Evaluation of electrically conducting fabrics for use as layers protecting against mechanical damages

Ocena tkanin elektroprzewodzących pod kątem zastosowania jako warstw chroniących przed uszkodzeniami mechanicznymi

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Abstract

The unique characteristic of the electroconductive fabric-based sensor is its ability to generate an electric signal directly in response to external stimuli. A fabric-based layer can protect objects and simultaneously monitor changes in resistance. It was found that the electrical resistance of fabric increases with increased mechanical damage to its surface. As the resistance increases, the fabric loses its protective properties, which may damage the object. The analysis of static characteristics enabled the selection of fabrics characterised by the widest range of electrical resistance, which results in a desirable higher sensitivity factor of the fabric-based sensor.

Abstrakt

Unikalną cechą sensora na bazie tkaniny elektroprzewodzącej jest jego zdolność do generowania sygnału elektrycznego bezpośrednio w odpowiedzi na bodźce zewnętrzne, np. uszkodzenia mechaniczne. Warstwa tkaniny może chronić obiekty i jednocześnie monitorować zmiany rezystancji. Stwierdzono, że rezystancja elektryczna tkaniny wzrasta wraz ze wzrostem uszkodzeń mechanicznych jej powierzchni. Wraz ze wzrostem oporu tkanina traci swoje właściwości ochronne, co może skutkować uszkodzeniem obiektu. Analiza charakterystyk statycznych umożliwiła wybór tkanin charakteryzujących się najszerszym zakresem rezystancji elektrycznej, co skutkuje większą czułością sensora.

Keywords: electroconductive fabrics, resistance, sensors, damages, protection

Słowa kluczowe: tkaniny elektroprzewodzące, rezystancja, sensory, uszkodzenia, ochrona

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1. Introduction

Wearable devices have become an integral part of human life. However, the products have to meet ever-greater demands and expectations. Wearable technology is developing, and wearable electronics are evolving along with it [1,2]. Electroconductive fabrics combine the advantages of traditional woven fabrics with the ability to sense and transmit electrical signals. They are a significant part of wearable electronics [3-6]. The flat textile materials can be integrated into composite structures. The thin, flexible textile-based products called wearable textronics [1] can act as heating elements, electrodes, connectors, signal lines, and sensors [7-13]. From the point of view of a wide range of applications, textile-based sensors deserve attention. They are resistive, capacitive, piezo-electric, and electrochemical sensors [14-17]. The resistive sensor operation relies on the detection and response in the form of a change in electrical resistance to some input from the physical environment [15,18]. The electroconductive woven fabrics can be used as a resistive sensor for damage detection [16,19,20]. Development of advanced application techniques to obtain electrical conductivity of textile materials, emphasizing metal-containing coatings, is observed [21-24]. Obtaining a continuous and uniform coating layer on the non-conductive fabric is essential from an electroconductive properties point of view. Cracks in the conductive layer influence its electroconductive properties, resulting from changes in the distribution of the potential and current density around the defects [25,26]. The increase in textile material electrical resistance is observed that is caused by defects [26]. The electroconductive fabric can be embedded within the structure, and any damage or structural changes can alter its electrical properties, enabling the detection of defects, cracks, or structural failures. The electrical resistance change technique has advantages over other methods since it employs the electroconductive properties of fabric coating as a sensor to measure the changes in the resistance. Therefore, the detection of damage can be measured directly [19].

The four-point probe (FPP) method [27] was used to measure the electrical resistance of samples to observe changes in resistances before and after testing [19,28]. The carbon fiber composite laminates were taken into consideration to detect barely visible impact damage [19]. Changes in electrical resistances resulting from damage were noticed. Moreover, it was observed the magnitude of resistance changes is dependent on the carbon fiber volume fraction. The higher the fiber content in the composite, the lower the resistance. The detection of defects in woven, knitted, and embroidered electrodes as a result of mechanical and chemical impact was the subject of research [28]. The content of copper and silver on the electrode surface guaranteed the ability of the products to conduct electric current. It was found, that the tests of resistance to washing, abrasion, and pilling caused an increase in the electrical resistance of the electrodes. Tests showed that the copper-based electrodes suffered the most damage, resulting in the greatest increase in resistance. An electrical response to damage of carbon fiber-reinforced polymer composites was also tested based on the multi-probe resistance method [29]. The change of different electrical potentials was observed for samples. It was stated, that no external sensors are needed because the technique provides direct information from the original output signal pointing at the sample damage. Detection of cracks from boundary measurements, voltages, and current was performed [30,31]. The Electrical Impedance Tomography (EIT) method was used as a non-destructive tool for building a conductivity map of the entire structure to localise cracks.

