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Influence of Knitting Structure and Metal Wire Amount on Electromagnetic Shielding Effectiveness of Knitted Fabrics

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ABSTRACT

In this study, the influence of knitting structure and metal wire amount on the electromagnetic shielding effectiveness (EMSE) of knitted fabrics were investigated comparatively. Single jersey, single pique, weft locknit, and cross miss fabrics involving stainless steel or copper wires were produced on a flat knitting machine. In order to measure the EMSE, a free space measurement method was used in an anechoic chamber because of its high reproducibility and accuracy. The variance analysis results of the EMSE values showed that knitting structure, metal wire type, metal wire amount, and incident wave frequency is highly significant. It was observed that fabrics with tuck and miss loop structures had higher EMSE values than single jersey fabrics. Also, single pique fabrics had higher EMSE than single jersey fabrics that contain twice as much metal wire. It indicates that the knitting structure has a great effect on EMSE rather than the amount of the conductive material.

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1. INTRODUCTION

The proliferation of electricity demand, ever-advancing technologies such as AM and FM radio, television, cordless and mobile phones, base station transmitters, wireless networks, cordless baby monitors, garage door openers, global positioning systems, microwave ovens, radar, etc. and changes in social behavior have dramatically increased our exposure to electromagnetic radiation (EMR), or electromagnetic fields (EMF) in the last two decades. Therefore, everyone is exposed to a complex mix of weak electric and magnetic fields, both at home and at work[1]. While the health impacts of this form of radiation are inconclusive[2–4], many people are concerned about how long-term exposure to excessive EMR may impact human health and nature. As a result, a need to develop textile products that implement electromagnetic shielding has occurred[5].

The electromagnetic shielding effectiveness (EMSE) of a shielding material is related to the residual traveling energy after applying the shield. The residual energy is the energy that is neither reflected nor absorbed by the shield, but that emerges out of the shielding material[6]. EMSE can be measured with different methods as reported by the standards [7–10].

Conductive fabrics have been used to shield electromagnetic fields in the defense, electrical, and electronic industries[6]. Metallic coated yarns, metal wires, metallic fibers, conductive polymers, or composite yarns are used for producing electromagnetic shielding textile materials. Electromagnetic shielding fabrics are produced via various types of fabric production techniques, including knitting, weaving, or nonwoven. Conductive fabric reinforced composites and conductive material coated fabrics are also used as electromagnetic shielding textile materials. [11].

There have been some researches about the EMSE properties of knitted fabrics in literature. Researchers used the free space measurement technique, the shielded box shielding efficiency measurement technique, and the coaxial transmission line technique. Palamutçu et al.[12]

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designed a new setup to measure EMSE based on the free space technique. They investigated the EMSE of four kinds of single jersey knitted fabrics (860 - 960 MHz, 1.750 - 1.850 GHz). Çeken et al.[13–15] and Kayacan[16] also designed an EMSE setup based on the free space technique as well. In their study, they investigated the EMSE of knitted fabrics (750 MHz - 3 GHz) under room conditions. Çeken et al. investigated the EMSE of plain, rib, full cardigan, plain knitted fabrics with one and two miss stitch rows [13], cross-miss 1x1 plain knit, single pique, interlock, double pique [14] and six types of knitted fabrics with their backside covered with conductive yarns [15]. Kayacan [16] also investigated the EMSE of single jersey and interlock knitted fabrics before and after washing cycles. Ciesielska-Wróbel and Grabowska[17] examined the EMSE of three kinds of knitted fabric samples, namely single -left-right stitch, double - a sleeve type - left-right stitch, and double - left-right stitch - layer exchange. The EMSE values were measured for the electric field (30 Hz - 6 GHz) and for the magnetic field (10 Hz - 1 GHz) using isotropic E-field and H-field probes. Özkan studied the antimicrobial and EMSE properties of metal composite single jersey[18] and 1x1 rib fabrics[19, 20]. EMSE of samples was measured according to the free space test method (0.8 - 5.2 GHz). Tezel et al.[11] investigated the EMSE with both the coaxial transmission line (100 MHz - 1.5 GHz) and free space measurement (1 GHz - 18 GHz) techniques on single jersey fabrics. Mühl and Obelenski[21] investigated the EMSE of jersey fabrics which consist of cotton yarns including silver coated polyamide fibers and warp-knitted fabrics produced with a weft lapping technique. A shielded box shielding efficiency measurement set-up (800 MHz - 3 GHz) was used to measure the EMSE. Stegmaier et al.[22] designed a shielded box EMSE test device. The researchers measured the EMSE of knitted fabrics including silver coated filaments (250 MHz - 3 GHz). Perumalraj and Dasaradan[23] examined the EMSE of rib, interlock, and single jersey samples produced with Cu wire/cotton fiber core yarns. They used shielded box shielding efficiency measurement method (800 MHz - 3 GHz). Örtlek et al.[24] examined the EMSE of pique, plain (E28), and double-knit structures (E18) with the shielded box shielding efficiency measurement method (30 MHz - 9.93 GHz). Apart from the studies performed with the free space measurement technique[11–20] and the shielded box shielding efficiency measurement technique[21–24], there are also studies on EMSE of knitted fabrics performed with the coaxial transmission line technique[11, 25–44]. Knitted fabrics give different EMSE values for each frequency when measured with different measurement techniques and / or different polarizations[11]. In other words, the results of the coaxial transmission line technique are not directly comparable with shielded box and free space measurement techniques.

