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Estimation of the EMR Shielding Effectiveness of Knit Structures

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Abstract
This paper describes the creation of and tests performed on knit structures of three types (left-right stitch (I), double-layer (II), and double-layer with additional fillings (III)), which contain ferromagnetic materials and electroconductive materials and are designed for individual protection against occupational hazard. The ferromagnetic material is composed of two bunches of twisted filaments of ferromagnetic stainless steel made by Bekaert, Belgium, and the electroconductive material is a thread made of cotton and copper wire covered by silver made by Swiss Shield® yarns, Switzerland. Both the ferromagnetic and electroconductive materials form a hybrid yarn. Shielding effectiveness (SE) tests on knit structures were performed by the Central Institute for Labour Protection – National Research Institute, Poland and by the Institute of Architecture of Textiles, Poland. Analysis of the structures indicates a SE from both the electrical field and magnetical field in some narrow ranges.

Key words: *electromagnetic radiation, shielding effect, knitted structures.*

Introduction

Industrial and technical development has led to the creation of a great number of devices that generate electromagnetic radiation (EMR). EMR has both electric and magnetic field components, which oscillate in phase perpendicular to each other and perpendicular to the direction of energy propagation.

Those engaged in the service, control or renovation of such devices (for example, dryers, welding equipment and antenna installations) are exposed to EMR. A significant problem of huge exposure to EMR concerns activities performed at retaining masts for objects such as Radio Telecommunication Emitting Centres. The basic activities connected with exposure at such centres are those undertaken during the renovation of mast and electrical installations. During such construction and reconstruction activities performed at masts, when the whole installation and apparatuses are on, certain special conditions of extraordinary exposure to EMR take place. In such conditions there are also a number of additional disadvantages such as working at high altitudes, intensified air movement, gusting winds, low air temperatures, the proximity of many original EMR sources that generate EMR of different characteristics, as well as derivative EMR sources such as platforms and barriers under antennas. These special and difficult conditions require specific kinds of protection against EMR, which should at the same time meet the following requirements of working comfort: freedom of movement (conditions of ergonomic comfort in clothes), elasticity, tensile behaviour, the exchange of heat and mass through perspiration (conditions of thermophysiological comfort). This complex array of requirements follows from the single and most important requirement - the need to ensure the safety of human beings working in the vicinity of strong sources of EMR [1 - 3].

A certain number of currently available materials designed to protect the individual from EMR either do not meet all these comfort and protection criteria or meet them all but to a limited extent. The existing solutions, which involve the application of coated composite materials creating a Faraday cage, are mainly effective against the electrical component of EMR but do not shield the individual from, or shield only to a limited extent and in a limited range, its magnetic component.

Some existing solutions

The obligatory European directive 2004/40/EC [4] of the Council of 29th April 2004 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic field) (18th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC) permits the execution of professional activities in areas with very strong EMR which exceeds the admissible intensity values only on condition that an employee applies suitable individual protection with appropriate effectiveness (e.g. coveralls). However, the issue of decreasing the exposure of workers to EMR is significant and still not fully solved. The contemporary solution to that problem is screening by means of synthetic raw materials blended with electroconductive materials.

There are studies [5] that describe a textile fabric containing electroconductive wire in every fourth thread of the warp, a textile fabric which is an electroconductive non-woven made of electroconductive wire and polyester monofilament, needle-punched with polyester monofilament in one direction, a textile fabric in the form of non-woven, stitched with polyester monofilament covered with a finishing substance, and finally two types of electroconductive needle-punched nonwovens, 2 mm and 3.5 mm thick, all of which can be used as protection against an electromagnetic field (EMF).

Another study [6] gave results of tests on the efficiency of EMF attenuation by non-wovens. The non-wovens varied according to the number of component layers and their mutual arrangement. It was also concluded that both the efficiency of EMF shielding by non-wovens and the comfort of their use still require improvement.

Moreover, a fabric with EMF shielding properties intended for protective clothes, containing an electroconductive thread as one of the fabric weft threads, has been described in a polish patent application P 387580 [7]. The electroconductive thread is a three-component bunch yarn containing an electroconductive ferromagnetic core thread in braid made of electroconductive, special-effect yarn forming random braid thick places on the core thread in a solenoid shape, which are strongly fixed to the core thread with a binding thread. Other weft and warp threads are non-conductive, preferably these are cotton yarn. All weft and warp threads are favourably connected in a plain weave [8, 9].

Preliminary studies [10] of the development of stainless steel/polyester woven fabrics for electromagnetic shielding applications were performed to facilitate the weaving of stainless steel wires and to reduce material costs. Initially, blended yarns of stainless steel and polyester staple fibres are produced by the ring spinning method and then woven into a variety of structures. The electromagnetic SE of these fabrics was in the frequency range of 300 kHz to 3 GHz, which was measured by means of a coaxial transmission set-up. Variations in electromagnetic SE with the woven structure, number of layers, and blend ratio of stainless steel to polyester in the yarns are described. The new textile material may be suitable for shielding home electronic and electrical appliances from electromagnetic fields but not for the protection of individuals.