Electroconductive woven fabrics exhibit an electrical in-plane anisotropy, meaning that their electrical properties vary depending on the direction of measurement within the fabric [32-35]. It is observed that when multiple conductive yarns intersect within the fabric, the electrical resistance tends to be higher compared to fabrics with fewer intersecting yarns [32,35]. This suggests that the presence of intersections creates additional barriers to the flow of an electric current. The metallization process applied to non-conductive textile material significantly impacts the electrical resistance of electroconductive fabrics [36-38]. The surface percentage occupied by the coating is significant from the point of view of forming percolation channels with metal conductivity begins [39]. The coating of a non-conductive fabric with a conductive material such as nickel, copper, silver, tin, or titanium results in a smoother surface. This smoothness leads to a decrease in woven fabric resistance, as the conductive coating reduces potential barriers or irregularities on the fabric surface [32]. Considering that electroconductive fabrics are anisotropic materials, it is essential to use an appropriate measurement method to evaluate their properties. In this context, the van der Pauw (VDP) method [40] proves to be a reasonable choice. The VDP method utilizes a specific configuration of four electrodes for resistance measurement, which enables the determination of electrical in-plane anisotropy in the fabric [14,32,33]. This method offers advantages over other methods. The FPP method is commonly used for resistance measurements but does not provide information on anisotropic behavior [41]. The EIT method [30,31] is time-consuming, and the multi-probe resistance method requires multi-variant measurements. In the case under consideration, when the size of the damage is essential, not its localization, the VDP method is entirely sufficient for the resistance determination of the electroconductive woven fabric. A relationship between changes in the resistance of the fabric and the properties being monitored or controlled needs to be specified for the fabric-based sensor. Understanding how variations in the fabric's electrical characteristics correspond to changes in the monitored parameters can be leveraged while designing electroconductive fabrics for various applications.

The unique characteristic of the fabric-based sensor is its ability to generate an electric signal directly in response to external stimuli, which is the damage to the fabric structure. The main aim of the research was to evaluate the electroconductive woven fabrics as a material intended for the damage sensors. Static characteristics of the fabric-based resistive sensors were determined. An electrical anisotropy of fabrics was considered when assessing the suitability of the textile material as a protecting layer adjacent to an object flat surface while simultaneously monitoring changes in electrical resistance.

2. Materials and methods

Electroconductive woven fabric can play a significant role in measuring systems intended for damage detection. Woven fabric is a thin, non-stretchable, and flexible textile material that can easily adhere to a protected surface. A general idea of a measuring system is shown in Fig. 1. The electroconductive woven fabric can act as a protective layer adjacent to a flat surface of a monitored object, aiming to safeguard against mechanical damage. In the case under consideration, the location of the damage is irrelevant, but its size.

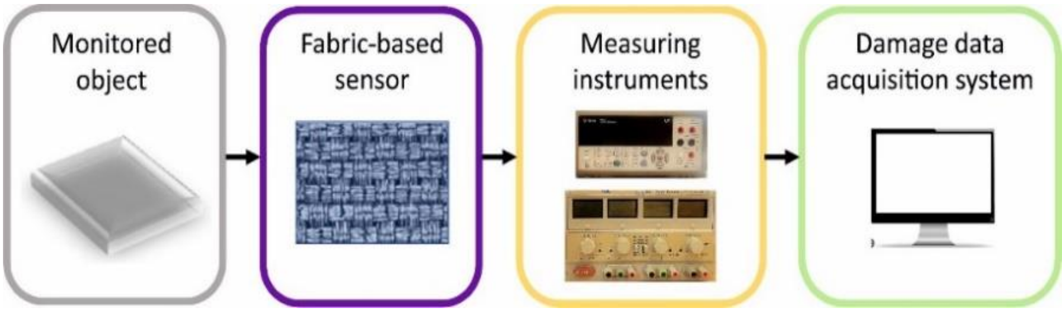

Fig. 1. Idea of measuring system for damage detection.

Due to the need for the fabric to adhere to the object, the frame can be used to clamp the fabric and object. The frame should enable leading the wires connecting four electrodes with the measuring instruments.

Four electroconductive woven fabrics were selected for testing. The parameters of fabrics are given in Tab. 1, where the variation coefficient is given in paratheses.

Tab. 1. Parameters of electroconductive woven fabrics.

Fabric	Raw material composition	Thickness, [mm]	Areal density, [g/m^2]	Warp/Weft density, [yarns/cm]
S1	Silver-coated polyamide plain-weave fabric; declared surface resistance below 0.30 Ωsq^{-1}	0.106 (5%)	42 (0.1%)	45/44
S2	Nickel-coated polyester twill-weave fabric; declared surface resistance below 0.40 Ωsq^{-1}	0.270 (4%)	152 (0.2%)	46/35
S3	Copper and nickel-coated polyester plain-weave fabric; declared surface resistance below 0.05 Ωsq^{-1}	0.086 (6%)	77 (0.1%)	56/47
S4	Silver-coated polyamide plain-weave fabric; declared surface resistance below 0.03 Ωsq^{-1}	0.116 (8%)	72 (0.1%)	51/51

Square samples with a side of 5 cm were prepared in a variant without any damage and in variants with circular-shaped damages of different diameters □ located in the central part of the sample. As was confirmed, the maximum and minimum values of resistances of the textile material are connected directly with the weft/warp direction [32]. During the preparation of the samples, particular attention was paid to ensuring that the sides of the squares aligned parallel to either the warp or weft threads of the fabric. This alignment enabled controlling measurement results regarding the structural orientation of textile material. The variants considered in the investigation are presented in Fig. 2. In total, seven variants of samples from each electroconductive woven fabric were prepared to evaluate changes in resistance being an effect of sample structure damage.

