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# Measuring resistance of textile materials based on Van der Pauw method

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A new approach has been made to determine electro-conductive properties of a textile product on the basis of the idea of Van der Pauw method. This method is used to determine only two characteristic resistances associated with four electrodes. Surface resistivity of the sample is not determined because this technique requires some special conditions. The influence of the contact diameter of electrodes as well as the electrodes arrangement on the resistance value of textile sample has been studied. The results show that in case of selected range of the electrodes diameters, the contact diameters do not affect resistance when constant force is applied. However, the impact of electrodes arrangement on the resistance measurements is found to be noticeable. Anisotropy of electrical properties of the textile sample is also studied.

**Keywords**: Anisotropy, Electro-conductive textile, Resistance measurement, Surface resistivity, Van der Pauw method

Measuring electrical resistivity has acquired particular importance because of the increasing number of potential applications of electro-conductive textiles. They can be used as textile sensors[1], conductive paths[2], transmission lines[3], systems monitoring selected physiological parameters[4] or electrodes for electrotherapy[5]. The simplest method of measuring resistivity of an electro-conductive material is a two-point probe technique[6]. In this method however some resistance can be usually observed between the contact wires and the sample, or in the measuring equipment itself. Another problem is that the contacts between the electrodes and the sample tend to have different electrical properties than the sample itself, which distorts the estimates of the actual sample resistivity. The four-point probe technique overcomes these problems[6].

The four-point probe method was developed by Wenner[7] to measure the resistivity of the earth. This method assumes homogenous and isotropic rectangular bar samples. The accuracy of these bar samples may be a problem in this method. The method can be used to determine resistivity of thin films or sheets of various electro-conductive materials. The resistivity of a thin film of material is measured by four collinear metal electrodes equidistant from one another, which are pressed against the surface of the film[6].

Another way of determining electric resistivity is Van der Pauw method[8]. This method avoids the classical geometry of the samples in the form of a bar. The method was developed for homogenous, isotropic, flat and arbitrarily-shaped samples without holes or non-conducting islands. The samples should be characterized by uniform thickness. All four Ohmic contacts must be placed at the circumference of the sample. The contacts should be sufficiently small. The area of a single contact should be at least an order of magnitude smaller than the area of the whole sample[6]. Electrical resistivity of a flat sample is independent of the current flow pattern inside this sample. Currently, this method is used by many researchers for isotropic and anisotropic samples[9-13]. It was applied to determine resistivity of polypyrrole-coated para-aramide woven fabrics[14] or anisotropic electro-conductive layers printed on textile substrates[15].

It was found out that Van der Pauw method is more accurate for determining samples resistivity and especially resistance. The method precisely specifies the arrangement of the electrodes on the sample. This arrangement identifies the size of the sample surface for which surface resistivity is determined.

The aim of the present study was to carry out resistance measurements of a flat fabric sample on the basis of the idea of Van der Pauw method. Van der Pauw method was only used to determine two characteristic resistances associated with four electrodes. Surface resistivity of the sample was not determined because the technique requires some special conditions to be satisfied.

Based on the received results the influence of the contact diameters of the electrodes on the resistance value was investigated. The influence of the electrodes arrangement on the sample on the resistance value was analyzed as well.

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Fabric sample having the structure similar to that used by Van der Pauw as far as possible was selected. An electro-conductive Shieldex® fabric (produced by Statex®) was used[16]. It is a plated nylon woven fabric of rip-stop weave (three metalized layers: Sn, Cu, Ag). The fabric can be used for fabric-over-goam gaskets, EMI/RFI cable shieldings, base material for EMI/RF garments or wall covering for RF shielding. The parameters of the fabric are given in Table 1. Analysis for the measurement inaccuracy of the fabric parameters was also carried out.[17] Relative expanded uncertainty of each parameter was determined. The analysis was carried out at expansion coefficient $k_p$=2, corresponding to a confidence level of 0.95.

