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CORRELATION BETWEEN ELECTRIC RESISTANCE AND ELECTROMAGNETIC SHIELDING OF HYBRID WEAVES

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The electromagnetic interference shielding efficiency needs to use special devices. Simpler are measurements of surface or volume resistivity or reciprocal values of conductivity. It is known from theory that at sufficiently high frequencies in is possible to measure characteristics of electrical part of electromagnetic field only and therefore it should be linear relation between total shielding effectiveness S_T [dB] and fabric resistivity or conductivity. The main aim of this work is investigation the form of relation between resistivity and total shielding effectiveness $S_{T.}$ for special types of fabrics. First group of fabrics are made from hybrid yarns containing metal fibers and second group of fabrics are cotton twill with mesh composed from hybrid yarns containing PES and metal fiber.

1. INTRODUCTION

It is well known that electric or electronic machinery and communication appliances are producing electromagnetic wave. If the electromagnetic wave are not isolated effectively, they will cause interfere with each other and result in technical errors. If gets exposed under the electromagnetic, radiate environment, physical harms may occur on human body. Electromagnetic radiation effects can be divided into two categories according to its level and time:

1) Stochastic health effects are associated with long-term, low-level (chronic) exposure, caused by ionizing radiation.

2) Non-stochastic health effects appear in cases of exposure to high levels of radiation, and become more severe as the exposure increases. Short-term, high-level exposure is referred to as 'acute' exposure, caused by non-ionizing radiations.

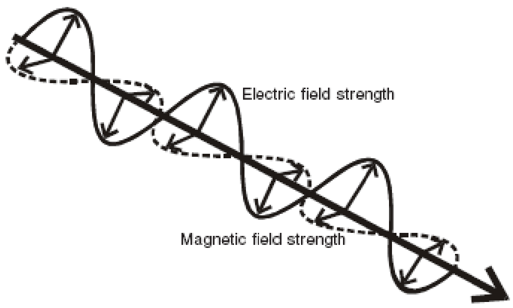
Electromagnetic (EM) fields below 10 GHz (to 1 MHz) penetrate exposed tissues and produce *heating* due to energy absorption. The depth of penetration depends on the frequency of the field and is greater for lower frequencies. Absorption of EM fields in tissues is measured as *a specific absorption rate* (SAR) within a given tissue mass [4], [5]. Most mobile phones transit and receive EM radiation at a frequency of 900 MHz. This is in the range of non-ionizing radiation but still it may cause heating, which can lead to severe health effects (These effects are known as thermal effects). For a phone to pass US certification [6], that phone’s maximum SAR level must be less than 1.6 W/kg . Current standards for EM exposures include limits expressed in terms of SAR. Reduction of SAR of EM protective clothing will vary significantly with certain EM field characteristics, particularly frequency.

EM fields above 10 GHz are absorbed at the skin surface, with very little of the energy penetrating into the underlying tissues. The basic quantity for EM fields above 10 GHz is the intensity of the field [4], [5] measured as power density [W m^{-2}]. The electromagnetic environment is dominated by high-powered radio and television transmitters, and that 95% of the population is exposed to a radiated power density of 0.1 μW cm^{-2} or less.

The main aim of this work is investigation the form of relation between resistivity and total shielding effectiveness S_T. for special types of fabrics. First group of fabrics are made from hybrid yarns containing metal fibers and second group of fabrics are cotton twill with mesh composed from hybrid yarns containing PES and metal fiber.

2. ELECTROMAGNETIC FIELD

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 Picture 1.



Picture 1. Electromagnetic waves

Radio frequency RF energy includes broad range of frequencies ranging from 10 kHz to 300 GHz, and is non-ionizing. The frequency range up from 30 kHz to 300 MHz includes mobile phones, radio and television Radar and micro waves covered frequencies up to 300 GHz.

The ratio of E to H is defined as the wave impedance Z_w, [Ω] and depends on the type of source and the distance from the source. Large impedances characterize electric fields and small ones characterize magnetic fields.

Depending on the distance to the source, field components with different directional vectors and properties dominate [4]. The far field area begins when the distance to the source is large enough to form a coupled electric and magnetic field for which the field components are perpendicular to each other. Besides, this field can be considered locally to be a plane wave, so that the exposure is uniform over the body or body part. The radiation part of the field dominates in the far field area.

