FACULTY OF TEXTILE ENGINEERING TUL

KNITTED CONDUCTIVE FABRICS WITH ENHANCED ELECTROMAGNETIC INTERFERENCE SHIELDING

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SUMMARY OF THE THESIS

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ABSTRACT

The work deals with the development of electrically conductive knitted fabrics and their deformation characteristics. This work is divided into two basic parts: a part of the analysis of electrically conductive yarn and a part of the production and analysis of electrically conductive knitted fabrics. In the yarn analysis part, a conductive commercially available silver-plated polyamide yarn (Statex Inc., Bremen) with a fineness of 60 tex containing 36 filaments with a specific electrical resistance of 68±14 Ω/m and a tensile strength of 47 cN/tex was used. To simulate the electrical resistance of the yarn related with its length and to simulate the effect of contact resistance, three different yarn configurations (single yarn (SY), single loop yarn (SLY) and multiloop yarn (MLY)) were used. Electrical resistance was tested for all yarn arrangements. The tensile strength of the yarn arrangements was analyzed by tensile stress at a strain rate of 50 mm/min. Multiloop yarn has been found to have higher strength than other forms of yarn. Changes in electrical resistance during tensile stress were evaluated using Arduino resistance circuit probes that were connected to the jaws of the tensile strength tester and real-time values were recorded using a MATLAB programming language program. It was confirmed that the electrical resistance decreases as the number of loops increases.

In the subsequent part of the work, two patterns of knitwear were produced on a flat knitting machine, a plain "single jersey" and a 1x1 ribbed "double jersey". Three different densities were produced in each design: low, medium and high. The effectiveness of the electromagnetic shielding (SE) of knitted fabrics was tested using a frequency range of 30 MHz to 1.5 GHz according to the ASTM D4935-18 standard. It was found that the higher the sample density, the higher the SE. The double jersey had a higher SE than the single jersey and the difference was around 15 dB at 1.5 GHz frequency. The thickness of the knitted fabric and the porosity have decreased due to the increase in stitch density.

A special device with four independent jaws was used for tensile deformation of knitted samples in one direction (transverse and longitudinal) and in two directions (biaxial). The knitted fabrics were stretched up to 25% strain and electromagnetic shielding, electrical resistance and porosity were measured.

"Single Jersey" shielding efficiency has an increasing trend in all stretching directions. The effectiveness of the double Jersey shield has an increasing trend in vertical stretching, but horizontal and biaxial deformation initially reduces the shielding effectiveness. The porosity and electrical resistance results against stretching of the knitted fabric in all directions were also analyzed. The reason for changes in fabric behavior was analyzed using data from the electromechanical survey of simple yarn formations. A stochastic model based on multiple regression analysis and using partial regression graphs was proposed to predict the effectiveness of electromagnetic shielding of knitted fabrics based on knowledge of their electrical conductance/resistance and porosity.

Keywords: Wireless strain sensor, silver coated polyamide yarn, tensile strength, single loop yarn, multiloop yarn, single jersey, double jersey, flat knitting, electromagnetic shielding effectiveness, fabric porosity, electrical resistance, and biaxial elongation.

ABSTRAKT

Práce se zabývá vývojem elektricky vodivých pletenin a jejich deformační charakteristikou.

Tato práce je rozdělena na dvě základní části: část analýzy vodivé příze a část výroby a analýzy vodivých pletenin. V části analýzy příze byla použita vodivá komerčně dostupná postříbřená polyamidová příze (Statex Inc., Bremen) jemnosti 60 tex obsahujících 36 filamentů s měrným elektrickým odporem 68±14 Ω/m a pevností v tahu je 47 cN/tex. Pro simulaci elektrického odporu příze souvisejícího s její délkou a vlivu kontaktního odporu byla použita tři různá uspořádání příze (jednoduchá příze (SY), příze s jednou smyčkou (SLY) a příze s více smyčkami (MLY)). Pro všechna uspořádání přízí byl testován elektrický odpor. Pevnost v tahu přízových uspořádání byla analyzována tahovým namáháním při rychlosti deformace 50 mm/min. Bylo zjištěno, že příze s více smyčkami má vyšší pevnost než jiné formy příze. Změny elektrického odporu během tahového namáhání byly hodnoceny s využitím sond odporového obvodu Arduino, které byly spojeny s čelistmi trhacího přístroje a hodnoty v reálném čase byly zaznamenávány pomocí programovacího jazyka MATLAB. Bylo potvrzeno, že elektrický odpor klesá s růstem počtu smyček.

V navazující části práce byly na plochém pletacím stroji vyrobeny dva vzory pletenin, hladký „single Jersey“ a 1x1 žebrový „double Jersey“. V každém provedení byly vyrobeny tři různé hustoty: nízká, střední a vysoká. Byla testována účinnost elektromagnetického stínění (SE) pletenin od frekvence 30 MHz do 1.5 GHz podle normy ASTM D4935-18. Bylo zjištěno, že čím vyšší je hustota vzorku, tím vyšší je SE. Pletenina „double Jersey“ měla vyšší SE než pletenina „single Jersey“ a rozdíl byl kolem 15 dB při frekvenci 1,5 GHz. Tloušťka pleteniny a porozita se snížily díky zvýšení hustoty oček.

Pro tahovou deformaci pletenin v jednom směru (příčném i podélném) a ve dvou směrech (dvouosé) bylo použito speciální zařízení se čtyřmi nezávislými čelistmi. Pleteniny byly protaženy až do 25 % deformace a bylo měřeno elektromagnetické stínění, elektrický odpor a porozita.

Účinnost stínění „single Jersey“ má rostoucí trend ve všech směrech protažení. Účinnost stínění „double Jersey“ má rostoucí trend ve vertikálním i podélném protahování, ale biaxiální deformace zpočátku účinnost stínění snižuje. Rovněž byly analyzovány výsledky poréznosti a elektrického odporu proti napínání pleteniny ve všech směrech. Důvod změn v chování tkaniny byl analyzován pomocí dat z elektromechanického průzkumu jednoduchých přízových útvarů. Pro predikci účinnosti elektromagnetického stínění pletenin na základě znalosti jejich elektrické vodivosti/odporu a porozity byl navržen stochastický model na bázi vícenásobné regresní analýzy a s použitím parciálních regresních grafů.

Klíčová slova: Bezdrátový snímač deformace, stříbrem povrstvená polyamidová příze, pevnost v tahu, příze s jednou smyčkou, příze s více smyčkami, hladká pletenina, 1x1 žebrová pletenina, ploché pletací stroje, elektromagnetická stínící účinnost, porozita pleteniny, elektrický odpor, and dvouosé tahové namáhání.

SUMMARY

1 INTRODUCTION

Textile based materials and composites are generally suitable for EMI shielding applications. Traditional textile materials are electrically nonconductive, but the coating, deposition, and blending with conductive materials make them electrically conductive, which is suitable for EMI shielding applications. It is also possible to observe a change in electrical conductivity as well as a change in electromagnetic radiation during their mechanical stress, which is an interesting property for other purposes of use.

In the preliminary investigations, the nonconductive and conductive textile materials with different electrically conductive additives were analyzed for electromagnetic shielding effectiveness [1]. The effect of moisture content in the textile on its ability to shield electromagnetic fields was also investigated [2]. Further, the copper-coated nonwoven strips are modeled to study porosity and contact resistance on EMI shielding [3]. Since most of the findings are published in high-impact journals, the results of these studies are discussed in more detail in the literature review section of this thesis.

The main theme of the thesis is to study the deformation sensitivity of the weft-knitted fabrics made of silver-coated yarns. First, the electrical and mechanical properties of yarns were investigated, then the electromechanical properties of simple structural elements were explored, and then the change in electrical conductivity, electromagnetic shielding and other interesting characteristics during tensile stressing of two knitted fabrics were studied. A stochastic model is presented, which can be used to predict the level of the electromagnetic shielding ability of the knitted fabrics based on the knowledge of their electrical conductivity and the porosity.

2 PURPOSE AND AIM OF THE RESEARCH

The main objectives of the work are:

To study the contact force resistance of different arrangements of silver coated yarn simulating their interaction in knitted fabrics

From the previous investigation, it was noticed that the contact points at the electrically conductive yarn-yarn interface affect the electrical resistance and also affect the EM SE of the knitted fabrics made of electrically conductive yarns. That is why the effect of the yarn contact points was analyzed using the silver-coated yarn. In the knitted textile fabric, the yarn was interlaced with each other to form the fabric. The silver coated PA yarn is taken to prepare three basic structural elements simulating structural elements of knitted fabrics and they are: single strand, single loop, and multiple chain loops.

To design the special device measuring electrical resistance of linear structures during stretching

The tensile instrument with an Arduino resistance circuit, and the MATLAB software program were used for construction of system measuring the electrical resistance response during stretching. Electromechanical behavior of single yarn, single loop and multiple loop were beneficial in predicting the yarn behavior in knitted fabric during the stretching process and justified the fabric stretching results.

To prepare silver coated knitted fabrics suitable for deformation sensors design

The silver coated PA yarn was used to prepare single jersey and double jersey fabric samples at three different stitch densities. The prepared samples were introduced in a biaxial device (in-house model) for deformation at uni- and bi-directional stretching using controlled lengths.

To investigate the strain sensing ability of the weft-knitted samples against the EM waves and electrical conductivity

The aims are to investigate the change in electrical resistance with respect to the stretch direction of weft-knitted conductive samples made of silver coated yarns. The produced knitted structures are used to analyze its EM SE with respect to the direction of stretch applied to it.

3 OVERVIEW OF THE CURRENT STATE OF THE PROBLEM

Textile based materials and composites are generally suitable for EMI shielding applications. Traditional textile materials are electrically nonconductive, but the coating, deposition, and blending with conductive materials make them electrically conductive, which is suitable for EMI shielding applications. It is also possible to observe a change in electrical conductivity as well as a change in electromagnetic radiation during their mechanical stress, which is an interesting property for other purposes of use.

It is known from theory that the electrical resistance of a wire increases with the increasing distance of the probes in a relaxed state. The same phenomenon can be observed in textile structures containing a conductive component continuously throughout the length of the yarn. As per Ohm's law ($R=\rho L/A$), the resistance (R) is directly proportional to the yarn length (L) and indirectly proportional to the cross-section area of the yarn (A), and ρ is the resistivity [4].

The electrical properties of yarns were studied in several papers[5][6][7]. In paper [8], the antistatic yarn (containing bi-component fibres with carbon part) was studied, and a linear relationship between the electrical resistance and clamping length was confirmed. On the other hand, the nonlinear behavior of the electrical resistance on the clamping length was observed for yarns containing 20 % of stainless-steel fibres of staple length in their structure. Therefore, the method of conductive yarn production influences the length-resistance results. During extension, the length of the conductor (wire, single fibre, or single yarn) increases its diameter decreases and the resulting electric resistance increases.

Contact resistance is another interesting phenomenon that may affect the resulting electrical conductivity of the textile structure. The contact resistance is generated at yarn – the yarn interface. According to the contact resistance theory [9], contact resistance factors are material resistivity, material hardness, number of contact points, and contact pressure between yarns.

The stretching of the knitted fabric is influencing the structure of the knit. During wale way stretching, the expansion of wale at maximum and contraction of course, to a minimum was noticed. During the course-wise stretching, the course extension until maximum and wale contraction to a minimum was noticed. During biaxial stretching of the knitted fabric, both the course and wale were expanded and represented as course bias and wale bias. The yarn contact points are shifting, while a biaxial stretching of the fabric [10][11]. The 1x1 rib fabric is the highest elastic textile structure, easily stretching in uniaxial and biaxial directions. This structure has more easily stretched in the course-wise direction because of loosely constructed courses. In wale-wise stretching, the elongation occurs in the side limbs of the loop and contraction in the head and sinker loop, as noticed in this work [12]. In a study [13], the glass and polypropylene yarns were co-knitted with a 1x1 rib structure, and the fabric was stretched in uniaxial and biaxial directions to test its tensile, bending, and impact. The wale-wise stretching has more stress compared with the course-wise stretching. In bias (biaxial) stretching, the wale-wise exhibited more stress than the course-wise.

From the above, it can be assumed that the length-related resistance will increase with increasing uniaxial force, whereas the contact resistance will decrease with increasing contact points and contact force [4].

A survey of the electro-mechanical behavior of electro-conductive fabrics can be found in several professional publications. For example, in paper [8], three different forms of conductive yarn, single yarn, two overlapped yarn, and knit stitch yarn, were taken for study. Unidirectional tensile force is applied to those samples, and the electrical resistance reading is taken. It was observed that the single yarn and overlapped yarn have an increase in electrical resistance with increasing tensile, but the knit stitch yarn has a decrease in electrical resistance during increasing tensile. A study [14] noticed that the contact resistance in knit stitch form has decreased with an increase in unidirectional stretching. The conductive yarn in knit form has lesser resistance values than single-strand and overlapped yarn. In fabric form, the contact resistance affects the total resistances more than the length resistance.

In the preliminary investigations, the nonconductive and conductive textile materials with different electrically conductive additives were analyzed for electromagnetic shielding effectiveness [1]. The effect of moisture content in the textile on its ability to shield electromagnetic fields was also investigated [2]. Further, the copper-coated nonwoven strips are modeled to study porosity and contact resistance on EMI shielding [3]. Since most of the findings are published in high-impact journals, the results of these studies are discussed in more detail in the literature review section of the main thesis.

Commercial textile materials are mainly manufactured from cotton, polyester, viscose, linen, and wool. These materials are non-conductive materials but contain a certain percentage of moisture content. The EM shielding is mainly produced with highly conductive materials and semi-conductors, and insulators are not shielding the EM radiations. Palanisamy et al. [1] studied the nonconductive textile materials for shielding against EM radiation.

The literature review revealed some studies with different conductive textile materials, and their structure. Mostly the same material with different structure or different material with the same structure was studied separately. So, to fulfill the research gap in the comparative study, the various textile materials and different structures were taken and tested for electrical resistivity, electromagnetic shielding, and fabric parameters in the initial work of this thesis and recommendations for the creation of electromagnetically shielding textiles for different applications with different requirements were summarized. A survey of the effect of moisture in the textile material on its shading ability was carried out.

Effect of structural parameters including amount and size of pores on SE was evaluated using the copper-coated nonwoven strips simulated as textile structures and using the design of the experiment methodology. The final part of the review is based on the elongation of the textile fabric and its electrical resistance and EM SE.

There are many studies on changes in electrical resistance concerning changes in fabric elongation, but there are very few studies on EM SE against fabric elongation. In such studies, the difference in SE against the elongation of fabric is not exactly studied. No research reported on deformation sensing using conductive textiles with EM waves as a detector, so that is also considered and studied.

4 MATERIALS AND METHODS USED

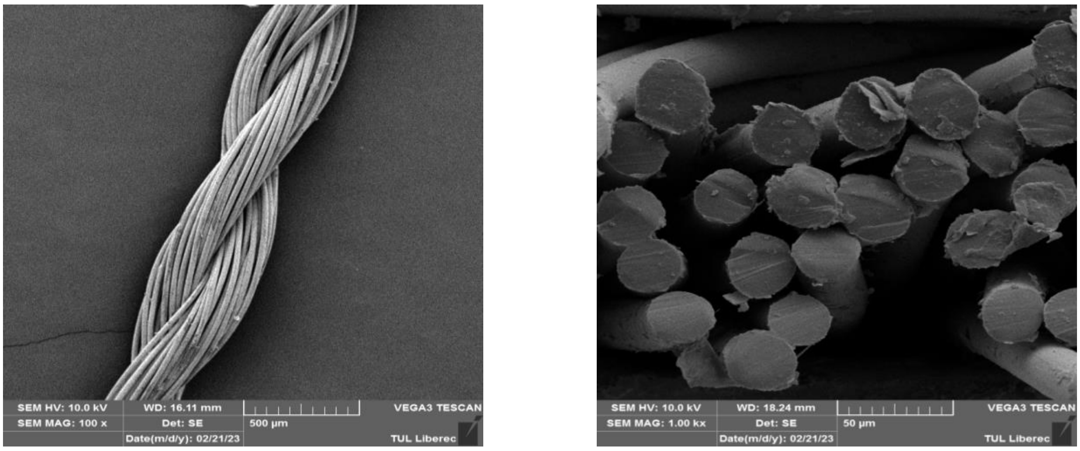
The materials and methods used for the experiments are given in this part.

4.1. Electrically conductive silver-coated yarn

The silver-coated polyamide (AgPA) yarn with linear density 60 tex was procured from Statex Inc., Bremen, Germany. The yarn's main parameters are shown in Table 1. The SEM images of the yarn at longitudinal and cross sectional views are shown in Figure 1(a) and Figure 1(b) respectively.

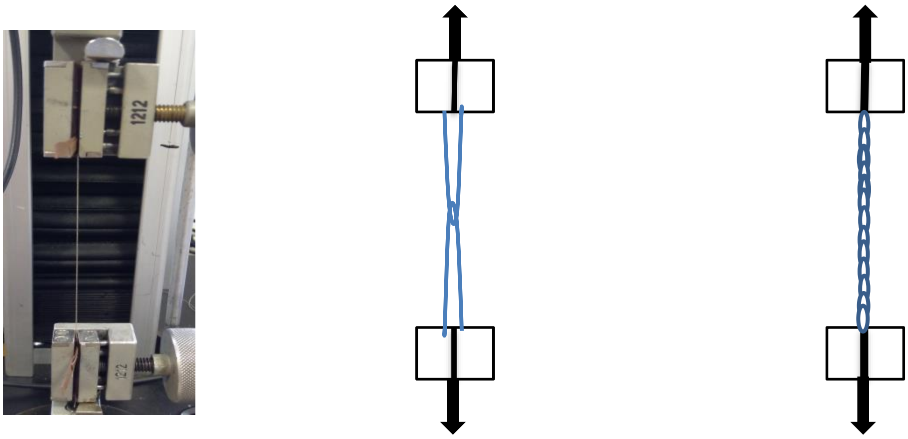
Table 1. Yarn parameters and their mean values with a 95% confidence interval.