Other authors have worked on twill copper fabrics (3/1) produced using a single cylinder handloom jacquard weaving machine [11]. The effect of varying the weft density, warp density, wire diameter, and lay-up angle on electromagnetic SE was studied. Electromagnetic SE of various copper woven fabrics was obtained using a coaxial transmission line holder in the frequency range of 144 – 3000 MHz. With an increase in the number of conductive fabric layers, warp density and weft density, an increase in SE is observed, whereas with an increase in wire diameter, a decrease in SE is observed.

An attempt has been made [12] to design and develop core-sheath conductive yarns with copper filament as the core and cotton as the sheath using the Dref-3 friction spinning system. A special guide mechanism was designed and used to produce a uniform structure of the core—sheath conductive yarns. Copper wires were used to develop conductive fabrics. These fabrics have very good scope for many applications in the development of electromagnetic shielding wearable textiles, mobile phone charging and body temperature sensing garments.

A multi-layer textile-polymeric structure for EMR shielding systems has been developed [13] for protective cloth application. It was concluded that in the production of materials for component layers, there should be electro-conductive and ferromagnetic substances, with appropriately high permittivity and permeability values, durably incorporated into a polymeric coat with non-conductive properties, e.g. polyurethane as well as intrinsically conductive polymers, e.g. polyaniline, formed on the surface of the textile substrate.

Other types of mulit-layer shielding materials have been made of PET knitted fabric (3D) with steel fibres + an urethane coat with Graphite 390, an urethane coat with Al + knitted fabric with steel fibres and silver plated fibres + PET woven fabric with coating paste based on polyaniline (2×), a non-crosslinked acrylic coat + layer of steel fibres + non-crosslinked acrylic coat + PET woven fabric with coating paste based on polyaniline (2×), knitted fabric with steel fibres and silver plated fibres + PET woven fabric with coating paste based on polyaniline (2×), and PET woven fabric (3D) with steel fibres and an urethane coat with Al (2×) + knitted fabric with steel fibres and silver plated fibres [14]. The authors also proposed a modified testing method for emissivity measurement especially intended for textile and textilepolymeric shielding materials that could be used for making equipment and protective clothing [15].

Measuring the SE of nonwoven structures made of polyacrylonitrile fibres with metal salts, produced under the trade name Nitril-Static, proved the possibility of their application as electromagnetic shields. Their practical application was presented for physiotherapy where short-wave and microwave diathermy is used [16].

Woven fabrics comprising of 2-ply and 3-ply of copper-cotton yarns have also been produced for the shielding of EMR. It has been proved that conductive fabric produced from 2-ply and 3-ply of cotton copper yarns provides an attenuation of 40 dB to 74 dB at a medium frequency range of 700 MHz to 5,000 MHz. These fabrics may be used to shield household appliances, FM/AM radio broadcasts, wireless phones, cellular phones, computers, buildings, secret rooms and various electronic gadgets that operate at a frequency of up to 5,000 MHz [17].

Finally, a good example of fabric surface modification in order to achieve a shielding ability of fabric is the metallisation of polypropylene fabric by pulse magnetron sputtering. It gives the possibility to obtain metallic layers with very good adhesion, with a screening efficiency approaching 45 dB [18].

The knit structure of SE has also been extensively studied [19], and it was proven that not only the diameter of materials influences the SE - in this case, not only the copper wire but also the kind of knitted structure. An increase in walse density, course density and tightness factors causes an increase in the SE of knit structures. It has also been found [20] that the tightness factor in knitted fabrics increases the SE of the material. It was proved that an increase in copper diameter decreases SE in the final knitted product. Based on these findings, they chose one of the finest cotton-copper hybrid yarn mixtures available to ensure the highest screening ability with the best possible production parameters and final hand-feel, with its elasticity leading to general wear comfort at the highest possible level.

According to the producers of Swiss Sheild® yarn, a woven plain structure made with this yarn with a mass surface of 115 g/m^2 presents an attenuation of 25 dB (99.5% SE) at 1 Ghz. These tests were performed by the Swiss Textile Research Institute, Swiss Federal Laboratories for Materials Testing and Research, University of the German Federal Armed Forces, Munich, according to MIL-STD 285 [21].

Aim of the research

The aim of the current research was the elaboration of a knit structure made of a hybrid yarn that is a combination of fine steel, fine copper and fine cotton, the last element of which was applied to increase the positive haptic sensorial aspects. This specific combination of fine materials applied to knit structures in the form of hybrid yarn, which is a novelty, is intended for overalls for individual protection by muffling a near EMF. However, the final product can be used both as individual protection for those who work in an EMR zone and as shielding material for devices that emit EMR.

