http://dx.doi.org/10.5755/j01.eee.20.8.8443 ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392–1215, VOL. 20, NO. 8, 2014

Modelling of Conductive Textile Materials for Shielding Purposes and RFID Textile Antennas

M. Neruda[1], L. Vojtech[1]
[1]*Department of Telecommunication Engineering, Czech Technical University in Prague, Technicka 2, 16627 Prague, Czech Republic*
marek.neruda@fel.cvut.cz

***Abstract*—Present production of electronic devices requires gently handling with raw materials, whereas production costs and demands on environmental friendliness increase. This lack largely solves modern conductive textile materials that can be used as a barrier against electromagnetic and electrostatic fields as well as functional electrically conductive structures for use in the manufacture of textile antennas. The basic parameter of these materials is electrical conductivity, which is determined by resistance measurement of the fabric. Production therefore precedes measurement. This paper focuses on optimization of consumption of raw materials by the method of modelling of conductive textile structures so that electrical conductivity can be calculated preferentially to the fabric production. Model focuses on the calculation of resistance of the fabric to derive the electrical conductivity according to the methods specified in the standard EN 1149-1.**

***Index Terms*—Analytical models, antennas, measurement standards, textiles.**

I. INTRODUCTION

Development of high-frequency telecommunication technology requires the need to protect users and electronic equipment from adverse effects of interferences of electromagnetic signals. The device must not affect its environment, i.e. it cannot generate electromagnetic fields with intensities of electromagnetic field which would be disruptive to other devices or even threaten the operator of electrical equipment. This can be prevented by appropriate shielding with standard metal cover. Such a solution, however, consumes large quantities of metal material. This problem is dedicated to document the EU Horizon 2020 [1], which prefers ecological solution of shielding covers or electrically conductive components for green-electronics. This criterion meets the technical textiles with electrically conductive matrix.

These materials can be used in applications such as protective canopy [2] or protective suits [3], [4]. Perspective seems to be particularly the implementation of textile antennas for RFID tags for the identification of protective suits [5]. However, these antennas are produced by other methods such as printing [6], or directly on a silicon chip [7], the use of textile antennas is highly prospective application. Textile antennas can also be used as a textile sensor [8] or communication system built into clothing [9].

As shown in [8] and [10], the electrical conductivity of used textile material is an essential parameter for the above mentioned applications. This parameter directly relates to the quantities of the raw materials during the manufacture of textile materials. Nowadays textile materials with conductive properties are produced in a way that several samples with different content of metals impurity are produced and then the value of electromagnetic shielding efficiency (ESE) is measured [10]. This technology leads to inefficient production of textile shielding materials, the uneconomic and environmentally unfriendly behaviour on the part of the manufacturer and mainly to excessive lengthening the introduction of new textile shielding material on the market. Indispensable is also the influence on the consumption of raw materials and thus ecological production.

This paper therefore focuses on the method of modelling and optimization of such textile shielding and conductive materials, whereas it leads to determination of electrical conductivity before the material is produced.

The model is based on the following observation. Textile material, strictly speaking textile fabric, can be seen from circuit theory point of view as series-parallel connection of resistors. Standard EN 1149-1:2006 describes measurement method of resistance with the aid of two circle electrodes of defined dimensions. The dimensions of electrodes determine factor k, ohmmeter measures resistance and surface resistivity ρ is then calculated. This parameter is a constant for every material and relates with specific conductivity σ by reciprocal value, i.e. $\rho = 1/\sigma$. Considering textile material as a grid of resistors, the resultant resistance can be calculated. The resistance can be then used to the formula for surface resistivity calculation with respect to dimensions of electrodes. Since the electrodes are circular, it is necessary to calculate the resistance of grid of resistors for this shape, which is the main approach described in this paper.

The results show the calculation of specific resistivity by modelling of textile material as a grid of resistors limited by circle shape is a valid method, which is verified by surface resistance and length resistance measurements.