Yarn parameters	Values
No. of filament per yarn	36
Double yarn count - silverized [dtex]	602 ±5
Single yarn count – silverized [dtex]	301 ±10
Double yarn - twist per meter (‘Z’ twist)	457 ±8
Single yarn - twist per meter (‘S’ twist)	614 ±4
Electrical resistivity [ohm/m]	68 ±14
Elongation at break [%]	28 ±10
Tenacity [cN/tex]	47 ±2
Yield [m/kg]	Min. 16600
Double yarn dia. [µm]	426 ±30
Single yarn dia. [µm]	273 ±30



(a) (b)

Figure 1. SEM images of AgPA yarn, (a) longitudinal view at 100x magnification and (b) cross sectional view at 1000x magnification.



(a) (b) (c)

Figure 2. Experimental setup of (a) SY, (b) SLY, and (c) MLY samples (with chain loop formation by crochet hand knit needle) clamped in the tensile instrument for the measurement.

To explore length related resistance and the effect of contact resistance; three experiments were conducted with three different yarn forms: single yarn (SY), single-loop yarn (SLY), and multi-loop yarn (MLY), and its experimental setup are shown in Figure 2.

SY sample is prepared with a single strand of yarn (see Figure 2(a)), which is clamped between two jaws of a tensile instrument. The SLY sample is formed by overlapping the two AgPA yarns to form a single loop, as shown in Figure 2(b). The MLY sample is formed by a hand-knitted continuous chain loop with a crochet needle, and it is shown in Figure 2(c).

4.2. Mechanical properties of yarns

The mechanical properties of silverized yarn were tested with Lab test 2.010 instrument (Labor tech Inc., Czech Republic) as per ISO 2062 standard using 50 mm clamping length and 50 mm/s speed.

4.3. Electrical properties of yarns

The yarn resistance is measured with two probes as per ASTM D257, and as stated by [15] the yarn irregularity makes the measurement complicated.

4.4. Electromechanical properties of yarns

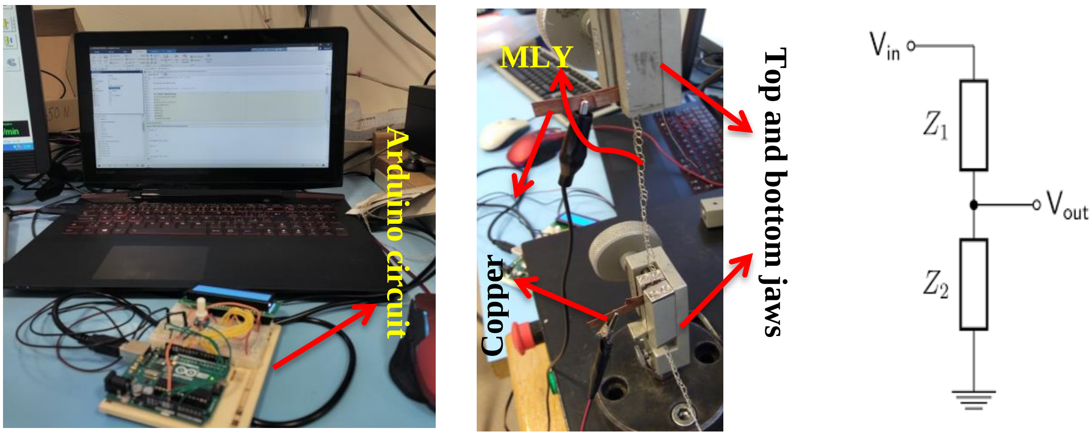
The electrical resistance of the yarn was measured using the Arduino® circuit with two probes, and its experimental setup with circuit diagram is shown in Figure 3. By this setup direct recording of the electrical resistance varying with the tensile stress of the sample is possible. The Arduino circuit with breadboard was connected to a laptop, as shown in Figure 3(a); two probes from the circuit were connected with a copper plate extended from two jaws, as seen in Figure 3(b). The circuit diagram of the Arduino is shown in Figure 3(c).
The resistance of the yarn is measured with the formula given in Eq. 1, and the MATLAB program script is written and runs to record continuous electrical resistance measurement.

$$\boldsymbol{Z_2} = \boldsymbol{Z_1}\left(\frac{\mathbf{1}}{\frac{\boldsymbol{V_{in}}}{\boldsymbol{V_{out}}} - \mathbf{1}}\right) \qquad \text{Eq. 1}$$

where, Z_1= known resistance, Z_2= unknown resistance, V_{in} = input Voltage, and V_{out} = output voltage. The copper plate electrode with a 3 mm width is placed on the gripper and connected with an Arduino circuit (see Figure 3) to measure the electrical resistance of yarn. Resistances of the yarn strands are recorded at a speed of 0.2 sec per reading. The resistor sensitivity of 0.02 Ω is used for the measurement. Each measurement was repeated five times for each yarn category to be able to describe the variability of each measured quantity.

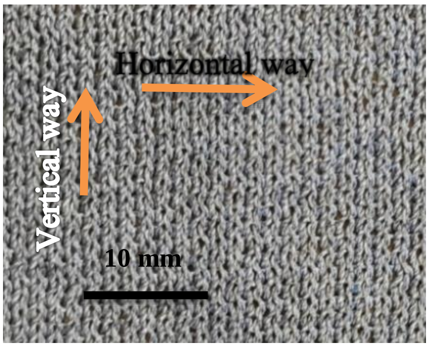
4.5. Electrically conductive fabrics

Conductive silver AgPA yarn was used to knit single jersey (SJ) and double jersey rib (DJ) on a 14 gauge flat needle bed knitting machine (Shima Seiki Ltd., Japan, and Model SRY 123LP). These two structures were chosen as they are the basic ones, rib knit fabric stretches more than single jersey.



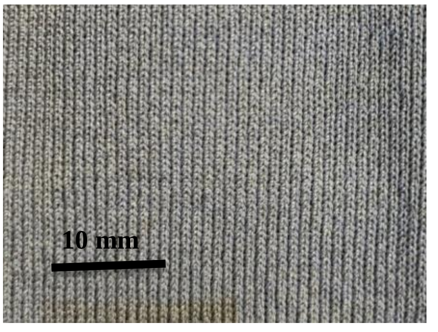
(a) (b) (c)

Figure 3. Experimental setup for measuring electrical resistance during elongation of yarn (a) Arduino circuit board attached with MATLAB software in laptop, (b) two probes in the tensile machine along with MLY sample, and (c) circuit diagram of Arduino board.



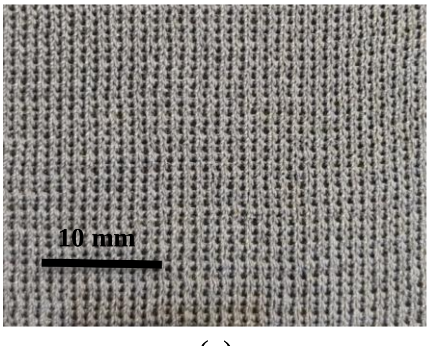
(a)

(b)

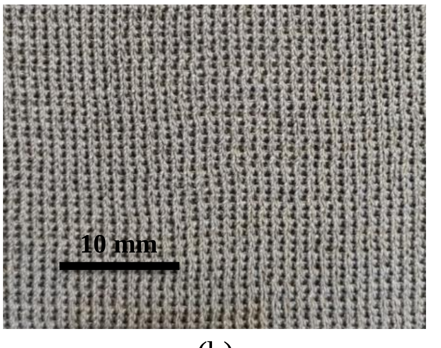


(c)

Figure 4. Images of (a) SJL, (b) SJM, and (c) SJH.



(a)



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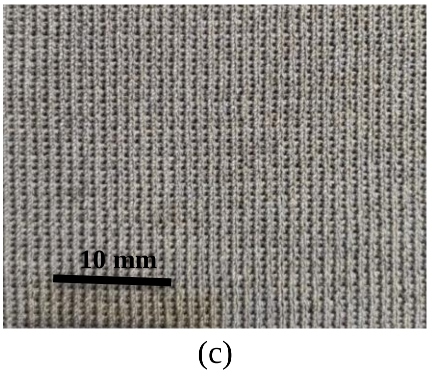


(c)

Figure 5. Images of (a) DJL, (b) DJM, and (c) DJH.

In addition, these two structures of the fabric are widely in use of wearable applications. The knitted fabrics are prepared at three different densities; low (L), medium (M), and high (H). The basic parameters of knitted fabrics are shown in Table 2 and their images are shown in Figure 4 and Figure 5. All the images are captured as per ISO 125 with 4.73 focal lengths and a 64 MP camera.

Table 2. Flat knit fabrics parameters and their mean values.

Test parameters	SJL	SJM	SJH	DJL	DJM	DJH
Structure		Single Jersey			1x1 Rib	
Thickness [mm]	0.85	0.83	0.84	1.52	1.48	1.37
Courses per [inch]	20.39	25.40	32.38	24.04	27	32.67
Wales per [inch]	18.29	19.30	20.46	18.62	19.05	19.27
Areal density [g/m^2]	230.79	261.66	314.46	442.01	456.02	538.96
Stitch density [per sq. inch]	361.26	475.00	641.54	447.62	514.35	680.72
Loop length [mm]	5.79	5.22	4.77	5.37	5.26	4.92
Porosity [%]	33	27.9	25.9	19.4	8.5	6.5

4.6. Basic properties of fabrics

The fabric mass per unit area (*w*) [g/m^2] was measured using the standard ASTM D 3776, and the sample size was 100 cm^2. Fabric thickness (*h*) was measured using the thickness gauge [mm], as per the standard ASTM D1777 (knitted samples). The loop length of the fabric samples was calculated with the Dalidovich method [16].

4.7. Electrical properties of the fabrics

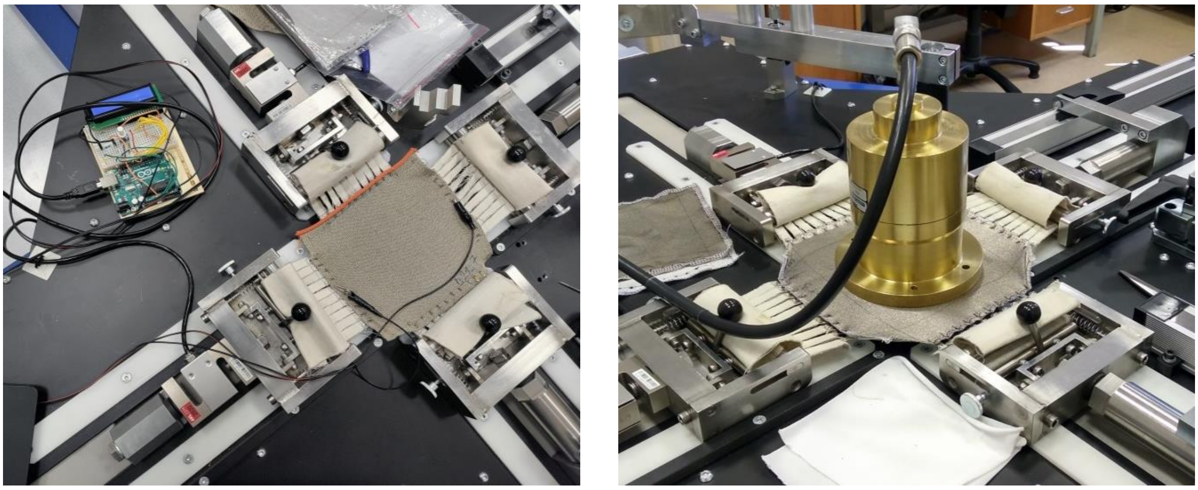
The surface resistance of the sample set was measured according to the standard ASTM D257, under a DC power supply, using two probe electrodes at the temperature T = 21°C and the relative humidity RH = 54 %.

4.8. Electromagnetic shielding effectiveness of fabrics

SE of the sample set was measured according to the ASTM D4935-18 for the planar materials using a plane wave, the far-field EM wave at the temperature T = 21°C, and the relative humidity RH = 54 %. SE of the samples was measured over the frequency range of 30 MHz to 1.5 GHz. The measurements were performed at five different places of the textile samples because of the subsequent statistical analysis. The mean values and 95% confidence intervals for means of the *SE* for 1.5 GHz frequency are summarized.

4.9. Electromechanical properties of fabrics

The continuous measurement of the electrical resistance of the knitted fabric sample is done with an Arduino resistance setup, as seen in Figure 6(a). The edges of the fabric samples were connected with two probes from the resistance circuit board at a distance of 14 cm, and the sample was stretched at a speed of 3.5 mm/sec to measure electrical resistance until 30 % fabric elongation. It was found that the elongation of the fabric until 30 percent was not causing any damage to the knit structure. The fabric structure was disturbed by unraveling and breaking after exceeding 30 % elongation. While uniaxial stretching, the probes are connected to the stretching direction for a measurement. During biaxial stretching, the probes are connected in the vertical direction of the sample, and only wale way resistance is measured. The resistance readings were recorded online using MATLAB software and then saved in a data file for further analysis.



(a) (b)

Figure 6. Experimental setup of fabric attached in the biaxial device to measure (a) electrical resistance and (b) electromagnetic shielding effectiveness.

The electromagnetic shielding effectiveness (EM SE) of the sample was measured using the coaxial transmission line method, as seen in Figure 6(b). The stretching cycle is programmed with Fabris 5K software. The stretching speed was 3.5 mm/sec, and for every 5% elongation of fabric.

The pore area of the fabric sample during the biaxial stretching process is measured using the Nikon NIS element software as per internal standard number 23-107-01/01. The fabric's total open pore area value, called porosity, was obtained by the NIS element image analysis and used for plotting graphs.

5 SUMMARY OF THE RESULTS ACHIEVED

In this chapter, the conductive yarn and conductive knitted fabrics test results are evaluated deeply and discussed statistically as well as logically for strain sensing applications.

5.1. Conductive yarn and its forms

The three forms of the yarns were tested for electrical resistance, resistance during elongation, tensile strength, and in addition SEM images after yarn break are discussed here.

5.1.1. Mechanical properties of yarn and its forms

The electrical length resistance results of the yarn forms at relaxed state are given in Table 3. The tensile strength of the yarns was measured at 5 cm gauge length and 50 mm/min traverse speed. The results of SY, SLY, and MLY stress–strain curves are shown in Figure 7, and the average of five readings was used for this plot; the average yarn breaking strength and breaking elongation values with a 95% confidence interval (CI) are shown in Figure 7. The mean values of breaking force and elongation at the break of yarn forms with 95% CI are given in Table 4.

Figure 7(a) shows the results of the single yarn at 5 cm gauge length test at 50 mm/min speeds. The rapid increase in single yarn tensile was noticed between 5 % and 22 %; after that, the yarn break at 34.7 % strain with 42.4 cN/tex force. Apart from SY behaviors, the SLY was initially zero stress until 3 % strain; after that, the stress acted on it (see Figure 7(b)). The SLY breaking strength is 40 % higher compared to SY. The SLY sample is constructed with two threads of SY (see Figure 2(b)), which means the yield strength of SLY is double that of SY, which is why the strength and elongation at the break of the samples also increase. In MLY results (Figure 7(c)), the load is acting after a certain percentage of occurred strain which is because of the loosely constructed loops structure (see Figure 2(c)). Once the loops get in contact with each other, then the load is acting. The MLY has 70 % higher breaking strength compared with SY. The yarn strain at break is higher for MLY, but SY has higher than SLY; this is because of more rupture occurs at the SLY contact point. The higher the number of loops, the higher the breaking strength was noticed.

5.1.2. Electromechanical properties of yarn and its forms

In this part, the strain or stress versus electrical resistance of yarn forms was studied. The dependence of electrical resistance on tensile for SY, SLY, and MLY samples at 5 cm gauge length using 50 mm/min test speed is shown in Figure 8. When observing this dependence for the SY sample (see Figure 8(a)), it is visible that during the initial tensile process (T < 3.34 cN/tex), for this gauge length and test speed), the resistance increases slightly. After a certain point, resistance increases steeply. A single linear model may not adequately describe the relationship between electrical resistance and yarn tensile. In this case, a segmented or piecewise linear regression allows multiple linear models to fit the data for different ranges of x. In our case, piecewise linear regression with two segments was used when the breakpoint (the point where the slope of the linear function changes) was unknown. The breakpoint was found as the minimum of the sum of RSS (residual sum of squares) of the two linear models. Figure 8(a) shows two straight lines with a very high coefficient of determination defining the breakpoint.

Table 3. Electrical length resistance of different yarn forms with 95% CI**.**

Yarn form	Electrical length resistance R_L [Ω/cm]	
	Mean	CI
SY	0.45	0.03
SLY	0.25	0.02
MLY	0.40	0.09

Table 4. Tensile strength and strain of yarn forms with 95% CI.