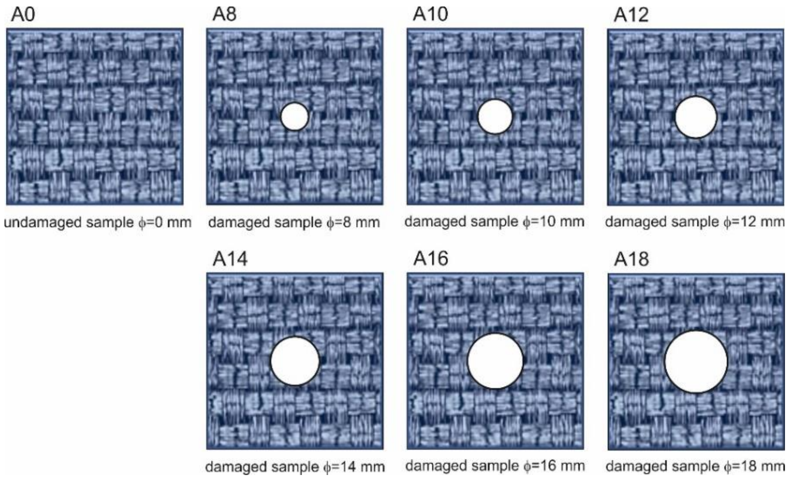

Fig. 2. Variants of woven fabric structure damage.

The van der Pauw method [40] was used for electrical resistance measurements of woven fabrics. Four cylindrical electrodes with a contact diameter with the substrate equal to 2 mm were placed in the corners of the sample (Fig. 3). Between two adjacent electrodes, the direct current *I* was fed. The remaining two electrodes were used to measure the voltage drop *V*. Based on Ohm's law; two resistances can be determined depending on how the electrodes are connected: a horizontal resistance R_h (Fig. 4a) and a vertical resistance R_v (Fig. 4b). In the electrode configuration, the electric current flows on the woven fabric surface, along the warp/weft threads.

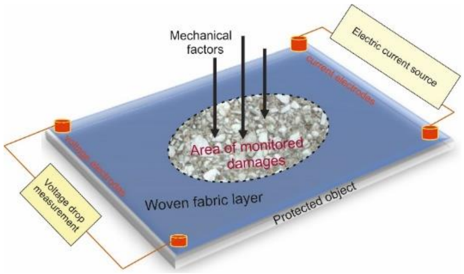

Fig. 3. Woven fabric as a layer protecting against mechanical damages.

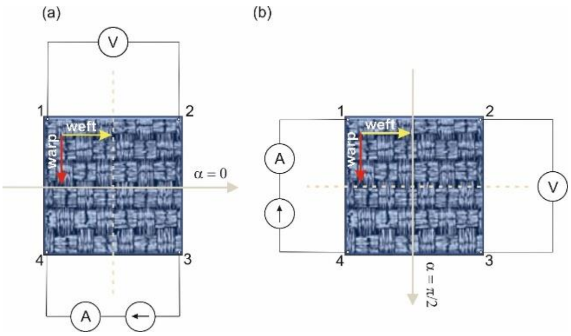

Fig. 4. Resistance measurement: a) horizontal, b) vertical.

Uncertainty analysis [42] of electrical resistance measurement was carried out. Assuming the 0.95 confidence level, the expanded uncertainty of output estimate (resistance) was obtained from the formula:

$$U = k_p u_c(R) \tag{1}$$

wherein

$$u_C^2(R) = \left(\frac{\partial R}{\partial I}\right)^2 [u_A{}^2(I) + u_B{}^2(I)] + \left(\frac{\partial R}{\partial U}\right)^2 [u_A{}^2(V) + u_B{}^2(V)] \tag{2}$$

where: k_p - the coverage factor (k_p=2), $u_C(R)$ - the combined standard uncertainty of R, $u_A(\cdot)$ - the Type A standard uncertainty, $u_B(\cdot)$ - the Type B standard uncertainty.

