The effects of fabric structural parameters on the electromagnetic shielding effectiveness

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In this paper, stainless steel core yarn was selected as a conductive yarn to produce conductive fabrics. The electromagnetic shielding effectiveness of twill and some diced woven fabrics with different metal densities were measured by free space measurement technique at horizontal polarization of the antenna. It was found that woven fabric samples shielded well in high frequency band, namely industrial, scientific and medical band. The electromagnetic shielding effectiveness of fabric samples woven increased in accordance with the steel core yarn density in high frequency band if the fabric samples were positioned so that the weft yarns were vertical to the antenna polarization. When the effective surface conductivity increased, the decrease in the electromagnetic shielding effectiveness of woven fabric samples, which were positioned so that the weft yarns were parallel to the antenna polarization, was observed as adverse.
Key words: *diced woven fabrics, twill weave, electromagnetic shielding effectiveness, conductive core yarns*

1. Introduction

Wireless communication links have been used worldwide for many years as solutions for connectivity in point to-point and point-to-multipoint applications. Especially, Wi-Fi, radiophones and baby monitors have been common in recent years. These devices used industrial, scientific and medical (ISM) band of 2400 MHz. Another important issue to be addressed with electromagnetic (EM) waves is their possible health effects on humans [1-2]. The World Health Organization (WHO) suggests that a wide range of environmental EM influences cause biological effects [3]. To shield and protect against EM influences, conductive textile surfaces, which are lightweight, flexible and non-expensive, have begun to manufactured instead of electrically conductive metal sheet or wire mesh shielding materials for various shielding applications in the electrical, and electronic industries, especially for electronic housing materials. Perumalraj et al. [4] selected copper as a conductive filler to produce copper core yarns with cotton fibre as sheath material to make plain and twill woven fabrics, and measured the electromagnetic shielding effectiveness of these fabrics in the frequency range of 20-18,000 MHz with coaxial transmission equipment. They observed an increase in shielding effectiveness with an increase in the number of conductive fabric layers, finer yarn count, warp density, weft density, cover factors and a decrease in shielding effectiveness with copper wire diameter. Roh et al. [5] used metal composite yarns, which were used in the construction of plain woven metal composite fabrics, were produced with commercially available metal filaments and polyester (PET) filaments. Plane-wave shielding properties of the composite fabrics were measured between 30-1500 MHz using the coaxial transmission line method. They observed that while the overall EM shielding effectiveness increased with metal content, different frequency dependence related to the aspect ratio of metal grid structure. Su and Chern [6] selected stainless steel as the conductive filler to produce stainless steel hybrid yams to make plain and twill woven fabrics. The electromagnetic shielding effectiveness (EMSE) of these fabrics was measured by coaxial transmission equipment in the frequencies range from 9 kHz to 3 GHz. The experimental results showed that denser structures of stainless steel fabrics had a higher EMSE. The fabric made from the core yarns had a higher EMSE than that made from the cover yarns and the plied yarns. Analyses of the weave types reveal that the plain weave had a higher EMSE than twill weaves. Cheng et al. [7] produced twill copper fabrics (3/1) and obtained their electromagnetic shielding effectiveness using a coaxial transmission line holder in the frequency range of 144–3000 MHz. They observed that with an increase in the number of conductive fabric layers, warp density, and weft density, an increase in shielding effectiveness occurred, whereas with an increase in wire diameter, a decrease in shielding effectiveness occurred. Chen et al. [8] measured plane-wave shielding properties of 2/2 twill woven fabrics and laminated composites at 30–1500 MHz using the coaxial transmission-line method. Duran et al. [9] investigated the electromagnetic shielding effectiveness of 3/1 twill woven fabrics with electromagnetic competence test device in 5 different frequencies; 200, 400, 600, 800 MHz and 1 GHz. While 100 % cotton yarns was used as warp yarns, two different weft yarns, copper/cotton core yarns and 100% cotton yarns were used in two different weft densities. It was observed that fabrics woven with cupper/cotton core yarns had considerably higher electromagnetic shielding effectiveness values than the fabrics woven with 100 % cotton wefts. Varnaıtė et al. [10] wove plain fabrics with only PES warps. Conductive yarns were inserted in the fabrics in three different variants: 1) 25 picks PES + 1 pick PES/INOX; 2) 49 picks PES + 1 pick PES/INOX; 3) 71 picks PES + 1 pick PES/INOX. The fabric with only the PES picks was used as control fabric. It was found that the bigger quantity of conductive weft yarns increased values of the shielding factor. Sandrolini and Reggiani [11] tested the five electrically conductive woven and non-woven fabrics by circular coaxial transmission line holder in the frequency range 300 kHz-3.6 GHz. The results showed that a low surface resistivity value was a requirement for a higher shielding effectiveness especially for woven materials. The nickel amount used for the metallization did not have such a strong relation with the SE, as the geometry of the warp and weft of the textile played an important role in the shielding performance, too. Palamutçu et al. [12] developed an electromagnetic shielding efficiency measurement set and tested its reliability within the circumstance of the produced electrical conductive plain knitted and plain woven fabrics. In these fabrics, Co/Cu and Co/Cu/Ag yarns with different ratios were used. For woven specimens at the 860-960 MHz frequency range the highest level of average EMSE value was found belong to the specimen, which had the lowest level (finest conductive fiber) of conductive fiber content. It was also observed that the highest attenuation was obtained at 1790 MHz with the woven specimen, which had the finest conductive fiber. Joyner et al. [13] examined protective suit consisting of an overall with an integral hood, gloves, and oversocks, constructed of an electrically conductive fabric, theoretically and experimentally for electromagnetic shielding effectiveness (SE) at radiofrequencies (RF) in the range from 200 kHz to 4 GHz. They found that at microwave frequencies, the fabrics were certainly capable of providing SE of greater than 20 dB. Więckowski and Janukiewicz [14] discussed about the scope of application of the measurement methods of EMSE of textiles, their limitations and the possibilities for comparisons of the results.

Diced weaves are a group of weaves, which are produced by quartering and reversing a weave element, thus forming opposite surfaces and directions in each quarter and clean cuts between the sections. Weaves tend to repeat on relatively small areas, but longer versions are possible [15].