Parameters	SY		SLY		MLY	
	Mean	CI	Mean	CI	Mean	CI
Yarn tensile, T [cN/tex]	42.40	1.51	61.25	4.59	73.08	12.60
Yarn strain, ε [%]	34.79	2.56	29.19	2.22	73.32	10.48

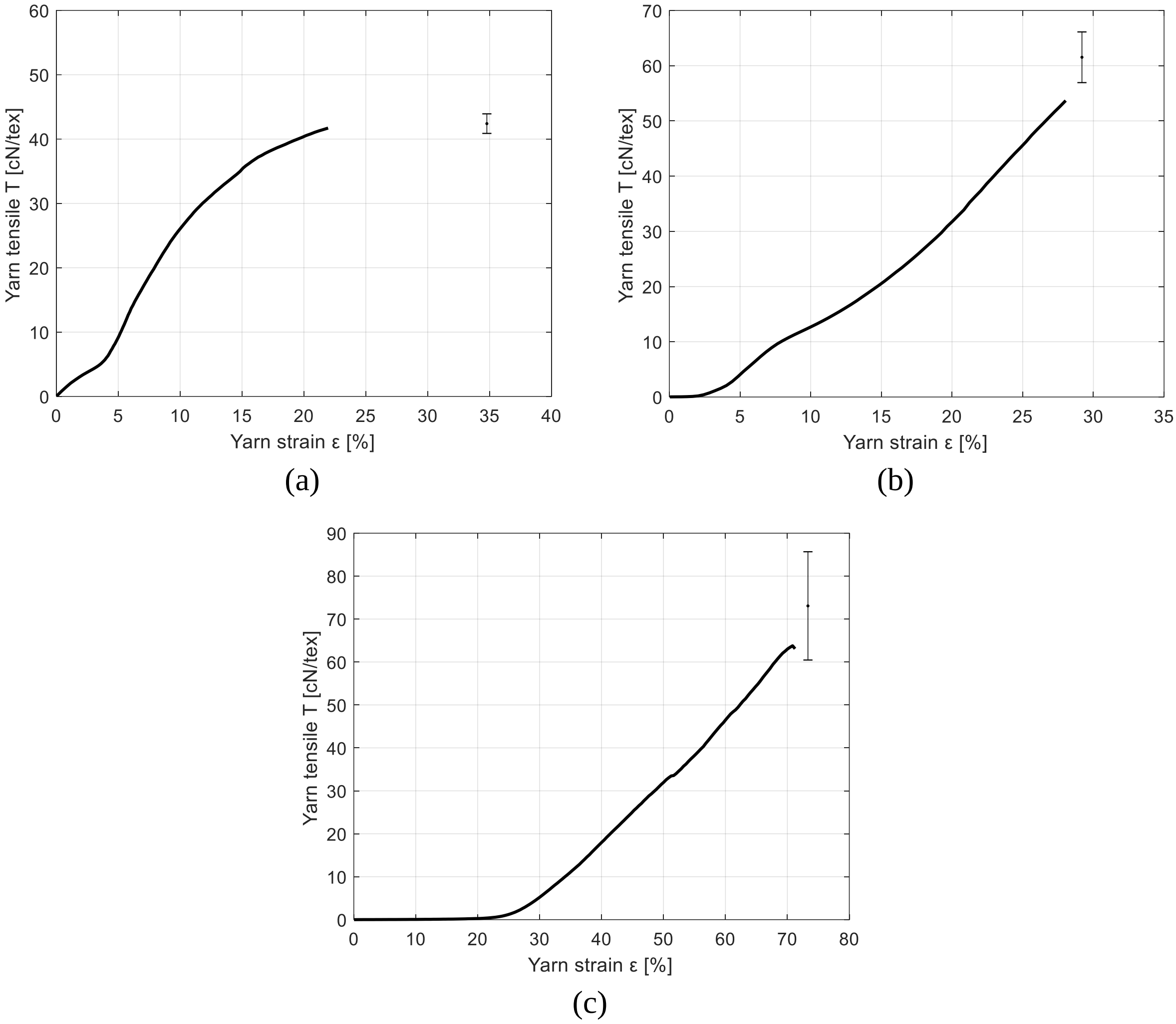


Figure 7. Yarn strain *ε* [%] versus tensile, *T* [cN/tex] of (a) SY, (b) SLY, and (c) MLY.

It was confirmed that there are two phenomena during the tension process: length-related resistance and contact resistance. The contact resistance occurs during the initial tension due to the twist of conductive yarn and the increasing number of contacts between fibres, reducing total length-related resistance. After the changing point, only length-related resistance occurs. It could also be assumed that the continuous conductive layer on the fibre surface during large deformations may be disturbed, and therefore the electrical resistance will increase.

The dependence of electrical resistance on the tensile force for single loop yarn (two overlapped yarns, SLY) is shown in Figure 8(b). It is visible that the resistance decreases until 3.34 cN/tex, which is caused by contact resistance dominating at the initial stressing.

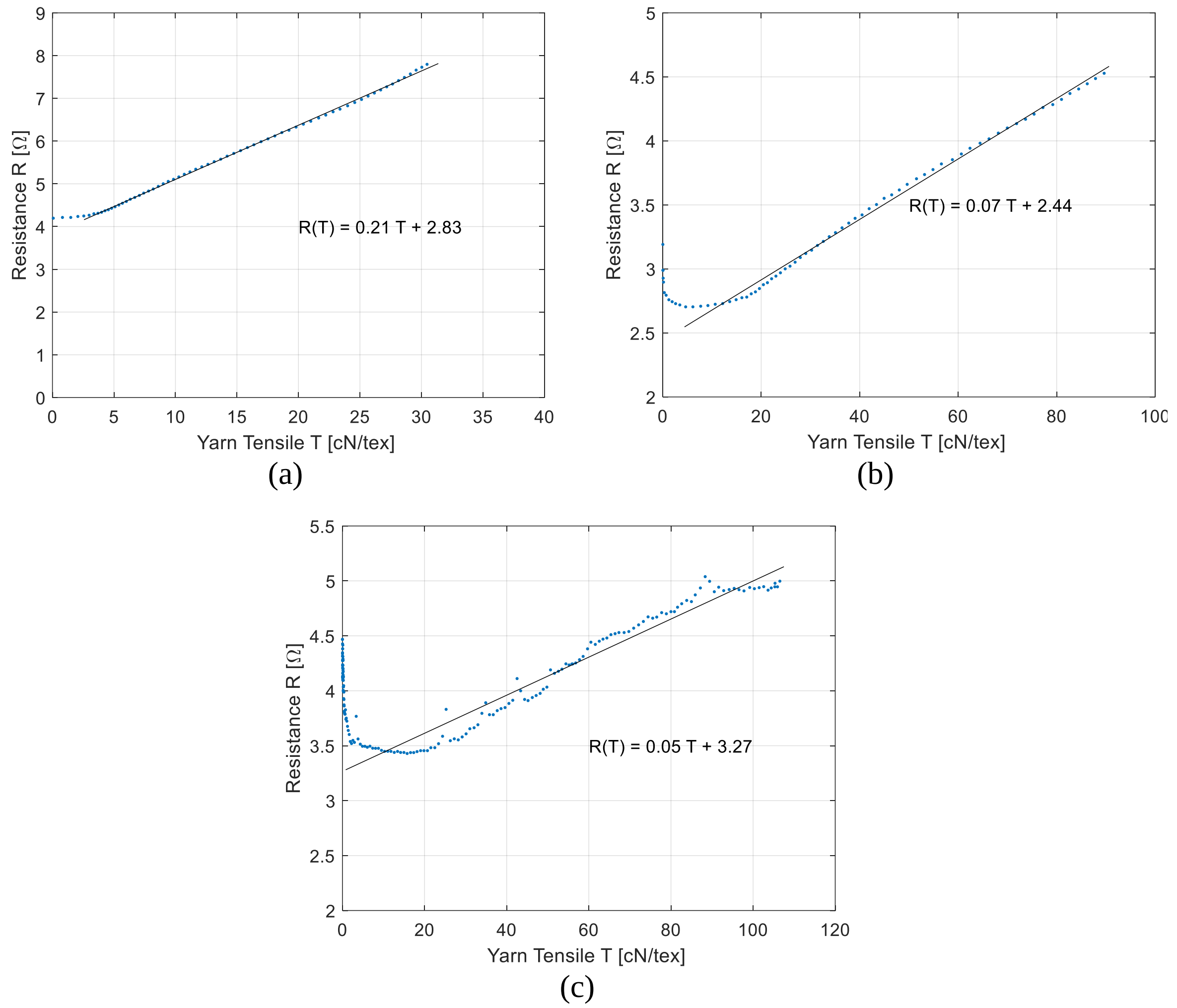


Figure 8. Dependence of resistance, *R* [Ω] on yarn tensile, *T* [cN/tex] for (a) SY, (b) SLY, and (c) MLY.

After reaching the change-point, the resistance increases steeply due to length-related resistance, and contact resistance has little effect on this region. Also, in this case, it is possible to fit two regions by straight lines to find a change-point. It is observable that the length-related resistance and contact resistance behave as competing factors which confirms that the electrical resistance of knitted fabric can be modeled by the superposition of the length-related resistance and the contact resistance. When comparing the initial resistance and also the rear area of measured resistances of SY and SLY, the resistances in Figure 8(b) are almost half of that in Figure 8(a) because, in the case of SLY, two conductive yarns were connected in parallel.

The dependence of electrical resistance on the tensile force for multi-loop yarn (multiple overlapped yarns, MLY) is shown in Figure 8(c). It is visible that the resistance decreases until 8.35 cN/tex, which is caused by contact resistance between the yarn loops dominating at the initial stressing. After reaching the change point, the resistance increases steeply due to length-related resistance, and contact resistance has little effect on this region. Also, it is possible to fit one region by a straight line to find the change point in this case. This multiple loops model helps to model the knitted fabric for electrical resistance change during elongation. When comparing initial resistance and also a rear area of measured resistances of SY, SLY, and MLY, resistances in Figure 8(c) are almost half of that in Figure 8(b) and a quarter of that in Figure 8(a); due to the case of MLY, multiple loops of conductive yarn were connected in parallel. When comparing the slope of the increasing linear models of all yarn-type structures, the highest slope (the steepest growth of R) has the SL sample, and the lowest slope has the MLY sample.

The dependence of yarn electric resistance R on yarn elongation ε is shown in Figure 9(a-c). Mean values together with 95 % confidence intervals of means displayed by dotted lines, are presented for SY, SLY, and MLY. The breaking strain is marked as a point with errors, as shown in Figure 9; MLY has a higher value following SY and SLY.

When observing R versus ε dependence, two regions of the tension process corresponding to length-related resistance and contact resistance are also visible, whereas the contact resistance has the smallest effect for SY samples and the highest effect for MLY samples. This phenomenon is connected to the number of contact points in the yarn-forming structure. For example, contact resistance is dominating factor of up to 30 % elongation for the MLY sample. The single contact point has a smaller effect on the R-value in Figure 9(b); SLY resistance decreases initially and then increases. Once the yarn rupture increases, the R-value also increases. Due to the multiple connecting points, the curve in Figure 9(c) has wave formation; throughout the graph, there are many waves indicating the sudden rupture and slip between the contact points occurred.

5.2. Electro-conductive knitted fabrics

The study of EM SE against fabric stretching is a new approach to measure strain sensitivity applied in the present thesis. In this way, the strain is measured with wireless technology, and it takes sensor technology to the next level of development. This work produces the plain jersey and rib knitted fabric using silver-coated yarn to analyze its sensing properties. As mentioned above, the SJ and DJ samples, developed at three different densities, L, M, and H, were tested for electromagnetic shielding effectiveness at a frequency range from 30 MHz to 1.5 GHz as shown in Figure 10 (mean values are shown). The average SE at 1.5 GHz frequency together with its 95% CI of SJ and DJ samples is shown in Table 5 and Table 6.
The EM SE of the single jersey fabrics decreases logarithmically with increasing frequency, as seen in Figure 10(a). Also, the density of the fabric influenced the SE value positively; SE of the SJL, SJM, and SJH fabrics is 46 dB, 49 dB, and 52 dB at 1.5 GHz frequency (see Table 5). The density of the sample influences the fabric thickness as well as the fabric porosity, increase in density increases the thickness, stitch density, and areal density but decreases the loop length (see Table 2). The EM waves are reflected by thicker conductive layers and lesser porous structures. That is the reason why higher-density fabric has higher SE than lower-density fabric.

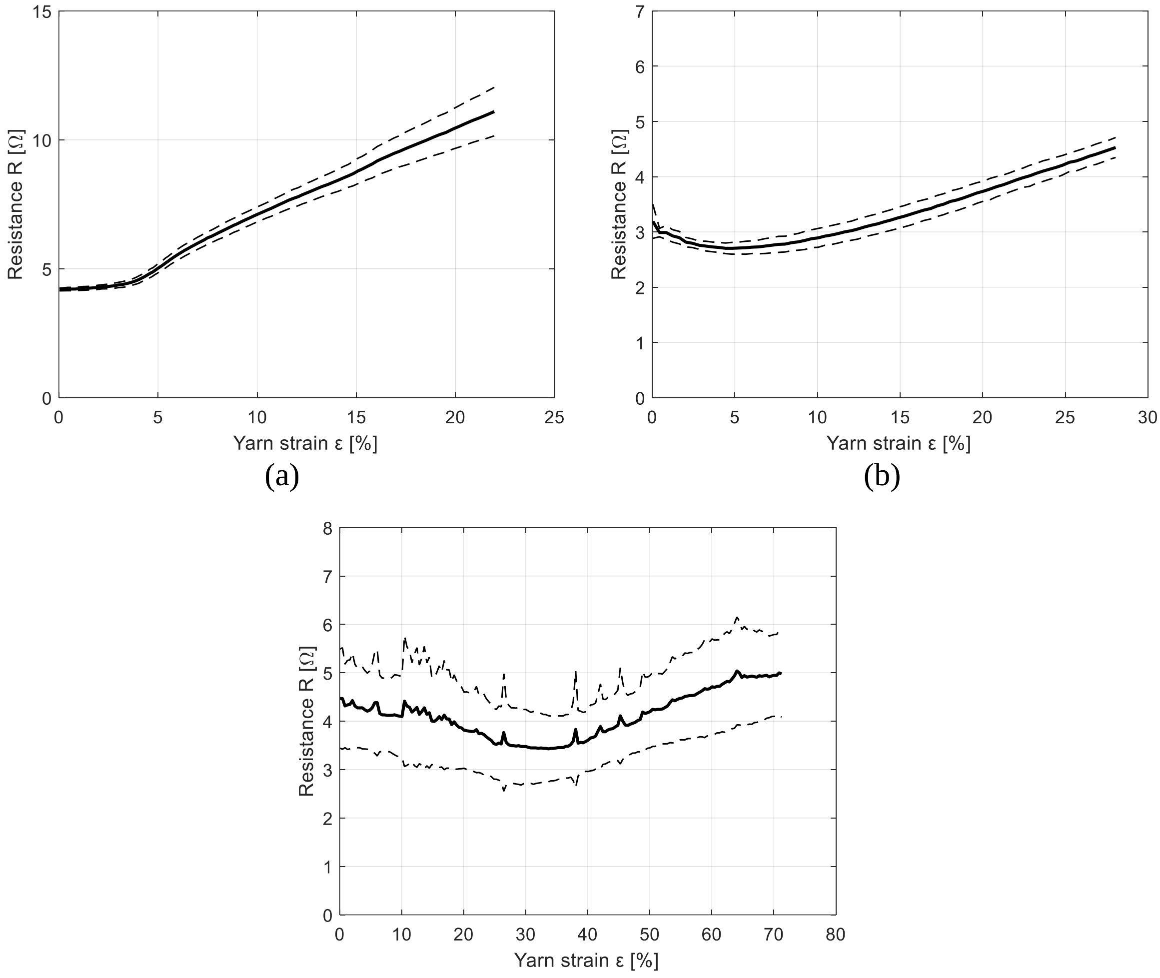


Figure 9. Dependence of electrical resistance, R [Ω] on yarn strain, ε [%] of (a) SY, (b) SLY and (c) MLY.

5.2.1. Electromagnetic shielding effectiveness of the knitted fabrics

DJ fabric's SE has an ambiguous trend (SE is more or less constant) throughout the frequency range of 30 MHz to 1.5 GHz, as seen in Figure 10(b). The SE of DJ rib fabrics are close to the dynamic range of the measurement device used, therefore the shape of the curves of samples with higher SE is not smooth. This kind of structure has an identical appearance on both sides with paired curves. Also for this sample set it was confirmed that the SE value increases with increasing fabric density; the DJL, DJM, and DJH samples have 62 dB, 65 dB, and 65 dB at 1.5 GHz frequency (see Table 6). The increase in density of DJ is an increase in the amplitude of the SE readings in the graph because higher density fabric has closer loops and increased curves in structure, which creates the higher amplitude. The SJ fabric SE results also have noises, but the amplitude of the SE readings is lesser than the DJ results. This kind of wave is formed with the presence of the pore or aperture in the structure; according to plane wave theory [17], the aperture size induces the amplitude of the SE results. Overall, the DJ fabric sets have higher SE than SJ fabric sets; another reason is the DJ is thicker as well as dense than the SJ.

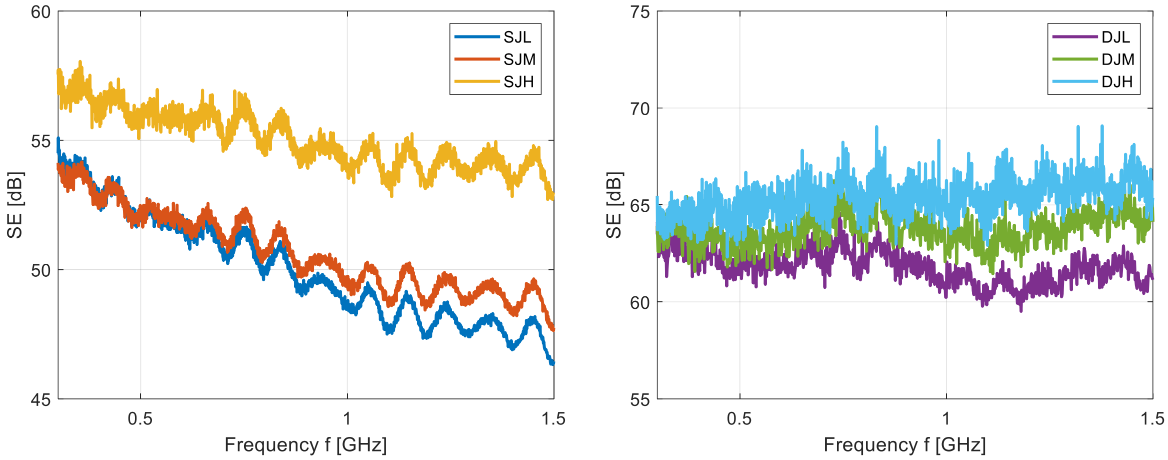


Figure 10. Dependence of EM SE [dB] vs. frequency, *f* [Hz] (*f* = 30MHz - 1.5 GHz) of the (a) SJ and (b) DJ samples.