The constant value of electric current I=0.020 A was assumed. A DC power supply AX-3003D-3 Agilent E3644A with a resolution of r_1=0.001 A was used as an ammeter. Therefore $u_A(I)$=0 A, and $u_B(I) = \frac{r_1}{\sqrt{3}} = 5.8 \cdot 10^{-4}$ A. A multimeter Agilent 34410A with a resolution of r_2=0.001 mV was used as a voltmeter. Therefore $u_B(V) = \frac{r_2}{\sqrt{3}} = 5.8 \cdot 10^{-7}$ V. Measurements of the voltage drop V were repeated n=6 times, and the mean value $\bar{V}$ was calculated, and the Type A standard uncertainty was determined from the formula:

$$u_A(V) = \sqrt{\frac{\sum_{i=1}^{6}(V_i - \bar{V})^2}{n(n-1)}} \tag{3}$$

The relative expanded uncertainty was calculated using the formula:

$$U_{rel} = \frac{U}{R} 100\% \tag{4}$$

Static sensor characteristics were used for the assessment of electroconductive fabrics as sensory fabrics:

- input range is the maximum and minimum value of the physical variable that can be measured; damage diameter ϕ_{min} and ϕ_{max},

- operating range defines the minimum and maximum values of the measured quantity within which the sensor can provide accurate and reliable measurements; electrical resistance range $[R_{h\min}, R_{h\max}]$ and $[R_{v\min}, R_{v\max}]$,
- sensitivity is a measure of how well a sensor responds to changes in the measured quantity; it indicates the smallest detectable change in the input that the sensor can reliably measure; sensitivity factor $|dR_h/dA|$ and $|dR_v/dA|$, where A is fabric surface area.

3. Results and discussion

The voltage drop for the woven fabrics was measured according to the measuring scheme (Fig. 4). An uncertainty analysis was conducted for all undamaged and damaged samples. The expanded uncertainty *(1)* and relative expanded uncertainty *(4)* of the horizontal and vertical resistances were determined. Received results are juxtaposed in Tab. 2-5.

Tab. 2. Measurement uncertainty results for fabric S1.

Quantity	A0	A8	A10	A12	A14	A16	A18
$R_{h,}$ [Ω]	0.1359	0.1284	0.1456	0.1636	0.1713	0.1673	0.2033
U, [Ω]	0.0083	0.0110	0.0086	0.0112	0.0102	0.0101	0.0136
$U_{rel,}$ [%]	6	9	6	7	6	6	7
$R_{v,}$ [Ω]	0.0173	0.0181	0.0216	0.0236	0.0268	0.0322	0.0336
U, [Ω]	0.0019	0.0015	0.0021	0.0060	0.0027	0.0054	0.0044
$U_{rel,}$ [%]	11	8	10	25	10	17	13

Tab. 3. Measurement uncertainty results for fabric S2.

Quantity	A0	A8	A10	A12	A14	A16	A18
R_h ,[Ω]	0.0844	0.1015	0.0867	0.1031	0.1052	0.1167	0.1441
U, [Ω]	0.0097	0.0063	0.0091	0.0080	0.0072	0.0075	0.0089
$U_{rel,}$ [%]	11	6	10	8	7	6	6
$R_{v,}$ [Ω]	0.0339	0.0361	0.0468	0.0454	0.0462	0.0604	0.0571
U, [Ω]	0.0046	0.0028	0.0040	0.0055	0.0032	0.0039	0.0040
$U_{rel,}$ [%]	14	8	9	12	7	6	7

Tab. 4. Measurement uncertainty results for fabric S3.

Quantity	A0	A8	A10	A12	A14	A16	A18
$R_{h,,}$ [Ω]	0.0153	0.0183	0.0180	0.0204	0.0214	0.0243	0.0228
U, [Ω]	0.0028	0.0020	0.0031	0.0039	0.0022	0.0040	0.0041
$U_{rel,}$ [%]	18	11	17	19	10	16	18
$R_{v,}$ [Ω]	0.0095	0.0119	0.0126	0.0129	0.0132	0.0147	0.0154
U, [Ω]	0.0010	0.0020	0.0020	0.0014	0.0020	0.0023	0.0020
$U_{rel,}$ [%]	11	17	16	11	15	16	13

Tab. 5. Measurement uncertainty results for fabric S4.

Quantity	A0	A8	A10	A12	A14	A16	A18
$R_{h,}$ [Ω]	0.0083	0.0104	0.0099	0.0118	0.0126	0.0127	0.0139
U, [Ω]	0.0018	0.0016	0.0014	0.0016	0.0010	0.0020	0.0015
$U_{rel,}$ [%]	22	15	14	14	8	16	11
$R_{v,}$ [Ω]	0.0033	0.0043	0.0040	0.0043	0.0053	0.0055	0.0058
U, [Ω]	0.0006	0.0005	0.0006	0.0004	0.0005	0.0014	0.0007
$U_{rel,}$ [%]	18	12	15	9	9	25	12

Planar anisotropy of electroconductive woven fabrics is observed when the value of electrical resistance depends on the sample's orientation on a plane. Differences between mean values of vertical and horizontal resistances measured for seven variants (Tab. 2-5) of each fabric were assessed. The Mann-Whitney U-Test was used [43]. The test was performed using Statistica®, and the p-value (p) was calculated. The p-value is compared with the critical value α for rejecting the null hypothesis. If $\alpha<p$, the null hypothesis must not be rejected. The critical value of α=0.05, being a significance level, was assumed. Results of the Mann-Whitney U-Test obtained for fabrics S1, S2, S3, and S4 are given in Fig. 5.

