



Electrical conductivity of a closed-circuit embroidery element

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Abstract. The electrical conductivity of the embroidery system and its resistance against the static charge depend on various factors, such as the properties of the textile materials, the direction of the embroidering, the form of the element, the technological parameters of the embroidery process, etc. Therefore, the factors that have an impact on the embroidered electrically conductive system are a relevant topic of scientific research. The aim of this work was to investigate and analyse the influence of the technological parameters of the embroidery processes on the electrical conductivity of embroidery elements. Three fabrics of the same fibre composition but of different structure were used in the research. The electrical conductivity of the embroidery element was found to differ when the technological parameters of the embroidery process were not the same.

Key words: embroidered element, fabric, conductive thread, resistance.

1. INTRODUCTION

In technical areas materials and embroidery systems with electrically conductive fibre are being used more and more frequently. The electrically conductive fibre is often used in the manufacture of sensors or as conductors and protection against static charge [1–6]. Exploration of electrically conductive rectangular embroidered antennas designated for mobile conversations that had been made using different textile materials and applying different stitches of 0.4 and 0.8 mm revealed that the performance of the antenna depends on the accuracy of the form of the element and stitch density and its direction [4].

Scientists of the United Kingdom performed a research where they analysed the functionality of the

frequency-selective surfaces (FSS) of the electrically conductive closed-circuit embroidery elements and design flexibility in portable programs. The research demonstrated that it is possible to regulate and control the resonance frequency and variations of the FSS system by means of the electrical conductivity of the embroidery elements, which is influenced by their size. The textile FSS array created on 0.8 mm thick felt material using a fast and cost-effective embroidery technique with conducting threads, while the distance between the antennas varied, could be characterized as having a steady resonance [5]. This shows that factors that have an influence on the accuracy, conductivity, and quality of the embroidery elements are of extreme importance.

In the creation of ‘electronic’ systems of embroidered textiles a circular loop-form contour (chain), i.e. a copolar strip (CPS) dipole system antenna, having great protection against static charge, is often used [6,7]. Research

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shows that the values of the vertical and distinctive surface resistances depend on the amount of the polyester (PES)+INOX conductive threads in the fabric [1]. The smaller the distances between those threads, the smaller are the values. One of the possibilities of improving the electrostatic properties of the tested materials is to interweave electrically conductive threads into the warp [1]. Electrically conductive threads are produced from conductive metals, their mechanical behaviour is close to the behaviour of the textile threads, but they also possess some drawbacks: they are rather expensive and their surface structure is rough, which causes failures of weaving machines in the process of manufacturing [8–10]. Despite this fact, in order to achieve an identical stronger electrical conductivity to fill the embroidery area, it is recommended that the upper and bottom threads should be electrically conductive [2–4,6,7].

Scientists of Wrocław University, Poland, investigated the electrostatic properties of a computer embroidering ‘electronic’ system that was made by using different contour structures, and compared it with a CPS-dipole system antenna working at the same wave frequency of 2 GHz [7].

It is evident from the cited literature that the electrical conductivity of embroidered elements is mostly influenced by the technological parameters of the process, the form of the element, and the properties of the used materials; therefore, there is a need for accomplishing a more exhaustive investigation on electrically conductive embroidery elements. The aim of this work is to explore and to analyse the influence of the technological parameters of the embroidery process on the electrical conductivity of embroidery elements.

2. EXPERIMENTAL DETAILS

Three fabrics of the same fibre composition of different weave were chosen for the experiment (Table 1). The characteristics of the tested fabrics were determined according the standards: the thread density according to LST EN 1049-2 [11], linear density and surface density

according to LST ISO 3801 [12], and the thickness of the material according to LST EN ISO 5084 [13]. The filling index of the fabrics e_s and the linear filling indexes e_m, e_a were calculated applying medium warp and weft density P_m and P_a for the unit of length (cm^{-1}), and the thread contouring diameter of the fabric (d_{km}, d_{ka}) (when $e_m \geq 1$ or $e_a \geq 1, e_s = 1$). Electrically conductive polyamide embroidery threads with silver strands Elitex 110/34 dtex 2 ply were used. To achieve a greater electrical conductivity during the embroidery process, the same thread was used as the upper and the bottom thread.