Table 5. Mean values of SJ knitted samples SE with 95% CI

Sample name	SE [dB] at 1.5 GHz frequency	
	Mean	CI
SJL	46.1	0.25
SJM	48.9	0.31
SJH	52.5	0.24

Table 6. Mean values of DJ knitted samples SE with 95% CI

Sample name	SE [dB] at 1.5 GHz frequency	
	Mean	CI
DJL	61.5	0.54
DJM	64.9	1.89
DJH	64.7	1.07

5.2.2. Effect of knitted fabric parameters on SE

In this subchapter the comparison of SE sample set will be done with respect to different sample parameters. The basic parameters of the fabric samples are stitch density, areal density, thickness, and porosity are compared and shown in Figure 11. The SE is increase with increase in stitch density of the SJ linearly and DJ in nonlinear trend as seen in Figure 11(a). Figure 11(b) shows the SE is increases with increase in areal density for SJ and DJ fabrics, DJ has sudden increase at medium range and no change after.

The increase in fabric thickness has different effects on SE, for SJ samples SE has different values but the thickness has no significant difference; DJ samples thickness increases then the SE is decreases slightly as seen in Figure 11(c). Another main parameter is the porosity of the SJ and DJ fabrics are compared with their SE values in Figure 11(d).

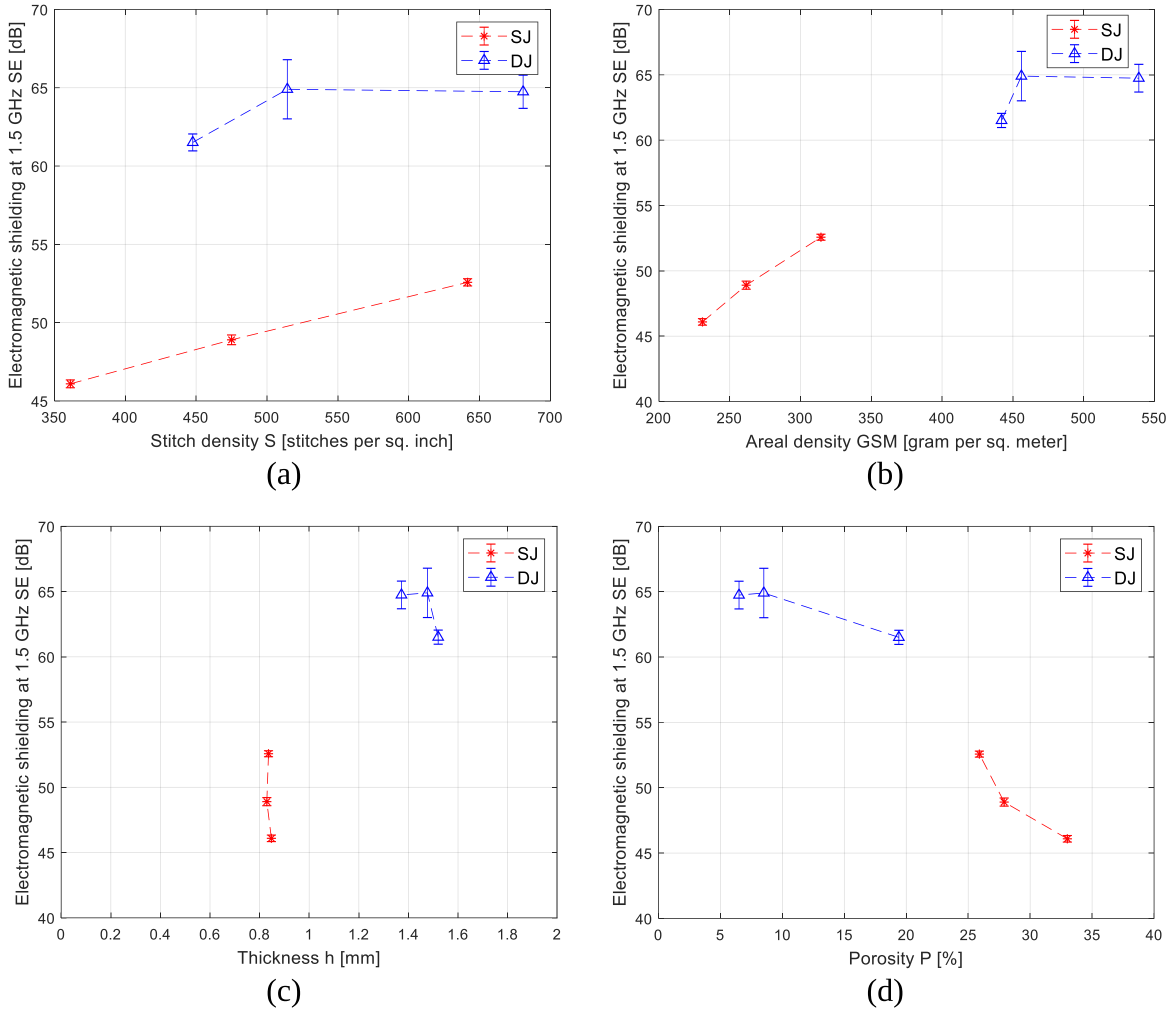


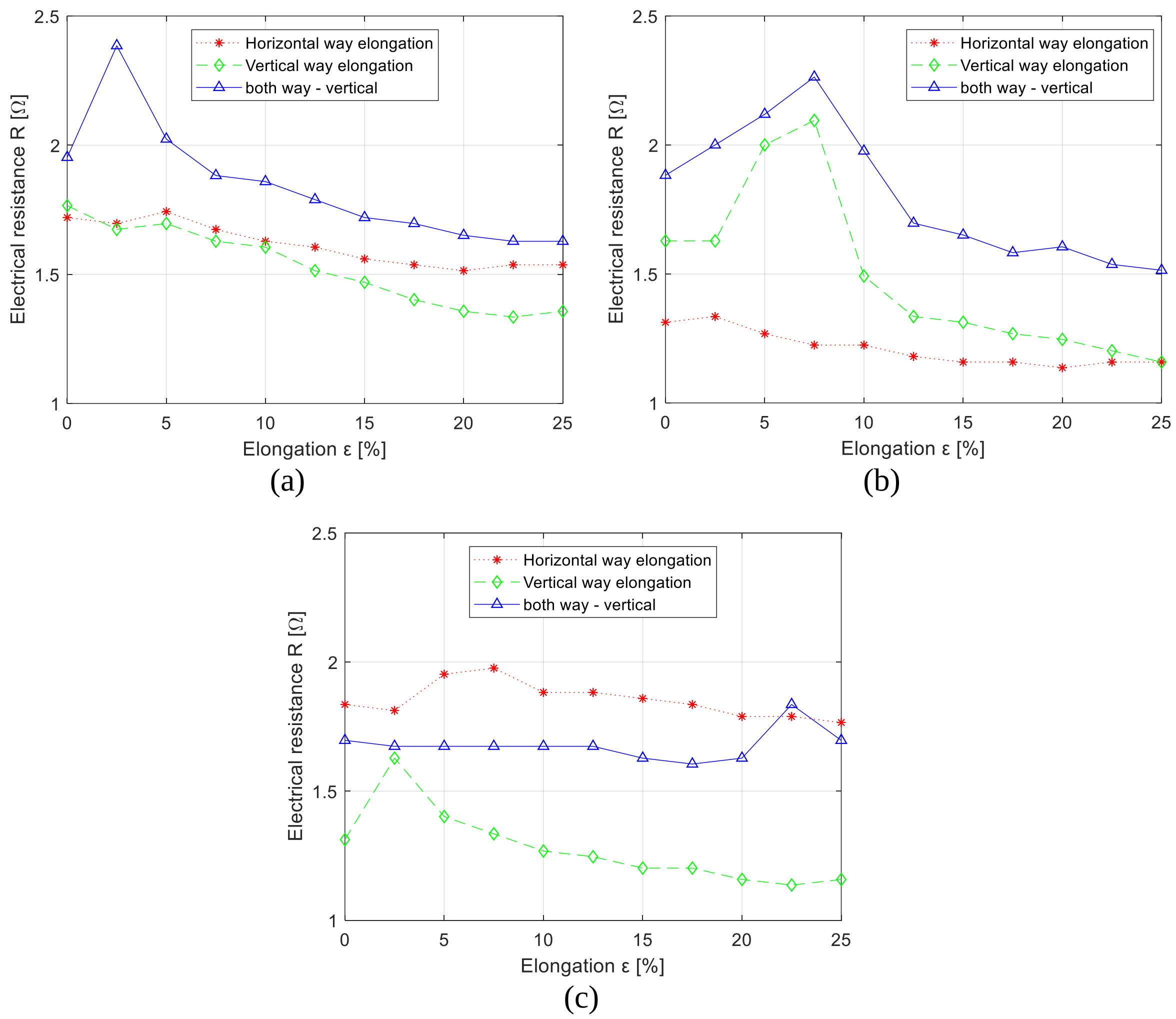
Figure 11. Dependence of SE at 1.5 GHz frequency on (a) stitch density, (b) areal density, (c) thickness, and (d) porosity of the fabric samples.

An increase in porosity has decreased the SE of the SJ and DJ fabrics; a more open area is transmitting the EM radiation, and the reason the SE decreases with increasing porosity. Those results show the difference in SE with the fabric structure and its densities; it might be helpful to decide the suitable fabric for the sensor range. The DJ's medium density and high density fabrics has no significant difference in SE values was noticed.

5.2.3. Effect of knitted fabric elongation on its electrical resistance

The electrical resistance (ER) is indirectly proportional to the electromagnetic shielding effectiveness if other variables are held constant, which means higher the resistance lowers the shielding and vice versa.

The SJ sample's ER behavior is different for different densities; mostly, the ER is decreased while stretching the fabrics. ER for SJ lies between the 1 to 2.5 ohms range for all the samples and there is an observable decrease in electrical resistivity with increasing density of the knitted fabric. During the increasing horizontal way of fabric elongation, the ER is slightly decreasing for all densities of samples. When increasing vertical way fabric elongation ER is decreasing more steeply. During both ways of fabric elongation, ER is deviating moderately between horizontal and vertical ways results. ER of SJL sample has decreased with an increase in elongation at all directions of loading, as seen in Figure 12(a). At both ways of stretching of SJL, the ER increases slightly and then decreases drastically; from 2 to 5 % elongation, the ER increases suddenly because of the relaxation of fabric. SJM sample has decreased in resistance with an increase in elongation at the horizontal way; at vertical and both ways stretching, the resistance increases initially until 7.5 % elongation and then decreases drastically, as seen in Figure 12(b). SJM is constructed with moderate stitch density so that the ER is increased vertically as well as both ways of elongation of the fabric and fabric loops loosen in this direction. SJH sample ER slightly decreased with an increase in elongation of the sample, as seen in Figure 12(c). SJH vertical way elongation causes increase in ER initially due to fabric relaxation or pre-tension, but in horizontal way elongation, the resistances increase after 2.5 % to 7.5 % elongation, proving the loose connection between the loops at this point. Based on the stitch densities, the ER results vary with fabric elongation. The loose structure has constantly decreased in ER, but the tight structure has slightly decreased in ER against the elongation. ER trend is somehow similar to the SE results of the SJ fabrics.



(a) (b)

(c)

Figure 12. Dependence of electrical resistance R [Ω] on elongation of fabric ε [%] for single jersey fabrics having: (a) low, (b) medium, and (c) high density.

The DJ fabrics have different trends on ER for different densities during fabric elongation, as seen in Figure 13. An increase in fabric density is shifting the ER trend from downward to upward against the fabric elongation. DJ fabrics ERs are behaving similarly for vertical elongation. There is a peak shift in ER results related to fabric density; an increase in the density of the fabric is shifting ER peak from the initial to the final point of elongation. Such kind of shift in the peaks is due to the following reasons. In tightly constructed structures, the loop yarns surface coating was affected by abrasion after a certain point of elongation and tend to loss in electrical connection, which is why the ER increases at the final stage of elongation. The moderate structure lies between the loose and tight one; here, the wider increase in ER is because of pre-tension. In horizontal way of elongation of DJ samples, ER is almost constant. In vertical way of elongation of DJ samples, ER is decreases after 5% elongation for low and medium densities. In both ways of elongation of DJ samples, the ER decreases after 5% elongation for low and medium densities. Compared with SJ samples, the DJ samples ER is opposite in horizontal way elongation. The SJ or plain knit structure has a moderately loose course, but the DJ or rib structure is looser.

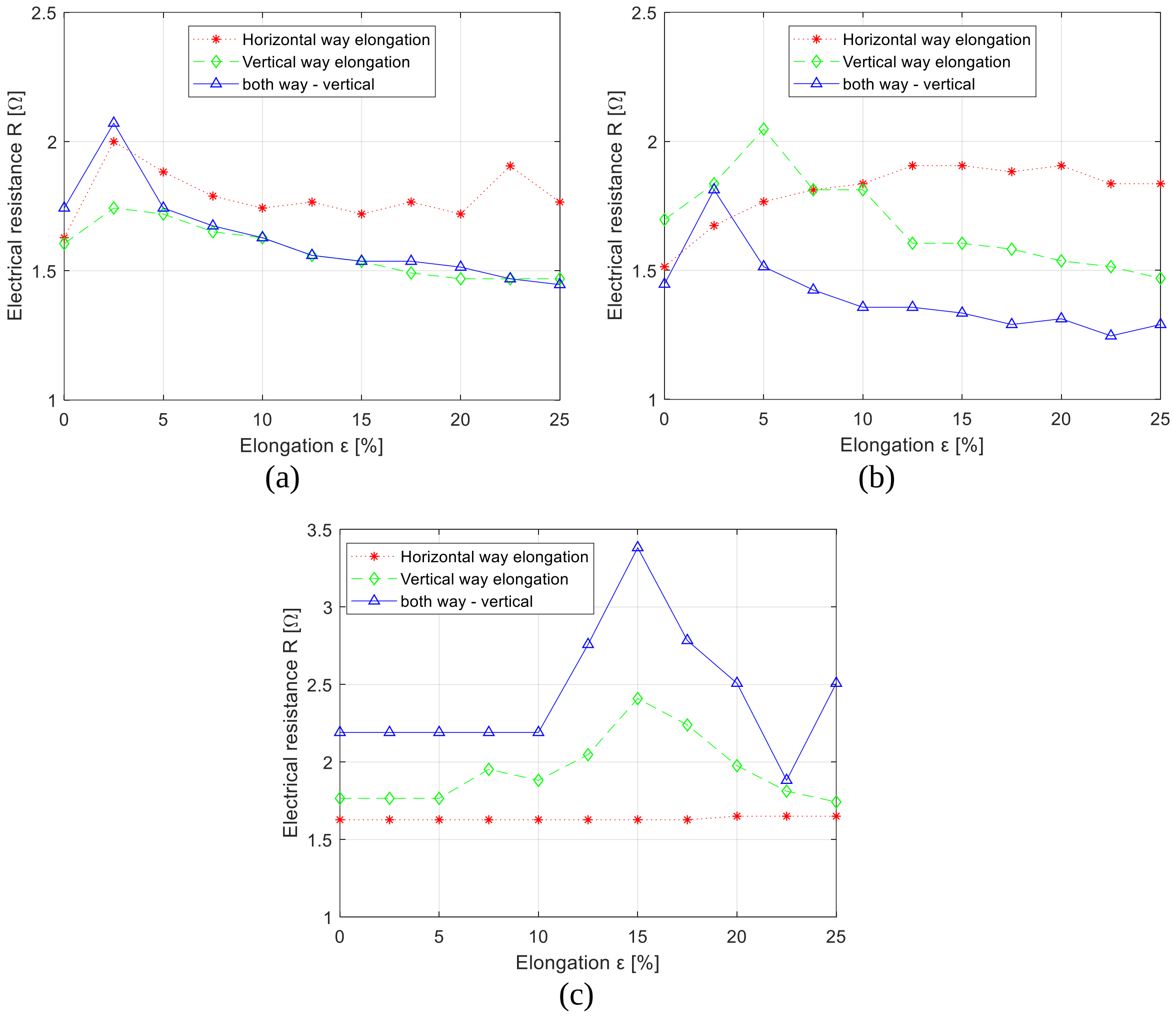


Figure 13. Elongation of fabric ε [%] versus electrical resistance R [Ω] for double jersey having(a) low, (b) medium, and (c) high density.

This is the reason that the DJ and SJ horizontal results vary due to structural differences. DJL has an increase in ER initially and then decreases with respect to an increase in elongation at all ways of stretching shown in Figure 13(a). DJM sample also increases ER at an initial stretch and then decreases with vertical and both ways of elongation, as shown in Figure 13(b). DJH sample follows a similar trend to others, but at horizontal way stretching, the resistance has no change with an increase in elongation (Figure 13(c)). The electrical resistivity trends are most closely related to the SE results of the DJ fabrics.

5.2.4. Effect of knitted fabric elongation on its porosity

The porosity or aperture of the shielding material has significantly affected the SE results, as stated by the theory and also as confirmed in the work Palanisamy et al. [3]. The elongation versus porosity of the SJ fabric is shown in Figure 14. It is visible that the porosity at 0 % loading (P_0) decreases with higher sample density. The extension of the fabric causes increase of the porosity in most cases, and increasing porosity could affect the shielding effectiveness. SJL, SJM, and SJH fabric's porosity increase with an increase in elongation at vertical, horizontal, and both ways, as seen in Figure 14(a-c), whereas the trend is almost linear.

