ANNALS OF THE UNIVERSITY OF ORADEA
FASCICLE OF TEXTILES, LEATHERWORK

MATHEMATICAL MODELLING OF THE SHIELDING EFFECTIVENESS FOR PES/STAINLESS STEEL FABRICS

RADULESCU Ion Razvan[1], SURDU Lilioara[1], BADIC Mihai[2], MORARI Cristian[2]

[1] INCDTP, Str. L. Patrascanu 16, 030508, Bucharest, Romania, certex@certex.ro

[2] ICPE-CA, Splaiul Unirii 313, 030138, Bucharest, Romania, office@icpe-ca.ro

Corresponding author: Radulescu, Ion Razvan, E-mail: razvan.radulescu@certex.ro

Abstract: *Textile screens for electromagnetic radiation represent a modern solution, due to their flexibility, lightweight and good mechanical resistance. Electromagnetic shielding is a must in various applications, while strict regulations are set for electromagnetic compatibility. Conductive fabrics are widely used for electronic equipment covers, RF suits or EMI protection tents. This paper aims to investigate the shielding effectiveness of conductive woven fabrics with stainless steel yarns at different weft distances [2,3,4,5 mm]. These conductive fabrics were investigated for their physical-mechanical properties (mass per surface unit, density on warp and weft direction and thickness), within the INCDTP accredited laboratories. The conductive fabrics as well as combinations thereof where tested for their shielding effectiveness accordingly to the standard ASTM ES 07, within the EMC laboratories of ICPE-CA. A signal generator, an amplifier, a TEM Cell and a spectrum analyser were used were used for this purpose. Graphs in logarithmic scale were issued for the shielding effectiveness analysis. Moreover, an experimental factorial plan was conceived for obtaining a mathematical model for the studied fabrics in relation to the weft distance between the conductive yarns. The coefficients of the mathematical model were obtained through the least squares regression method in Excel, while the response curve was designed in Matlab. The response curve enables the computation of intermediate values of the shielding effectiveness in relation to the distance between conductive yarns.*

Key words: *Electromagnetic compatibility (EMC), fabrics, conductive, shielding effectiveness, physical-mechanical properties, mathematical modelling*

1. INTRODUCTION

The shielding of electromagnetic radiation is an important issue in nowadays environment. Several research studies have been conducted in the domain of modelling conductive fabrics for electromagnetic shielding. The model of equivalent circuits of recurrent structures makes possible the determination of the equivalent impedance for a grid conductive fabric [1]. The inductive and capacitive character result in a RLC equivalent structure of the conductive fabric, whose electrical parameters were computed by mathematical regression, based on physical measurements values. The resulting RLC model has good values when compared to the physical measurements. The modelling of the electrical conductivity was studied for yarns [2], analysing the dependence of the electrical resistance R on the yarn length l. The methods for evaluating the shielding effectiveness of textile fabrics have been extensively studied [3]. The standards MIL-STD 285 and ASTM 4935 using an antenna-receiver system and respectively a TEM-cell were assessed in the testing of conductive fabrics. A new method for testing the shielding effectiveness of PES-metal textile materials, doubled by a related simulation process, proved the justness of this testing method [4]. The testing method proposes a measurement device composed of transmitting antenna, textile material, waveguide, receiving antenna and carbon foam for insulation. Research studies in the field tackle the accomplishment of personal protection equipment (PPE) for protection against EM radiation [5]. The reflection and transmission coefficients of fabrics destined for PPE, were measured in relation to the frequency of electromagnetic radiation: the higher the content of conductive material, the higher the shielding effectiveness.

This paper aims to analyse different samples of conductive woven fabrics with stainless steel yarns. The samples have been especially produced for the study with different distances between the weft conductive yarns. The goal of the approach was to perform an optimization computation for identifying the adequate distance for the optimal shielding effectiveness of the fabrics.

2. MATERIALS AND METHODS

2.1 Materials

Four variants of woven fabrics were produced at the textile enterprise SC Majutex SA – Iasi. The woven fabrics are composed of PES and stainless steel yarns (Beckaert Bekinox BK) with the yarn count Nm50/2. The Bekinox BK yarn is a blended yarn with 80% cotton content and 20% Bekinox VS fibre (from 100% stainless steel). The woven fabrics were produced on a SOMET rapier weaving machine with the width of 1,90 m (Fig. 1). The woven fabrics have a twill weave. The four variants produced are presented in Table 1:

Table 1: *The four variants of the woven fabrics with relation to the sequence of the yarns*