Rest of the paper is organized as follows: Section II describes standard EN 1149-1:2006, Section III presents modelling of textile material with respect to EN 1149-1. Model verification describes Section IV. Conclusions are mentioned in Section V.

Manuscript received January 27, 2014; accepted June 21, 2014.
This research was funded by a grant Kompozitex (No. FR–TI4/202) from the Ministry of Industry and Trade

II. STANDARD EN 1149-1:2006

The European Standard EN 1149-1:2006 describes test method for the resistance measurement of homogeneous and inhomogeneous materials [11]. The limitation of inhomogeneous materials is a maximum spacing of 10 mm between the conducting threads. Conductive fibres have to form a grid.

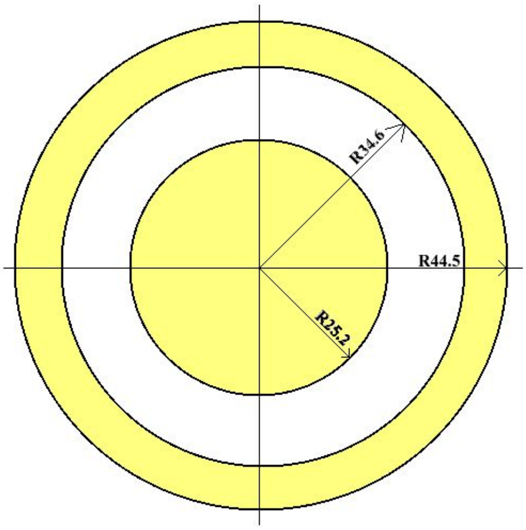

Fig. 1. Dimensions of two coaxially ordered electrodes.

Test method presents specification of electrodes, flat base plate, ohmmeter or electrometer, preparation of specimen and it also describes calculation of surface resistivity *ρ*. The assembly is formed by two coaxially ordered electrodes (Fig. 1), specimen of the textile material is put between them and the resistance of circular ring is measured. The surface resistivity is then calculated as

$$\rho = R \times k, \tag{1}$$

where *ρ* – calculated surface resistivity [Ω/square], *R* – measured resistance [Ω], *k* – geometrical factor of electrodes.

Geometrical factor of electrodes is calculated according to following equation

$$k = 2 \times \pi / \ln\left(r_2 / r_1\right), \tag{2}$$

where r_2 – inner radius of outer (ring) electrode [mm], r_1 – radius of inner (cylindrical) electrode [mm].

III. MODELLING OF TEXTILE MATERIAL WITH RESPECT TO EN 1149-1

The model of textile material has to follow the described requirements of standard EN 1149-1:2006, i.e. conductive threads form a grid pattern, maximum spacing between conducting threads is 10 mm, fabrics do not have core conducting fibres and electrodes are circular. Grid pattern can be also used in model as series-parallel connection of resistors. The distance between resistors less than 10 mm relates to warp and weft texture, which determines number of threads per cm, i.e. texture *d* > 2 threads/cm fulfils this condition. The last requirement is realized by considering silver nanoparticles in threads [8].

Modelling of grid pattern of resistors is shown in Fig. 2. Inner square, the central one, is connected to one pole of battery, the second one connects outer resistors of grid pattern. The battery is used because standard EN 1149-1 describes dc power supply. This setting can be used for resistance calculation of circular electrode and then also for ring electrode. The difference between resistance values of both electrodes determines calculated resultant resistance. This simplification, i.e. two values of resistance are calculated for two electrodes instead of calculation of resistance of circular ring, is based on homogeneity of textile material, i.e. it is produced from one specific thread and it forms regular grid pattern with same warp and weft textures.