The embroidery process was accomplished with a Brother PR-600II one head embroidering machine using embroidery speed $V = 600 \text{ min}^{-1}$. To evaluate the influence of the direction of the embroidering on the threads, square-shaped elements were chosen for the experiment. Digital closed-circuit contour drawings were made using the Embroidery Cad software Brother PE Design program package. Test samples of $21 \text{ cm} \times 21 \text{ cm}$ embroidered with square $60 \text{ mm} \times 60 \text{ mm}$ closed-circuit elements were prepared.

The embroidered closed-circuit elements of the widths 6 mm and 14 mm were made using type T filling with two stitch densities: 3 stitches/mm and 4.5 stitches/mm. Filling type T is widely applied in embroidering elements of large measurements. In the process, a solid filling of the form is achieved by accomplishing short basting stitches of different density from one side to the other.

Two sides of a square element were embroidered in parallel with the warp direction and two others, with the weft direction. Therefore, it was possible to quite precisely evaluate the influence of the properties of the textile materials and the direction of the embroidering on the stability of the form. The embroidery process was carried out in the clockwise direction with the primary and final points coinciding (point A, Fig. 1).

The measurements of the resistance to the electrical conductivity of the tested closed-circuit embroidery chain, i.e. the measurements of electrical conductivity $R (\Omega)$, were performed in the square-form diapason (Fig. 2a). The measuring wires were tightly connected to the measured circuit by reinforcing them into a special frame

Table 1. Characteristics of the fabrics (composition of all fabrics 65% 35% cotton)

| Fabric symbol | Weave | Thread density, cm^{-1} | | Surface density, g/m^2 | Thickness TS (100), mm with load | Linear density, tex | | Fabric linear filling indicators | | Fabric surface filling indicator e_s |
|---------------|-------------|----------------------------------|-------------------|---------------------------------|----------------------------------|---------------------|----------|----------------------------------|-------------------|--|
| | | P_{warp} | P_{weft} | | | T_{m1} | T_{a1} | e_{warp} | e_{weft} | |
| A1 | Plain weave | 40 | 22 | 257 | 0.46 | 37 | 37 | 0.971 | 0.534 | 0.986 |
| A2 | Twill 4/1 | 45 | 29 | 287 | 0.56 | 37 | 40 | 1.092 | 0.732 | 1.000 |
| A3 | Twill 3/1 | 39 | 19 | 251 | 0.65 | 30 | 50 | 0.852 | 0.536 | 0.931 |

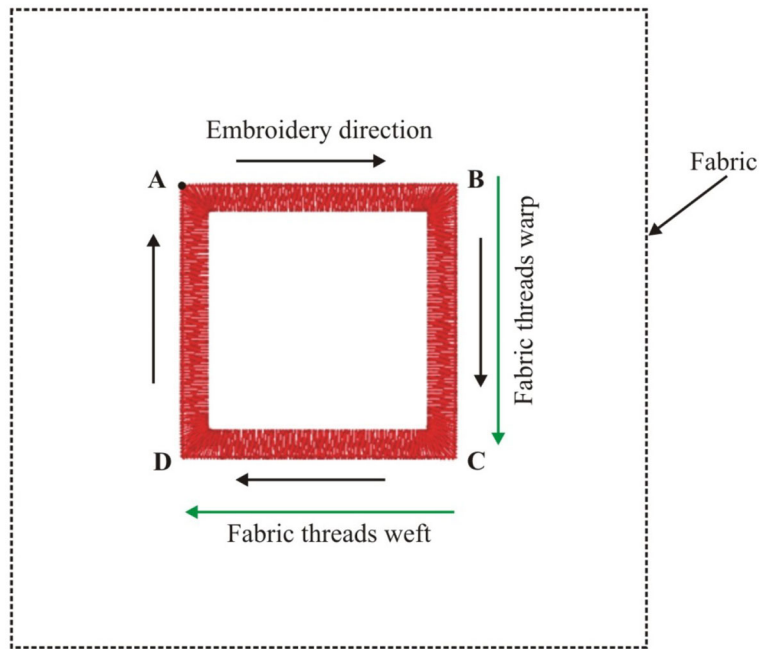


Fig. 1. The form of the studied electrically conductive element.