Material and methods

The idea of this solution to the problem of a lack of efficient and comfortable individual protection against EMR was created on the basis of the thesis of protecting oneself from phenomena of a 3-D nature, such as an electromagnetic wave (in which the electric component is perpendicular to the magnetic component, and both are perpendicular to the direction of the propagation of the wave),

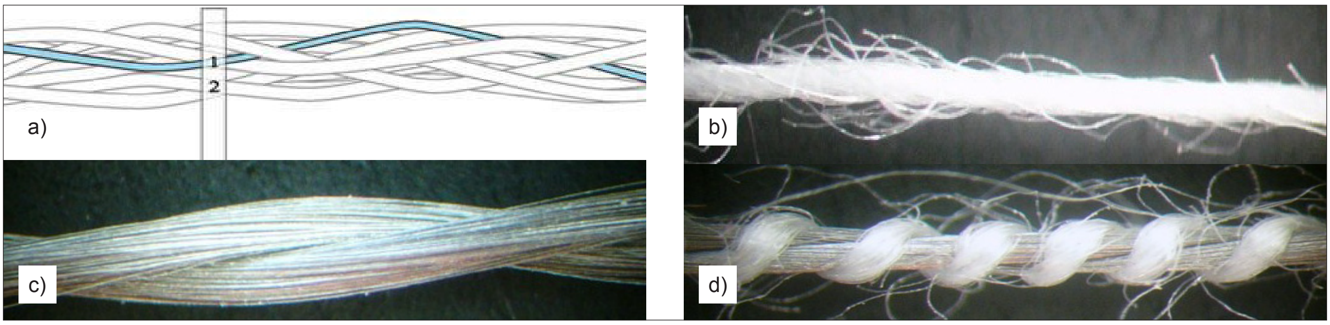

***Figure 1.** Hybrid yarn (d) and its component: (a) a schematic view of Swiss Shield® yarn [21], (b) a Swiss Shield® yarn, optical microscope view, magnification 12×, (c) two bunches of steel filaments, optical microscope view, magnification 12×. As a result of the braiding of (b) and (c), (d) was obtained; 1 - Spun-in metalic filament, 2 - base material - cotton.*

where one needs to design a structure that responds to the challenge of this 3-D phenomenon. That is, the internal and external structure of the solution proposed should be modelled in such a way that it can adapt to the requirements of the situation and to protection requirements. Latest scientific research, published in 2009 [19, 22], seems to confirm this thesis.

Preparation of the yarns

Several samples of materials protecting against EMR were produced within the framework of the studies. These samples were produced from the following components:

1. Swiss Shield® yarn made of cotton and copper (***Figure 1.a, 1.b***),
2. Steel filaments (***Figure 1.c***),
3. Hybrid yarn composed of steel filaments braided by Swiss Shield® yarn (***Figure 1.d***).

A description of the components is given in ***Table 1***.

There were two reasons for performing the braiding process in this manner: Firstly, the external surface (braids), made of cotton, improved the hand of the yarn, and we predicted that it may improve that of the final product as well, which was one of the main reasons for including cotton raw material in the design of the experiment. We presumed that a better hand may provide greater sensorial comfort for the wearer in contact with the final product. Secondly, as has been noted in previous research [13, 19, 22], braiding a ferromagnetic material (in our research case, two bunches of steel filaments) with electroconductive material (in our case, Swiss Shield® yarn) may provide better shielding efficiency than opposite braiding. That is why the design of the experiment did not include braiding electroconductive material with ferromagnetic material.

Knit structures

Three knit structures were produced using the yarns presented in ***Figure 1***. The intention was to first produce a plain structure to serve as a reference point and then produce a series of more developed structures with increased potential shielding efficiency, thereby allowing to 'trace' the influence of material structure changes on shielding efficiency possibilities.

The first structure (I) was made of two twisted bunches of 100% steel filaments (***Figure 1.c***), produced on an Italian flat knitting machine - APM ECO-2, gauge 7. This knitting machine is designed for the production of mono - and multicolour knit fabrics for clothing and decoration. The machine was adapted manually by the authors to produce technical textiles, like this structure. The adaptation consisted of decreasing the machine's production speed to 1 - 2% of the maximal production speed, thereby decreasing the density of the structure, and the introduction of two additional providers of steel monofilaments. The structure was produced with a left-right stitch (***Figure 2.a*** see page 56).