The margins of outer resistors can be calculated as ratio of resistor value and thread length. Then it improves Fig. 2 about resistors in margins, as shown in Fig. 3. It further shows voltage analysis in application Oregano [12], i.e. points with the same electrical potential, which are marked as nodes with the same graphical symbol in Fig. 2. As a result, the whole grid pattern is symmetrical in vertical and horizontal axe under the conditions warp and weft textures are equalled and fabric is compound from one type of thread. It means resultant resistance of the model can be calculated as four parallel connected resistors R_x, where this R_x is equalled to resultant resistance of one quadrant of grid pattern in Fig. 2.

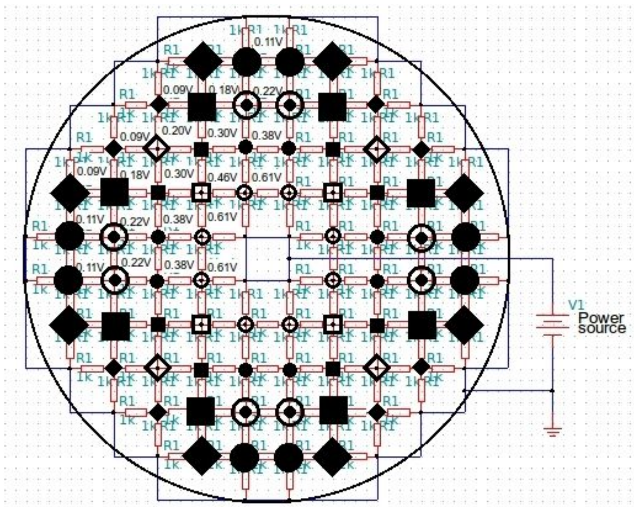

Fig. 2. Model of grid pattern of resistors with connected battery.

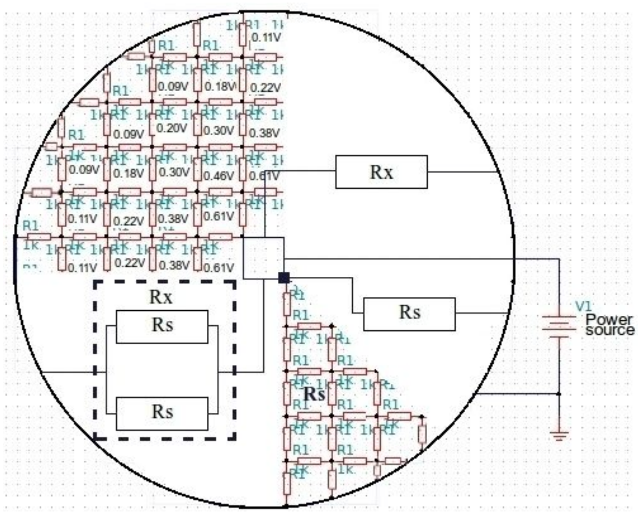

Fig. 3. Simplified model of grid pattern of resistors.

The grid pattern of resistors can be divided into four R_x resistors because of basic physical rule of nodes with the same electrical potential. If the same electrical potential is in the two nodes connected by conductor, there is no voltage between them because no current can flow by their connecting conductor. Therefore these two points in a circuit can be disconnected or connected (merge into one point), without changing the total resistance of the circuit. The same voltage values indicate these points with the same potential. Important note to the Fig. 2 is that the left lower node specifies voltage values. Furthermore, shown voltage values indicate symmetry also in one quadrant. So, the R_x is parallel connection of two resistors R_S (Fig. 3). These principles conclude the possibilities of circuit simplification.

A. Calculation of Resistor R_S

Electrical circuit is basically solved by several methods with respect to complexity of the circuit diagram. The basic method uses rules for series and parallel resistors and also Y-Δ transform. It is possible to use these rules for small number of resistors, i.e. about 5 resistors in vertical direction between poles of battery as shown in Fig. 3. With increasing number of the resistors, the calculation is more difficult and therefore different method has to be considered.

Kirchhoff's circuit laws can be taken into account. Number of loops, i.e. equations, nevertheless enormously increases computational demands.