	Variant 1	Variant 2	Variant 3	Variant 4
Weft Sequence PES / Bekinox BK	**1/1**	**2/1**	**3/1**	**4/1**

Fig. 1: *Rapier loom at SC Majutex SA – Iasi for weaving the fabrics*

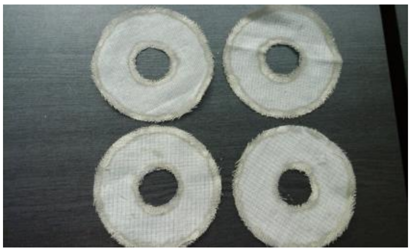

Fig. 2: *The fabric variants tailored accordingly to the standard ASTM ES07*

2.2 Methods

The physical-mechanical and electrical properties of the woven fabrics were investigated in INCDTP and ICPE-CA laboratories, accordingly to up-to-date standards. The data obtained for the physical-mechanical properties is presented in Table 2.

Table 2: *Physical-mechanical properties of the conductive fabric variants*

Physical-mechanical properties	Mass on surface unit [g/m^2]	Density [no yarns/10cm]		Fabric thickness [mm]
		Warp	Weft	
Standard	EN 12127:1999	SR EN 1049:2:2000		SR EN ISO 5084/2001
Variant 1	114	130	120	0,47

Variant 2	114	136	120	0,47
Variant 3	114	134	120	0,469
Variant 4	115	130	120	0,479

The standard ASTM ES07 was used for measuring the shielding effectiveness. A signal generator, an amplifier, a TEM Cell and a spectrum analyser were used were connected and the woven fabric variants were placed individually and in combinations within the TEM cell (Fig. 3).

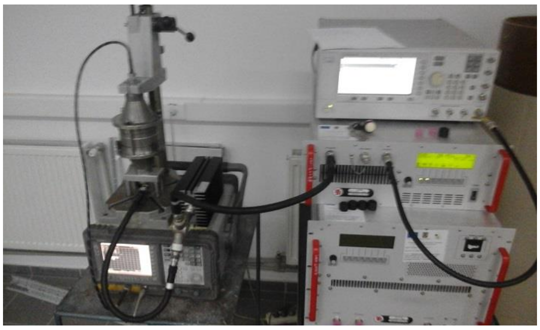

Fig. 3: *Electrical device system for measuring the shielding effectiveness*

The experimental factorial plans were chosen for the mathematical modelling of the shielding effectiveness. The distance on vertical / horizontal direction between the stainless steel conductive yarns was set as input, independent factor and the shielding effectiveness was chosen as result, dependent factor. A mathematical polynomial model second degree was chosen [6]:

$$z_1 = a_0 + a_1*x + a_2*y + a_{12}*x* + a_{11}*x^2 + a_{22}*y^2 \quad \textbf{(1)}$$

where:
x = distance on vertical direction [mm]
y = distance on horizontal direction [mm]
z_1 = shielding effectiveness [dB]

3. RESULTS

The results of the shielding effectiveness measured accordingly to the standard ASTM ES 07 are presented in table 3.

Table 3: *Experimental results for shielding effectiveness*

No.	Screen structure	Shielding effectiveness Standard ASTM ES 07 (dB)							
		1 MHz	10 MHz	30 MHz	100 MHz	300 MHz	600 MHz	900 MHz	1 GHz
1	Variant 1.1	11.99	9.78	14.40	19.00	14.92	12.44	9.05	4.50
2	Variant 2.1	10.19	8.28	13.15	16.84	13.60	11.84	8.56	4.20
3	Variant 3.1	10.36	7.87	11.65	15.00	11.99	11.10	8.42	4.40
4	Variant 4.1	9.60	7.10	10.87	13.95	10.93	11.16	8.64	4.50
5	Variant 1.2	11.57	9.70	14.78	18.95	15.95	13.02	9.44	4.70
6	Variant 2.2	12.15	9.48	14.06	18.50	13.37	12.00	8.68	4.20
7	Variant 3.2	8.98	7.15	11.42	15.33	13.44	12.30	9.06	4.50
8	Variant 4.2	10.78	8.32	12.09	15.32	11.34	11.18	8.48	4.30
9	Variant 1 with	15.00	11.67	16.95	23.20	22.30	25.70	21.07	16.50