Based on the statistical analysis, it was found a significant difference between horizontal and vertical resistances at 0.05 significance level for all tested samples ($\alpha>p$). Moreover, it can be concluded that electroconductive fabrics are characterized by planar electrical anisotropy.

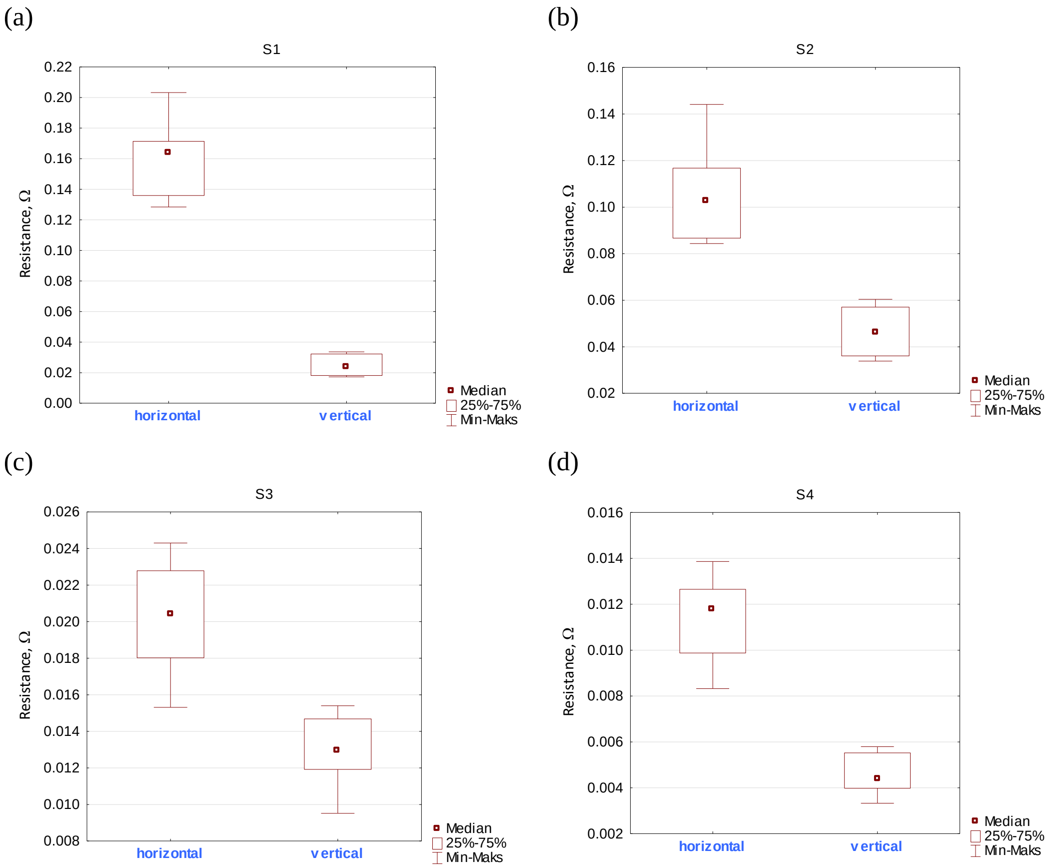

Fig. 5. Mann-Whitney U-Test: a) p=0.003, b) p=0.002, c) p=0.002, d) p=0.002.

The impact of fabric damage on electrical resistance was investigated. The initial fabric surface area was equal to 25 cm^2. Every damage caused a decrease in the area of a sample as presented in Tab. 6.

Tab. 6. The surface area of undamaged and damaged samples.

Variant	**A0**	**A8**	**A10**	**A12**	**A14**	**A16**	**A18**
Damage diameter ϕ, [mm]	0	8	10	12	14	16	18
Surface area A, [cm^2]	25.0	24.5	24.2	23.9	23.5	23.0	22.5

The dependence of the sample resistance on its surface, and thus the degree of fabric damage, is shown in Fig. 6 for fabrics S1, S2, S3, and S4.