The main point of EMSE measurement is to minimize the electromagnetic noise caused by electrical devices, mobile phones, base stations, and Wi-Fi transmitters. In other words, the electromagnetic noise caused by the environment affects the test accuracy. In this study the free space measurement technique by using an anechoic chamber was preferred for the EMSE measurements because of its high reproducibility and accuracy[45–48]. Therefore, the noise caused by the environment was eliminated. In addition to this, a mathematical-based software solution to remove the contribution due to scattering, namely the time-gating technique was applied. As a result of using a professional EMSE test operation system, we could able to measure the EMSE results with high accuracy.

In this study the effects of the knitting structure and metal wire amount on the EMSE of knitted fabrics comparatively. Therefore, four knitting fabric structures (single jersey, single pique, weft locknit, cross miss) were produced. For the comparison of metal wire amount and knitting structures, single jersey fabrics were knitted with three different amounts of stainless steel (SS) and copper (Cu) wires.

2. MATERIAL AND METHOD

2.1 Material

A hollow spindle twisting machine was used to produce conductive composite yarns (CCYs). Same machine settings were applied for all productions. In order to investigate the metal wire type effects, AISI 316L type 50 µm SS and 50 µm Cu conductive metal wires were doubled with Ne 60/2 count cotton yarns (Co). The linear resistance of SS and Cu wires were 400 Ω/m and 14 Ω/m respectively. In Table 1, linear density of the Co and CCYs are given.

Single jersey, single pique (lacoste), weft locknit and cross miss knitting structures were produced to investigate the influence of plain, tuck and miss loop structures on the EMSE of the knitted fabrics. While single jersey fabrics have only loop structure, single pique fabrics have loop and tuck structures. Both, weft locknit and cross miss fabrics have loop and miss loop structures. In Figure 1, the knitting structures and schematic views of the fabrics that were investigated in the study are given.

Fabrics were knitted with the same machine settings on an E12 Stoll CMS 411.6 flat knitting machine. Tezel et al.[49] reported that while spandex yarn usage improves the residual extension properties of the knitted fabrics with CCYs, they do not have an effect on the EMSE of the fabrics. In this respect, for having better fabric quality, three yarns and a 70 denier spandex yarn (EL) were not wrapped, but they were fed together during the knitting process. Each single jersey, single pique, weft locknit and cross miss fabric sample was produced with one CCY, two cotton yarns, and a spandex yarn. In order to understand the metal wire amount effects on EMSE, Single Jersey fabrics involving a spandex yarn were also produced with 3 different composite yarn amounts. In Table 2, yarn composition and fabrics’ dimensional properties are given.