After the analysis of the fabric structure it was found that the thickness of the sample is in the range from 0.11 mm to 0.13 mm. In case of textiles this value is quite satisfactory and the sample can be considered as flat. The sample possesses twisted pores inside its structure, which in this case do not form isolated holes. Fabric sample of seventy square millimeters was prepared to make the sample as homogeneous as possible.

According to the idea of Van der Pauw method, only two characteristic resistances associated with four electrodes- vertical and horizontal resistance were determined. Four packages containing four cylindrical brass electrodes were used for this purpose. The diameters of the electrode contact areas were $\phi$1=2 mm, $\phi$2=4 mm, $\phi$3=6 mm and $\phi$4=8 mm in each package.

The mass of a single electrode was 24 g, which means that the electrode force affecting the sample was constant and amounted to 0.24 N. Pressures exerted by the electrode on the sample were 74 kPa ($\phi$1=2 mm), 18 kPa ($\phi$2=4 mm), 8 kPa ($\phi$3=6 mm) and 5 kPa ($\phi$4=8 mm).

The contact areas of electrodes were coated with silver in order to ensure good electro-conductive properties. Low values of contact resistance are important to prevent heating of the contact by the flowing current.

Table 1—Parameters of the conductive fabric

| | |
|---|---|
| Thickness | 0.12 (1 ± 8%), mm |
| Aerial density | 80 (1 ± 3%), g/m$^2$ |
| Apparent density | 656 (1 ± 10%), kg/m$^3$ |
| Linear density of warp | 7.7 (1 ± 1%), tex |
| Linear density of weft | 10.1 (1 ± 1%), tex |
| Number of warp threads | 47 (1 ± 2%) per 1cm |
| Number of weft threads | 44 (1 ± 2%) per 1cm |

The sample was connected to an electrical system through four electrodes attached at four corners. In the presented works three variants of electrodes arrangements on the sample surface were tested (Fig. 1). In Variant I the distance between the electrodes, measured between the center of the contact areas, was $L$=60 mm. In Variant II the distance was $M$=40 mm. In Variant III it was $S$=20 mm.

The resistances were measured as indicated in Fig. 2. Two adjacent electrodes were powered by a precision current source. DC power supply agilent E3644A (range 0-8 V and 8 A) was used as ammeter. Between the two electrodes on the opposite side of the sample voltage drop was measured. Multimeter agilent 34410A (6½ digit, range 100 mV) was used as voltmeter. Figure 2 shows, in particular, the case in which Variant I and electrodes with diameter of 8 mm were chosen.

In the first case (Fig. 2a), two sample resistances $R_v^{(1)}$ and $R_v^{(2)}$, called vertical resistances, were measured. The vertical resistances are expressed as follow:

$$R_v^{(1)} = \frac{U_{1-2}}{I_{3-4}} \text{ and } R_v^{(2)} = \frac{U_{3-4}}{I_{1-2}} \quad \ldots (1)$$