In the far field area the ratio between the electric field E [V m^{-1}] and the magnetic field H [A m^{-1}] remains nearly constant

$$\frac{E}{H} \approx °377\ \Omega$$

where 377 Ω, is the intrinsic impedance of free space. It is thus sufficient to measure only the electric field or only the magnetic field to establish that the action values are not being exceeded.

In the near field area, the magnetic and electric fields are no longer coupled and the components of each field must be evaluated separately. Exposure in the near field area is no longer uniform. In the near field the exposure depends on the spatial distribution of the electric or magnetic field, the frequency used, the specific conductivity of tissue σ, the dielectric permittivity of tissue ε, the contact of the body with the ground and the machine, and the position and thus the geometry of the exposed person. The far field starts at a distance *r* from the source, for which

$$r \geq \frac{2\ D^2}{\lambda}$$

where D is the maximum dimension of the antenna and λ the wavelength, both in meters.

Conductive textile characteristics connected with protection against electrostatic field were studied in numerous publications [1...3]

3. ELECTROMAGNETIC SHIELDING

In electromagnetic shielding, there are two regions, the near field shielding region and far field shielding region. When the distance between the radiation source and the shield is larger than λ/2π (λ is the electromagnetic source wavelength), it is the far field shielding region. The electromagnetic plane wave theory is generally applied for electromagnetic shielding in this region. When the distance is less than $\lambda/2\pi$, it is in the near field shielding and the theory based on the contribution of electric and magnetic dipoles is used for electromagnetic shielding.

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 interfaces is large compared to the skin depth δ [m] (the penetration depth) defined as

$$\delta = \frac{1}{\sqrt{\pi\, f \mu\, K}} ,$$

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."

Efficiency of electromagnetic shields is commonly expressed by the total shielding effectiveness S_T [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.

$$S_T = -10\ \log\left(\frac{P_2}{P_1}\right), \qquad (1)$$

where log(x) id decadic logarithm.

For electromagnetic shielding applications, typically a SE of at least 20 dB (indicates that 99% of the electromagnetic (EM) energy is reflected or absorbed by the material) is needed. A SE of 30 dB indicates that 99.9% of the EM energy is reflected or absorbed by the material, with only 0.1% exiting the shielding material.

When electromagnetic radiation is incident on a shielding material, the reflection, absorption, and transmission phenomena take place [7]. The total shielding effectiveness S_T is then summation of the S_A due to absorption (S_A), reflection (S_R), and multiple reflection (S_M), i.e.,

$$S_T = S_A + S_R + S_M .$$

For a single layer of shielding material, when S_A is >10 dB, then $S_M \sim 0$ and can be neglected.

The shielding due to reflection S_R can be expressed by relation

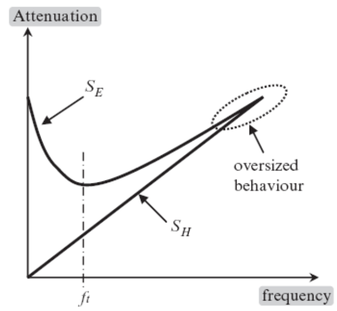
$$S_R = 20 \log \left| \frac{(1+n)^2}{4n} \right| ,$$

where n is the index of refraction of the shielding material.

According to definition of shielding effectiveness, it is possible to express the shielding effectiveness S_E for electric field and the shielding effectiveness S_H for magnetic field by relations

$$S_E = -20\ \log\left(\frac{E_2}{E_1}\right),\ S_H = -20\ \log\left(\frac{H_2}{H_1}\right),$$

where E_1 [V m^{-1}] (or magnetic H_1 [A m^{-1}]) is the electric field strength outside of shielding layer and E_2 (or H_2) is the resulted electric field strength after passing through shielding layer.



Picture 2. Dependence of electric and magnetic shielding effectiveness on frequency [10]

Typical behaviors of S_E and S_H vs. the frequency are given in Picture 2 [10].

It is clear that below a certain frequency f_t electric and magnetic field behave in opposite sense. Above f_t, shielding effectiveness for electric field increases to join the shielding effectiveness for magnetic field at higher frequencies. This characteristic frequency f_t corresponds to the condition where the skin depth δ becomes smaller than shield thickness t i.e.

$$f_t = \frac{1}{\pi \mu K t^2},$$

where μ is the magnetic permeability of the medium.