Impedance matrix or Z-matrix is other useful method. It orders individual loops into rows of matrix, i.e. it is based on Method of loop currents. Every loop in the circuit diagram represents one equation and one row in the impedance matrix. Fig. 4 shows 10 loops for resistor R_S, which consists of the same resistors *R'*. Resistor *R*' can be measured as described in [13]. Let's assume $R' = 1\ \mathrm{k}\Omega$. Specific identification of loops defines appropriate equations.

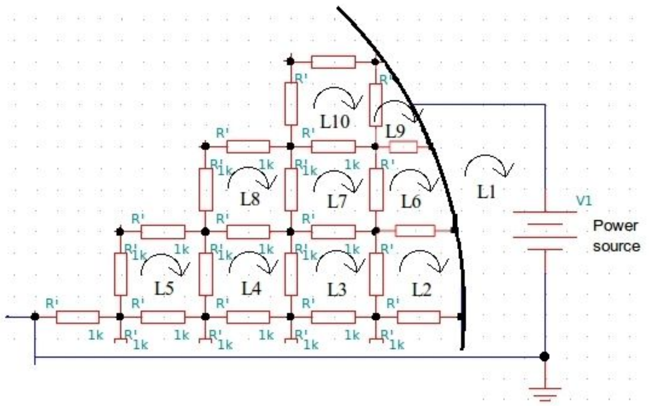

Fig. 4. Marking of loops in simplified circuit diagram.

The equation for L_1 loop is than defined, considering all resistors *R'* are equalled, as

$$U_{v1} = R'(I_1 - I_2) + R'(I_1 - I_3) + \\ + R'(I_1 - I_4) + R'(I_1 - I_5), \quad (3)$$

where U_{v1} – power supply, *R'* – resistor value, I_1 – current corresponds to L_1, I_2 – current corresponds to L_2, etc.

Other example is for L_7

$$0 = R'(I_7 - I_3) + R'(I_7 - I_6) + R'(I_7 - I_8) + R'(I_7 - I_{10}). \quad (4)$$

The rows are then described in impedance matrix for (3) and (4) as

$$\begin{bmatrix} U_{v1} \\ 0 \end{bmatrix} = \\ = \begin{bmatrix} 4R' & -R' & -R' & -R' & -R' & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -R' & 0 & 0 & R' & 4R' & -R' & 0 & -R' \end{bmatrix} \times \\ \times \left[\begin{pmatrix} I_1 \\ I_7 \end{pmatrix} \right]. \quad (5)$$

The first row indicates circuit equation for loop L_1 in impedance matrix illustration. The loop L_7 is for illustration in second row. The real position of loop L_7 is in the 7th row in impedance matrix. On the left side there are placed all power sources for individual circuit equations. On the right side there are placed corresponding currents. Matrix with resistors *R'* consists of 10 columns which represent 10 resistors of appropriate 10 currents I_1–I_{10}. The first column on the left indicates all resistors which correspond to current I_1. Equation (3) shows four resistors R' for current I_1. It also presents –*R*' for current I_2 and therefore this resistor is located in the second column of impedance matrix illustration. The loop L_1 indicates no resistors for currents I_6 –I_{10} and therefore there is value 0 in the impedance matrix illustration. Complete impedance matrix is described as (6):

$$\begin{bmatrix} U_{v1} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 4R' & -R' & -R' & -R' & -R' & 0 & 0 & 0 & 0 & 0 \\ -R' & 3R' & -R' & 0 & 0 & -R' & 0 & 0 & 0 & 0 \\ -R' & -R' & 4R' & -R' & 0 & 0 & -R' & 0 & 0 & 0 \\ -R' & 0 & -R' & 4R' & -R' & 0 & 0 & -R' & 0 & 0 \\ -R' & 0 & 0 & -R' & 4R' & 0 & 0 & 0 & 0 & 0 \\ 0 & -R' & 0 & 0 & 0 & 3R' & -R' & 0 & -R' & 0 \\ 0 & 0 & -R' & 0 & 0 & -R' & 4R' & -R' & 0 & -R' \\ 0 & 0 & 0 & -R' & 0 & 0 & -R' & 4R' & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -R' & 0 & 0 & 2R' & -R' \\ 0 & 0 & 0 & 0 & 0 & 0 & -R' & 0 & -R' & 4R' \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \\ I_7 \\ I_8 \\ I_9 \\ I_{10} \end{bmatrix} \quad (6)$$