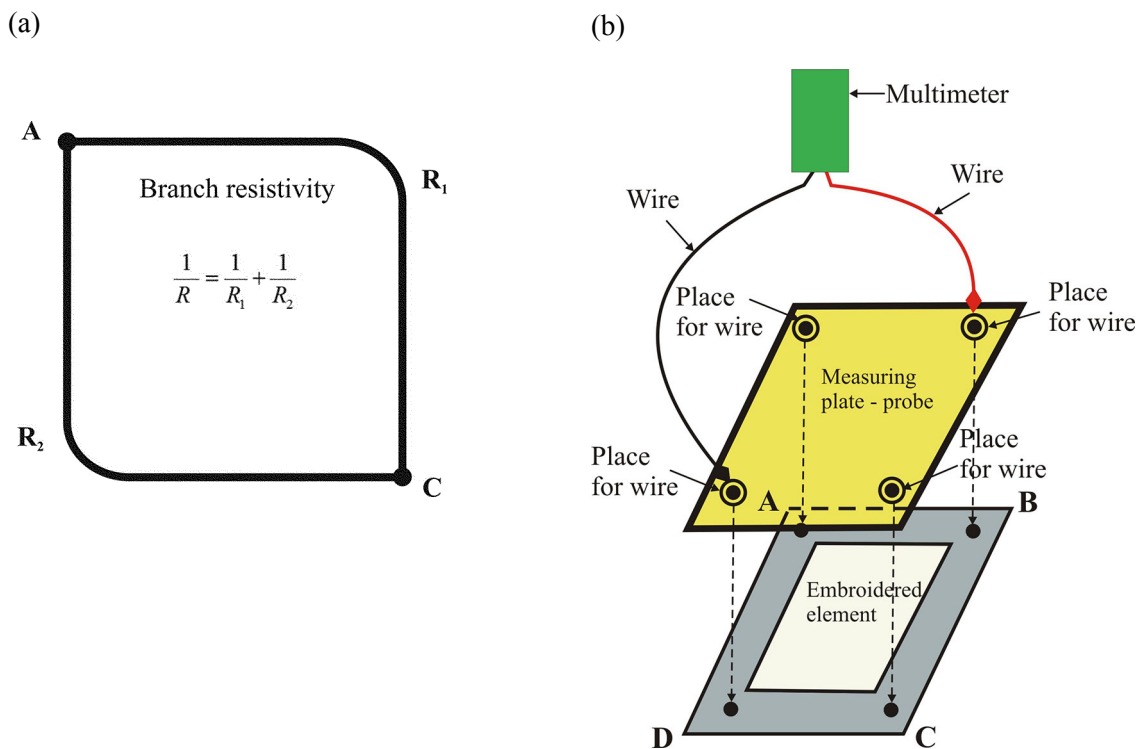


Fig. 2. Schemes of the analysed chain of the embroidered closed-circuit element: a – scheme of the resistance to electrical conductivity, where $R (\Omega)$ is electrical resistance; b – scheme of the measurements of the electrical resistance.

(Fig. 2b). The measurements of the electrical resistance of the embroidered square-shaped contour embroidery elements were performed with the multimeter BRYMEN BM811S.

The obtained averages of electrical resistance R of the embroidered closed-circuit element were analysed. Statistical processing determined the value of the variation coefficient to be up to 6%, and the relative error of the measurements was from $\pm 1\%$ to $\pm 7\%$.