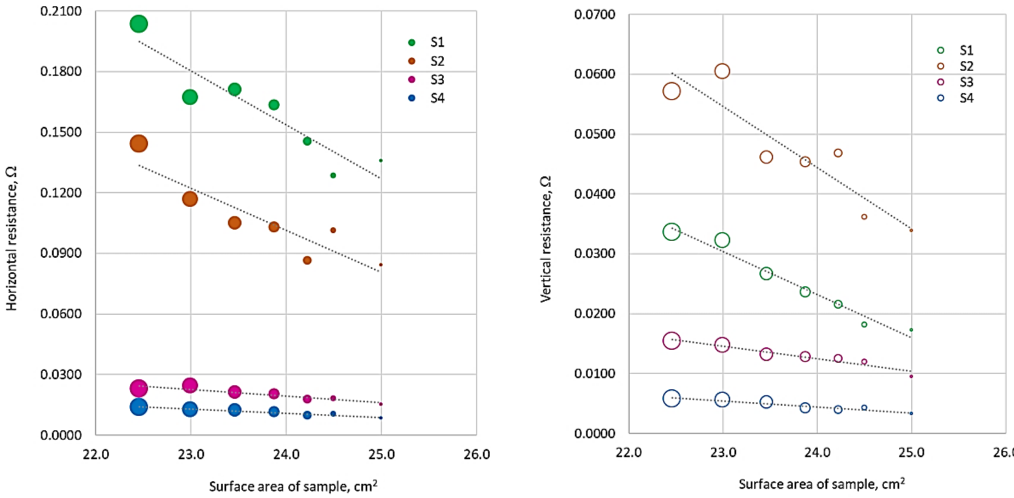

Fig. 6. Surface area of sample vs. electrical resistance (horizontal and vertical).

As the area of damage in the fabric increased, the increase in the electrical resistance exhibited by the sample was observed. This indicates a direct relationship between the size of the damage and the electrical properties of the fabric. Based on the results presented in Fig. 6, it was assumed that the dependence of the electrical resistance *R* (horizontal or vertical) on the surface area A can be described by a linear model $R(A)=aA+b$, where a, b are the model parameters. Statistical tests were used to assess the significance of the model parameters (Student's t-Test) and the model adequacy (Fisher F-Test). A significance level of α=0.05 was assumed. Results of statistical analysis for models $R_h=f(A)$ and $R_v=f(A)$ are presented in Tab. 7 and 8, respectively. A coefficient of determination (R^2) is given additionally.

Tab. 7. Statistical analysis of model R_h=f(A).

Fabric	**Significance of model parameters,**				**Adequacy of model,**	
	a [Ω/cm^2]	**p-value**	***b*** [Ω]	**p-value**	R^2	**p-value**
S1	-0.026741	0.002417	0.795437	0.000883	0.8645	0.000000
S2	-0.020779	0.004626	0.600213	0.001990	0.8254	0.000002
S3	-0.003273	0.002039	0.097955	0.000719	0.8732	0.000000
S4	-0.002082	0.000564	0.060881	0.000213	0.9235	0.000000

Tab. 8. Statistical analysis of model R_v=f(A).

Fabric	Significance of model parameters,				Adequacy of model,	
	a [Ω/cm^2]	p-value	b [Ω]	p-value	R^2	p-value
S1	-0.007193	0.000060	0.195853	0.000031	0.9685	0.000000
S2	-0.010200	0.003375	0.289189	0.001556	0.8456	0.000002
S3	-0.002093	0.000503	0.062666	0.000169	0.9269	0.000000
S4	-0.000981	0.000541	0.027971	0.000230	0.9248	0.000000

It was found that the model parameters are significant, and the models are adequate at the significance level of α=0.05. Fabric-based sensors are linear sensors. They produce an output proportional to the input quantity. The input range being the range of damaged surface area [0.5,2.5] cm^2 is assumed for all sensory fabrics. It means that the minimum damage diameter equals ϕ_{min}=8 mm. Chosen sensor parameters were determined based on obtained linear characteristics (Tab. 9).

Tab. 9. Fabrics-based sensor static characteristics.

Fabric	Operating range [Ω]		Sensitivity factor [Ω/cm^2]	
	[$R_{h\min}$,$R_{h\max}$]	[$R_{v\min}$,$R_{v\max}$]	$\lvert dR_h/dA \rvert$	$\lvert dR_v/dA \rvert$
S1	[0.127,0.195]	[0.016,0.034]	0.027	0.007
S2	[0.081,0.134]	[0.034,0.060]	0.021	0.010
S3	[0.016,0.024]	[0.010,0.016]	0.003	0.002
S4	[0.009,0.014]	[0.003,0.006]	0.002	0.001

Statistical analysis allows us to conclude that there are significant differences between horizontal and vertical resistances for all electroconductive woven fabrics. The horizontal resistance is higher than the vertical one, so that is why the horizontal resistance should be measured in the system for damage detection. The sensitivity factors are also higher in this case. From the point of view of the sensory, fabrics S1 and S2 have an advantage over others (S3, and S4). The highest values of sensitivity factors are observed for S1 and S2 fabrics. The operating range is also the widest.