2.2 Method

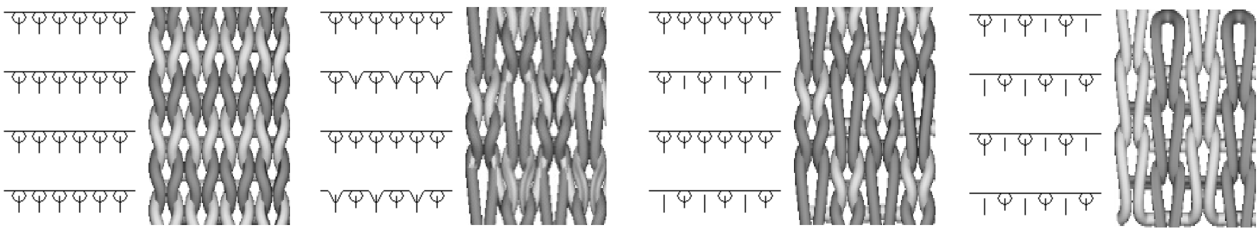
The fabrics were subjected to dry-relaxation. The samples were laid on a flat and smooth surface and kept in atmospheric conditions for one week (20±2°C and 65±4% relative humidity). The fabric properties were measured according to ISO 7211-2 (course and wale per cm) and ISO 3801 (fabric weight) standards. The yarn loop length values were determined by using a Hatra-like tester. The test was conducted as suggested in the literature [50, 51]. Loop length values of the single pique and weft locknit fabrics that have different knitting structures for alternating courses such as knit and tuck or miss loop structures were also measured and calculated separately for each alternating course.

EMSE Measurements

EMSE measurements were conducted in an anechoic chamber by using the free space measurement technique because of its high reproducibility and accuracy[45–48]. Measurements were performed at 200 different frequencies (1 GHz- 18 GHz) with 85 MHz intervals by positioning two horn type directive antennas (Figure 2).

Table 1. Linear density of the cotton yarn and CCYs

Yarn Composition			Linear Density	
Metal Wire		**Cotton Yarn**	**Ne**	**Nm**
50 µm SS	+	Ne 60/2 Co	Ne 17,28	Nm 29,26
50 µm Cu	+	Ne 60/2 Co	Ne 15,30	Nm 25,91
-	+	Ne 60/2 Co	Ne 30,76	Nm 52,08



(a) (b) (c) (d)

Figure 1. Knitting notations and schematic views of the fabric samples, (a) Single Jersey, (b) Single Pique, (c) Weft Locknit, (d) Cross Miss

Table 2. Yarn composition and dimensional properties of the fabrics

Knit Structure	Fabric Code	Yarn Composition	Courses per cm	Wales per cm	Stitches per cm²	Weight (g/m²)	Loop Length (mm)
Single Jersey	RL-CO	(Ne60/2Co)+(Ne60/2Co)+(Ne60/2Co)+70DenEL	13,7	8,9	121,9	358,2	4,76
	RL-SS	(50µmSS+Ne60/2Co)+(Ne60/2Co)+(Ne60/2Co)+70DenEL	14,0	7,9	110,6	381,3	4,68
	RL-SSx2	(50µmSS+Ne60/2Co)+(50µmSS+Ne60/2Co)+(Ne60/2Co)+70DenEL	15,7	6,1	95,8	416,7	4,69
	RL-SSx3	(50µmSS+Ne60/2Co)+(50µmSS+Ne60/2Co)+(50µmSS+Ne60/2Co)+70DenEL	15,0	5,8	87,0	444,6	4,65
	RL-CU	(50µmCu+Ne60/2Co)+(Ne60/2Co)+(Ne60/2Co)+70DenEL	13,2	8,4	110,9	432,6	4,71
	RL-CUx2	(50µmCu+Ne60/2Co)+(50µmCu+Ne60/2Co)+(Ne60/2Co)+70DenEL	13,7	7,8	106,9	515,6	4,71
	RL-CUx3	(50µmCu+Ne60/2Co)+(50µmCu+Ne60/2Co)+(50µmCu+Ne60/2Co)+70DenEL	15,0	6,7	100,5	564,9	4,65
Single Pique	PIQ-CO	(Ne60/2Co)+(Ne60/2Co)+(Ne60/2Co)+70DenEL	22,3	7,3	162,8	392,6	Knit:4,51 Tuck:4,15
	PIQ-SS	(50µmSS+Ne60/2Co)+(Ne60/2Co)+(Ne60/2Co)+70DenEL	22,3	5,9	131,6	392,0	Knit:4,38 Tuck:4,08
	PIQ-CU	(50µmCu+Ne60/2Co)+(Ne60/2Co)+(Ne60/2Co)+70DenEL	21,7	6,6	143,2	485,3	Knit:4,43 Tuck:4,15
Weft Locknit	MIS-CO	(Ne60/2Co)+(Ne60/2Co)+(Ne60/2Co)+70DenEL	17,7	9,0	159,3	389,7	Knit:4,78 Miss:3,37
	MIS-SS	(50µmSS+Ne60/2Co)+(Ne60/2Co)+(Ne60/2Co)+70DenEL	18,3	7,1	129,9	424,1	Knit:4,68 Miss:3,32
	MIS-CU	(50µmCu+Ne60/2Co)+(Ne60/2Co)+(Ne60/2Co)+70DenEL	18,0	8,0	144,0	471,6	Knit:4,72 Miss:3,33
Cross Miss	MISS-CO	(Ne60/2Co)+(Ne60/2Co)+(Ne60/2Co)+70DenEL	19,3	10,6	204,6	413,4	3,51
	MISS-SS	(50µmSS+Ne60/2Co)+(Ne60/2Co)+(Ne60/2Co)+70DenEL	23,3	8,2	191,1	468,2	3,04
	MISS-CU	(50µmCu+Ne60/2Co)+(Ne60/2Co)+(Ne60/2Co)+70DenEL	23,3	8,8	205,0	500,1	3,42