The studies in the literature focused on electromagnetic shielding effectiveness of twill and sateen woven fabrics in low and medium frequency bands. The aim of the study is to investigate the EM shielding effectiveness of diced woven fabrics and to compare those with twill woven fabric, which were woven with steel core weft yarns, inserted in certain intervals. And also the effect of conductive weft yarn density on the EM shielding effectiveness of fabric samples was searched. The other aim of this study is to investigate the usability of diced woven fabrics with conductive yarns as electromagnetic shielding material for Wi-Fi, radiophone and baby monitors.

2. Theoretical part

2.1. Electromagnetic shielding

Shielding is a term that explains the protection from the unwanted signals by using any material and method which decrease the signal penetration in the media interested. In shielding methodology, the signal strength in the media depends on several parameters related to material properties such as electric and magnetic behavior, conductance on the surface and in the volume, material thickness, and of course system material can be seen in Fig.1, where: -γ, γ_0 - Propagation constants, Z, Z_0- Characteristic impedance of the medium, d - Thickness of the shield [14]. The SE term explains the level of prevention and describes the performance of shield. Equation (1) gives a general definition of shielding efficiency (SE) [16]:

$$SE_P = 10.\log_{10}.\frac{\text{incident power density}}{\text{transmitted power density}} = \\ = 10.\log\frac{P_I}{P_T} \quad (1)$$

The two power densities in this ratio are the measured powers before and after the shield are placed, respectively. The angle of incident wave to the media under test is known as polarization. In regular wave propagation tests, vertically and horizontally directed (polarized) waves are used in measurements shown in Fig.4. By changing wave direction, the behavior of material under test can be tested for changing conditions of polarization depending on material internal structure. The polarization can be changed by antenna rotation physically or manipulation of signal source electrically.

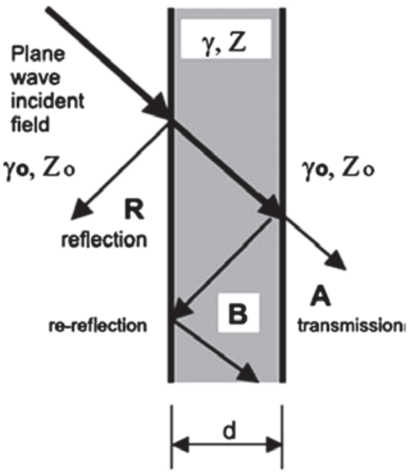


Fig.1 Wave transmission on a thin layer of media [14]

3. Experimental part

3.1. Production of woven samples

In this research 20 types of diced woven fabric samples and five types of twill woven fabric (35×35 cm) were produced in Weaving Workshop of in-house by CCI automatic sample rapier loom (Evergreen 8900, Taiwan). 100% polyester and stainless steel core yarns with cotton fibre as sheath material were used. The specifications of yarns are given in Tab.1. Weave patterns are shown in Fig.2. While the conductive yarns were inserted in certain intervals to obtain different open grid structures of conductive yarn within the fabrics, which resulted in different conductive weft yarn densities, the polyester and the conductive yarns were used in 1 to 1 order as warp yarns. The characteristics of the conductive fabrics are shown in Tab.2. The open grid structures of the conductive yarns are represented with gray squares and letter of C, whereas the polyester yarns are represented with white squares and letter of P in Fig. 3. Both white and gray squares also represent intersection points between warp and weft yarns. Warp and weft settings of 20 kinds of diced woven fabric samples on the loom were 25 cm^{-1}, which were equal to 1/3 twill weave settings, which was calculated for the loom state, in order to compare these fabric samples with twill woven fabric sample. No finishing process was applied on the fabric samples.

Fabric samples were coded according to their weave pattern, warp and weft densities as in Tab.2. The letter and number in each fabric code represent weave patterns and weft yarn arrangement respectively. These are square unit weaves, so the number of each warp and weft yarn interlacing is equal to each other, namely the average yarn interlacing is equal to number of yarn interlacing. And also the average float length of warp yarn is equal to the average float length of weft yarn. The average float length F has been calculated according to Ashenhurst [17] by Equation (2);

$$F_{1/2} = \frac{R_{2/1}}{t_{1/2}} \quad (2)$$

where $R_{2/1}$ is the weft (2) or warp (1) repeat, and $t_{1/2}$ the number of warp or weft intersections in the weave repeat. Subscripts 1 and 2 are used throughout to denote warp and weft respectively. The other fabric property, the weave interlacing coefficient, defined by Galcerán [18] has been calculated by Equation (3);

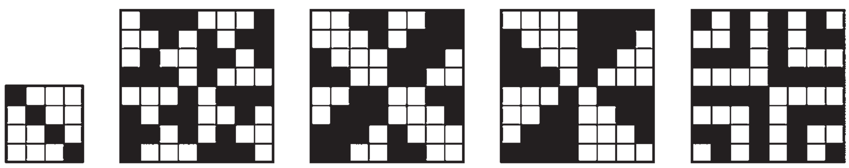
$$KL = \frac{i}{w_1 \times w_2} \quad (3)$$

where i is the number of interlacing points in weave repeat, w_1 *is* the number of ends in weave repeat w_2 is the number of picks in weave repeat.