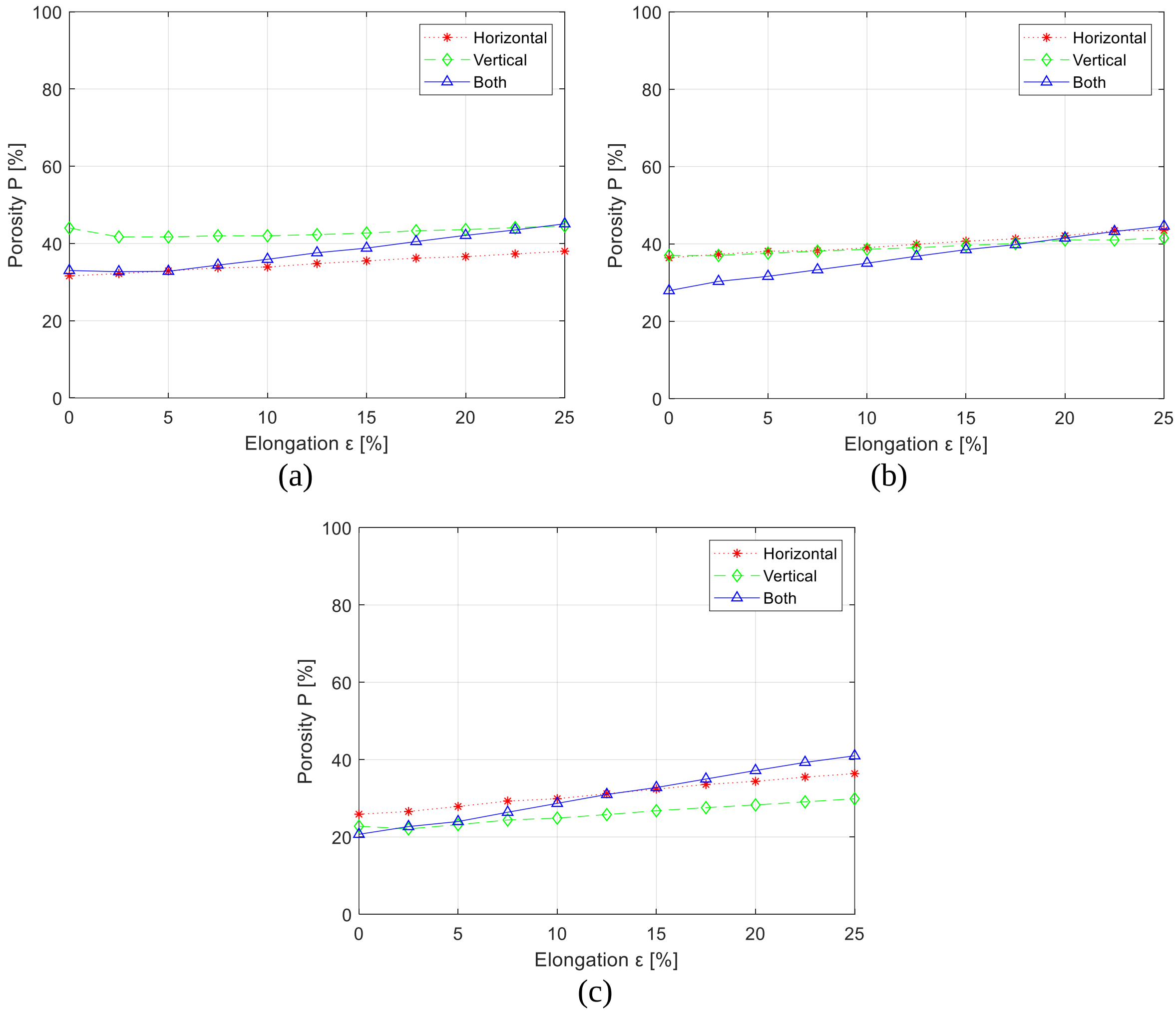


Figure 14. Dependence of open pore area P on fabric elongation ε [%] for single jersey having: (a) low, (b) medium, and (c) high density.

At both ways of elongation, the samples porosity increased much higher than in other ways and the slope of the approximation line would have the highest slope. The second most increase in porosity during elongation was noticed at the horizontal way elongation of the fabric. The loops are tightly arranged in a vertical direction or course-wise of the SJ structure, which is not elongating much at this direction of stretch and the effect of stretch on porosity is the lowest one. The density of the fabric also affects the porosity; the higher the density, the greater change in porosity against the elongation noticed. The SJL, SJM, and SJH have a maximum difference in porosity of 16 %, 18 %, and 24 %, respectively, during both ways stretch. In a horizontal direction or wale-wise, the knit loops are arranged loosely to elongate the fabric easily, and the pores are opened wider in this direction of stretch. The knit loop structures affect the porosity with respect to the direction of the stretch.

The elongation versus porosity of the DJ fabric is shown in Figure 15. DJL, DJM, and DJH fabric's porosity increase with the elongation at vertical, horizontal, and both ways, as seen in Figure 15(a-c). Also, in this case, the increase of porosity with increasing elongation is almost linear. During the both way elongation of the samples, the porosity increased significantly, the slope of the approximation line would be the highest.

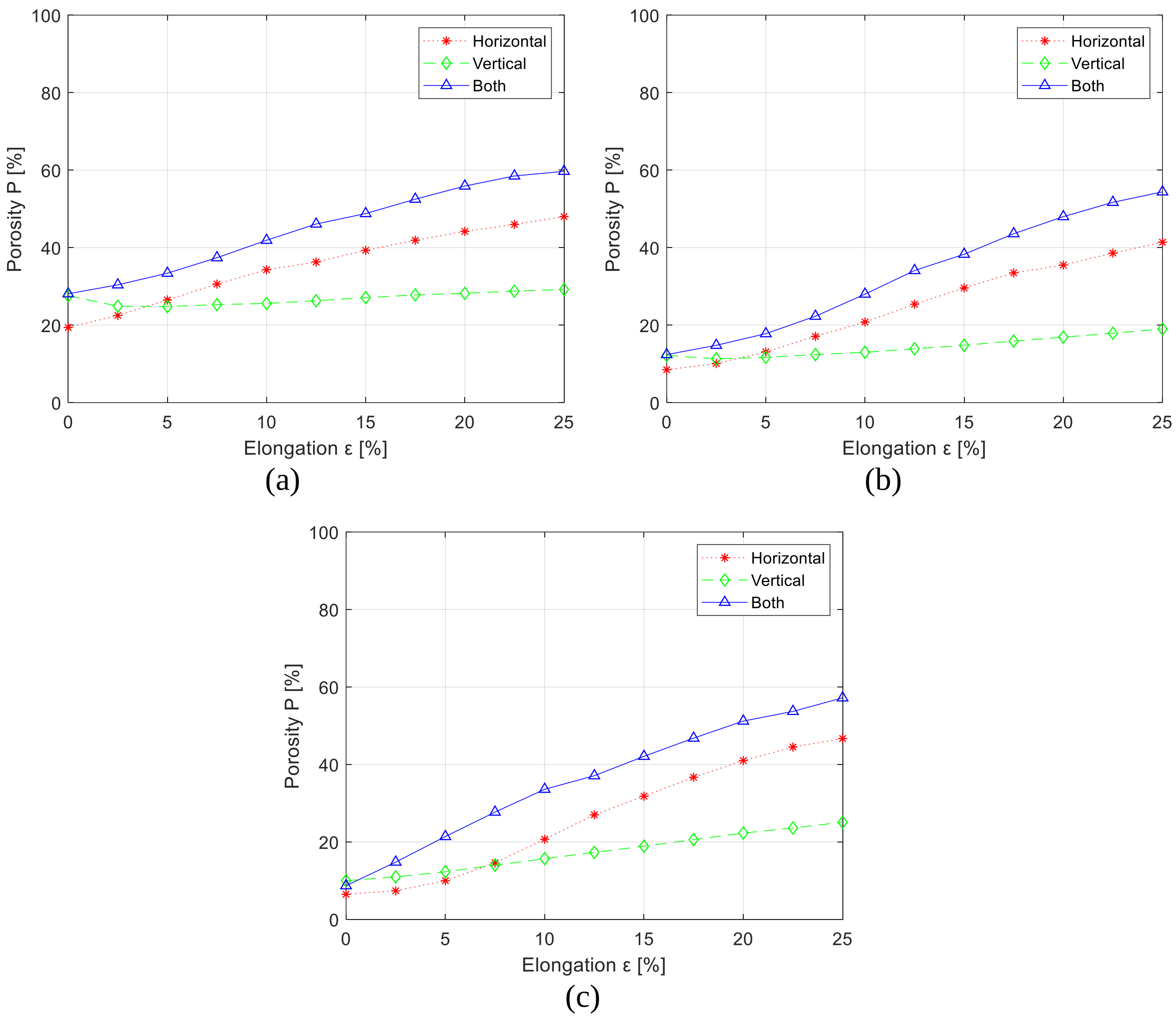


Figure 15. Elongation of fabric ε [%] versus open pore area P [%] for double jersey having (a) low, (b) medium, and (c) high density.

Significant effect of elongation on porosity can be observed also during horizontal type of elongation, the increase of *P* is around 40 %. The loops are tightly arranged in a vertical direction or course way of the double jersey structure and that is why samples are not elongating much at this direction of stretch. The loading in vertical direction has the lowest effect on porosity. The density of the fabric also affects the porosity; the higher the density, the greater change in porosity against the elongation noticed. The DJL, DJM, and DJH have a maximum difference in porosity of 30 %, 40 %, and 48 %, respectively, during both ways stretch. In horizontal direction or wale ways, the knit loops are arranged loosely to elongate easily. The porosity is affected by the knit loop structures with respect to the direction of stretch.

5.2.5. Effect of knitted fabric elongation on its SE

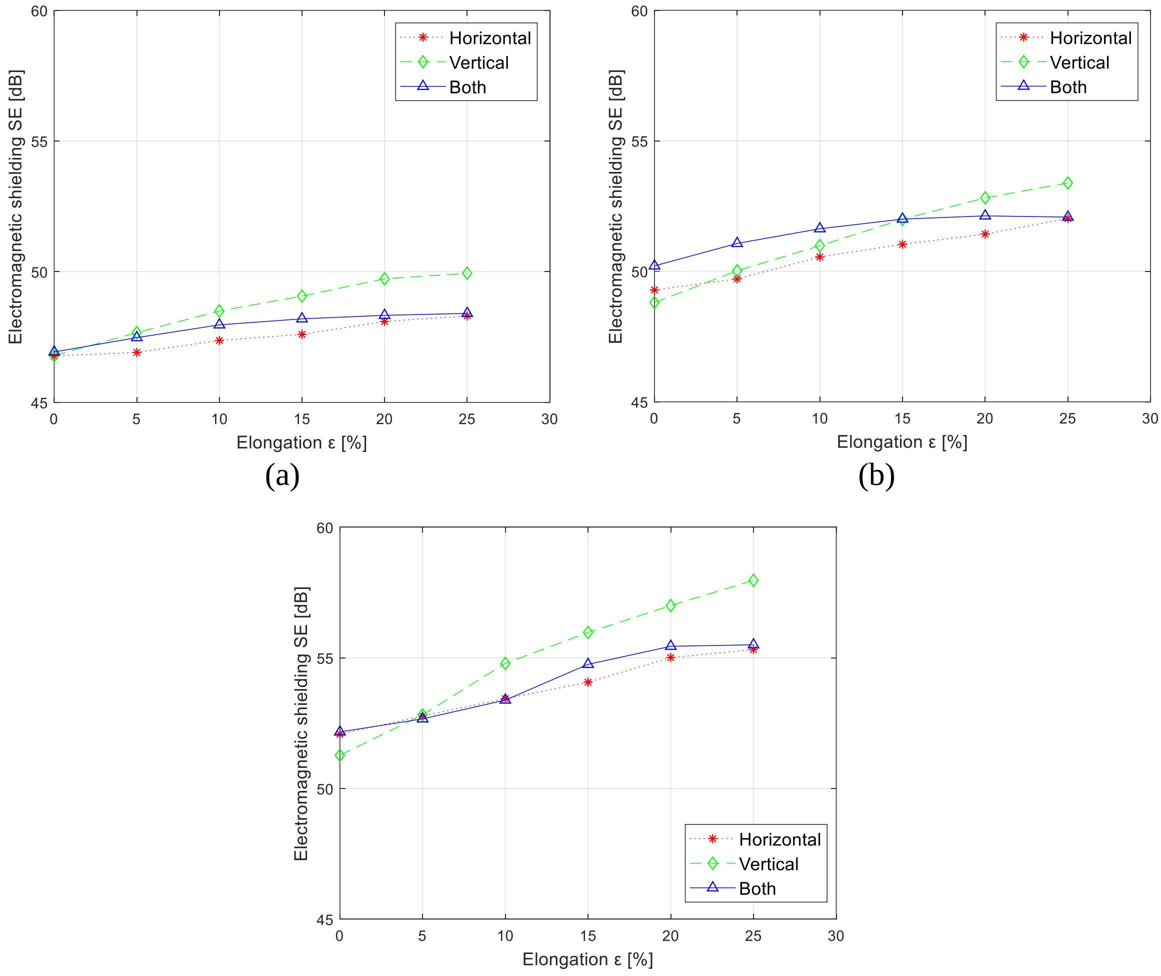
The stretching of the fabric in a uniaxial and biaxial direction changes the fabric geometry, as discussed in the literature review. Equations 30 and 31 determine the change in resistance with a change in fabric strain values. If the electrical resistance changes, then the EM SE also changes because those are indirectly proportional to each other.

In case of knitted fabric extension, the increase of electrical conductivity is expected during the initial extension process as shown during electromechanical analysis of crochet chain, which is caused by an increase in the number of contacts between the yarns in the knit structure. This phenomenon could increase the EM SE. On the other hand, it is expected that the porosity of the sample could increase with sample loading, which could have a negative effect on the SE level. That is why, SE of knitted sample set (single jersey, double jersey having 3 different densities) will be studied during all types of elongation experimentally.

The elongation of the SJ fabrics in a horizontal way, vertical way, and both ways versus EM SE at 1.5 GHz frequency is shown in Figure 16. Studied is SE response during the extension of sample to 25 % elongation. The SJ fabrics are produced at three densities: low, medium, and high, based on their stitch density. All three densities of SJ fabrics increase in SE with an increase in fabric elongation at all directions of stretches, as shown in Figure 16. In Figure 16(a), the SJL fabric SE results are shown, and SE increases with all directions of the elongation. Especially, the vertical direction of the stretch has increased the SE value higher compared with horizontal and both ways stretching with increases in elongation. Both ways, points lie in between vertical and horizontal points. The deviation in the SE is higher in the vertical direction and lowest in the horizontal direction. For SJM and SJH, fabric samples also have higher SE differences at vertical way stretch, but at horizontal and both ways stretching of the samples also increases the SE value with increases in elongation (Figure 16(b,c)). In the vertical direction elongation of the fabric, the wales are expanding, and courses are contracting; wales are tightly constructed, and contact between the yarns increases with elongation; that’s the reason why the SE increases much. The SJL, SJM, and SJH have the SE of 50 dB, 53 dB, and 57 dB at 25 % vertical way elongation. SE is higher for high-density fabric, and the difference between the initial and final elongated SE values also had more difference than other densities.

For the creation of sensors, it seems that the most interesting stretching mode is the vertical stretching of the sample, when a linear increase in SE with elongation is observed for all densities of samples and also during vertical stretch the highest ΔSE ($SE-SE_0$) is achieved, namely approx. 5 dB for a sample with low and medium density and approx. 7 dB for a sample with high density.

The elongation in the percentage of the DJ fabrics in a horizontal way, vertical way, and both ways directions versus EM SE at 1.5 GHz frequency results are shown in Figure 17. The double jersey fabric was prepared also in three densities: low, medium, and high. All the fabrics have the same trend in SE versus elongation graph: the vertical way stretch of the fabric causes linear increase of SE with increasing elongation; the horizontal and both ways stretching fabrics cause first a decrease in SE followed by an increase in SE, however, SE does not exceed SE_0 at 25 % elongation. DJL, DJM, and DJH fabrics results are shown in Figure 17(a), 51(b), and 51(c); all the results follow the same trend as described above. In a vertical way, the difference in SE values at initial to final elongation increases with an increase in fabric density from low to high.



(c)

Figure 16. Dependence of SE [dB] at 1.5 GHz frequency on elongation ε [%] for sample: (a) SJL, (b) SJM, and (c) SJH.

Fabric stretch in a horizontal way for DJ fabrics decreases steeply until 10 % elongation and then increases by 1 dB until 25 % elongation, the SE values from 10-25 % elongation is very less changes. During the both ways stretching, the DJ fabrics SE decreases steeply until 10% elongation and then increases by 3 dB from 10 % to 25 % elongation, the SE value from 10-25 % elongation has average change. Both ways of stretching have very less change in SE values during fabric elongation. The reason for the change in SE with respect to the direction of elongation is further studied with electrical properties and porosity analysis. The main reason behind the change in SE is the changing number of contact points between the yarns; the vertical way produces more contacts, and the horizontal way loosens the structure to create lesser contact points.

If we look at the results considering the requirements for the creation of strain sensors, the use of vertical tensile stress of the samples seems to be the most interesting, where a linear change of SE with a change in elongation is observed, while the average ΔSE is about 3-5 dB.