The second structure (II) was a double structure made of hybrid yarn (***Figure 1.d***) composed of two twisted bunches of 100% steel filaments (***Figure1.c***) braided by Swiss Shield® yarn (***Figure 1.b***). The braiding process was performed at Legs, Ltd. in Aleksandrów Łódzki on a hollow spindle machine. The structure was produced on the same flat knitting machine as the first structure. The machine was adapted to the process of knitting with such yarn in the same way as in the case of the first structure. The structure was produced in the form of a sleeve with a left-right structure. The sides (layers) of the sleeve do not present any exchange; that is, there are no connections between the layers (***Figure2.b*** see page 56).

The third structure (III) was a double structure made of hybrid yarn (***Figure 1.d***) composed of two twisted bunches of 100% steel filaments (***Figure 1.c***) braided by Swiss Shield ® yarn (***Figures 1.a), 1.b***). The structure was produced on the same flat knitting machine as the first structure and the machine was adapted to the process of knitting with such yarn in the same way as in the case of the first structure. The structure has a left-right stitch. However, it was produced as 'a two-face' structure with an exchange of layers at each 9th column at a distance of 7 rows from each exchange.

***Table 1.** Characteristics of components.*

Material no.	Material name/description	Material parameters/characteristic
1	Swiss Shield® composition: cotton yarn (90%) + fine copper wires (10%). Cotton fibre with a gossamer-thin 0.02 mm silvered and PU-coated spun-in copper thread [21].	Linear density Tt: 30 tex Diameter: 0.75 mm Colour: natural (ecru/white)
2	Bekaert Bekinox® Two bunches of steel monofilaments: 100% stainless steel.	Twist: 175 t/m S Electrical resistance: 13.97 Ω/m Linear density: Tt 300 tex Number of filaments: 370 Diameter of a single filament: 0.01 mm Colour: metallic grey
3	Two bunches of steel filaments braided by a Swiss Shield® yarn [(1) brided by (2)].	Linear density Tt: 350 tex S Diameter: 2 mm Number of brids: 1200/m

Figure 2. *The knit shielding structures: (a) face view of the left-right knit structure (I) made of 100% steel filaments, and (b) view of the double knit structure (II) made of left-right stitch, the structure has the form of sleeve without connections between sides (layers), and (c) view of double structure III with internal tunnels. Two separate fillings were introduced into the tunnels, which can be observed as loose threads. Wooden sticks were also introduced into the tunnels to make these spaces more visible in the picture.*

Both layers were made of the same yarn and the same left-right stitch. The structure was produced with an exchange of layers that ensured the creation of inter-layer space-tunnels. Two additional fillings made of the same yarn as the structure were introduced into the tunnels (***Figure 2.c***).

Additional fillings were introduced into the tunnels of the third structure to modify the internal structure. The manner of connection between layers proposed is to create possibly extensive inter-layer tunnels (***Figures 3** & **4***).

Characteristics of the knit structures are presented in ***Table 2***.

Basic shielding efficiency measurements

The parameter characterising textile fabric shielding properties is the SE. SE indicates the attenuation of an EMF existing at a specific point in space as a result of introducing a shielding material between the point and EMF source. SE can be defined as the ratio of electric field intensity E_0 (or magnetic field intensity H_0) at a specific point of the system analysed without a shield to the electric field intensity E_1 (or magnetic field intensity H_1) at the same point but in a shielded system. SE can be expressed in decibels - dB [23]:

- for an electric field
  $$SE(E) = 20 \log E_0/E_1$$
- for a magnetic field
  $$SE(H)=20 \log H_0/H_1.$$

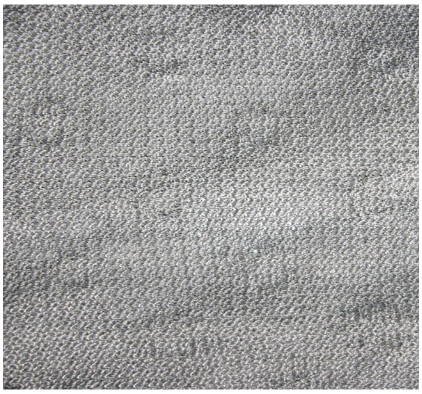

Figure 3. *Face view of a double layer structure with inter-layer tunnels.*

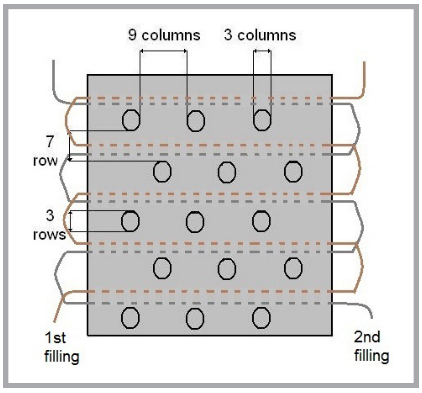

Figure 4. *Schematic presentation of the surface and architecture of the III structure.*