Fig.3 Schematic diagram of open-grid structures formed in the woven fabrics
(gray squares: conductive core yarns; white squares: polyester yarns)

Tab.1 The specifications of yarns

Material	Yarn count (dtex)	Diameter of wire (mm)	Conductor resistance (Ωmm²/m)
Polyester yarn	300	-	-
SS/Co core yarn	455	0.05	0.62



a b c d e

Fig.2 Weave patterns used in experimental: a - 1/3 twill; b - Diced weave 1; c - Diced weave 2; d - Diced weave 3; e - Diced weave 4

Tab.2 The specifications of conductive fabrics

Fabric code	Weave pattern	Warp density on the reed	Weft density on the loom	Yarn type*	Composition (warp × weft)	The weave interlacing coefficient	The average float length
A1	1/3 Twill	25	25	CP	1C1P × C	0,5	2
A2				CP 1:1	1C1P × 1C1P		
A3				CP 1:3	1C1P × 1C3P		
A4				CP 1:7	1C1P × 1C7P		
A5				CP 1:15	1C1P × 1C15P		
B1	Diced weave 1	25	25	CP	1C1P × C	0,625	1,67
B2				CP 1:1	1C1P × 1C1P		
B3				CP 1:3	1C1P × 1C3P		
B4				CP 1:7	1C1P × 1C7P		
B5				CP 1:15	1C1P × 1C15P		
C1	Diced weave 2	25	25	CP	1C1P × C	0,5	2
C2				CP 1:1	1C1P × 1C1P		
C3				CP 1:3	1C1P × 1C3P		
C4				CP 1:7	1C1P × 1C7P		
C5				CP 1:15	1C1P × 1C15P		
D1	Diced weave 3	25	25	CP	1C1P × C	0,4375	2,5
D2				CP 1:1	1C1P × 1C1P		
D3				CP 1:3	1C1P × 1C3P		
D4				CP 1:7	1C1P × 1C7P		
D5				CP 1:15	1C1P × 1C15P		
E1	Diced weave 4	25	25	CP	1C1P × C	0,625	2,08
E2				CP 1:1	1C1P × 1C1P		
E3				CP 1:3	1C1P × 1C3P		
E4				CP 1:7	1C1P × 1C7P		
B5				CP 1:15	1C1P × 1C15P		

*C represents stainless steel/cotton core yarn, P represents polyester yarn

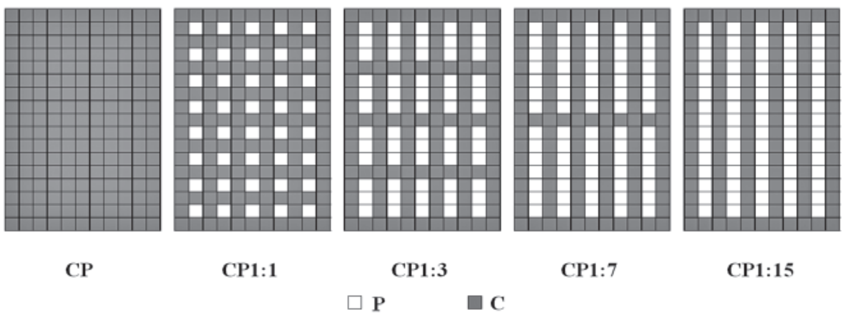


Fig.3 Schematic diagram of open-grid structures formed in the woven fabrics (gray squares: conductive core yarns; white squares: polyester yarns)

3.2. Measurement of electromagnetic shielding effectiveness

In this study, free space measurement technique was used in order to determine SE of woven fabrics. Fundamental measurement method was based on the signal attenuation on two sides of woven fabric material located on far field zones of transmitter and receiver antennas. Far field region for interested frequency band is between 0.3 to 1m approximately depending on frequency. Because of that, antennas are placed far away from that distance. Transmitter antenna had horizontal polarization. Woven fabrics behaved as a reflector, absorber, and attenuator on incident field. The ratio of total amount of transmitted signal strength over total incident signal strength determined the SE term related to material properties given above. The measurement set-up and the practical measurement set-up are shown in Fig.4 and 5. A spectrum analyzer, Anritsu MS2711D (Anritsu, Morgan Hill, CA, USA) with the option of transmission measurement was used for the tests. In transmission measurement option, reference level without shielding material under test was taken automatically with normalization process and the signal level with the material was compared in logarithmic scale in terms of RF power.

In other words, initially, the reference signal was collected without the shielding material at all frequencies. Afterwards, the woven fabrics were attached on the foam layer which was placed between receiver and transmitter equipments. Finally, the signals obtained from both states were compared. Each fabric sample was

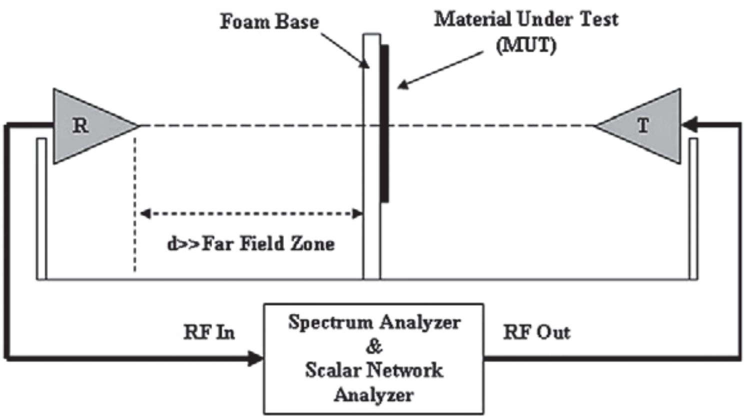


Fig.4 The measurement set-up [19]

measured two times; the fabric sample was positioned in the manner that the warp yarns were firstly vertical to the antenna polarization, in a word vertical measurement, secondly parallel to the antenna polarization, in a word horizontal measurement. The measurements were realized within a band of 800–3000 MHz. In this spectrum, GSM 900, GSM 1800, several industrial, scientific and medical (ISM) bands which can be used for personal purposes in limited power levels such as IEEE811.1 bg band were available. Conductive woven fabrics were investigated for attenuation levels and the frequencies in a wide band.

The received signal may be affected by reflections from surrounding environments such as walls, metal equipments and etc. in each case, with and without material under test, when the equipment can not overcome that interference conditions. The spectrum analyzer used in these measurements has a capability of transmission mode operation. In this operation, the system calibrates received power for every frequency component in working spectrum, then, the attenuation is stored for each frequency. This option prevents reflection effects by considering with or without material cases, and a relative signal attenuation is stored. By the same interference signal is applied both cases, the result is more accurate.

