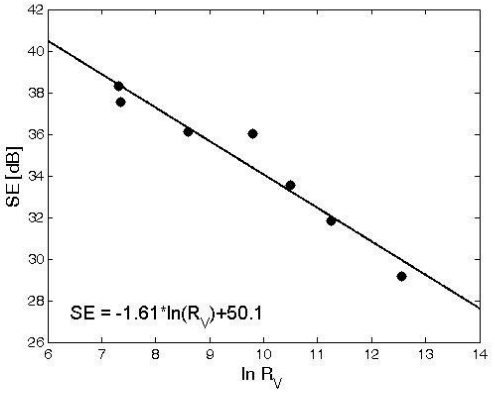


Fig. 6 The dependence between *SE* and ln (ρ_V) for woven samples – above percolation threshold.

Numerical estimation of special fabrics electromagnetic shielding efficiency

Suitability of different numerical models proposed in literature was studied. It was found that models based on the White model provide the best results for hybrid fabrics especially above percolation threshold:

$$SE = A - B\,log\left(\frac{K_C\,f}{K}\right)C\,t\sqrt{\frac{K}{K_C}}f \qquad (10)$$

where *A*,*B*,*C* are constants, *K* [S cm^{-1}] is the volume conductivity and K_c is copper conductivity (5.82 10^5 S cm^{-1}).

By optimizing the constants in (10), the numerical model for hybrid fabrics made of 100% of antistatic yarn was proposed:

$$SE = 88 - 4\,log\left(\frac{K_C\,f}{K}\right)1.315t\sqrt{\frac{K}{K_C}}f \qquad (11)$$

Comparison of calculated and measured values of electromagnetic shielding effectiveness for sample with relatively low conductive component content (below percolation threshold – sample 1) and for sample with conductive component above percolation threshold (sample marked 6) in a more extensive frequency range is shown in Fig. 7. It is clear, that the proposed model fits better for samples with higher conductivity, more precisely for samples with conductive component content above percolation threshold. In Fig. 8 there is a comparison of measured and calculated values of electromagnetic shielding efficiency for whole group of samples with different portion of conductive phase for frequency 2.4 GHz (measured by waveguide method). The model fits very well and therefore it was confirmed that the frequency 2.4 GHz is sufficient for predicting the electromagnetic shielding efficiency of textiles structures based on electric characteristics knowledge.

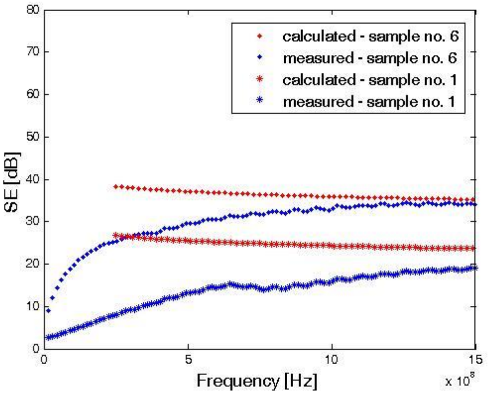


Fig. 7 The dependece between *SE (measured and calculated)* and frequency for 2 types of samples.

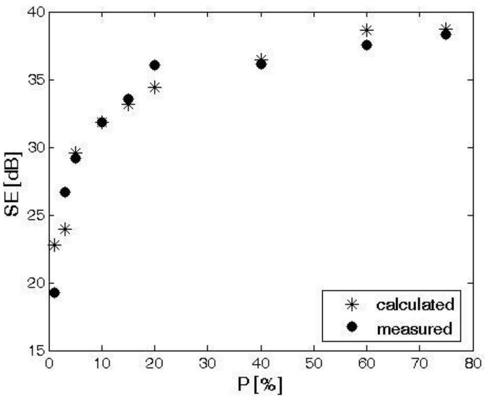


Fig. 8 The dependence between *SE* and P – comparison of measured and calculated data.

4. CONCLUSION

Low cost conductive fabrics with sufficient electromagnetic shielding efficiency conserving the main properties, e.g. drapability and process ability characteristics were created.

Fabrics with the same structure and different portion of conductive phase in hybrid yarn were studied. Hybrid yarns forming weaves and knitted fabrics were composed of polypropylene and staple stainless steel fiber. Samples were characterized by its volume resistivity (standardized method) and its electromagnetic shielding efficiency was measured by means of simple waveguide type device on frequency 2.4 GHz.

So called percolation threshold, dependence of total shielding effectiveness *SE* on the amount of conductive component *P* in hybrid yarn and dependence of total shielding effectiveness S_T on volume resistivity was examined. It is clear that the portion of conductive component has a significant effect on increasing conductivity (decreasing resistivity) and improvement of electromagnetic shielding efficiency.

The dependence between total shielding effectiveness and volume resistivity above percolation threshold is possible to express by linear function at the frequency of 2.4 GHz. Model for prediction of the value *P* for desired shielding was proposed.

Numerical models for calculation of shielding effectiveness based on electrical properties knowledge were studied. It was shown that modified White model is useful for prediction of hybrid fabrics electromagnetic shielding. The prediction ability of this line model is restricted to the relatively high frequency – above 1.5 GHz.

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