Table 2. *Characteristics of knit structures.*

Material no	Material name/description	Material parameters/characteristic
I	Knitted structure – single – left-right stitch	Course number: 44 courses/10 cm, Wale number: 30 wales/10 cm, Thickness: 2 mm Mass surface: 286 g/m^2
II	Knitted structure – double – a sleeve type – left-right stitch	Course number: 44 course/10 cm, Wale number: 33 wales/10 cm Thickness: 3.8 mm Mass surface: 595 g/m^2
III	Knitted structure – double – left-right stitch – layer exchange	Course number: 46 course./10 cm, Wale number: 33 wales/10 cm Thickness: 3.9 mm Mass surface: 605 g/m^2 Number of additional fillings: 2

Measurements concerning the estimation of the range of frequency in which the first structure (I) would present screening abilities were performed at the Central Institute for Labour Protection – National Research Institute.

Measurements of the first structure's (I) EMR shielding effectiveness were made within the range 30 Hz – 6 GHz for an electrical field and 10 Hz – 1 GHz for a magnetic field. The apparatus arrangements for the electrical field were as follows:

- a broadband analyser of the electric field intensity effective value - EFA-3 Field Analyser from Wandel & Goltermann, with an isotropic probe whose measuring range was from 2.0 V/m to 100 kV/m, within the frequency range 5 Hz - 30 kHz;
- a broadband analyser of the electric field intensity effective value - EMR 300 from Wandel & Goltermann, with an isotropic E-field probe, type 8.1, whose measuring range was from 0.8 V/m to 800 kV/m (1600 V/m), within the frequency range 100 kHz - 3 GHz, and with an isotropic E-field probe, type 9.2, whose measuring range was from 0.8 V/m to 800 kV/m (1600 V/m), within the frequency range 3 MHz - 18 GHz;

The apparatus arrangements for the magnetic field were as follows:

- a broadband analyser of the effective magnetic induction value - EFA-3 Field Analyser from Wandel & Goltermann with isotropic probes, whose measuring range was from 10 nT to 10 mT, within the frequency range 5 Hz - 30 kHz;
- a broadband analyser of the effective electric intensity value - EMR-300 from Wandel & Goltermann with an isotropic H-field probe, type 12, whose measuring range was from 0.017 A/m to 17 A/m, within the frequency range 300 kHz - 30 MHz;

- a broadband analyser of the effective electrical intensity value - EMR-300 from Wandel & Goltermann, with an isotropic H-field probe, type 10, whose measuring range was from 0.026 A/m to 16 A/m, within the frequency range 27 MHz - 1 GHz.

Some additional improvements in the devices were made so that both could be used for measurements in the frequency range 30 kHz – 50 kHz for a magnetic field and at a frequency of 50 kHz for an electrical field for EFA-3, as well as in the frequency range of 50 kHz - 300 kHz for an electrical field for EMR-300. The expanded measurement uncertainty (at a reliance level of 95% and for expansion coefficient k = 2) when using the above-mentioned measuring instruments is as follows:

- for the electric field measurements:
  - 4.8% for a frequency band up to 50 kHz
  - 18.0% for a frequency band from 50 kHz to 100 MHz
- for the magnetic field measurements:
  - 13.0% for a frequency band up to 100 kHz
  - 18.0% for a frequency band from 20 MHz to 100 MHz.

The measurements were carried out for a frequency band from 10 Hz to 100 MHz with a constant values of electric and magnetic field intensity (magnetic induction) generated on test stands in the spot of placing the sample.

The stand used for testing the shielding properties of the first structure (I) is the same as in [23]. It consists of an EMR field gauge, test textile material, and a screening chamber. The source of the electromagnetic field is a Helmholtz coil system, an air capacitor, a TEM line, and the supply and control of the EMR field generated. The sample material tested was placed in a straight line of sight between the field source and measuring probe in a shielding enclosure.

The parameter of the shield is its SE characteristic as a function of the frequency. The measure of SE is attenuation, which defines the reduction in the intensity of the electric and/or magnetic field after penetrating the shield. The SE depends on the physical parameters of the shielding material, e.g. its thickness, composition and architecture, as well as the distance between the shielding surface and EMF source [16].