4. Results and discussion

The EMSE results of the fabric samples woven automatic sample loom are shown in Fig.6–10. When compared the effect of weave pattern, among the fabric samples woven with 100% stainless steel core yarns, the EMSE of fabric sample woven with diced weave 1 has been 5 dB higher than other samples in all frequency band for the vertical EMSE measurements as shown in Fig.6a-10a. The reason for this difference could be explained so that, the diced weave 1 has the highest weave interlacing coefficient, namely the highest number of contacts between vertical and horizontal yarns, therefore the shielding effectiveness increases. Su and Chern [6] reached the similar results. It is observed that the EMSE values of woven fabric samples have been 10 dB higher than in high frequency band, which is from 2000 MHz to 3000 MHz. Because; the distance between conductive yarns is the smallest, namely the smallest meshes, thus smaller wavelength and the higher frequency can be shielded better. The results of horizontal EMSE measurements of fabric samples woven with 100% steel core yarns have been similar to the results of vertical EMSE measurements of fabric samples, and have been 3-5 dB lower as seen in Fig.6b-10b. This is due to the fact that the density of conductive warp yarns are lower than that of conductive weft yarns and warp yarns are parallel to the antenna polarization during horizontal measurements, so shielding effectiveness of fabric samples decrease.

It is observed in Fig.6c, 7c, 8c, 9c and 10c that the EMSE of fabric samples coded as B2, C2 and E2 have been better than fabric samples A2 and D2 in high frequency band for the vertical measurements. This is due to the facts that diced weave 3 has the lowest weave interlacing coefficient, namely the lowest number of contacts between vertical and horizontal conductive yarns, and also in twill weave conductive warp yarns are in back face so shielding effectiveness decreases during vertical measurements. The EMSE values of fabric sample E2 have been 10 dB higher than fabric samples woven with CP 1:1 weft arrangement for the horizontal measurements as shown in Fig.6d-10d. This is probably because of the facts that diced weave 4 has the highest

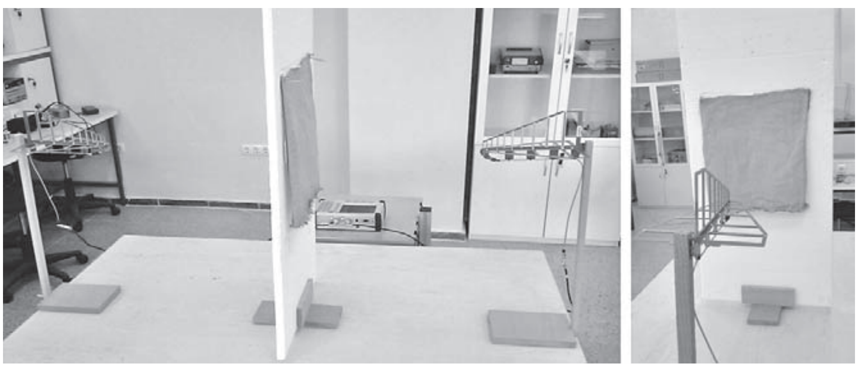


Fig.5 Practical measurement set-up

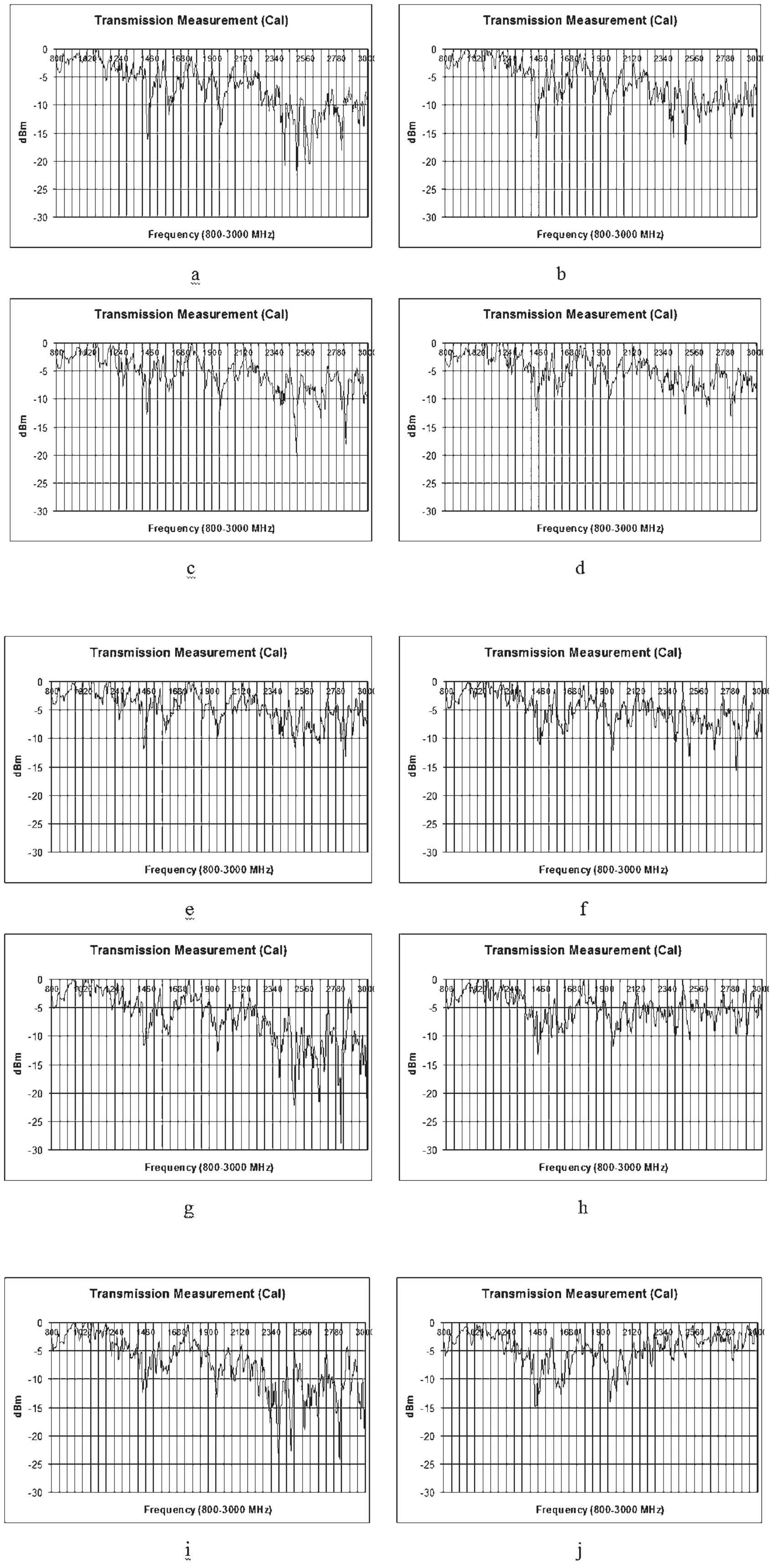


Fig.6 The EMSE of 1/3 twill weave: a, c, e, g, i - vertical measurements of A1, A2, A3, A4 and A5 respectively; b, d, f, h, j - horizontal measurements of A1, A2, A3, A4 and A5 respectively

weave interlacing coefficient and also higher average float length.