4. Conclusions

Fabric-based sensors can be used as a protective layer of objects and, due to their ability to generate an electric signal, can directly monitor changes in electrical resistance. It was found that the electrical resistance increases with increased mechanical damage to the fabric surface; the dependence is linear for all fabrics. As the resistance increases, the fabric loses its protective properties, which may damage the object. The minimum area of damage that can be detected using the fabric-based sensors is 0.5 cm^2, while the maximum is 2.5 cm^2. The permissible area of fabric damage should be determined individually depending on the protecting object. The attention was drawn to the fact that fabrics exhibit an electrical in-plane anisotropy. Significant differences exist between horizontal and vertical resistances for all electroconductive woven fabrics. From the sensory point of view, fabrics S1 and S2 are the best due to their highest values of sensitivity factors and widest operating ranges.

References

[1] Choudhry N.A., Arnold L., Rasheed A., Khan I.A., Wang L.: *Textronics - A review of textile-based wearable electronics*, Advanced Engineering Materials, 23(12), 2023, pp. 1-19.

[2] Simegnaw A.A., Malengier B., Rotich G., Tadesse M.G., Van Langenhove L.: *Review on the integration of microelectronics for E-Textile*, Materials, 14(17), 2021, pp. 1-27.

[3] Biermaier C., Bechtold T., Pham T.: *Towards the functional ageing of electrically conductive and sensing textiles: A review*, Sensors, 21(17), 2021, pp. 1-32.

[4] Chatterjee K., Tabor J., Ghosh T.K.: *Electrically conductive coatings for fiber-based e-textiles*, Fibers, 7(6), 2019, pp. 1-46.

[5] Gaubert V., Boddaert X., Djenizian T., Delattre R.: *Textile electronic circuits from laser-patterned conductive fabric*, Advanced Engineering Materials 25(9), 2023, pp. 1-9.

[6] Du K., Lin R., Yin L., Ho J.S., Wang J., Lim C.T: *Electronic textiles for energy, sensing, and communication*, iScience, 25(5), 2022, pp. 1-24.

[7] Horrocks A.R., Anand S.C. (red.) *Handbook of technical textiles, 2nd edition, Vol. 2: Technical textile applications*, Elsevier 2016.

[8] Leśnikowski J.: *Research into the textile-based signal lines made using ultrasonic welding technology,* Autex Research Journal, 22(1), 2022, pp.11-17.

[9] Krzemińska S., Greszta A., Bartkowiak G., Dąbrowska A., Kotas R., Pękosławski B., Małachowski B., Miśkiewicz P.: *Evaluation of heating inserts in active protective clothing for mountain rescuers - preliminary tests*, Applied Sciences, 13(8), 2023, pp. 1-19.

[10] Kubiak P., Leśnikowski J., Gniotek K.: *Textile sweat sensor for underwear convenience measurement*, Fibres and Textiles in Eastern Europe, 24(6), 2016, pp. 151-155.

[10] Lam E., Alizadeh-Meghrazi M., Schlums A., Eskandarian L., Mahnam A., Moineau B., Popovic M.R.: *Exploring textile-based electrode materials for electromyography smart garments*, Journal of Rehabilitation and Assistive Technologies, 9, 2022, pp. 1-18.

[11] Leśnikowski J.: *Research on poppers used as electrical connectors in high speed textile transmission lines*, Autex Research Journal, 16(4), 2016, pp. 228-235.

[12] Husain M.D., Kennon R., Dias T.: *Design and fabrication of Temperature Sensing Fabric*, Journal of Industrial Textiles, 44(3), 2014, pp. 398-417.

[13] Shabani A., Hylli M., Kazani I.: *Investigating properties of electrically conductive textiles: A review,* Tekstilec, 65(3), 2022, pp. 194-217.

[14] Pizarro F., Villavicencio P., Yunge D., Rodríguez M., Hermosilla G., Leiva A.: *Easy-to-build textile pressure sensor,* Sensors, 18(4), 2018, pp.1-13.

[15] Cho S., Chang T., Yu T., Lee C.H.: *Smart electronic textiles for wearable sensing and display*, Biosensors, 12(4), 2022, pp. 1-30.

[16] Zhou Z., Chen N., Zhong H., Zhang W., Zhang Y., Yin X., He B.: *Textile-based mechanical sensors: A review*, Materials, 14(20), 2021, pp. 1-22.

[17] Capineri L.: *Resistive sensors with smart textiles for wearable technology: from fabrication processes to integration with electronics*, Procedia Engineering, 87, 2014, pp. 724-727.

[18] Alsaadi A., Meredith J., Swait T., Curiel-Sosa J.L., Hayes S.: *Damage detection and location in woven fabric CFRP laminate panels*, Composite Structures, 220, 2019, pp. 168-178.

[19] Hou L., Hayes S.A.: *A resistance-based damage location sensor for carbon-fibre composites*, Smart Materials and Structures, 11(6), 2002, pp. 966-969.

[20] Ojstršek A., Plohl O., Gorgieva S., Kurecic M., Jancic U., Hribernik S., Fakin D.: *Metallisation of textiles and protection of conductive layers: An overview of application techniques*, Sensors, 21(10), 2021, pp. 1-28.