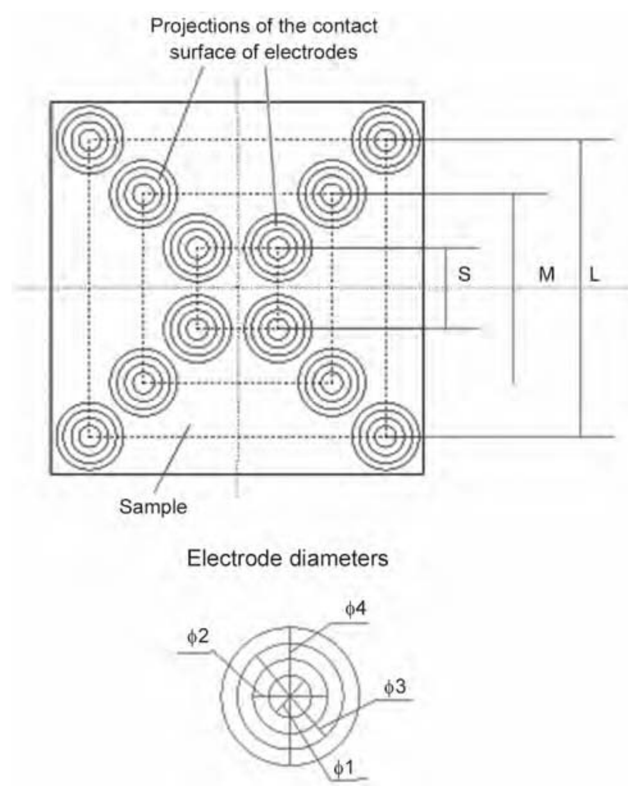


Fig. 1—Arrangement of electrodes with different diameters on the sample surface

where $I_{3\text{-}4}$ and $I_{1\text{-}2}$ represent respectively the current applied between the electrodes 3-4 and 1-2; and $U_{1\text{-}2}$ and $U_{3\text{-}4}$ stand for the voltage drop between these respective electrodes. In the second case (Fig. 2b), two sample resistances $R_h^{(1)}$ and $R_h^{(2)}$, called horizontal resistances, were measured. The horizontal resistances are expressed as follow:

$$R_h^{(1)} = \frac{U_{1-4}}{I_{2-3}} \text{ and } R_h^{(2)} = \frac{U_{2-3}}{I_{1-4}} \quad \ldots (2)$$

where $I_{2\text{-}3}$ and $I_{1\text{-}4}$ represent respectively the current applied between the electrodes 2-3 and 1-4; and $U_{1\text{-}4}$ and $U_{2\text{-}3}$ stand for the voltage drop between these electrodes. On the basis of the measurements results, average resistance values $R_v$ and $R_h$ were obtained.

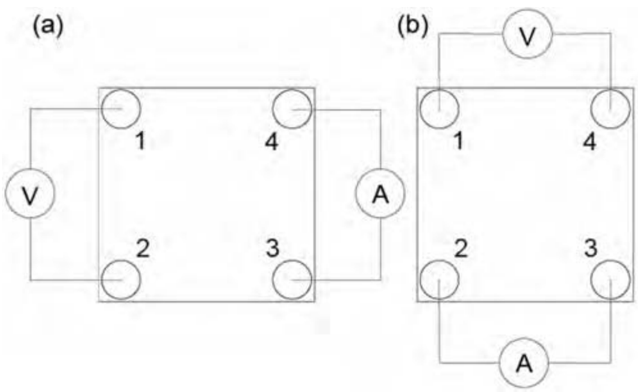


Fig. 2—Measurement of the sample resistance in Van der Pauw geometry (A– ammeter, V– voltmeter) [a– vertical resistance measurement, and b– horizontal resistance measurement]

Resistance measurements were carried out at ambient conditions such as temperature 24.0°C and relative humidity 35%. The fabric sample was acclimatized under the same conditions. Current flow (0.5 A) was forced between two electrodes. Voltage drop between the other two electrodes was read after 30 s. The measurements were repeated three times. The average values of horizontal and vertical resistances of the electro-conductive fabric and uncertainty budget are shown in Table 2.

Table 2 presents a selected part of the uncertainty budget of determination of the average values of vertical and horizontal resistance, assuming the significance level at 0.05. Standard uncertainty of quantities $R_v^{(1)}$, $R_v^{(2)}$ [Eq.(1)] and $R_h^{(1)}$, $R_h^{(2)}$ [Eq.(2)] were calculated using the law of uncertainty propagation[17]. Type B evaluation of standard uncertainties was carried out assuming uniform distribution.

The obtained resistance values confirm good electro-conductive properties of the sample. Vertical resistance is in the range from 0.99 Ω to 1.25 Ω. Horizontal resistance is in the range from 2.22 Ω to 4.35 Ω. Relative expanded uncertainty of vertical and horizontal resistances does not exceed 17%. Relatively high values of uncertainty are due to the rheological properties of the fibre sample.