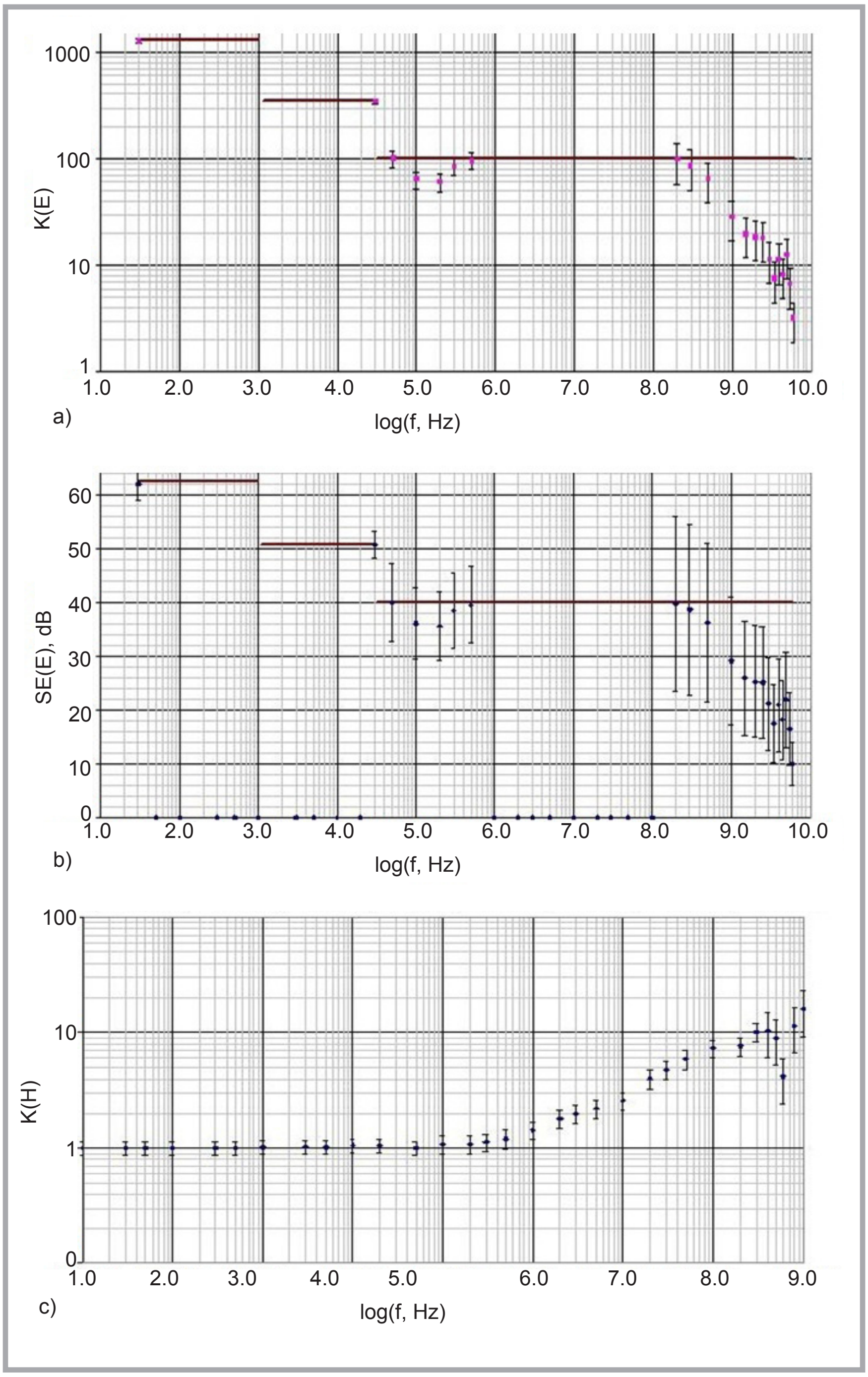

Figure 5. *a) attenuation K(E), b) shielding efficiency SE(E) of an electrical field in the frequency range f 30 Hz ÷ 6 GHz, and c) attenuation K (H) of a magnetic field in the frequency range f 10 Hz – 1 GHz by knit structure I. An analytical description of the dependence is presented in a): $y = 507 – 1.2 \times 10^{-7} x$; $R^2 = 0.3$, b): $y = 47 – 6.70 \times 10^{-9} x$; $R^2 = 0.59$, c): $y = 2 + + 1.6 \times 10^{-8} x$; $R^2 = 0.82$ (0.05 level of significance, 2-tailored correlation).*

Results of measurements of the attenuation of an electrical field K(E) and magnetic field K(H) and shielding efficiency of the electrical field SE(E) performed on knit structure I are presented in ***Figures 5***.

On the basis of the presumption that the simplest knit structure - I might have the worse attenuation abilities of the group of knit structures presented due to the lack of copper wire in the yarn construction and to a lower number of wales in the structure construction, it was decided not to perform other tests at the Central Institute for Labour Protection – National Research Institute on knit structures II and III. It is believed that an increase in the structure density and introduction of additional shielding materials will