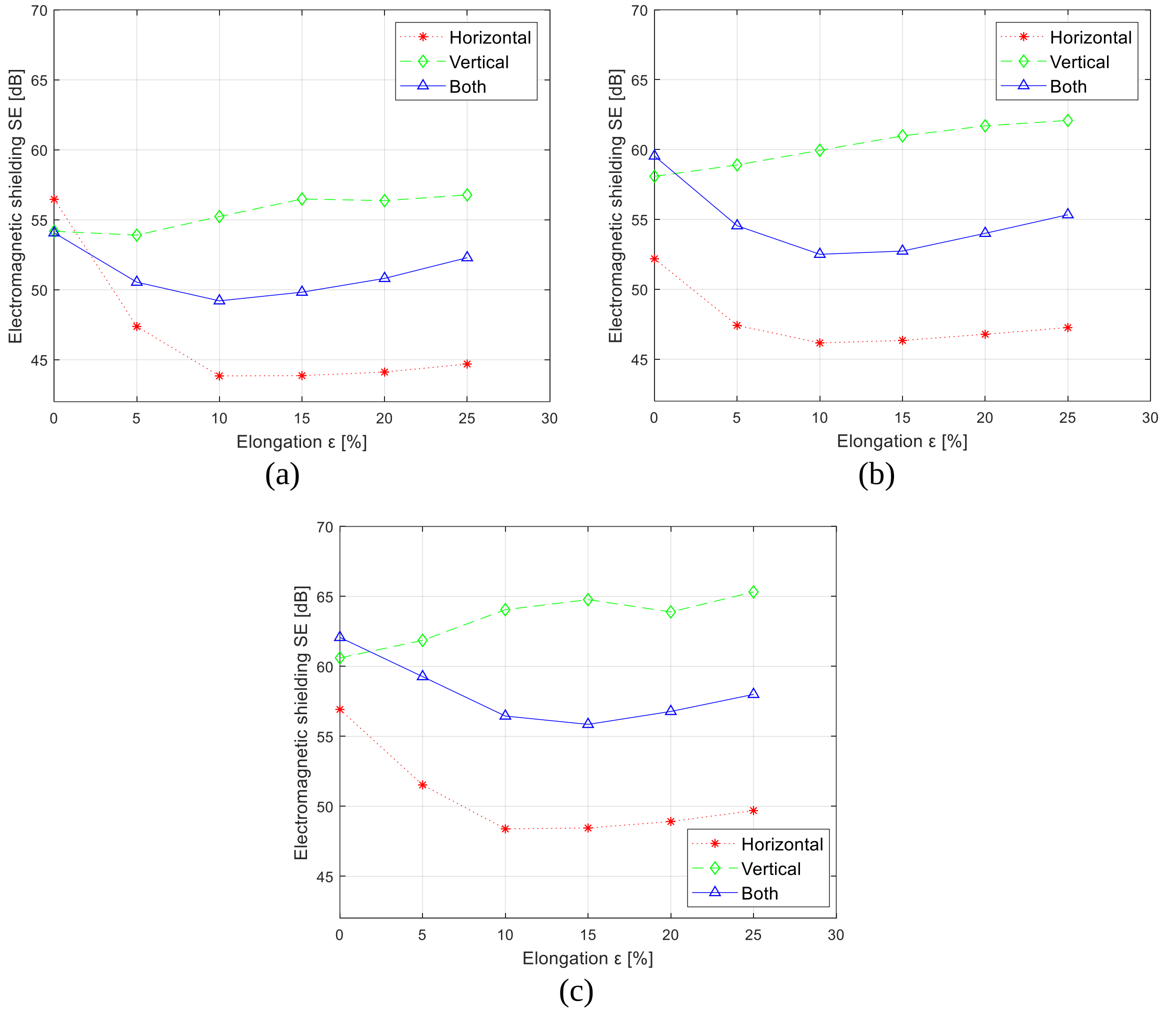
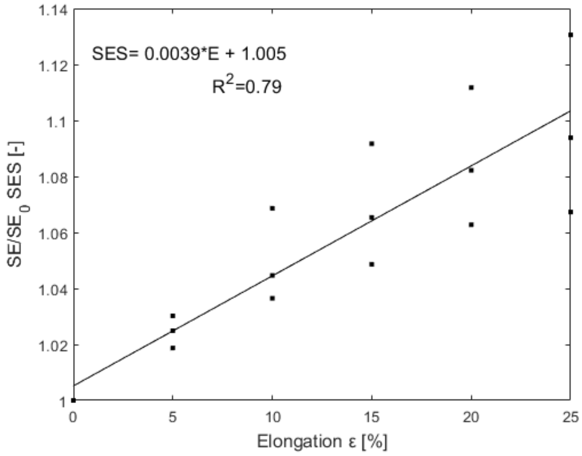
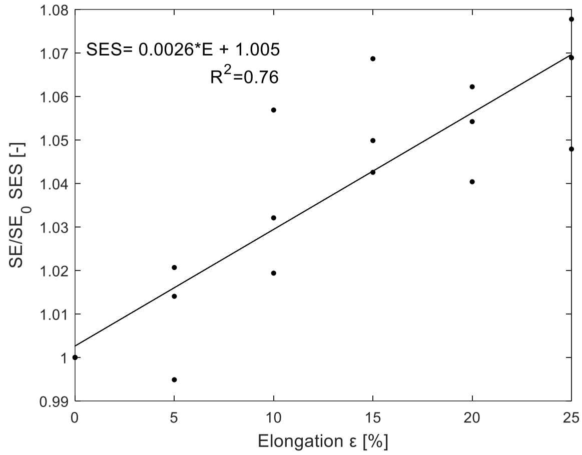


Figure 17. Dependence of SE [dB] at 1.5 GHz frequency on elongation ε [%] of (a) DJL, (b) DJM, and (c) DJH.



(a)



(b)

Figure 18. Dependence of SE sensitivity SE/SE$_0$ [-] at 1.5 GHz frequency for vertical direction of elongation ε [%] of (a) SJ, and (b) DJ.

5.2.6. Effect of knitted fabric elongation on SE sensitivity

The SE sensitivity (SES) or gauge factor is the important parameter for describing the fabrics strain sensitivity results. The gauge factor (GF) is used to indicate the strain sensitivity of the fabric and its formula is given in Eq. 2.

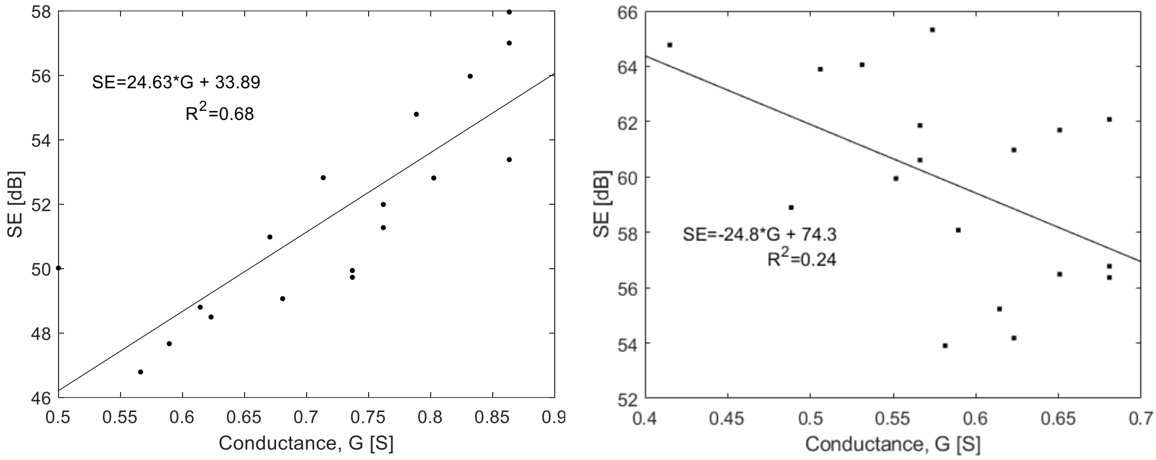
Here the sensitivity based on SE values is shown against the vertical elongation of the fabric samples (Figure 18); because there is one directional change was noticed at vertical elongation for SJ and DJ fabric.

$$\boldsymbol{GF = SES = \frac{SE_x - SE_0}{SE_0} = \frac{\Delta SE}{SE_0}} \quad , \qquad \text{Eq. 2}$$

where, SE_x is the SE value at x % elongation, SE_0 is SE value at 0% elongation, and ΔSE is difference between SE_x and SE_0. The elongation of the SJ fabrics versus EM SE with respect to SE at 0% elongation (SE_0) as also called as SE sensitivity (SES) was shown in Figure 18(a). The SES of the SJ fabrics increases with the increase in elongation at vertical direction. The dependence of SES on elongation has very good correlation and its R^2 is 0.80. The DJ fabrics dependence of SES on vertical elongation of fabric is shown in Figure 18(b). Here, the linear increase of SES with increase in fabric elongation at vertical direction was noticed. The predictability and correlation of SES on elongation for DJ fabrics is very good and its R^2 is 0.76. The vertical elongation of the fabrics results are taken further for regression analysis to find out the correlation between explanatory variables.

5.2.7. Empirical model building

As mentioned above, measurement of SE needs special devices. In addition, measurements of electrical conductivity and porosity of textiles are common tests. Another goal of the work was therefore to describe the behavior of the electromagnetic shielding parameter of knitted fabrics based on the knowledge of their conductivity and porosity in a certain degree of elongation. The aim is therefore to propose 2 prediction equations, for single jersey and for double jersey knitted fabric, valid for all 3 types of samples in terms of their density.



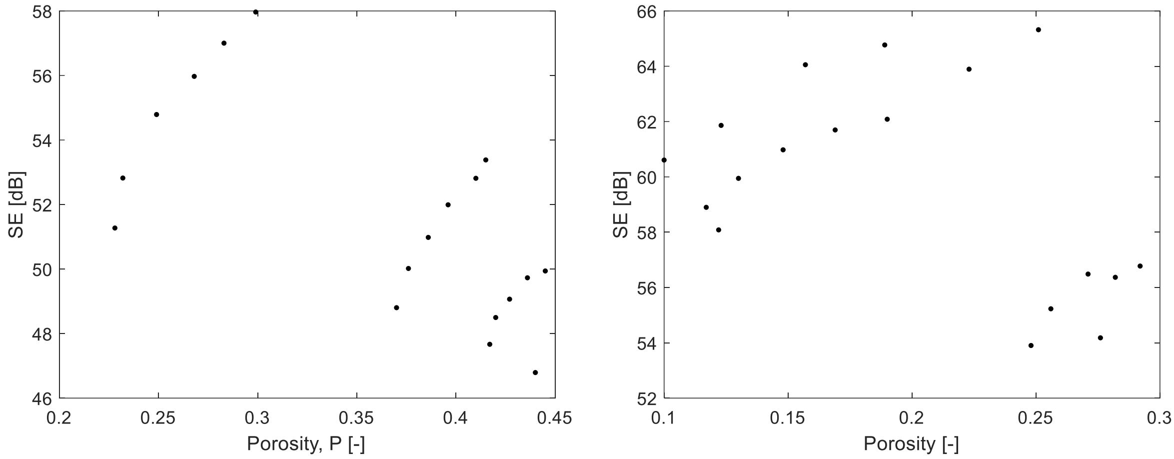
(a) (b)

Figure 19. Dependence of SE on *G* for (a) SJ, (b) DJ fabrics.

This modeling was limited to only one type of such stress, namely in the vertical direction, which seems to be the most interesting for the creation of sensors.

A linear regression model is formed by a linear combination of explanatory variables *x* or their functions. A linear model generally means linear according to the model parameters. This analysis is in fact valid for all types of model where the least-squares criterion is used for model adjustments. Principal regression attacks the problem by regressing y variable on the important principal components and then parceling out the effect of the principal component variables to the original variables [18]. The linear regression model is used for analysis of the results in this part to find out the predictability of *x* variable with respect to *y*. In the first step, dependence of SE on electrical conductance *G* [S] and the dependence of SE on porosity *P* [%] were plotted and investigated in order to choose a suitable approximation model. In Figure 19, the dependence of SE on *G* for both knitted structures is shown, whereas a linear relationship with a relatively high correlation coefficient between the two variables can be observed. The SE at 1.5 GHz frequency versus electrical conductance graph was plotted for wale-wise elongation of SJ fabrics (Figure 19(a)). It was noticed that the increase in fabric electrical conductance increases the SE. Some points in conductance are scattered and make a 2 dB difference in the results; this change in SE is due to the difference in fabric parameters. In Figure 19(b) the conductance, *G* versus SE at 1.5 GHz frequency graph was plotted for wale-wise elongation of DJ fabrics. It was noticed that the increases in electrical conductivity have decreased in SE, but three separate trends were noticed because of three fabric densities.

In Figure 20, the SE dependence on porosity *P* was plotted for SJ and DJ fabric samples during wale-wise elongation. In general, the porosity of the SJ fabrics increases which also increases the SE values as seen in Figure 20(a). This phenomenon is probably not caused by increasing pores in the knitted fabric only, but increasing contact between the yarns as the elongation increases. There are three different data clouds which indicate the three different densities; for higher density fabric the less porosity was noticed and the change in SE was higher and vice versa to lower density fabric.



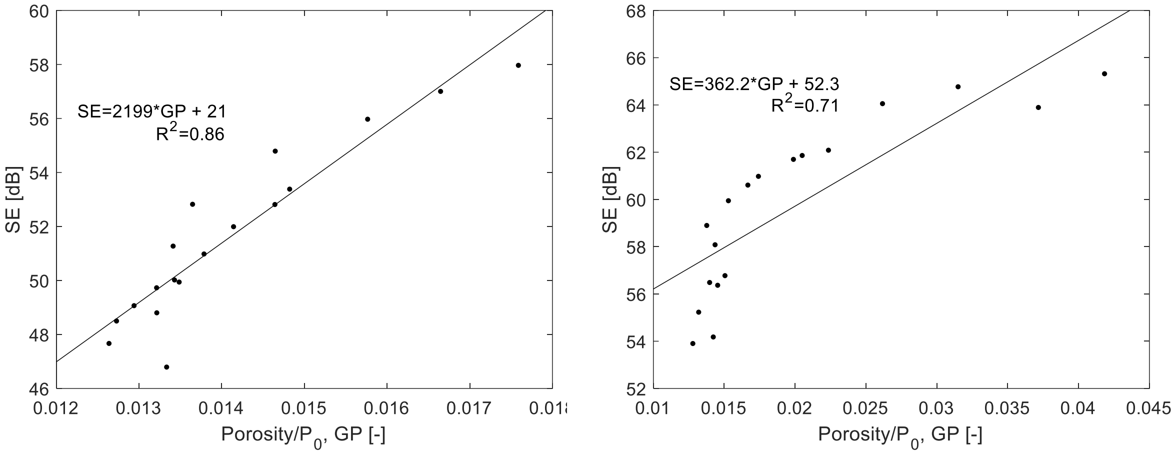
(a) (b)

Figure 20. Dependence of SE on *P* for (a) SJ, (b) DJ fabrics.

The porosity versus SE for DJ fabrics is in Figure 20(b), the porosity increases then the SE values also increase was noticed. Higher density fabrics has higher SE values and changes in SE also higher, lower density fabrics has lesser SE and the changes in SE is lesser compare with medium and higher density fabrics. For exact analysis of the porosity results with irrespective of fabric densities, the gauge porosity was introduced and the results were analyzed.

Figure 21 shows dependence of SE on *P* for both knitted structures. It is visible from the SE, *P* dependence that 3 data groups are distinguishable because the samples differ in the density of rows and columns. For this reason, the relative variable P/P_0 was used (where P is actual porosity at actual level of extension and P_0 is sample porosity in the relaxed state, see Table 2), which describes this dependence better (see Figure 21 where dependence of SE on P/P_0 is shown and approximated by linear model with relatively high correlation coefficient) and the intended relationship will be able to be used universally for any density of knitted sample. SJ fabrics gauge porosity (*GP*) (Porosity/ P_0 (porosity at zero elongation)) was calculated and plotted against the SE at 1.5 GHz frequency in Figure 21 (a); gauge porosity (*GP*) increases which increase the SE is seen in the result. Usually, the increase in porosity increases the transmission of EM radiation. In this case, it is quite the opposite; the reason is that the yarn-to-yarn contact increases during stretching, which leads to an increase in conductivity, so porosity is not affecting the SE. The SE on GP has a high coefficient of determination of 0.86 and it indicates the GP has very good correlation with SE. DJ fabrics GP (Porosity/ P_0 (porosity at zero elongation)) was calculated and plotted against the SE at 1.5 GHz frequency in Figure 21(b).

The SE increases with an increase in GP, and its coefficient of determination is 0.71 means GP has a good correlation. The wale-wise elongation of all the fabric samples follows the linear trend for SE versus GP.



(a) (b)

Figure 21. Dependence of SE on P/P_0 for (a) single jersey, (b) double jersey fabrics.

The modelling part mainly discusses the measured and calculated SE value comparison and regression analysis of the SJ and DJ fabrics elongated in vertical directions. Based on preliminary analysis, two main variables $x_1 = G$, $x_2 = GP$ were selected, see Table 7. The corresponding linear regressing has the form:

$$\boldsymbol{SE = b0 + b1.x1 + b2.x2} \qquad \text{Eq. 3}$$

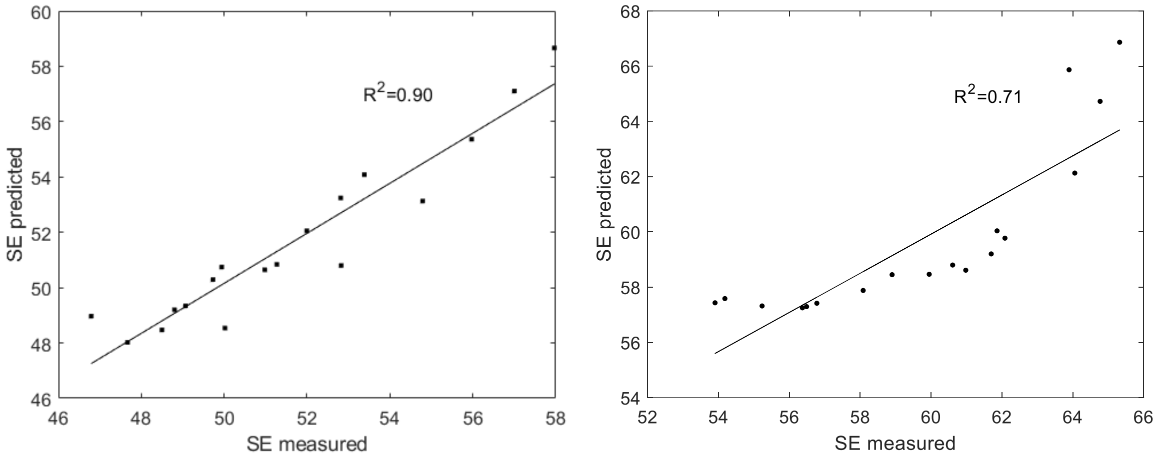
The dependence between measured and predicted SE is shown in Figure 22. The linear regression between the SE predicted versus SE measured for SJ fabrics in Figure 22(a) follows a linear trend, and its coefficient of determination is 0.90, which means the linear model is acceptable for predicting the SE value. The linear regression between the SE predicted versus SE measured for DJ fabrics in Figure 22(b) follows a linear trend, and its R^2 is 0.71, which means the linear model has a good correlation to predict SE value. The coefficients for the linear regression model (Eq. 3) for both types of knit are shown in Table 8. Because the dependences between measured and predicted SE are slightly curved and scattered (especially for the DJ fabric), the partial regression graphs were constructed and explored [18], see Figure 23 and Figure 24.