Co: cotton yarn, SS: stainless steel wire, Cu: copper wire, EL: spandex yarn

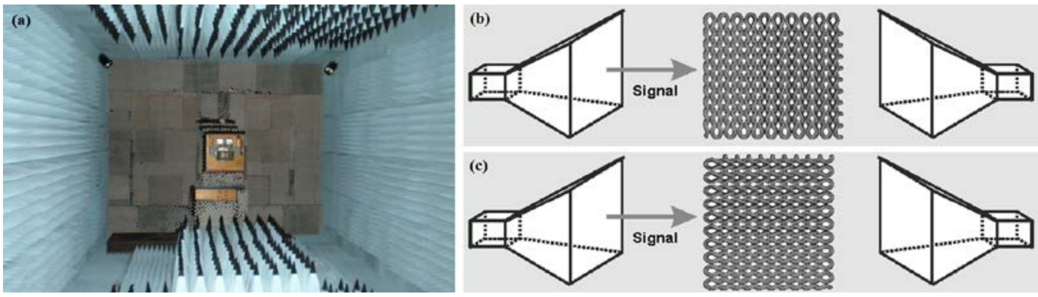


Figure 2. Free space measurement: (a) anechoic chamber, illustration of fabric positions: horn antennas and the fabric sample, in (b) horizontal, and (c) vertical direction.

A dedicated mathematical algorithm was applied to remove the contribution due to scattering. More information can be found in [11, 45–48, 52]. EMSE properties of fabrics were measured in both horizontal, and vertical directions (Figure 2) related to the electric field polarization of the antennas. The test was repeated three times for each direction. However, the EMSE test of horizontal positioned cross miss knitted fabric with SS wire (MISS-SS) could not be performed because of an insufficient sample size. EMSE is defined as the ratio of the field before and after applying the shield. EMSE is logarithmically expressed in decibels (dB). The percentage of electromagnetic shielding efficiency (%) represents the material's ability to block waves in terms of percentage. EMSE [dB] is converted into percentage of electromagnetic shielding (%) using the Equation (1) as in [53]:

$$\text{Percentage of electromagnetic shielding (\%)} = 100 - \frac{100}{10^{EMSE/10}} \quad (1)$$

In order to show the significance of the knitting structure or the amount of metal and the frequency on the EMSE of horizontally positioned knitted fabrics with SS and Cu wire content, a two factor completely randomized ANOVA analysis was carried out with a significance level of %5. "Student Newman Keuls" (SNK) method was used to compare the means for a rejected hypothesis. The levels of the treatment were noted in accordance with the mean values. The levels with the same letters indicate insignificant differences.

3. RESULTS AND DISCUSSION

Consistent with former studies [11, 21, 24, 38], the free space measurement technique EMSE results indicate that the knitted fabrics with CCYs that are investigated in the study have an EMSE ability in the main direction where the conductive materials are running. It was found that all horizontally positioned knitted fabrics with metal wire have 14 dB or more EMSE in the frequency range from 1 GHz to 3 GHz, 10 dB, or more EMSE up to 6.695 GHz and 5 dB or more EMSE up to 11.710 GHz (Figure 3). Vertically positioned fabrics and 100% cotton fabrics did not show any EMSE.