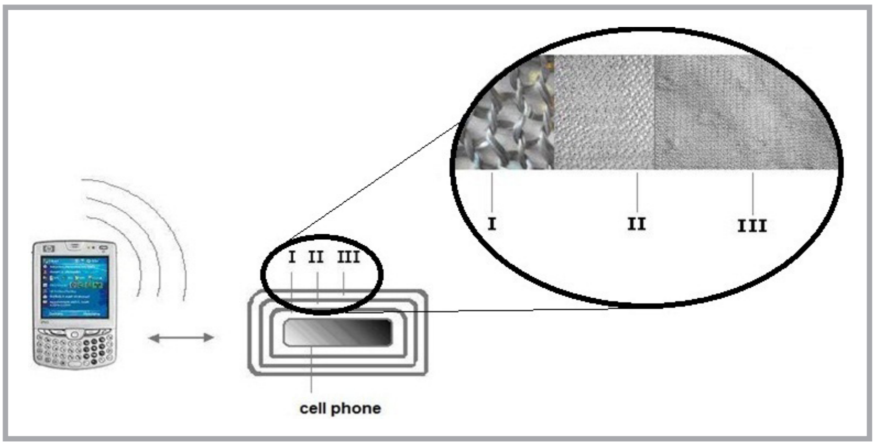

Figure 6. *Scheme of the course of the experimental phone call between the uncovered cell phones and those covered by the three knit structures. The order of the layers of knit structures which cover the cell phone apparatus is schematically presented in circles, with knit structure I being closest to the cell phone apparatus.*

increase the shielding properties of knit structures II and III.

Preliminary test of the screening of cell phone signals

The aim of this provisional test was a preliminary verification of the shielding ability of all three knit structures against the radio signals of cell phones, referring to the results from basic screening efficiency measurements in the case of knit structure I. Further tests are required to fully analyse and verify differences between the knit structures, referring them to the results of measurements performed on other shielding materials.

That test was performed on the territory of the Republic of Poland between two cell phone networks using the Global System for Mobile Communications (GSM 1800).

The uplink and downlink present a frequency range for GSM 1800. An uplink is the portion of a communications link used for the transmission of signals from an Earth terminal to a satellite. An uplink pertains to data transmission from a data station to the headend and to GSM, as well as to cellular networks. The uplink in GSM 1800 is defined as the frequency band 1710-1785 MHz.

A downlink is a frequency band pertaining to cellular networks. A radio downlink is the transmission path from a base transceiver station to the mobile station (cell phone). The Downlink in GSM 1800 is defined as the frequency band 1805 - 1880 MHz.

All cell phone apparatus used in the tests were adjusted to European Union standards by their producers by limitation of the exposure of humans to radio frequency energy. The specific absorption rate (SAR) coefficient for all cell phone apparatus of well known trade-marks did not exceeded 0.6 W/kg.

The scenario of the test was as follows:

1) A test phone call between two cell phones was made. The connection succeeded.
2) The first cell phone apparatus was tightly covered by knit structure I. A connection was attempted from the second cell phone apparatus to the first one – tightly covered by knit structure I. The connection succeeded, meaning that knit structure I did not shield the cell phone radio signal in the range 1710 - 1785 MHz, which is in line with the results of the test performed on knit structure I by the Central Institute for Labour Protection.
3) Next the same cell phone, which was covered by knit structure I, was additionally tightly covered by knit structure II, thus being covered by two knit structures – I and II from that moment. A connection was made from the second cell phone to the first one – tightly covered by knit structures I and II. The package of both knit structures does not shield the cell phone radio signal in the range 1710 - 1785 MHz.
4) Subsequently, the same cell phone apparatus, which has been tightly covered by knit structures I and II, was additionally covered by knit structure III. The order of covering the cell phone by the knit structures and the manner of the test performance are presented in ***Figure 6.***

   A connection between an uncovered cell phone and covered one was performed but did not succeeded. The cell phone tightly covered by a package of three knit structures did receive a radio signal. The package of three knit structures shielded the radio signal effectively.
5) The whole course of the test was repeated, in which the cell phones were replaced, allowing to eliminate accidental results that could come from the failure of the cell phones. However, the results achieved were the same.
6) Next the course of the test was repeated but without the engagement of knit structure I. Accordingly, one of the cell phones was tightly covered by knit structure II and a connection made with the second cell phone - being uncovered and arranged towards the one tightly covered. The connection succeeded, meaning that knit structure II does not shield the radio signal at the cell phone frequencies.
7) The same cell phone, tightly covered by knit structure II, was additionally covered by knit structure III. A phone call was made to the second cell phone - being uncovered and arranged towards the one tightly covered. The connection did not succeed, meaning that covering a cell phone by both knit structures II and III shields the cell phone from the radio signal.
8) The test was repeated, in which the knit structure covering order was changed. It did not influence the result of the test. The scenario of the tests was repeated with two other cell phone apparatuses to eliminate accidental results.

   The results of that test prove that a package of two double knit structures (in total four layers) is necessary to shield the cell phone radio signal, meaning that knit structures II and III together present a barrier for an electromagnetic wave at least in the range 1710-1785 MHz.

   Internal reflections and resonance near the cell phone apparatus covered by the knit structures were not measured.