	Variant 1								
10	Variant 1 with Variant 2	14.66	11.96	17.40	22.10	20.70	24.00	20.40	15.33
11	Variant 1 with Variant 3	12.40	10.63	16.07	21.56	20.30	22.41	17.98	12.79
12	Variant 1 with Variant 4	13.28	10.79	15.66	20.85	19.30	22.60	20.18	15.53
13	Variant 2 with Variant 2	13.00	10.67	15.40	21.50	19.92	22.80	19.51	15.03
14	Variant 2 with Variant 3	13.15	10.52	15.63	20.90	18.82	22.22	19.62	14.96
15	Variant 2 with Variant 4	12.82	10.60	15.70	20.38	17.53	21.55	19.90	15.45
16	Variant 3 with Variant 3	12.79	9.80	14.42	19.15	17.60	21.10	18.58	13.87
17	Variant 3 with Variant 4	11.88	9.93	14.62	18.60	14.82	20.85	18.89	14.35
18	Variant 4 with Variant 4	12.66	9.94	14.36	17.70	15.35	19.44	18.65	14.53

4. DISCUSSION

4.1. Figures

The obtained results for the shielding effectiveness in dB were represented in a graph with logarithmic scale for the frequency (Fig. 4). The analysed frequency range was [1Mhz – 1 Ghz]. The four fabric variants were represented with different colours. Px corresponds to Variant x.

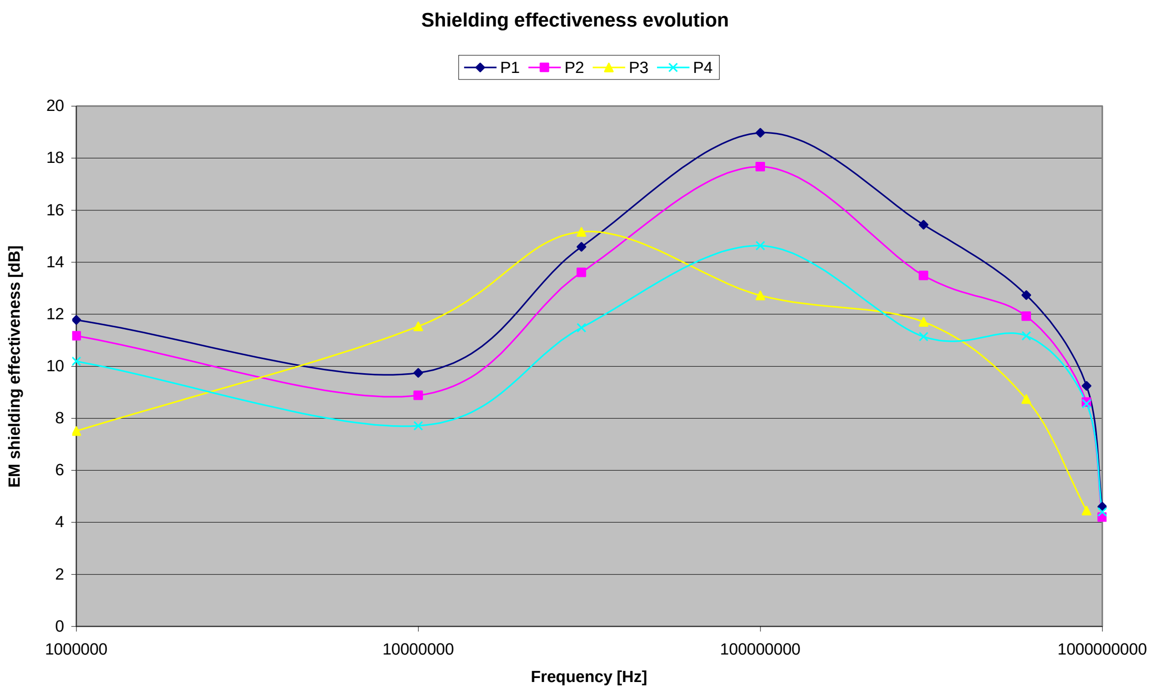

Fig. 4: *Shielding effectiveness in dB of the four fabric variants on logarithmic frequency scale*

4.2. Mathematical modelling

In order to analyse the evolution of the shielding effectiveness also for other, intermediate values of the distance between the conductive yarns, a mathematical modelling was proposed, accordingly to the factorial plans.