The resistance of the knitted fabrics involving conductive materials differs according to the direction of the measurement procedure [54]. In weft knitted fabrics, the conductive material runs in the horizontal direction by forming loops. For this reason, weft-knitted fabrics have very low resistance in the horizontal direction. The resistance of the fabric in the vertical direction is higher than in the horizontal direction. The resistance in the vertical direction is realized by the contact of the conductive material with each other. If the fabric contains both the conductive material and insulating material (for instance in this study we have both metal wires and cotton yarns), the resistance in the vertical direction will be very high because of the limited contact points. Since the contact points are excessive in fabrics produced with pure conductive threads/wires, conductivity is also high in the vertical direction. The contact resistance property of the conductive material (Silver coated PA, Cu wire, SS wire, etc.) and the tightness of the fabric structure also affect the resistance in the vertical direction. Thus, course per cm values directly affect the EMSE values whereas wales per cm values have limited effect on the EMSE.

3.1. The Effect of Knitting Structure on the EMSE of Fabrics

Figure 3 shows the EMSE test results for the horizontally positioned diverse knit structures that are investigated in the study. Test results reveal that single pique fabrics have the highest EMSE values, and single jersey fabrics have the lowest EMSE values. 100% cotton fabrics (RL-CO, PIQ-CO, MIS-CO, and MISS-CO) do not have any EMSE ability.

According to variance analysis, the effect of knitting structure and frequency is highly significant and SNK tests showed that each fabric have different EMSE for each frequency value.

While single pique fabrics have the highest EMSE values, cross miss fabrics have higher EMSE values than weft locknit fabrics and single jersey fabrics have the lowest EMSE values according to SNK test results (Table 3). There are two criteria that affect the EMSE of the knitted fabric mainly resistance of the fabric and the apertures in the fabric. Liu et al. [55, 56] produced knitted fabrics with tuck and miss loop structures as well as RL fabrics. They demonstrated that, the fabrics with miss loops had lower resistance values than RL fabrics, while the fabrics with tuck loops had the lowest resistance values. In addition to this, Basyigit et al. [57, 58] also showed that aperture shape and the aperture length/width ratio in the conductive material are effective on the EMSE values. The tuck and miss loop structures reduce the gaps between the metal wires in the fabric structure, also with the help of increasing the course density. This is also consistent with former studies [14, 24].

3.2. The Effect of Metal Wire Amount on the EMSE of Fabrics

EMSE test results showed that single jersey fabrics involving three CCYs have the highest EMSE values and single jersey fabrics involving one CCY have the lowest EMSE values, as expected (Figure 4).

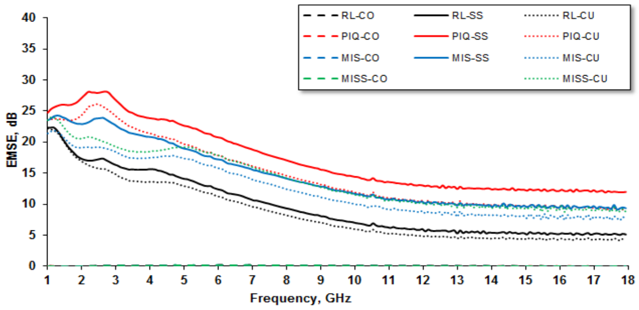


Figure 3. EMSE test results of diverse knit structures

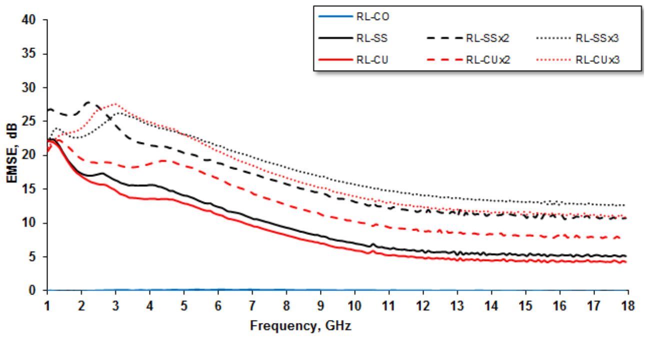


Figure 4. EMSE results of single jersey knitted fabrics with diverse metal wire amounts

Variance analysis results of the EMSE values indicate that the metal wire type and the amount is highly significant in single jersey knitted fabrics as well as the frequency.