The EMSE values of fabric sample B3 have been 10 dB higher than other fabric samples woven with CP 1:3 weft arrangement in high frequency band for vertical measurements as seen in Fig.6e-10e. The reason for this difference could be explained by the facts that floating sections of first and fifth wefts in weave unit, which are conductive yarns, connect with two conductive warp yarns and also these sections follow each other in horizontal direction. Furthermore; fabric sample B3 have been good at narrow frequency bands for horizontal measurements as seen in Fig.6f-10f**.** Other fabric samples woven with CP 1:3 weft arrangements have shown similar EMSE performances.

While the average EMSE values of fabric samples of A4, B4 and D4 have been 5 dB in low and medium frequency bands, these have been 10 dB in high frequency band for vertical measurements and also their EM shielding effectiveness values have been higher than those of C4 and E4 as seen in Fig.6g-10g. The reason for this difference could be explained by the fact that first wefts of A4, B4 and D4, which are conductive yarns, passing over high number of warp yarns, thus surface conductivity of these fabrics increase. The EMSE of these fabric samples presented in Fig.6h-10h have been 5 dB as mean within all frequency band for horizontal measurements, because; the electromagnetic waves pass thorough the big space between the conductive yarns during horizontal measurements.

It is seen in Fig.6i-10i that fabric sample D5 has shielded best, whereas fabric sample E5 has shielded worst in high frequency band for vertical measurements. The reason for this difference could be explained so that while first weft yarns, namely conductive yarn, in diced weave 3 pass over four warp yarns, those of diced weave 4 pass over only one warp, so D5 has the biggest surface conducti-

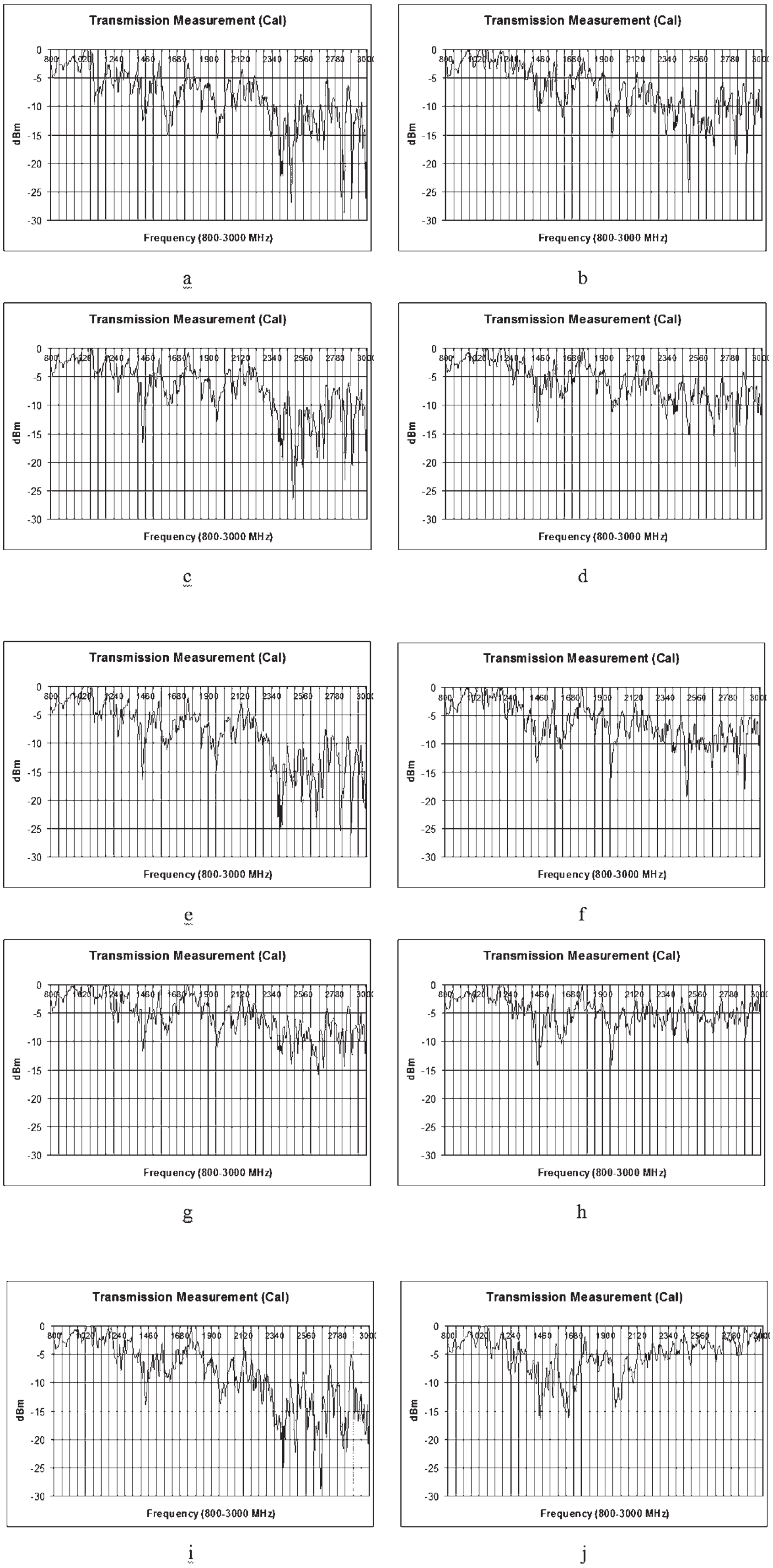


Fig.7 The EMSE of diced weave 1: a, c, e, g, i - vertical measurements of B1, B2, B3, B4 and B5 respectively; b, d, f, h, j - horizontal measurements of B1, B2, B3, B4 and B5 respectively

vity, namely the biggest EM shielding effectiveness. The average EMSE values of fabric samples woven with CP 1:15 weft arrangements have been 15 dB in high frequency band. Meanwhile the EMSE of these samples presented in Fig.6j-10j have been 5 dB as mean in high frequency band for horizontal measurements. The reason explained for fabric samples woven with CP 1:7 weft arrangements is valid here also.