Due to nonlinearity of the x_2 variable in particular the modified regression model was created using transformation of this variable. The model has the form:

$$\boldsymbol{SE = b0 + b1.x1 + b2.\sqrt{x2}} \qquad \text{Eq. 4}$$

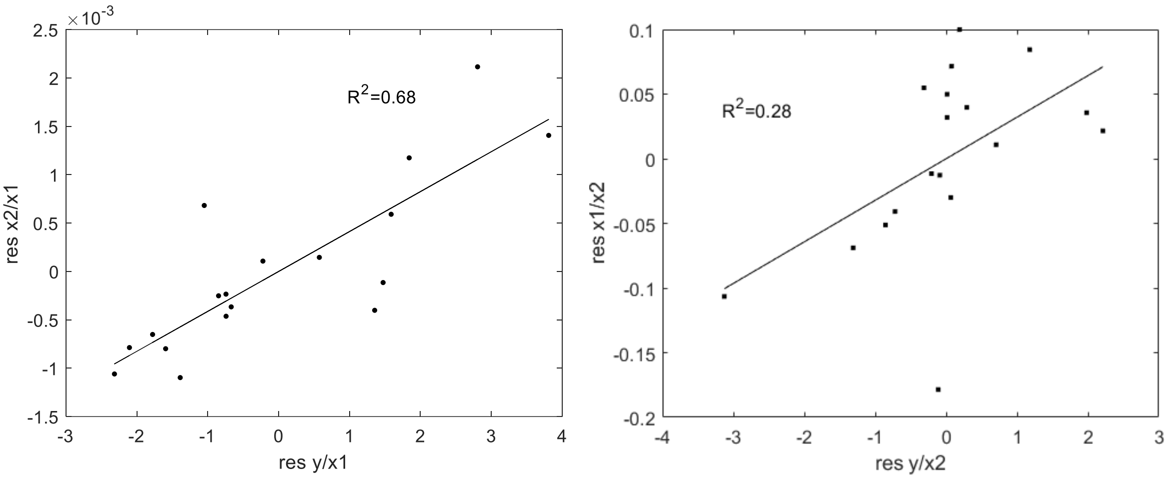
Table 7. Symbols and names.

Symbol	Characteristic name	Characteristic unit
G	Electrical conductance	S
P	Porosity	%
P_0	Initial porosity	%
GP or P/P_0	Gauge porosity	-



(a) (b)

Figure 22. SE measured versus SE predicted using Eq. 3 for (a) SJ, and (b) DJ fabrics.



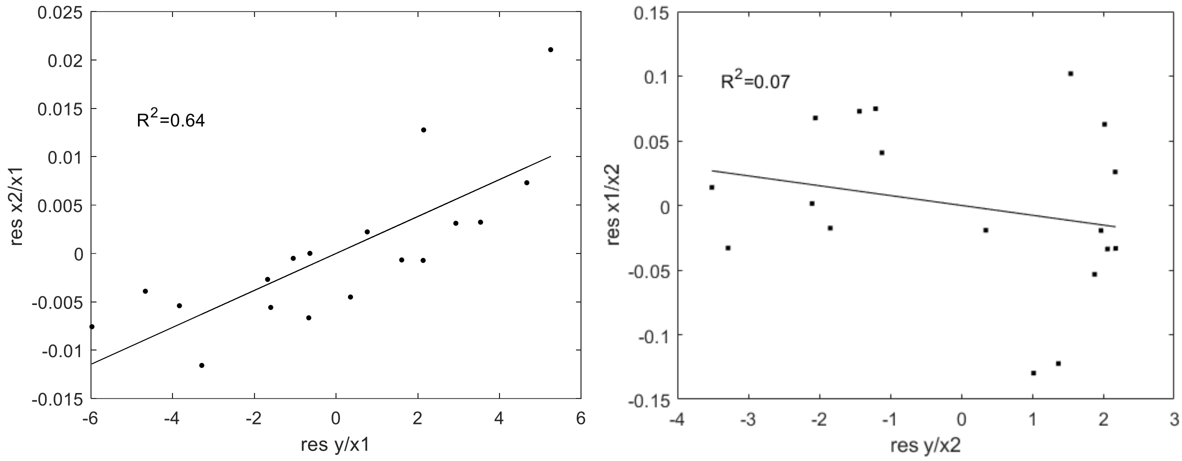
(a) (b)

Figure 23. Partial regression graphs for model (Eq. 3) (a) variable 1, (b) variable 2 for single jersey sample set.

The corresponding coefficient of determination is 0.91 and 0.87 for single jersey and double jersey respectively. The relation between predicted and measured SE for this model is shown in Figure 25. The regression model coefficients are shown in Table 9. The model with square root for x_2 variable or P/P_0 has higher predictability and it is recommended for modelling of the sensors made of electrically conductive knitted fabrics.

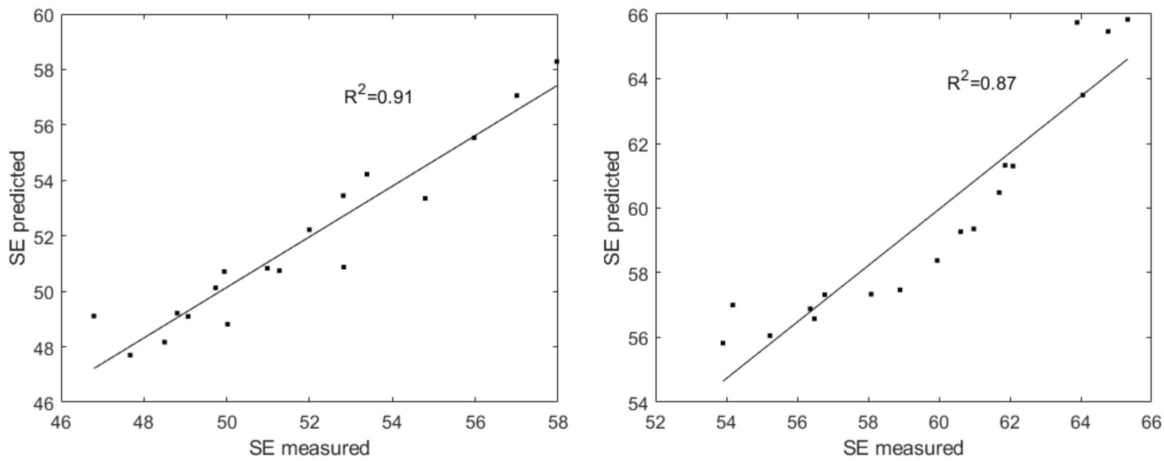
Table 8. Regression coefficients for regression model (Eq. 3) for SJ and DJ

Coefficients	Single jersey	Double jersey
b0	21.85	57.46
b1	8.91	-7.78
b2	1655.38	333.56
R^2	0.90	0.71
Adj. R^2	0.89	0.69



(a) (b)

Figure 24. Partial regression graphs for model (Eq. 3) (a) variable 1, (b) variable 2 for double jersey sample set.



(a) (b)

Figure 25. SE measured versus SE predicted at 1.5 GHz frequency using Eq. 4 of (a) SJ, and (b) DJ fabrics.

Table 9. Regression coefficients for regression model (Eq. 4) for SJ and DJ

Coefficients	Single jersey	Double jersey
b0	73.57	74.05
b1	7.51	-6.7
b2	-0.76	-0.36
R^2	0.91	0.87
Adj. R^2	0.90	0.86

6 EVALUATION OF RESULTS AND NEW FINDINGS

The conductive knitted fabrics were developed successfully for the deformation characteristic. The electromagnetic shielding during the deformation at biaxial stretching of the fabrics is measured.

The main part of the thesis work focused on developing deformation sensors with knitted fabrics. The Ag coated PA yarn was used for preparing the knitted fabric was initially analyzed for its electrical properties during its extension. Three forms of yarns, SY, SLY, and MLY, were used to simulate the simple elements of knitted structure. ER against gauge length was measured proving that ER is highly correlated with gauge length, whereas it was found that SL form has the lowest electrical length resistance caused by its structure. The tensile strength of the SY, SLY, and MLY are 42.4 cN/tex, 61.3 cN/tex, and 72.9 cN/tex, respectively, and breaking elongation is highest for MLY. MLY is imitating the single column of the knitted structure. The electromechanical properties of the yarn forms were analyzed with a tensile tester connected with an ARDUINO resistance circuit, and data were recorded in MATLAB. It was found out that ER decreases initially and then increases with an increase in elongation for MLY and SLY forms, but for SY, the ER increases with an increase in elongation. The number of contact points is influencing the ER against the elongation of yarn, MLY has multiple contact points, and SY has only one contact point. ER of MLY decreases up to 25 % during elongation, but for SLY, it decreases up to 10%; here, the electrical conductivity increases with the increase in contact points proven in yarn forms.

The SJ and DJ (1x1 rib) fabrics were knitted with a flat knitting machine with three various fabric densities, which are analyzed for deformation sensing ability. In most of the literature, ER is used for measuring the strain sensitivity but in this study, EM SE property of the fabric is used as wireless sensing measurement. It is known that the EM SE is inversely proportional to the ER functions of the fabric samples. Moreover, some additional factors like fabric porosity, number of yarn contact points in fabric, and fabric structure has singled out as influential for the SE results. In the relaxed state the EM SE of the SJ fabrics decreases logarithmically with increasing frequency, and the DJ fabric is almost constant throughout the frequency range (30 MHz to 1. 5 GHz). DJ fabrics have higher SE than SJ fabrics because of higher densities. SE difference between the low and high density DJ is 3dB at 1.5 GHz frequency. Increase in fabric density has decreases the porosity, thickness, and SE/GSM but increases the SE/*h*, and SE in SE/GSM. SJL has higher SE/GSM value among the whole set of samples which means the more efficiency of SE was obtained. In the fabrics' basic parameters, the porosity and GSM results are as expected; SE/GSM and SE/*h* are factors for developing the sensor fabrics.

The SJ and DJ fabrics' SE versus elongation results reflect deformation sensitivity. For uniaxial and biaxial elongation of the samples, the biaxial device was used equipped with four independent jaws. SE of SJ samples increased with increasing fabric elongation at all directions, and the change in SE was more significant for higher-density fabrics. DJ samples SE showed a parabolic trend during course-wise and both directional elongation and SE had an increasing trend at wale-wise elongation. On the basis of this research, for the creation of sensors, it is recommended to use SE changes in the wale wise direction of the knitted fabric, where a linear trend was observed under uniaxial tensile stress.

The electrical resistance is indirectly proportional to the SE, which also influences the fabric results. ER is decreased with an increase in elongation at all directions for SJ fabric; for DJ samples, ER increases and then decreases with an increase in elongation at all directions. It was noticed that the wale-wise elongation has a significant difference in SE values, and this way of fabric strain measurement will be suitable for sensor applications. SE increases with an increase in gauge porosity of the SJ and DJ fabric samples. The pore sizes of studied fabrics are in units of micrometers, and the wavelength of 1.5 GHz is 0.19 meters, so it expected that the electromagnetic wave of his frequency cannot penetrate through the fabric. According to the conductance results of wale-wise elongation, the SE increases with SJ and decreases in DJ elongation, but for DJ density wise it conductance was increases. The rib structure contact points loosen by wale-wise elongation, which decreases the fabric's electrical conductivity.

During the modelling of SE depending on the uniaxial tensile stress of knitted samples, two regression models were introduced. As predictor, variables electrical conductance and gauge porosity of the sample at given elongation were chosen. In the first proposed model, only the main effects of SE were considered. Based on the partial regression graph analysis the nonlinearity in the gauge porosity was identified and that is why optimal regression model was created using transformation of this variable. The corresponding coefficients of determination R^2 of this model are shown in Table 8 and Table 9, respectively, which is satisfactory.

This deformation sensor model will be used as wireless strain sensor is mainly focused on replacing the wired strain sensors, which are already used in structural health monitoring and wearable body moment measurements; also able to use in vehicle testing, structural health monitoring, and construction applications. This wireless sensor is cost-effective based on wire-free use. The light weight and portable measuring device for SE is helpful for development of such sensor in future.

7 FUTURE WORK

1. The weft knitted fabric with elastomeric yarn will be improve the fabric recovery after deformation and able to extend it up to 100%.
2. Warp knitted structures with elastomeric yarn also works well for deformation sensing application.
3. The light weight EM shielding measuring device with targeted frequency will be good for this kind of sensors. The device cost will reduce and easy to handle it.
4. The angle of incident EM radiation may change and checking the effect of the sensing ability will be helpful. Also, the absorption, reflection, and transmitted radiation during deformation are good to be analyzing the results.
5. Fabric structure stimulation relates with electrical resistance and contact points with MATLAB, ANSYS, or Python will be improving the design of the work.

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9 LIST OF PUBLICATIONS BY AUTHOR

Author's publications in impact factor journals

Journal Paper	Impact factor*	Quartile **	Citations
1. **S. Palanisamy**, V. Tunakova, and J. Militky, "Fiber-based structures for electromagnetic shielding – comparison of different materials and textile structures," *Text. Res. J.*, vol. 88, no. 17, pp. 1992–2012, 2018.	2.46	2	45
2. **S. Palanisamy** *et al.*, "Electromagnetic interference shielding of metal coated ultrathin nonwoven fabrics and their factorial design," *Polymers.*, vol. 13, no. 4, p. 484, Feb. 2021.	4.97	1	9
3. **S. Palanisamy**, V. Tunakova, J. Militky, and J. Wiener, "Effect of moisture content on the electromagnetic shielding ability of non-conductive textile structures," *Sci. Rep.*, vol. 11, no. 1, pp. 1–10, 2021.	5.00	2	6
4. **S. Palanisamy**, V. Tunakova, M. Tunak, and J. Militky, "Textile-based weft knit strain sensor: Experimental investigation of the effect of stretching on electrical conductivity and electromagnetic shielding," J. Ind. Text., vol. 52, pp. 1–23, 2022.	2.93	1	-
5. T. Yang, **S. Palanisamy** et al., "Experimental and modelling studies on thermal insulation and sound absorption properties of cross-laid nonwoven fabrics," Autex Res. J., pp. 1–8, 2021.	1.94	2	2
6. T. Yang, **S. Palanisamy** et al., "AFDeter: A MATLAB-based tool for simple and rapid determination of the structural parameters and the airflow-related properties of fibrous materials," SoftwareX, vol. 20, p. 101213, 2022.	2.69	2	-
7. M. Shahid, **S. Palanisamy** et al., "Copper-treated environmentally friendly antipathogenic cotton fabric with modified reactive blue 4 dye to improve its antibacterial and aesthetic properties," Coatings, vol. 13, no. 1, p. 133, 2023.	3.24	2	-

* – Impact factor was taken from year 2021. ** - JCR category quartile based on Web of Science.

Publications in conference proceedings

Conference paper/ abstract	Index
1. **S. Palanisamy,** V. Tunakova, D Karthik, et al., “Study on textile comfort properties of polypropylene blended stainless steel woven fabric for the application of electromagnetic shielding effectiveness,” IOP Conf. Series: *Materials Science and Engineering,* pp. 254, 2017.	Web of science
2. **S. Palanisamy**, V. Tunakova, et al.. “EMI shielding of the copper/ nickel coated nonwoven,” *AUTEX 2021 International conference*, pp. 410-411, 2021, Guimaraes, Portugal. (Published in Diffusion and Defect Data pt.B: Solid State Phenomena (2022, vol 333, pp 137-142))	Scopus
3. **S. Palanisamy,** V. Tunakova, et al. “Modeling of an electrically conductive nonwoven strip for electromagnetic shielding,” *TBIS 2021 international conference*, pp. 37-43, 2021, Roubaix, France.	Scopus
4. **S. Palaniamy,** et al.. “An analysis of the carbon preforms for electromagnetic shielding,” *International conference on polymers and composites (ICPC-2021*), 2021, Faisalabad, Pakistan	-
5. **S. Palanisamy**, V. Tunakova, et al. “Wireless sensing properties of electrically conductive knitted structures,” ***4th Indonesian Textile Conference,*** 2022, Bandung, Indonesia.	-
6. **S. Palanisamy**, V. Tunakova, et al. “Impact of bi-axial stretching of rib knitted fabric on its emi shielding” *The 15th Textile Bioengineering and Informatics Symposium, 2022,* Liberec, Czech Republic.	Scopus
7. **S. Palanisamy**, et al. “Bi-axial stretching of rib knitted fabric and its EMI shielding,” *23rd STRUTEX*, 2022, Liberec, Czech Republic.	-
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9. D. Karthik, V. Baheti, V. Tunakova, J. Militky and **S. Palanisamy**. “Development of electrically conductive activated carbon fabric from kevlar fabric for effective EMI shielding applications,” *Textile Bioengineering and Informatics Symposium,* 2017.	Web of Science
10. D. Karthik, V. Baheti, J. Militky and **S. Palanisamy.** “Studies on organic and inorganic micro/nano particle reinforced epoxy composites,” *Textile Bioengineering and Informatics Symposium Proceedings*, pp.149, 2018.	Web of Science
11. A. Ali, H. Taimoor A. Awan, A. Aslam, A. Ali**, S. Palaniamy**, D. kremenakova, “Electrically conductive sustainable green composites,” *International conference on polymers and composites (ICPC-2021),* 2021, Faisalabad, Pakistan.	-
12. A. Ali, J. Militky, **S. Palanisamy** et al., “Copper and silver coated cotton fabrics,” *23rd STRUTEX*, 2022, Liberec, Czech Republic.	-

10 CURRICULUM VITAE

PERSONAL INFORMATION

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E-mail	**sundar2026@gmail.com**
Nationality	Indian
Date of birth	13/10/1987

WORK EXPERIENCE

• Dates (from – to)	June 2010 – June 2015
• Name and address of employer	The South India Textile Research Association, Coimbatore 641014, India
• Type of business or sector	Textile industrial services, Liaison, Testing, Research & Development etc.,.
• Occupation or position held	Junior Scientific Officer
• Main activities and responsibilities	Research & Development coordinator for Medical Textile Products, Preparation of Project Proposal for Textile Research, Electrospinning Project Co-coordinator, Fabric Analysis Lab In-charge, Fabric Defect Analysis Technician (Production to Processing), Gave Lectures to Trainers in Technical Textiles, Nonwoven, Weaving & Knitting.