3. RESULTS AND DISCUSSION

The electrical conductivity of the chain was analysed after the evaluation of the electrical resistance R of the closed-circuit contour embroidery element had been performed. Analysis of the electrical conductivity of the embroidered closed-circuit element indicated that the magnitude of the electrical resistance was influenced by the parameters of the embroidery process. When the embroidery area was filled by stitches of a greater density (4.5 stitches/mm) and the widths of the contour were larger (6 mm and 14 mm), the electrical conductivity increased in all cases. The conductivity of the embroidered 14 mm contour width closed-circuit element was by $\sim 34\%$ to $\sim 61\%$ higher than the conductivity of the element of 6 mm contour width. The electrical resistance R varied from 0.59 to 0.80 Ω (Fig. 3).

Comparison of the electrical resistance R among all test samples embroidered on 6 mm contour width elements filled with a density of 3 stitches/mm and 4.5 stitches/mm, showed that a higher conductivity ($\sim 19\%$ to $\sim 21\%$) was obtained when the stitch density was 4.5 stitches/mm (Fig. 3b). Among all test samples under investigation the greatest conductivity was achieved when the elements were accomplished on fabric A2.

In this case the electrical resistance R of the test sample filled applying the stitch density 3 stitches/mm was 0.75 Ω and that of the elements filled with 4.5 stitches/mm was 0.59 Ω , that is from $\sim 6\%$ to $\sim 9\%$ smaller than the resistance of the other test samples (Fig. 3a). This shows that when the technological parameters of the embroidery element are different, the electrical conductivity is influenced by the differences of the characteristics of the fabrics.

Experimenting on the elements of a wider, 14 mm contour width filled with stitches of different density showed that the conductivity was by $\sim 45\%$ to $\sim 61\%$ higher when the stitch density was 4.5 stitches/mm. In this case also the electrical resistance R of the embroidered elements accomplished on fabric A2 was the smallest and their electrical conductivity in comparison to the elements accomplished on the other fabrics was by $\sim 32\%$ to $\sim 38\%$ higher (Fig. 3b).

As to the characteristics of fabric A2, it is evident that its filling index in the warp direction is up to $\sim 28\%$, in the weft direction up to $\sim 37\%$, and the overall e from $\sim 1.4\%$ to $\sim 6.9\%$ higher than those of the other fabrics under investigation (Table 1) [14]. The research proved that the linear indexes of the filling, which supplement the density characteristics, have an impact on the resistance of the thread composition to the mechanical impact as well as on the integrity of the embroidery surface and its electrical conductivity [2,3,15–20]. It is also worth mentioning that the surface density of this fabric (g/m^2) is by $\sim 12.5\%$ and its density (cm^{-1}) by $\sim 14\%$ higher than those of the other fabrics under investigation.

When the width of the contour and the stitch density were increased, the resistance to the electrical conductivity decreased (Fig. 4). The reverse correlation coefficient of the dependence between the index of the fabric filling