When compared the effect of metal content and grid openness, the fabric samples woven with twill weave have average EMSE value of 15 dB within high frequency band for vertical measurements as shown in Fig.6a, 6c, 6e, 6g and 6i. Fabric samples A4 and A5 have been higher EMSE values than other weft orders in high frequency band. This can be explained by the fact that the intersection and floating of conductive weft yarns in A4 and A5 are in the same positions, these parallel conductive weft yarns raise the EM shielding effectiveness by interacting with each other.

It is observed in Fig.6b, 6d, 6f, 6h and 6j that the EMSE values of fabric samples woven with twill weave have increased in high frequency band for horizontal measurements when the metal contents have been increased in fabric samples. This is due to the fact that the effective surface conductivity of fabric samples has increased in agreement with the metal content. Roh et al [5], Cheng et al. [7] and Varnaıtė et al. [10] obtained similar results. The differences between the highest and lowest EMSE values have been 10 dB. The fabric sample A1 woven with wefts of steel core yarn having CP weft arrangement has the highest EMSE value in high frequency band.

The average EMSE values of fabric samples woven with diced weave 1 have been 15 dB in high frequency band for vertical measurements. The fabric sample B5 has shielded better than the fabric sample B1, quite the contrary as presented in Fig.7a, 7c, 7e, 7g and 7i. This is probably becau-

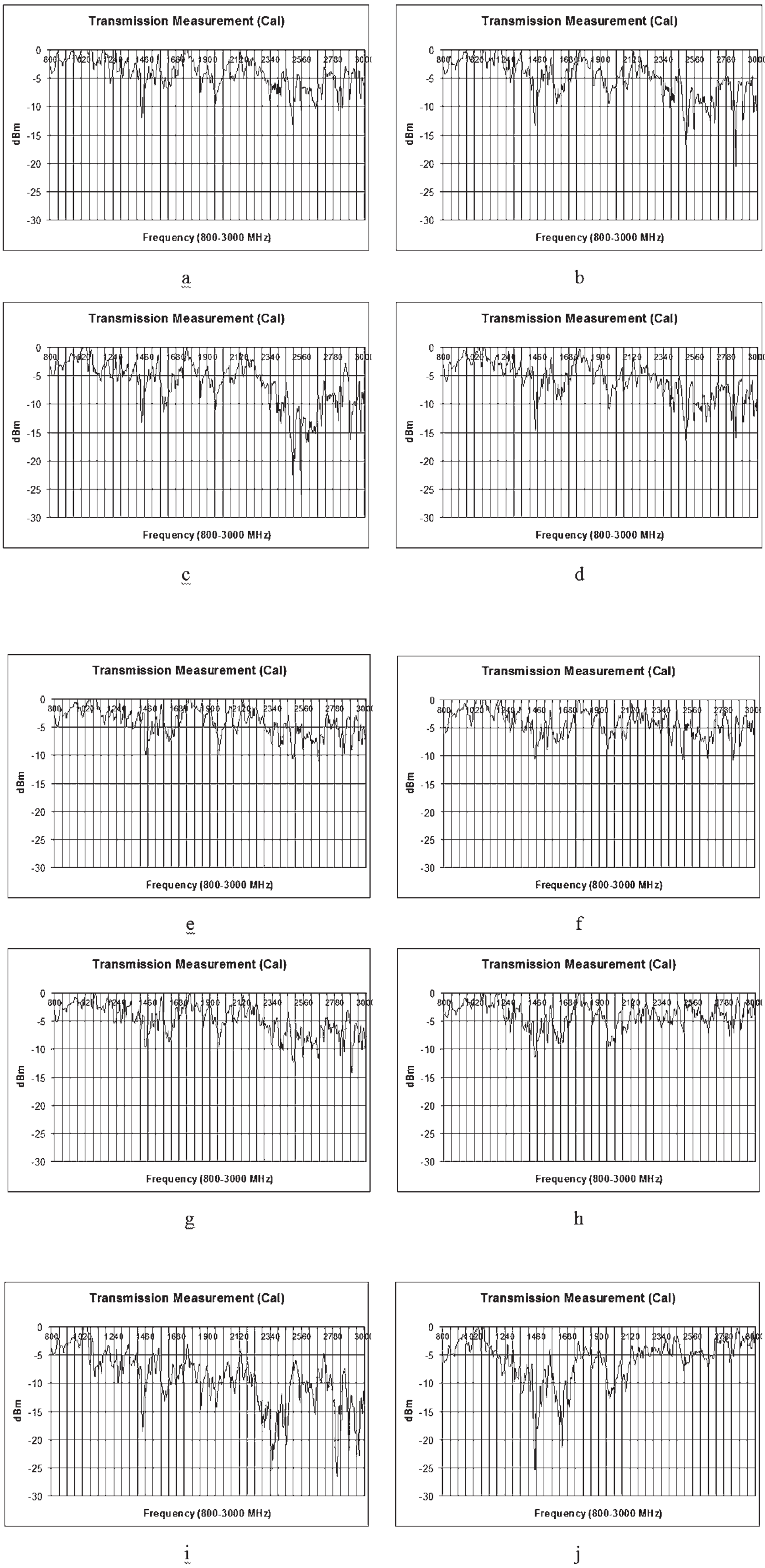


Fig.8 The EMSE of diced weave 2: a, c, e, g, i - vertical measurements of C1, C2, C3, C4 and C5 respectively; b, d, f, h, j - horizontal measurements of C1, C2, C3, C4 and C5 respectively

se of the fact that long floating of conductive warp yarns between the conductive weft yarns interact with each other against electromagnetic waves.