Now, the impedance matrix is complete. Matrix (6) can be for short written as

$$\mathbf{U} = \mathbf{Z} \times \mathbf{I}. \quad (7)$$

Equation (7) applies for any of independent loops L_1 – L_{10}. ***Z*** matrix is regular one and therefore it is possible to multiple (7) by inverse matrix $\boldsymbol{Z}^{-1}$ from the left. Current ***I*** is then calculated as [14]

$$\mathbf{I} = \mathbf{Z}^{-1} \times \mathbf{U}. \quad (8)$$

The current is calculated in the *k* loop as

$$I_k = 1/\Delta \times (\Delta_{1:k} \times U_1). \quad (9)$$

where I_k – current in *k* loop, Δ – impedance matrix determinant, $\Delta_{1:k}$ – algebraic complement of impedance matrix, 1 in $\Delta_{1:k}$ indicates omitted row in impedance matrix and *k* in $\Delta_{1:k}$ indicates omitted column *k* in this matrix, U_1 – power source.

Considering one power source in the circuit diagram and requirement of input impedance calculation, this impedance is calculated as

$$Z_{in} = U_1 / I_1 = \Delta / \Delta_{1:1}. \qquad (10)$$

It means determinant of whole impedance matrix is calculated. Then first row and first column of this impedance matrix is omitted and determinant is again calculated. The ratio of these determinant values is equalled to required resistor R_S.

The best way for determinant calculation is for example software MATLAB, which uses simple function *det(Z)*. The condition of this function, i.e. it has to be square matrix, is always fulfilled by method of impedance matrix creation.

B. Calculation of Resultant Resistor

Resultant resistor of one electrode is calculated as parallel connection of eight resistors R_s^r. Index *r* indicates ring electrode.

The second electrode is also circular with different dimensions, so the same mathematical procedure can be used. Resultant resistor of this electrode is also calculated as parallel connection of eight resistors R_s^c. Index *c* indicates cylindrical electrode.

Resultant resistance of the fabric is than calculated as difference of R_s^r and R_s^c.

IV. Model Verification

A specimen of textile fabric was prepared and tested in the lab. The texture of the specimen is 20 threads/cm. It consists of threads produced from 20 % Bekinox continuous stainless steel filament yarn and 80 % cotton in weft and 30 % SilverStat/30 % Shieldex/40 % PES in warp.

Value of resistor *R'*, which is necessary input model parameter, is calculated from the length resistance as (Fig. 5)

$$l_{R'} = \left(W - s \times d\right) / s, \qquad (11)$$

where $l_{R'}$ is length of R', *s* represents number of threads in weft, *d* is measured diameter and *W* represents width of measured specimen

$$R' = R_l \times l_{R'} / l_R, \qquad (12)$$

where R_l is measured resistance of fiber with length l_R.

Fibre diameter *d* can be measured with the aid of microscope or by precise micrometer, e.g. Oxford Precision OXD-331-5010K. Table I shows six measured values for microscope diameter measurement, however 47 values are measured. Only six of them are depicted because of lucidity.

Number of threads *s* is obtained from textile specimen width and the texture by its multiplication.

Resistance is measured by Voltcraft® LCR 4080 multimeter. Length resistance is measured for five different weft and warp threads and average value is calculated as well as value of resistor *R'*.

Surface resistance is measured on the surface of the specimen in five different places, Fig. 6.

Table I shows measured values and calculated average values.