[21] Castano L.M., Flatau A.B.: *Smart fabric sensors and e-textile technologies: a review*, Smart Materials and Structures, 23(5), 2014, pp. 1-27.

[22] Zeng W., Shu L., Li Q., Chen S., Wang F., Tao X.-M.: *Fiber-based wearable electronics: A review of materials, fabrication, devices, and applications*, Advanced Materials, 26(31), 2014, pp. 5310-5336.

[23] Guo R.H., Jiang S.X., Yuen C.W.M., Ng M.C.F., Lan J.W.: *Metallized textile design through electroless plating and tie-dyeing technique*, Journal of The Textile Institute, 104(10), 2013, pp. 1049-1055.

[24] Bierwagen O., Ive T., Van de Walle Ch.G., Speck J.S.: *Causes of incorrect carrier-type identification in van der Pauw-Hall measurements*, Applied Physics Letters, 93, 2008, pp. 1-4.

[25] Pawłowski S., Plewako J., Korzeniewska E.: *Influence of structural defects on the resistivity and current flow field in conductive thin layers*, Electronics, 9(12), 2020, pp. 1-12.

[26] Smits F.M., *Measurement of sheet resistivity with the four-point probe*, The Bell System Technical Journal, 37(3), 1958, pp. 711-718.

[27] uz Zaman S., Tao X., Cochrane C., Koncar V.: *Understanding the washing damage to textile ECG dry skin electrodes, embroidered and fabric-based; set up of equivalent laboratory tests*, Sensors, 20(5), 2020, pp. 1-16.

[28] Chen H.H.: *Damage detection of carbon fiber reinforced polymer using electrical measurement and analysis of acoustic emission signals*, Doctoral dissertation, University of Akron 2013.

[29] Liepa V., Santosa F., Vogelius M.: *Crack determination from boundary measurements reconstruction using experimental data*, Journal of Nondestructive Evaluation, 12(3), 1993, pp. 163-174.

[30] Schueler R., Joshi S.P., Schulte K.: *Damage detection in CFRP by electrical conductivity mapping*, Composites Science and Technology, 61(6), 2021, pp. 921-930.

[31] Tokarska M., Miśkiewicz P., Pawlak W.: *Research on the planar electrical anisotropy of conductive woven fabrics*, Advanced Engineering Materials, 25(13), 2023, pp. 1-10.

[32] Kazani I., De Mey G., Hertleer C., Banaszczyk J., Schwarz A., Guxho G., Van Langenhove L.: *Van der Pauw method for measuring resistivities of anisotropic layers printed on textile substrates*, Textile Research Journal, 81(20), 2011, pp. 2117-2124.

[33] Tyurin I.N., Getmantseva V.V., Andreeva E.G.: *Van der Pauw method for measuring the electrical conductivity of smart textiles*, Fibre Chemistry, 51(2), 2019, 139-146.

[34] Tokarska M., Gniotek K.: *Anisotropy of the electrical properties of flat textiles*, The Journal of The Textile Institute, 106(1), 2015, pp. 9-18.

[35] Kazakov F., Sattarova N., Aripova O.: *Metallized fabrics for environmentally safe applications in textile industry and filter production*, IOP Conf. Series: Earth and Environmental Science, 1112, 2022, pp. 1-7.

[36] Ojstršek A., Jug L., Plohl O.: A review of electro conductive textiles utilizing the dip-coating technique: their functionality, durability and sustainability, Polymers, 14(21), 2022, pp. 1-26.

[37] Lu X., Shang W., Chen G., Wang H., Tan P., Deng X., Song H., Xu Z., Huang J., Zhou X.: *Environmentally stable, highly conductive, and mechanically robust metallized textiles*, ACS Applied Electronic Materials, 3(3), 2021, pp. 1477-1488.

[38] Tomilina O.A., Berzhansky V.N., Tomilin S.V.: *The influence of the percolation transition on the electric conductive and optical properties of ultrathin metallic films*, Physics of the Solid State, 62, 2020, pp. 700-707.

[39] Van der Pauw L.J.: *A method of measuring specific resistivity and Hall effect of discs of arbitrary shape*, Philips Research Reports, 13(1), 1958, pp. 1-9.

[40] Kazani I., De Mey G., Hertleer C., Banaszczyk J., Schwarz A., Guxho G., Van Langenhove L.: *About the collinear four-probe techniques inability to measure the resistivity of anisotropic electroconductive fabrics*, Textile Research Journal, 83(15), 2013, pp. 1587-1593.

[41] ISO/IEC Guide 98-3:2008(En). Uncertainty of Measurement-Part 3: Guide to the Expression of Uncertainty in Measurement.

[42] Corder G.W., Foreman D.I.: *Nonparametric statistics for non-statisticians: A step-by-step approach*, Wiley, Hoboken 2009.