It is seen in Fig.7b, 7d, 7f, 7h and 7j that the EMSE of fabric samples woven with diced weave 1 have increased in accordance with the density of steel core yarn in high frequency band for horizontal measurements as expected.

The fabric samples woven with diced weave 2 have EMSE values of 15 dB as mean in high frequency band for vertical measurements as presented in Fig.8a, 8c, 8e, 8g and 8i. The EMSE values of fabric sample C5 have been 10 dB higher than fabric samples woven with denser steel weft arrangements in high frequency band, as opposed to expected.The reason explained for B5 is valid here also.

It is observed in Fig.8b, 8d, 8f, 8h and 8j that the fabric samples woven with diced weave 2 and denser steel yarn arrangement have shielded better in high frequency band than the fabric samples woven with looser steel yarn arrangement for the horizontal measurements as seen in diced weave 1. The EMSE values of fabric sample C5 have been 10 dB higher than fabric samples woven with denser steel weft arrangement in medium frequency band quite the contrary. The reason explained for B5 is valid here also.

The EMSE value of fabric sample D5 has been 15 dB higher than fabric samples woven with denser steel yarn arrangement for vertical measurements in high frequency band, which are shown in Fig.9a, 9c, 9e, 9g and 9i, as seen in diced weave 2. The reason explained for B5 is valid here also.

It is seen in Fig.9b, 9d, 9f, 9h and 9j that the EMSE values of fabric samples woven with diced weave 3 have increased in agreement with the density of steel yarn in high frequency band for horizontal measurements as expected. The fabric sample D5 has shielded better than samples woven with denser steel weft arrangement in

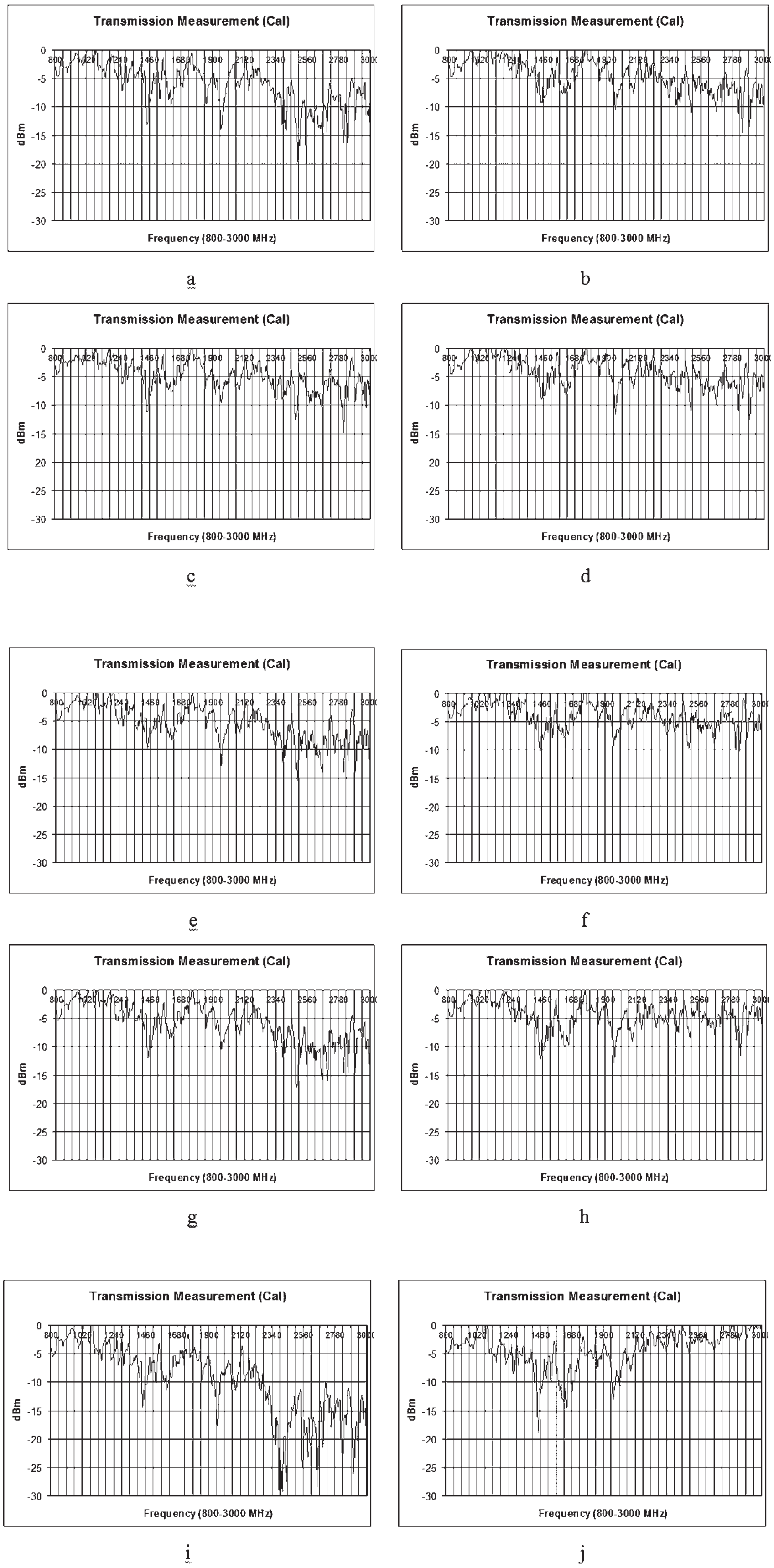


Fig.9 The EMSE of diced weave 3: a, c, e, g, i - vertical measurements of D1, D2, D3, D4 and D5 respectively; b, d, f, h, j - horizontal measurements of D1, D2, D3, D4 and D5 respectively

medium frequency band as has been observed in diced weave 2. The reason explained for B5 is valid here also.