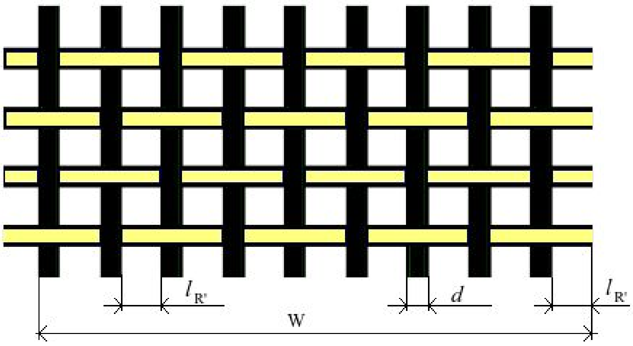

Fig. 5. Parameters for length resistance $l_{R'}$ determination.

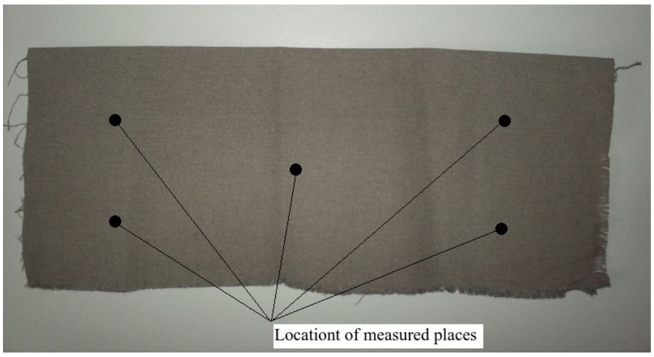

Fig. 6. Textile specimen with marked measured places.

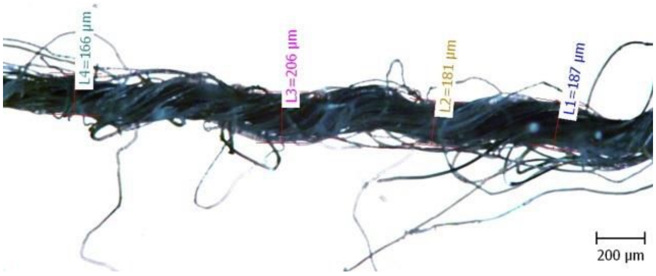

Fig. 7. Fiber specimen with marked measured places.

TABLE I. MEASUREMENT RESULTS.

Parameter	Value		Unit
R_s **Surface resistance**	0.608	0.456	Ω
	0.574	0.401	
	0.594		
	Avg.	**0.527**	
d **Microscope diameter measurement**	187	206	µm
	206	224	
	181	202	
	Avg.	**201**	
W **Width of measured specimen**	100		mm
R_l **Length resistance in warp** **l_R = 100 mm**	630.7	876.9	Ω
	610.5	748.6	
	815.1		
	Avg.	**736.36**	
R_l **Length resistance in weft** **l_R = 100 mm**	956.35	325.9	Ω
	960.85	643.15	
	793.25		
	Avg.	**735.9**	

Measurement results show length resistance of weft and warp is almost the same. Therefore *R'* is considered as constant for the model. It is calculated from (11) and (12) for $s = 200$, $d = 0.201$ mm, $l_R = 10$ cm and $W = 10$ cm. Then R' is equalled to $R' = 2.2\ \Omega$ and the model calculates surface resistivity as $\rho = 5.303\ \Omega$/square.

Considering (1), (2) and surface resistance measurement, surface resistivity is equalled to 5.267 Ω/square.

The results of measurement and model verify the method used for modelling of textile fabric.