Table 4: Variation levels at 10 MHz

Variable	***X* [mm] – distance between conductive yarns horizontal direction**	***Y* [mm] – distance between conductive yarns vertical direction**	**Z – Shielding effectiveness [dB]**
Level			
Superior level +1	4 (P3)	4 (P3)	12.79
Basis level 0	3 (P2)	3 (P2)	13.00
Inferior level -1	2 (P1)	2 (P1)	15.00
Variation range Δ	1	1	

The mathematical modelling is going to be performed by means of an experimental matrix with three levels of variation (table 5). It follows a factorial plan of the type 3^2. The variables in Table 5 were encoded with the formula (2).

$$x = \frac{X_1 - X_m}{\Delta X} \quad (2)$$

Table 5: *The experimental matrix with three levels of variation*

	x	y	xy	x^2	y^2	z_1
a_0	a_1	a_2	a_{12}	a_{11}	a_{22}	
1	1	1	1	1	1	12.79
1	1	0	0	1	0	13.15
1	1	-1	-1	1	1	12.40
1	0	1	0	0	1	13.15
1	0	0	0	0	0	13.00
1	0	-1	0	0	1	14.66
1	-1	1	-1	1	1	12.40
1	-1	0	0	1	0	14.66
1	-1	-1	1	1	1	15.00

The proposed mathematical model has a polynomic form second degree (1). The computation of the coefficients by regression with the least squares method was performed in Excel, yielding the following results (Table 6):

Table 6 The coefficients of the polynomic form second degree

a_0	a_1	a_2	a_{12}	a_{11}	a_{22}
13.74	-0.62	-0.62	0.74	-0.2	-0.2

The expression of the function results in:

$$z_1 = 13.74-0.62x-0.62y+0.74xy-0.2x\text{^}2-0.2y\text{^}2 \quad (3)$$

By decoding the variables, the following expression is obtained for the shielding effectiveness (4).

$$Z = 20.58 - 1.64X - 1.64Y + 0.74XY - 0.2X^2 - 0.2Y^2 \quad \textbf{(4)}$$

The response curve was performed in Matlab (Fig. 5).

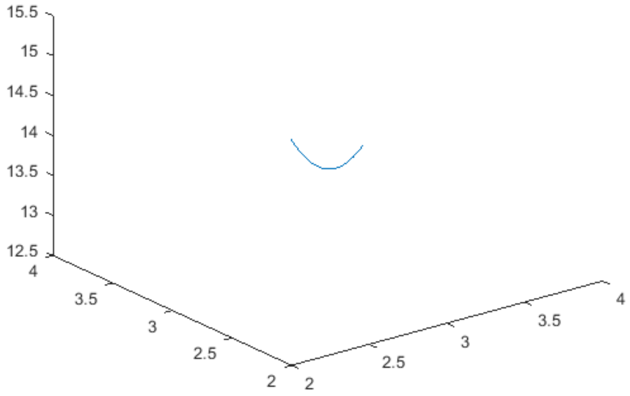

Fig. 5: *The response curve for the shielding effectiveness in relation to the distance between conductive yarns*

The response curve indicates a minimum point for the vertical / horizontal distances (X; Y) = (4.82; 4.82). For lower values of the distances the shielding effectiveness increases. This graphics shows the evolution of the shielding effectiveness for intermediate values of the distance between the conductive yarns of the shielding fabrics.

5. CONCLUSIONS

The electromagnetic shielding by means of textile materials is of great importance in the nowadays EM radiation polluted environment. Textile fabrics with conductive yarns represent a valuable alternative to usual EM screens, due to their flexibility. This paper approached a mathematical modelling of the shielding effectiveness produced by woven fabrics with different distances between the conductive stainless steel yarns. The obtained model achieves intermediate values and indicates an evolution of the shielding effectiveness.

REFERENCES

[1] Rybicki, T, Brzenski, S et al, *Modelling protective properties of textile shielding grids against electromagnetic radiation*, Fibers and Textiles in Eastern Europe 2013, 21, 1(97), pp. 78-92

[2] Safarova, V. et al, *A stufy of electrical conductivity of hybrid yarns containing metal fibers*, University of Liberec, Journal of Materials Science and Engineering 2010, pp. 197-202

[3] Więckowski, T, Janukiewicz, J., *Methods for Evaluating the Shielding Effectiveness of Textiles*, Fibres and Textiles in Eastern Europe January / December 2006, Vol. 14, No. 5 (59)

[4] Truhlar, M et al, *Electromagnetic shielding with the textile structures*, TEXSCI International conference 2010, Liberec, Czech Republic

[5] Porav, V, Doble, L, *Conceptual modelling considerations on a function of insurance of comfort clothes,* Annals of the University of Oradea. Fascicle of Textiles, Leatherwork 2/2011

[6] Țâțu M., Oprean C., Boroiu A., *Cercetarea experimentală aplicată în creșterea calității produselor și serviciilor*, Editura AGIR, 2011