The fabrics with SS wire have higher EMSE values than the fabrics with Cu wire (Table 4). This is also consistent with the former study of Tezel et al.[11] Resistance of the conductive metal wire affects the EMSE of the fabric. It is clear that, the decrease in the loop length value leads to a decrease in the resistance. However, with the decrease of the loop length value, the deformation of the metal wire increases. This deformation increases the resistance [23, 59]. The Cu wires used in this study have a resistance value of 14 Ω/m, and the SS wires have a resistance of 400 Ω/m. However, the fabrics with SS wire have higher EMSE values than the fabrics with Cu wire (for the same knitting structures). Thus, it is thought that the increase in the resistance caused by the deformation is much higher for Cu wires than SS wires. 100% cotton fabrics did not show any EMSE. SNK test results also reveal that fabrics involving three CCYs have the highest EMSE values. Fabrics involving two CCYs and one cotton yarn have higher EMSE values than fabrics involving one CCY and two cotton yarns. For instance, while RL-SS have 9,65 dB EMSE, RL-SSx2 fabrics have 15,96 dB EMSE and RL-SSx3 fabrics have 17,73 dB EMSE. This result is very interesting and unexpected: the EMSE values of the fabrics containing 3 times more metal wires are not as high as expected.

3.3. The Effect of Knitting Structure and Metal Wire Amount on the EMSE of Fabrics

Figure 5 shows the EMSE test results of the horizontally positioned knitted fabrics with diverse knitting structures and metal wire amounts that are investigated in the study. Single jersey fabrics with three CCYs involving SS wire have the highest EMSE values, and single jersey fabrics with one CCY involving Cu wire have the lowest EMSE values.

Table 3. SNK ranking for the EMSE of diverse knitting structures with SS and Cu wire content

Knitting Structure	EMSE (1 GHz - 18 GHz)			
RL	9.12903 a			
MIS		13.33747 b		
MISS			13.79144 c	
PIQ				16.03103 d

**Lower cases indicate significant differences between the values.*

Table 4. SNK ranking for the EMSE of single jersey fabrics with diverse metal wire amounts

Metal Wire	EMSE (1 GHz - 18 GHz)					
RL-CO	0.02998 a					
RL-CU		8.60867 b				
RL-SS			9.64939 c			
RL-CUx2				12.66529 d		
RL-SSx2					15.95900 e	
RL-CUx3						16.72949 f

RL-SSx3	17.72974 g

**Lower cases indicate significant differences between the values.*

Table 5. SNK ranking for the EMSE of fabrics with diverse knitting structures and metal wire amounts

Fabric Code	EMSE (1 GHz - 18 GHz)
RL-CU	8,61 a
RL-SS	9,65 b
MIS-CU	12,32 c
RL-CUx2	12,67 d
MISS-CU	13,79 e
MIS-SS	14,36 f
PIQ-CU	14,75 g
RL-SSx2	15,96 h
RL-CUx3	16,73 i
PIQ-SS	17,31 j
RL-SSx3	17,73 k

**Lower cases indicate significant differences between the values.*

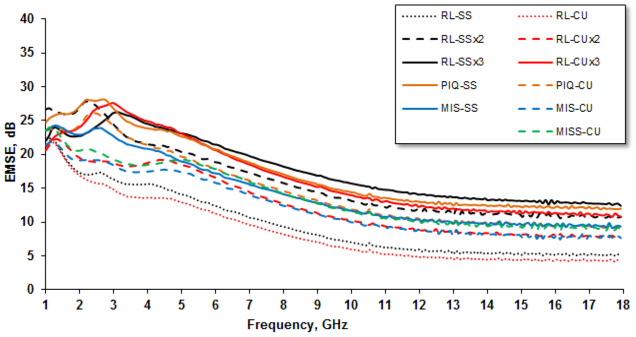


Figure 5. EMSE of the fabrics with diverse knitting structure and metal wire amounts

According to variance analysis the wave frequency and fabric type highly affect the EMSE results. Single jersey fabrics with three CCYs involving SS wire have the highest EMSE values (Table 5). Single pique knitted fabrics involving SS wire have the second highest EMSE values. For a better understanding, EMSE values (dB) of the fabrics and percentage of electromagnetic shielding (%) are shown in Figure 6.