V. CONCLUSIONS

The paper presents worldwide claim on economization with metals used in telecommunication for antenna or shielding covers production. The same function can be realized by conductive textile materials. Nowadays, the conductivity or resistivity of textile material is measured after production of the textile material. Paper presents modelling of conductive textile material, which can precede the production and therefore save quantity of used metals. Model uses standard EN 1149-1 which describes measurement method for specific resistivity determination, i.e. resistance is measured, factor of cylindrical electrodes is calculated as well as resultant specific resistivity. However the model calculates resistance, thereby it precedes production and subsequent measurement. Conductive textile material is seen as a grid pattern of resistors and resistance between cylindrical and ring electrodes is calculated. It describes mathematical-physical modelling method, i.e. physical rule of nodes with the same potential, Kirchhoff's circuit laws and impedance matrix determination. Subsequently these methods are modelled in MATLAB.

The model is consequently verified by surface resistance and length resistance measurement of manufactured textile fabric specimen. The results show presented model can be used in textile fabric production considering surface resistivity.

REFERENCES

[1] *Green Paper - From Challenges to Opportunities: Towards a Common Strategic Framework for EU Research and Innovation funding*, Horizon 2020, 2011. [Online]. Available: http://ec.europa.eu/research/horizon2020/pdf/com_2011_0048_csf_green_paper_en.pdf#page=2

[2] *Light duty faraday canopy*. EMF Shielding & Conductive Fabrics 2013. [Online]. Available: http://www.lessemf.com/fabric.html

[3] V. Safarova, J. Militky, "Electromagnetic field shielding fabrics with increased comfort properties", *Journal of Advanced Materials Research*, vol. 677, pp. 161–168, 2013. [Online]. Available: http://dx.doi.org/10.4028/www.scientific.net/AMR.677.161

[4] M. Neruda, L. Vojtech, "RF protective clothing development", in *Proc. Networking and Electronic Commerce Research Conf.*, Dallas, 2010, pp. 203–207.

[5] J. Svub, F. Benes, V. Kebo, P. Stasa, T. Jurco, "Smart suits for rescue units", in *Proc. 13th Int. Multidisciplinary Scientific GeoConf.*, Albena, 2013, pp. 235–240.

[6] F. Benes, J. Svub, V. Kebo, M. Stolba, "Experiments with custom manufactured rfid antenna tags", in *Proc. 13th Int. Multidisciplinary Scientific GeoConf.*, Albena, 2013, pp. 109–114.

[7] A. Vargas, L. Vojtech, *Near Field on Chip RFID Antenna Design, Radio Frequency Identification Fundamentals and Applications Design Methods and Solutions*. Intech, Vukovar, 2010, pp. 111–126.

[8] T. Holleczek, A. Ruegg, H. Harms, G. Troster, "Textile pressure sensors for sports applications", in *Proc. Sensors 2010 IEEE*, Kona, 2010, pp. 732–737. [Online]. Available: http://dx.doi.org/10.1109/ICSENS.2010.5690041

[9] L. Ukkonen, L. Sydanheimo, Y. Rahmat-Samii, "Sewed textile RFID tag and sensor antennas for on-body use", in *Proc. Antennas and Propagation (EUCAP)*, Prague, 2012, pp. 3450–3454.

[10] L. Vojtech, J. Hajek, "Measurement of electromagnetic shielding efficiency of planar textiles in frequency range 100 kHz - 1.5 GHz", *Access Server*. [Online]. Available: http://access.feld.cvut.cz/view.php?cisloclanku=2010030006

[11] *Protective clothing. Electrostatic properties. Test method for measurement of surface resistivity*. EN 1149-1:2006, 2006.

[12] *Package: oregano (0.69.1-1ubuntu1.10.04.1)* [universe], tool for schematical capture of electronic circuits. [Online]. Available: http://packages.ubuntu.com/lucid-updates/gnome/oregano

[13] M. Neruda, L. Vojtech, "Modeling of smart textile materials for ESD applications", in *Proc. Croatian Society Electronics in Marine, (ELMAR)*, Zadar, 2012, pp. 145–148.

[14] J. Cajka, J. Kvasil, "Teorie linearnich obvodu", *SNTL*, Praha, 1979. (in Czech)