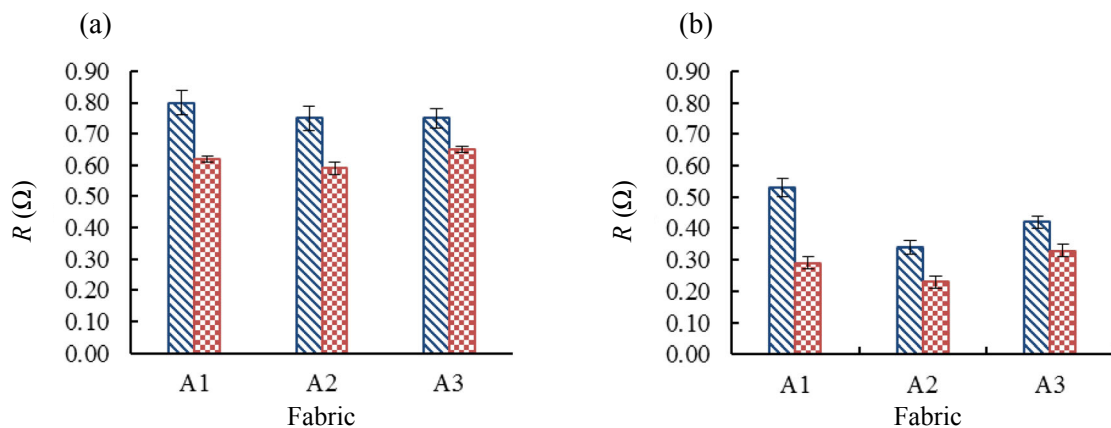


Fig. 3. Resistance of the embroidery closed-circuit element to the electrical conductivity R when the designed contour width of the element is 6 mm (a) and 14 mm (b) in case of stitch densities 3 stitches/mm and 4.5 stitches/mm.

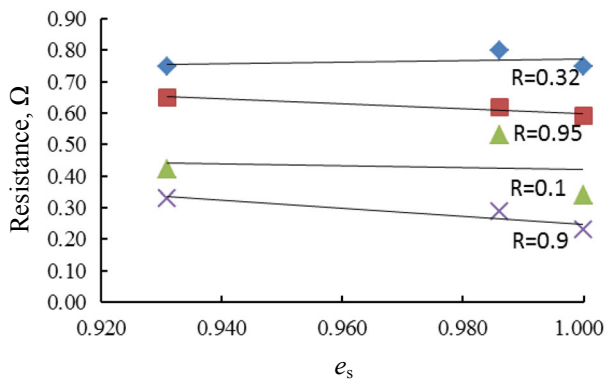


Fig. 4. Dependence of the resistance to the electrical conductivity of the closed-circuit embroidery element on the index of the filling of the fabric e_s for different parameters of the embroidery element: \blacklozenge – contour width 6 mm, density 3 stitches/mm; \blacksquare – contour width 6 mm, density 4.5 stitches/mm; \blacktriangle – contour width 14 mm, density 3 stitches/mm; \times – contour width 14 mm, density 4.5 stitches/mm.

and electrical resistance R in case the stitch density of the contour was 4.5 stitches/mm was from 0.9 to 0.95. It is evident from the analysis of correlation that there is a strong bond between those two indexes. A weaker correlation, from 0.1 to 0.3, was obtained when the stitch density was 3 stitches/mm. Thus, the analysis of correlation confirmed that the characteristics of the fabric have an influence on the electrical conductivity of the embroidery elements [2,3].

The results of research have shown that in general case the stitch density has the greatest influence on the electrical conductivity of the closed-circuit embroidery elements. Our analysis of the electrical conductivity of the square-shaped embroidery elements indicated that when the stitch density was higher (4.5 stitches/mm) and the contour was 14 mm wide, the resistance R was the smallest. This demonstrates that in the general case the highest electrical conductivity was achieved in the elements accomplished on fabric A2 (Fig. 3). It has been noted in the literature that in case different stitch density, filling type, and forms are used in the embroidery process, the force of the electrical field will change when the position of the threads of the fabric composition is changed [21]. It has been found that changes of the electrostatic force in the embroidery element activate the resonance and when its amplitude increases, the central wave frequency in the contour will decrease [14,21]. Research on embroidery elements of different contour with electrically conductive PVDF strands demonstrated that the embroidery system preserves the properties of functionality very well during exploitation

and that with a smaller embroidery area a higher electrical resistance is obtained [14,22]. These findings support our results.

The performed analysis showed that in most cases a higher electrical conductivity is obtained in the case of closed-circuit square-shaped 14 mm width contour fabrics of different weave than in 6 mm contour width elements (Fig. 3). Basically, the number of the embroidery stitches in the lines and the amount of the consumed electrically conductive thread may have an impact on that. When using filling type T in embroidering a closed-circuit square-shaped 6 mm contour width embroidery element with a density of 3 stitches/mm, about 1911 stitches are made and when the density is 4.5 stitches/mm, the number of the stitches rises to about 2800. When the contour width of the element is 14 mm and the stitch density is 3 stitches/mm, the embroidery area is filled by making about 3390 stitches, and when the density is 4.5 stitches/mm, the number of the performed stitches reaches 4980. For making more stitches a greater amount of electrically conductive thread is consumed. Researches also emphasize that the technical parameters of the sewing equipment and activated complex stretching, friction, compression, and shear forces have an influence not only on the accuracy of the stitches but also on the stability of the form [14–18,23,24]. Therefore, it is probable that while making a bigger number of stitches, the fabric surface is affected by stronger load forces than when the number of stitches is smaller, and thus, the embroidery area is filled more equally. Therefore, when the stitch density is higher and the contour width is wider, a stronger electrical conductivity is received (Fig. 3).