Table 2—Selected part of uncertainty budget for vertical and horizontal resistance

| Case | Estimate of output quantity value, Ω | | Expanded uncertainty of output quantity, Ω | | Relative expanded uncertainty of output quantity, % | |
|---|---|---|---|---|---|---|
| | $R_v$ | $R_h$ | $R_v$ | $R_h$ | $R_v$ | $R_h$ |
| **ϕ1** | | | | | | |
| Variant I | 1.12 | 4.32 | 0.18 | 0.71 | 16 | 16 |
| Variant II | 1.23 | 3.62 | 0.20 | 0.59 | 16 | 16 |
| Variant III | 1.12 | 2.22 | 0.18 | 0.36 | 16 | 16 |
| **ϕ2** | | | | | | |
| Variant I | 1.13 | 4.30 | 0.18 | 0.70 | 16 | 16 |
| Variant II | 1.25 | 3.62 | 0.20 | 0.59 | 16 | 16 |
| Variant III | 1.08 | 2.34 | 0.18 | 0.38 | 17 | 16 |
| **ϕ3** | | | | | | |
| Variant I | 1.12 | 4.35 | 0.18 | 0.71 | 16 | 16 |
| Variant II | 1.23 | 3.71 | 0.20 | 0.61 | 16 | 16 |
| Variant III | 1.19 | 2.22 | 0.20 | 0.38 | 17 | 17 |
| **ϕ4** | | | | | | |
| Variant I | 1.12 | 4.32 | 0.18 | 0.71 | 16 | 16 |
| Variant II | 1.22 | 3.64 | 0.20 | 0.60 | 16 | 17 |
| Variant III | 0.99 | 2.24 | 0.16 | 0.37 | 16 | 17 |

This kind of structure is constantly changing under the influence of environmental conditions and the tests conducted.

The study shows a difference between vertical and horizontal resistances of a woven fabric. This is especially evident in case of Variant I and demonstrates the anisotropy of electrical properties of the sample.

The results show that in case of the selected range of diameters of the electrode contacts, the contact diameters do not influence resistance measurements when constant force is applied, which is confirmed by Kruskal-Wallis test (significance level of 0.05). It means that the electrodes have good contact with the sample surface, regardless of the contact area. The contact resistance is small and insignificant. According to recommendations[6] the area of a single contact should be at least an order of magnitude smaller than the area of the whole sample. The area of the whole sample is 7854 $mm^2$ and the largest area of a single electrode ($\phi$4=8 mm) is 50 $mm^2$. Therefore, all the electrodes used met the condition mentioned above. Electrodes of different diameters can be used depending on the textile substrate to ensure good contact with the sample.

Generally, the impact of the contact area should be taken into account. The larger the contact area, the larger part of its resistance influences the resistance of the object. During the Kruskal-Wallis test, conducted at significance level of 0.05, it is noticed that the electrodes arrangement on the textile sample influences resistance measurements in case of horizontal and vertical resistance. Horizontal resistance decreases with increasing distance from the electrodes to the edge of the sample, in case of all diameters. The larger the measurement surface, the more contact points, lines and yarn areas influencing the object resistance. In case of vertical resistance such dependence is not observed.

The new approach, based on the idea of Van der Pauw method, has been successfully used to determine two characteristic resistances associated with four electrodes. Differences are observed between vertical and horizontal resistances of a woven fabric. It confirms anisotropy of the electrical properties of the sample.

The measurement results show that the contact diameters of the electrodes do not affect resistance measurements when constant force is applied. It means that the electrodes have a good contact with the surface of the sample, regardless of their contact area. However, it is found that the arrangement of the electrodes on the sample surface influences resistance value.

Van der Pauw method is developed for homogeneous, isotropic and uniform samples without isolated holes. It is difficult to fulfill these conditions, especially in case of textile materials. Therefore this method requires modification.

The modified Van der Pauw method is found to be useful especially because of a well-defined arrangement of the electrodes. This arrangement also defines the size of the measured sample surface for which surface resistivity is determined. The method is suitable for assessing electrical properties of textiles characterized by good conductivity.

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