RESEARCH INTERNSHIP

• Dates (from – to)	June 2016 – July 2016
• Name of organisation and place	G.V. Creations, Tirupur, India
• Main activity	Development of knitted fabric and testing of it.
• Dates (from – to)	September 2017 – November 2017
• Name of organisation and place	Georgia Institute of Technology, Atlanta, USA.
• Main activity	Development of conductive coating on the knitted fabric and analysis of it.
• Dates (from – to)	July 2018 – August 2018
• Name of organisation and place	Ghent University, Ghent, Belgium.
• Main activity	Development of pressure sensor using the conductive knitted fabrics.

AWARDS

• Conference	TBIS 2021 – Best oral presentation award.

EDUCATION AND TRAINING

• Dates (from – to)	July 2015 - Present
• Name and type of organisation providing education and training	Technical University of Liberec, Liberec, Czechia.
• Principal subjects/occupational skills covered	PhD Student in Textile Techniques and Material Engineering / Researcher. Research & Development of Textile Conductive Fabrics and Electromagnetic Shielding Property.

• Title of qualification awarded	Best presenter award 2021, TBIS conference.
• Dates (from – to)	2008 - 2010
• Name and type of organisation providing education and training	A.C. Tech Campus, Anna University, Chennai, India.
• Principal subjects/occupational skills covered	Master of Technology in Textile Technology / Student. Electrospinning of Nanofibers, Electromagnetic Shielding Test and Textile Testing Techniques.
• Title of qualification awarded	M.Tech
• Level in national classification	First Class
• Dates (from – to)	2004 - 2008
• Name and type of organisation providing education and training	K.S. Rangasamy College of Technology, Trichengode, Tamil Nadu, India.
• Principal subjects/occupational skills covered	Bachelor of Technology in Textile Technology / Student. Basics in Textiles, Electrical, Mechanical, Textile Testing Techniques, Textile Machinery Technology, Textile Processing
• Title of qualification awarded	B.Tech
• Level in national classification	First Class with Distinction

PERSONAL SKILLS AND COMPETENCES	LOGICAL THINKING, INNOVATIVE, RESPECTFUL, ADAPTABILITY, COLLABORATIVE, HONESTY.
MOTHER TONGUE	**TAMIL**
OTHER LANGUAGES	**ENGLISH, CZECH (BASICS), KANNADA.**
	TAMIL & ENGLISH
• Reading skills	EXCELLENT
• Writing skills	EXCELLENT
• Verbal skills	EXCELLENT
SOCIAL SKILLS AND COMPETENCES	PARTICIPATED IN TECHNICAL WORK SHOPS, PRESENTED RESEARCH WORK IN INTERNATIONAL CONFERENCES, COLLABORATIVE PROJECT WORK, INTERNSHIP WORK IN FOREIGN COUNTRIES.
ORGANISATIONAL SKILLS AND COMPETENCES	LAB IN CHARGE FOR FABRIC ANALYSIS LAB, VOLUNTEER IN CONFERENCE ORGANISING COMMITTEE, CONDUCTED TRAINING CLASSES FOR ENTREPRENEURS AND INTERNATIONAL STUDENTS.
TECHNICAL SKILLS AND COMPETENCES	MICROSOFT OFFICE (WORD, POWER POINT AND EXCEL), TUKA CAD FABRIC DESIGNING, MAT LAB BASICS, TEXTILE TESTING STANDARDS, MINITAB STATISTICAL ANALYSIS, ORIGIN PRO.
OTHER SKILLS AND COMPETENCES	SWIMMING, CRICKET, SKIING, TRX, CAROM, CHESS, AND VIDEO GAMES.
DRIVING LICENSE(S)	AM, B, B1 - (Europe), M/CYCL. WG, LMV - (India).
RESIDENTIAL STATUS	Czech Residence permit (Until August 2023).

11 Recommendation of Supervisor

Supervisor's recommendation on dissertation thesis of Sundaramoorthy Palanisamy, M.Tech.

Thesis title:
Knitted Conductive Fabrics with Enhanced Electromagentic Interference Shielding

The dissertation thesis of the student S. Palanisamy, M.Tech. is focused on the preparation and research of the properties of electrically conductive knitted fabrics under tensile stress (possible application for strain sensing). In particular, the change in electrical conductivity and the related ability to shield the electromagnetic field of the knitted sample under tensile stress were studied, both unidirectionally and bidirectionally. The thickness and porosity during tensile stress of the sample were also evaluated.

In order to be able to properly interpret the electro-mechanical behavior of knitted fabrics, student also performed experiments with basic textile elements such as single yarn, loop and crocheted chain. In this case, the change in electrical conductivity during stretching was also evaluated and the effect of length and contact resistance was identified.

Last but not least, the student proposed a multiple linear regression model that can be used to predict the level of electromagnetic shielding efficiency based on the knowledge of the electrical conductivity and porosity of the knitted fabric.

It should be mentioned that besides the main subject of the thesis, the student worked on several other research tasks related to the electromagnetic shielding ability of textiles. These results have been partially published and are mentioned in the literature review part of this thesis.

In terms of formality, the thesis is well prepared. The student was independent and patient during his work. The experiment was carried out systematically with specific objectives. The data processing and discussion of results is logical and well organized. The use of MatLab software can be positively evaluated both for basic statistical processing and for all visualization of measured data. The language level of the thesis is good and meets the PhD level. The plagiarism check was carried out on March 8, 2023 and any suspicious match with other works was found.

It can be concluded that some of results are quite innovative and were already published in journals with relatively high impact factor. In total he has already published (based on results from his research topic) 4 papers in journals included in 1st and 2nd JIF quartile based on Web of Science database, whereas another paper containing the main results of the dissertation will be submitted to the chosen journal soon. Student further presented the results of his thesis in the form of a poster or lecture at a number of international conferences. In 2021 he received an award for the best oral presentation during the Textile Bioengineering and Informatics Society conference.

The student was active in solving research projects. He was a member of 4 Student grant competition projects in the years 2017-2022. He also contributed by his research activities to the solution of the Hybrid Materials for Hierarchical Structures and Modular Platform for Autonomous Chassis of Specialized Electric Vehicles for Freight and Equipment Transportation projects (provider: Ministry of Education, Youth and Sports, Czech Republic).

During his studies, the doctoral student completed two two-month internships (G. V. Creations, India; Ghent University, Belgium) nad one three-month internship (Georgia Institute of Technology, USA). During the mentioned internships, the student devoted himself to the preparation of knitted samples, electrically conductive coatings and development of pressure sensors using electrically conductive knitted fabrics.

I believe that the goals of S. Palanisamy, M.Tech. thesis were fulfilled, the student demonstrated the ability of independent creative work, presented the results at international conferences and the results of the work have been published in scientific journals.

For the following reasons I recommend the thesis for a final defense.

March 10, 2023

Ing. Veronika Tunáková, Ph.D.
Department of Material Engineering
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12 Reviews of the Opponents

doc. Ing. Lukáš Vojtěch, Ph.D.
Department of Telecommunication Engineering
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Prague 31.05.2023

Report on doctoral dissertation

Knitted Conductive Fabrics With Enhanced Electromagnetic Interference Shielding
Author: Sundaramoorthy Palanisamy, M.Tech.

1. Relevance of the chosen topic of the dissertation

The work is focused on the study of the influence of deformations of electrically conductive knitted fabrics on their electrical parameters. The effect of deformations on electrical volume conductivity and electromagnetic shielding efficiency (ESE) in the band 30 MHz to 1.5 GHz is studied in particular. The motivation for solving the topic is the current need for knowledge of changes in the behavior of flat textile structures when they are stressed in applications of electromagnetic shielding and especially in the perspective area of the realization of textile sensors. The topic of the dissertation is highly topical in the field of electrically conductive textiles.

2. Definition and fulfillment of the objectives of the dissertation

In his dissertation, the author sets 4 basic goals, which he further fulfills in the work.

- To study the contact force resistance of different arrangements of silver coated yarn simulating their interaction in knitted fabrics
- To design the special device measuring electrical resistance of linear structures during stretching
- To prepare silver coated knitted fabrics suitable for deformation sensors design
- To investigate the strain sensing ability of the weft-knitted samples against the EM waves and electrical conductivity

In his work, the author discusses the current state of knowledge in the field of methods and approaches to the realization and measurement of textiles ESE, as well as the influences that affect ESE (used material, textile construction, operating conditions...). The basic analysis is also devoted to the use of textile structures for the realization of textile resistance sensors. At the end of the general part, the author defines research gaps.

- p. 45-47: "Effect of apertures on EM SE, Palanisamy et al. [3] studied structural parameters of samples affecting the EM SE. Instead of using the textile structures directly, the copper-coated nonwoven fabric was cut into strips and samples with different pore types were created to evaluate the effect of the contact points, pore size, and pore shape described by laying angle on EM SE." The observation about the effect of apertures on ESE is already quite clear from ESE theory and electromagnetic field theory.
- p. 54: "So, the contact resistance of the yarns plays an important role during fabric extension." Yes, it is the main point of contact that must affect the overall resistance of the structure.
- p. 54: "Most of the studies confirmed that the multiple contacts of conductive yarns in the fabric structure cause a decrease in electrical resistance during fabric elongation." Yes, it is a parallel connection of variable resistors
- p. 54: "An increase in contact force decreases the contact resistance of the knitted fabric, which was performed by Holm's electric contact theory." Yes, as the pressure on the contact increases, the contact resistance usually always decreases.
- p. 65: What is the input resistance of the circuit for measuring using the Arduino platform? What is the error of this measurement?
- p. 82, 83, 84, 92: The accuracy of the measurement of the ESE method using the ASTM adapter is significantly influenced by the calibration and the thickness of the material used. When stretching the fabric, its thickness and density certainly change. How was this effect taken into account when calibrating the product?
- p. 101: What is the reliability of the proposed model? How will the results change at other frequencies?

4. Methods of preparing a dissertation

The author of the thesis is very competent and also experimentally skilled in the field of textile materials. In his work, he was able to find and use interdisciplinary overlaps between textile technologies and electrical engineering.

The current state of knowledge and technologies used by the author are relatively well described in the work. In my work, however, I lack deeper analysis and clear delineation in relation to existing publications and projects, especially in the related field of electromagnetic field theory, electromagnetic compatibility and their connection with material structures used in electrical engineering. To a certain extent, however, this shortcoming can be understood and tolerated, especially considering the textile focus of the dissertation field and the author himself.

volume resistivity is due to the measurement error of individual types of resistivity, especially in the used band of 30 MHz to 1.5 GHz.

5. Evaluation of the formal side of the work, including the characteristics of the selection and use of resources

From a formal point of view, the work is at a good level. However, I lack deeper analytical work, systematic motivation and better use of scientific work methods and the inclusion of deeper knowledge from electrical engineering. Some observations made from the measurements and experiments carried out are certainly new in the field of textile technology, but are more or less known in the field of electrical engineering. However, this fact does not significantly reduce the contribution of the author, especially thanks to the connection between two scientific fields. The work would benefit from a set of recommendations for furthering the author's work.

6. Fulfillment of the conditions of independent creative scientific work and publication activity

The student demonstrated the ability of independent creative and publishing activity - see also the list of publications where the author of this work is a co-author and where the core of the dissertation is published. The author should clearly explain the scientific methods and procedures used (explain them during his defense). The work would benefit from a deeper theoretical investigation of the given issue, especially from the point of view of modeling related to theoretical electrical models and systems.

7. Defense questions

In the thesis, you state the motivation or assumption that monitoring (measurement) of electrical conductivity using ESE measurements is advantageous from a practical point of view. What practical advantages do you see in this approach?

Figure 14 describes the dependence of ESE on moisture content. You give the ESE values in the range of 0 to 1 dB. What is the error of the method you used? How did you calibrate the apparatus for individual samples?

In Figure 18, you publish the results of the experiment "dependence of electromagnetic shielding effectiveness on surface and volume resistivity". Please clarify the effect of surface and bulk conductivity on ESE, as well as the method used to measure these conductivity parameters.

On page p. 65 you describe the use of the Arduino platform. What is the input resistance of the circuit for measuring using the Arduino platform? What is the error of this resistance measurement (instrument and method error) method?

On pages p. 82, 83, 84, 92, you describe the effect of fabric deformation on the ESE change. The accuracy of measuring the ESE method using the ASTM D4935 adapter depends mainly on the calibration and therefore also on the thickness of the material used. When stretching the fabric, its thickness and density certainly change. How was this influence taken into account during the calibration of the sample and in the measurements you made?

On page 101, you describe model for calculating ESE based on electrical conductivity, porosity, and fabric deformation. What is the reliability and sensitivity of the proposed model? For which domain of input parameters does this model apply? Will the model be applicable to other frequencies?

8. Summary assessment

The results of the presented work are published in impact factor journals / proceedings. The author demonstrated the ability of independent scientific work in the given field and was able to involve interdisciplinary overlaps. I consider this fact to be a significant contribution both to the author himself and to the development in the field of technical textiles. The achieved results are a contribution to knowledge in the field of dissertation. I recommend this thesis for the defense.

OPPONENT'S ASSESSMENT OF A DOCTORAL DISSERTATION

Author: Sundaramoorthy Palanisamy, M.Tech.

Title: Knitted Conductive Fabrics With Enhanced Electromagnetic Interference Shielding

Opponent: Assoc. Prof. Dr. Deniz DURAN KAYA

The submitted dissertation is concerned with the development of electrically conductive knitted fabrics made of silver-coated yarns and their deformation characteristics. Electrically conductive textiles is one of the emerging fields of textiles. Protection of human beings and sensitive electronic devices from the hazardous effects of electromagnetic radiation is essential. The electrically conductive textile material has the property of shielding the EM radiation and it can be newly used also for deformation sensing applications. The applied strain on textile fabric changes the electrical conductivity and also changes the EM shielding; in this way, the sensor works as a strain sensor. The main goal of this reseacrh is development of a wireless sensor based on the principle of changing the electromagnetic shielding property of the textile during the applied tensile stress. Therefore it is a very current topic and the results an be applied to many sectors such as healthcare, automotive, military applications and etc.

The dissertation, written in English, is consisted of 114 pages. It was complied by researching fro 99 literature sources. Theoretical analyses is suitsble complemented with the results of the author's own research.

The experimental work is consisted of two parts. In the first part, electrically conductive yarn is analysed in means of electrical and tensile properties. For this purpose, a commercially available conductive silver-plated polyamide yarn was used. Three different yarn configurations, namelysingle yarn (SY), single loop yarn (SLY) and multiloop yarn (MLY) were used to simulate the electrical resistance of the yarn related with its length and to simulate the effect of contact resistance. Electrical resistance was tested for all yarn arrangements. The tensile strength of the yarn arrangements was analyzed by tensile stress. Changes in electrical resistance during tensile stress were evaluated using Arduino resistance circuit probes that were connected to the jaws of the tensile strength tester and real-time values were recorded using a MATLAB software program.

In the second part of the experimental work, electrically conductive knitted fabrics were analysed. Knitted fabrics were stretched and characterised in means of electromagnetic shielding, electrical resistance and porosity. For this purpose, two patterns of knitwear, namely a plain single jersey and a 1x1 ribbed double jersey were produced on a flat knitting machine, with three different densities (low, medium and high) for each pattern. Then, the effect of deformation on changes in electrical characteristics is measured by the high-frequency electromagnetic radiation (EM) shielding method. Electromagnetic shielding (SE) effectiveness of knitted fabrics was tested in of 30 MHz to 1.5 GHz frequency range, according to the ASTM D4935-18 standard. A special device was used for tensile deformation of knitted samples in one direction (transverse and longitudinal) and in two directions (biaxial).

Finally, a stochastic model based on multiple regression analysis and using partial regression graphs was proposed to predict the effectiveness of electromagnetic shielding of knitted fabrics.

I find the main objectives and results of the thesis very important and useful for both in means of design and development of new electroconductive and EM shielding products and in means of new researches in this field. Also, I really appreciate designing the special device measuring electrical resistance of linear structures during stretching, which can be used in further projects. The thesis is also valuable since both the yarn from which the knitted fabrics are created and the knitted fabric itself are investigated extensively.

In my opinion, thesis makes a significant contribution to the literature by describing the behavior of the electromagnetic shielding parameter of knitted fabrics based on the knowledge of their conductivity and porosity in a certain degree of elongation. The work done in the thesis is valuable since there are very few studies on EM SE against fabric elongation.

When evaluating the dissertation, it can be said that research results have become a basis for a number of academic outputs, namely; 7 articles and 12 conference papers. Most of the findings are published in high-impact journals, the results of these studies are discussed in more detail in the literature review section of the thesis.

In the whole, the thesis is carefully structured, the sections are logically linked and results are clearly laid and discussed in detail. The results obtained from the thesis will pace the way for many other projects in the filed of electrically conductive and electromagnetic shielding textiles.

Some minor remarks from my part are summarised below:

1. Page 15, second line in "Purpose and Aim of the Research" part, can be corrected as "….electrically conductive textiles are…… ".
2. Page 15, fifth and seventh lines in "Purpose and Aim of the Research" part, can be corrected as "….textile materials…… ".
3. Page 61, in " Research Gaps" part line 4 "…the…" is not necessary.
4. Page 63, in the title of Table 5,"a" is not necessary

To conclude, I state that the dissertation thesis fulfils the required criteria and the Ph.D. candidate has the required knowledge in the field. I recommend the dissertation thesis submitted by Sundaramoorthy Palanisamy, M.Tech.for dissertation defence and also i recommend that the Ph.D. degree should be awarded.

In Izmir, 7 May 2023 Assoc. Prof. Dr. Deniz DURAN KAYA