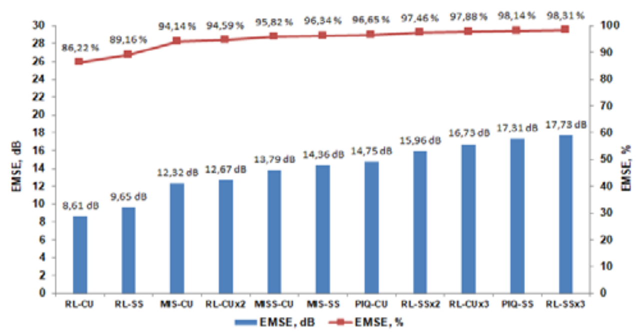


Figure 6. Comparison of EMSE values (dB) and percentage of electromagnetic shielding (%) of the fabrics according to SNK test results

4. CONCLUSION

In this study, the influence of knitting structure and metal wire amount on the EMSE of knitted fabrics via the free space measurement technique were investigated comparatively.

The parameters affecting the EMSE can be summarised as follows:

- Course per cm value
- Loop length value
- Increase in the resistance caused by the deformation of the metal wire
- Resistance change caused by the knitting structure and the metal wire amount
- Change in the aperture shape and the aperture length/width ratio caused by the knitting structure and the metal wire amount

The primary result of this study is that knitted fabrics with CCYs have an EMSE ability in the main direction in which the metal wires are running. Weft knitted fabrics have very low resistance in the horizontal direction due to the conductive material running in the horizontal direction by forming loops. The resistance in the vertical direction is realized by the contact of the conductive material with each other. In this study, we have both metal wires and cotton yarns in the fabric structure. EMSE results show that the knitted fabrics are not conductive in the vertical direction indicating that course per cm values directly affect the EMSE values whereas wales per cm values have limited effect on the EMSE.

Variance analysis for the EMSE indicate that the effect of knitting structure, metal wire type, metal wire amount, and incident wave frequency is highly significant. Also, the fabrics with SS wire have higher EMSE values than fabrics with Cu wire for all knitting structure types. The Cu wires have lower resistance value than the SS wires. However, the results showed that the fabrics with SS wire have higher EMSE values than the fabrics with Cu wire for the same knitting structures. This might be due to the higher increase in the resistance caused by the deformation of Cu wires than SS wires.

EMSE values increase as the metal wire amount in the fabric increases, as expected. However, it was also found that EMSE values do not increase as much as the metal wire amount in the fabric increases as it was expected. The resistance of the fabric and the apertures in the fabric affect the EMSE of the knitted fabric. Therefore, both the metal wire amount and knitting structure change the resistance of the fabric and the apertures in the fabric structure, resulting in the change of the EMSE values. EMSE test results of diverse knit structures show that fabrics with tuck and miss loop structures have higher EMSE values than single jersey fabrics. While single pique fabrics with tuck loop structures have the highest EMSE values, cross miss and weft locknit fabrics, that both have miss loop structures, have higher EMSE values than single jersey fabrics. Since cross miss fabrics have more miss loop structures, they have higher EMSE values than weft locknit fabrics.

In our study, single jersey fabrics with three CCYs involving SS wire (RL-SSx3) have the highest EMSE values (17,73 dB), and single pique knitted fabrics also involving SS wire (PIQ-SS) have the second highest EMSE values (17,31 dB). Although RL-SSx3 fabrics have three times as much SS wires as PIQ-SS single pique fabrics, the difference in EMSE between these two fabrics is not as high as it was expected. Although RL-SSx2 Single Jersey fabrics have twice as much SS wires as PIQ-SS single pique fabrics, they have lower (15,96 dB) EMSE values than PIQ-SS single pique fabrics. This result can be considered as the most interesting and the most important result of the study. The study shows that the knitting structure has a great impact on the EMSE of knitted fabrics. It can be concluded that single pique knitted fabrics involving SS wire combine a high EMSE with a lower production cost.

The aim of this research is to investigate the influence of the basic knitting structure and the metal wire amount on the electromagnetic shielding effectiveness of knitted fabrics experimentally. A detailed study on observing the complex knitting structures' EMSE properties via experimental investigations and/or full-wave electromagnetic modelling of the fabrics is recommended as follow-up research.

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