The phenomena of the shielding ability of knit structures II and III, containing a copper wire, relate to the change of EMF energy into that of alternating current generated in the copper circuit and stainless steel core, which is magnetised.

In the case of knit structure I, some of the EMF energy is changed into that which magnetises the stainless steel, which is a ferromagnetic. The remaining energy is still harmful (not shielded).

Discussion

Based on ferromagnetic and electroconductive materials available on the market, a hybrid yarn was fabricated in this study. The name hybrid has been used here intentionally as this fine yarn was made of stainless steel and copper together with fine, high quality cotton.

Next, three independent knit structures - meshes in fact, were fabricated.

The intention of the creation of three different structures was to build first a referential structure – a plain structure, and next to extend its internal and external structure by adding an additional layer and fillings. Such activity was to verify the authors presumption concerning the neutralisation of EMR, which is a 3-D phenomena, according to which, in order to protect oneself from physical phenomenon of a 3-D nature, one should design a structure responding to the demand of that 3-dimentionality.
According to own studies and tests, it may be concluded that the more complex the architecture of the shielding knit structures, the better their EMR shielding ability . The complexity refers to the number of layers and additional fillings.

Commercially available products e.g. stretch conductive fabrics fully silver coated [24] of similar structure to knit structure I have shielding effectiveness: 35 dB: 1 - 10 GHz, and COBALTEX™ woven fabric [24] designated for near magnetic field shielding has 65 - 80 dB tested over 30 MHz to 1 GHz; however a unique composition of the yarn was applied in this case, covering a polyester filament by nickel, copper, nickel again and finally by a nickel and copper alloy. Another product is made of 100% surgical stainless steel, 0.01 cm diameter, knitted into a shielding fabric with 26 dB at 800 MHz, 15 dB at 1900 MHz [24]. Knit structure I achieves 62 dB for the range 30 Hz to 20 kHz, 50 dB in the range of 30 kHz and 40 dB for the range 50 kHz to 300 MHz, and a reduction in SE is noticed from 29 dB - 10 dB in the range 1GHz to 6GHz, hence it is comparable to similar commercially available products.

One should consider the fabrication of a lower mass surface and higher density knit structure to be able to provide a comfortable knit structure preventing EMR penetration through it. The increase in density and decrease in loop size of knit structures strongly influence the shielding properties of the materials as well as the mechanical parameters with respect to the comfort and hand of the final product perceived by users.

The comfort and hand issues are also related to the cotton component material incorporated with electroconductive material and ferromagnetic material. The fabrication process of knit structures has been meaningfully improved by adding a cotton component to the yarn. According to the authors, adding a cotton component improved the hand of the hybrid yarn and that of knit structures II and III in comparison to knit structure I. Moreover it significantly limited the harshness of the structures in comparison to knit structure I. This feature of the structures has great significance because the knit structures are dedicated to individual protection against EMR. Total hand value estimation, according to the methodologies presented by Behery [25], has not been performed yet as it was not necessary, according to the authors, at that preliminary stage of research.

The application of a cotton component into the hybrid yarn improved the knitting process. The lubrication of beds on the knitting machine could be limited while knitting structures II and III, with the number of broken needles decreased from 8 to 0 at comparable production parameters of knit structure I. However, it should be mentioned that the fabrication of structures II and III required double the number of needles due to fabrication on both beds.

It was presumed that both knit structure II and knit structure III may have better shielding efficiency than knit structure I due to their double construction (two layers) and the application of an additional component - Swiss Shield ® yarn. However, this is only a presumption made on the basis of a literature review [13, 19] and own studies, not verified by tests.

The SE of Swiss Shield® yarn influenced the decision about cotton incorporation with copper yarn as a component of the hybrid yarn in the studies presented in this paper (see Introduction).

A disadvantage of individual protection made of such knit structures presented in this paper is the surface mass increase that occurs together with the application of any additional component. The authors considered two optional solutions related to the optimisation of the features of knit structures: The first one concerns the production of a low density or medium density structure with some additional fillings to improve shielding efficiency; however, this will give a high surface mass of the final product. The second one concerns the production of a high density product; however, this may influence the parameters of the wear comfort of the final product.

Conclusions

1) Ferromagnetic materials, e.g. stainless steel and electroconductive materials, e.g. copper joined in a proper manner and arranged in the knit structure may sufficiently shield against EMR.
2) Knit structures seem to be appropriate for implementation into individual protection coveralls or uniforms protecting against EMR on condition that they are produced from a proper ferromagnetic material incorporated into a structure.
3) An increase in the percentage of cotton raw material in hybrid yarns applied in knit structure production may significantly improve the haptic perception of the structure and sensorial comfort of the user wearing the final product.
4) The SE of knit structures depends on the arrangement of ferromagnetic and electroconductive materials in the knit structure.

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