The results of the measurements show that the difference of the electrical resistance depends on the technological parameters. The larger the contour width of the embroidery element and denser the stitch, the smaller the electrical resistance and, consequently, the better the electrical conductivity. It should be also emphasized that if the needle pierces the fabric more times during the process, the threads of the structure will change their orientation at the time of the mechanical impact. As a result, strong bond fields form among them, and therefore the number of free fields rapidly decreases [14,24,25]. When the needle pierces the structure of the fabric, the threads, which are in contact in the system, are compressed to each other very tightly [14,25]; therefore, when they come close to each other, the electrical conductivity increases [3,6–8].

Thus, in general, it can be stated that the characteristics of the fabric, contour width, and stitch density have an essential influence on the electrical conductivity of embroidery elements. A larger contour width and

stitch density weaken the resistance to the electrical conductivity. Therefore, in order to achieve a more equal and higher electrical conductivity of the embroidery system, there is a need for a thorough analysis of the factors influencing electrical conductivity. The results of this research can be useful in giving recommendations concerning the choice of the parameters of the technological processes and quality standards of the systems of the embroidery elements to technical institutions that sometimes encounter the appearance of defects of embroidery elements.

4. CONCLUSIONS

It was established that the electrical conductivity of a closed-circuit contour embroidery element is influenced by the size of the contour and the stitch density, depending on the characteristics of the fabric. The highest electrical conductivity was determined when the contour width was bigger, which in the case under investigation was 14 mm, and the stitch density was 4.5 stitches/mm. A strong correlation ($R = 0.95$) between the indexes of fabric filling (e) and the electrical resistance R (Ω) shows that the analysis of the influence of the technological parameters can be used in researches of the electrical conductivity of embroidery elements of different forms.

In general, the lowest electrical resistance R (Ω) was obtained when the embroidery elements were produced on fabric A2, the filling index (e) of which is by about 1.4% to ~6.9% higher than those of the other fabrics under investigation. Thus, the results showed that the electrical conductivity of the embroidery systems, other technological parameters being the same, differed depending on the physical characteristics of the fabric.

The research demonstrated that to achieve high-quality embroidery systems with precise electrical conductivity a filling type of thicker stitch density should be applied since the solid filling of the embroidery area most successfully guarantees an integral electrical conductivity of different forms. The performed research proved the necessity of the analysis of the factors influencing the quality of embroidered electrically conductive systems. Such an analysis could be of great importance in the creation of rapidly developing advanced technological processes.

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Elektrijuhtivuse uurimine kinnises tikitud kontuuris

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Tikandi elektrijuhtivus ja vastupanu staatilisele laengule sõltuvad mitmest faktorist, nagu tekstiilmaterjali omadused, tikkimise suund, tikitud elemendi kuju, tikkimisprotsessi tehnoloogilised parameetrid jne. Seega on faktorid, mis avaldavad mõju tikitud, elektrit juhtivale süsteemile, teaduslikuks uuringuks oluline teema. Artikli eesmärk on uurida ja analüüsida tikkimisprotsessi tehnoloogiliste parameetrite mõju tikitud elemendi elektrijuhtivusele. Uuringus kasutati kolme samakiulise koostise, kuid erineva struktuuriga kangast. Uuringu käigus leiti, et tikitud elemendi elektrijuhtivus muutub, kui muutuvad tikkimisprotsessi tehnoloogilised parameetrid.