Shielding effectiveness S_T of the conductive materials can be expected by the following expression [8], [9]:

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

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 [7], which is usually used to predict the shielding effectiveness of a sample of thickness t [cm] to an electromagnetic wave of frequency (Hz), given as

$$S_T = 168 - 10 \log\left(\frac{K_c f}{K}\right) + 1.315 t \sqrt{\frac{K}{K_c} f},$$

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 [1]. The shielding effectiveness is given by the equation

$$S_T = A_a + R_a + B_a + K_1 + K_2 + K_3,$$

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 [dB] is a correction term to account for the number of like discontinuities, K_2 [dB] is a low-frequency correction term to account for skin depth and K_3 [dB] is a correction term to account for a coupling between adjacent holes. The empiric relations for these attenuation are published e.g. in the work of Perumalraja [1]. Only in the evaluation of term K_2 is an implicit knowledge of the electrical characteristics (conductivity and permeability) of the fabric required. Since this term is valid only for low frequencies [11] it has been omitted from the calculation at microwave frequencies.

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.

For effective shielding the fabric it should contain as few portions of pores as possible.

The shield effectiveness S_T of materials with (carbon) filler depends on the volume percent of the filler material V [%] [12]:

$$ST = 2.46 V.$$

For a single layer, the theoretical value S_T can be written as

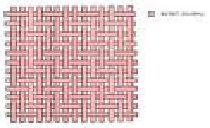
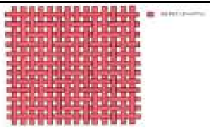
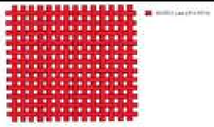
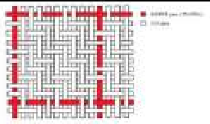
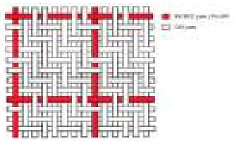
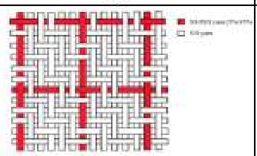
$$S_T = 20 \log\left(1 + \frac{K t Z_o}{2}\right),$$

where K is conductivity; t, the thickness of the sample; and Z_0, the free-space wave impedance, 377Ω. [6]

4. EXPERIMENTAL PART

The six fabrics with the same structure (weft and warp fineness 51 tex, warp sett 20 1/cm, weft sett 19 1/cm and twill weave) were used. First three fabrics are made from hybrid yarns containing metal fibers and second three fabrics are cotton twill with mesh composed from hybrid yarns containing PES and metal fiber. Details about fabrics are given in the table 1.

T a b l e 1

Fabrics	Yarn composition	Conductive yarn placement	Fabric thickness [mm]
 1	99% PES/ 1% steel	100%	0,65
 2	97% PES/ 3% steel	100%	0,62
 3	95% PES/ 5% steel	100%	0,62
 4	95% PES/ 5% steel 100% cotton	mesh 5x5 mm	0,66
 5	95% PES/ 5% steel 100% cotton	mesh 4x4 mm	0,67
 6	95% PES/ 5% steel 100% cotton	mesh 3x3mm	0,65

Surface and volume resistivity were measured according to the standard ČSN 34 1382, at temperature T = 24,8 °C, and relative humidity RH = 41 %. Surface resistivity was measured by applying a voltage potential across the surface of the sample and measuring the resultant current. Surface resistivity ρ_S [Ω/square] was calculated from relation

$$\rho_S = R_S \frac{o}{\ell},$$

where R_S is resistance [Ω], o [m] is the middle perimeter (width of electrodes) and l [m] is the distance between electrodes. Volume resistivity is tested in a similar fashion to surface resistivity; however, electrodes are placed on opposite faces of a test sample. Volume resistivity is measured by applying a voltage potential across opposite sides of the sample and measuring the resultant current through the sample. Volume resistivity ρ_V [Ω cm] was calculated from relation