The fabric sample E2 woven with CP 1:1 weft arrangement has shielded better than fabric samples woven with other weft arrangements in the frequency range from 1900 to 3000 MHz for vertical measurements as shown in Fig.10a, 10c, 10e, 10g and 10i. This is probably due to the fact that warp yarns constitute the meshes in upper side of the right diagonal, whereas weft yarns constitute the meshes in lower side of the right diagonal.

It is observed in Fig.10b, 10d, 10f, 10h and 10j that the EMSE values of fabric samples woven with diced weave 4 have increased with density of steel weft yarn in the frequency range from 1900 to 3000 MHz for horizontal measurements except for the fabric sample E2; the EMSE values of fabric sample E2 have been higher than other samples. The reason explained for vertical measurements of E2 is valid here also.

5. Conclusion

In this study, the electromagnetic shielding effectiveness of 1/3 twill and some diced woven fabrics produced on automatic sample loom with conductive stainless steel core yarns, inserted in certain intervals, were investigated. When compared twill weave with diced weaves, it is seen that the EMSE of diced weave 1, which has the highest weave interlacing coefficient, has been better than twill weave generally. Among the diced weaves, diced weave 1 and diced weave 4 with denser steel core yarn weft arrangements, which have the highest number of contacts between vertical and horizontal yarns, shielded well especially in high frequency band for all measurements.

It was observed that the EMSE of fabrics would increase if the metal yarn content was increased in high frequency band for the vertical measu-

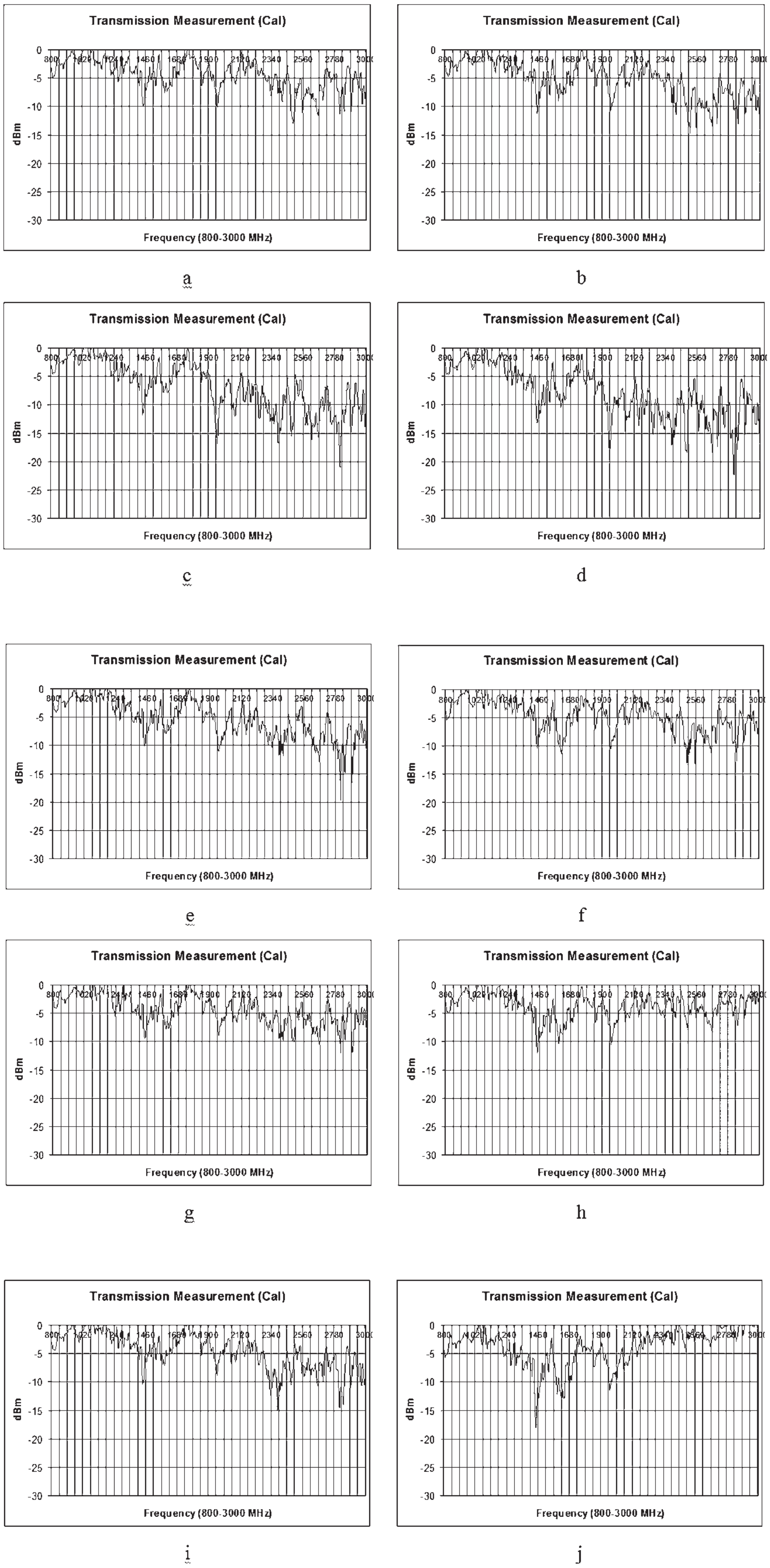


Fig.10 The EMSE of diced weave 4: a, c, e, g, i - vertical measurements of E1, E2, E3, E4 and E5 respectively; b, d, f, h, j - horizontal measurements of E1, E2, E3, E4 and E5 respectively

rements, as expected. On the other hand, twill and diced woven fabrics with less density of steel core yarn weft arrangement showed better shielding performances than the fabric samples woven with denser metal arrangements in all range of frequency band, because of the low density of conductive warp yarns, which are parallel to the antenna polarization during the horizontal measurements.

Consequently, the diced woven fabrics produced within the scope of this study have good EMSE values in high frequency bands, so these can be used as electromagnetic shielding material for Wi-Fi, radiophone and baby monitors. However; future studies are needed to improve the EM shielding properties of these fabrics in low and medium frequency bands.

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