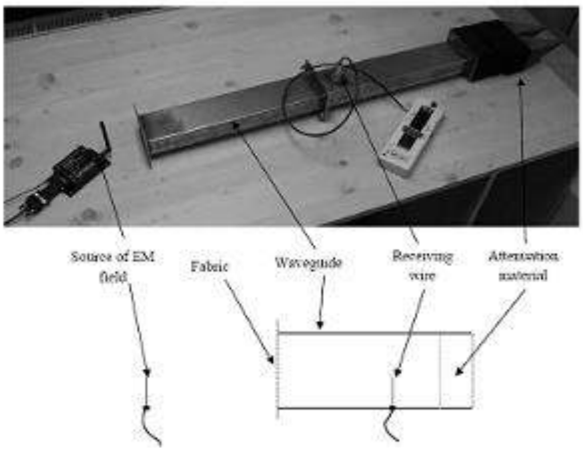
$$\rho_V = R_V \frac{S}{h},$$

where R_V [Ω] is volume resistance reading, h is thickness of fabric [cm], S is surface area of electrodes [cm^2]. All measurements were repeated 10 times and for calculation the arithmetic mean was used. These values are given in the tab. 2.

Table 2

Sample	ρ_S [kΩ]	ρ_V [kΩ cm]	S_T [dB]
1	56,23	56,92	19,69
2	26,33	33,20	22,56
3	18,04	22,24	23,06
4	187,12	155,99	16,86
5	124,16	110,75	19,09
6	46,79	82,77	20,36

Electromagnetic shielding was characterized by the attenuation of electromagnetic field power density by using of simple device (see Picture 3).

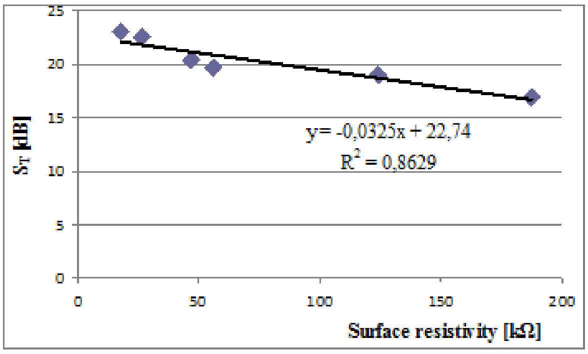


Picture 3. Apparatus for measurement of power density attenuation

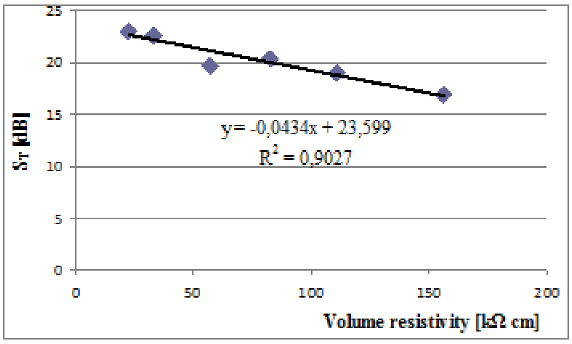
Basic parts of device are two waveguides. One waveguide is connected with receiving wire (antenna) skládá ze dvou vlnovodů. Textile sample is placed on the entrance of second waveguide. The end of this waveguide is filled by foam saturated by carbon absorbing the electromagnetic field passed through sample. Sample is oriented perpendicularly the electromagnetic waves. Transmitting antenna is placed in front of first waveguide input. As 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 eqn. (1) 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 S_T are given in the last column of table 2. It was found that the S_T in the direction of weft and warp were the same.

4. RESULTS AND DISCUSSION

The dependence of total shielding effectiveness S_T on surface resistivity ρ_S is given in the Pictyre 4 and the dependence of total shielding effectiveness S_T on volume resistivity ρ_V is shown in Picture 5.



Picture 4. The dependence between total shielding effectiveness S_T and surface resistivity ρ_S



Picture 5. The dependence between total shielding effectiveness S_T and volume resistivity ρ_V

In both cases the approximate linearity is visible. The solid lines in these graphs correspond to the linear model with parameters obtained by the minimizing sum of squared differences. Corresponding correlation coefficients indicate the good quality of fit. The limit for good shielding effectiveness is about 20dB. By using of these relations it is possible to estimate corresponding resistances or selects the portion of conductive component of suitable mesh size. It is visible that the lowest mesh size (3x3 mm) or lowest portion of metallic fibers (1% steel) in hybrid yarns is satisfying to the requirement of limit for good shielding effectiveness.

CONCLUSION

It was shown that dependence of total shielding effectiveness S_T on surface or volume resistivity is nearly linear for the frequency of 2.4 GHz. It was found that for good shielding effectiveness the lowest mesh size (3x3 mm)or lowest portion of metallic fibers (1% steel) in hybrid yarns should be used.

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