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MODELING OF SHIELDING TEXTILES

Relatore: Prof. Sergio Pignari (Politecnico di Milano)

Correlatore: Prof. Guy Vandenbosch (K.U.Leuven)

Tesi di Laurea Specialistica di:
Alessandro Chiumento
Matr. 720857

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Thesis voorgedragen tot het behalen van de graad van Master of Engineering: Electrical Engineering

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KATHOLIEKE UNIVERSITEIT LEUVEN

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Promotor:
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Assessoren:
Prof. dr. ir. Stepan Lomov
Prof. dr. ir. Robert Puers

Begeleider:
Dr. Vladimir Volski

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Preface

I would like to thank everybody who kept me busy the last year. Above anybody else my gratitude goes to Anna for at least giving me this chance.
You are the best thing that ever happened to me.

Alessandro Chiumento

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Abstract

The impressive increase in electromagnetic fields and relative health concerns have pushed the industry to combine the well know textile production techniques with the need of shielding people and instruments. These new products create not few difficulties to the electromagnetic community for their complex structures that render the modelling extremely difficult. A software alternative to the semi-empirical methods used in industry seems to be a valid way. With this tool some of the most known typologies of shielding textiles have been analysed the differences in morphologies in such structures may lead to the best way of designing these artefacts. The validity of this software approach is confirmed by different sets of simulations and comparison with actual measurements.

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Chapter 1

Introduction

Textiles have been employed, in many forms and uses, for centuries. Their versatility and diffuse industrial processing combined with today's advancements in miniaturization technology make them the best candidates for new and interesting engineering applications. This work will analyse fabrics in which conductive material has been added to obtain a planar structure capable of shielding a body, human or instrument, from the ever increasing electromagnetic radiation of today's environment. Furtherefore these materials might find application in fields other than personal safety and EMC but in the wide wireless world as substitutes of all those elements than normally act as ground planes or antennas. The issue the wireless community faces is the modeling of these new elements, their mechanical properties and design are well known to the textiles specialists but the complex and uncommon morphology are difficult to handle in the electromagnetic domain. For this reason, as far at it is known, there have been very few attempts in a fully software modeling of fibrous shielding structures, most of the works are empirical or pseudo-empirical as they relay solely on measurements or use these to complete some fitting curve analytically computed. The scope of this thesis is to model different variants of these fabrics with the in-house numerical tool developed here in Telemic, prove its validity through comparison with empirical results, found in literature and self performed. Also an extensive overview of the work available in literature on shielding textiles is also included. The second chapter presents an overview of the production techniques of shielding textiles. It delineates a path from the creation of the conductive fiber, different methods are listed and discussed, to the final structure, diverse topologies are analysed and the shielding behaviour is predicted. The third chapter deals with the modeling approaches found in literature, low frequency and high frequency methods are illustrated and discussed. An introduction on the software modeling used in this work is also present. The fourth chapter shows the different measurements techniques present in literature and part of these have actually been used in the assessment of the textile's properties. In the fifth chapter the simulations are presented, the results are shown and analysed, strong points and shortcomings of the tool are discussed. Finally in the last chapter the conclusion are presented.

Chapter 2

Production of Shielding Fabrics

The variety of conductive fibers present on the market is astonishingly high, an interested buyer may get lost amongst the totality of the products offered.

In this first section the most common typologies of conducting textiles and their characteristics will be explained. The detailed chemistry and processing techniques of these structures are not the scope of this work and hence they will be skipped but a basic overview of the products available is now presented.

2.1 Fibers

All the conductive fibers are created with one of the following three methods [1, 2]:

- The filling of fibers with conductive powders.
- The coating of fibers with conductive materials.
- The usage of conductive filaments.

2.1.1 Conductive-powder filled fibers

Carbon or metallic particles can be added to the mesh of the polymer composing the fiber, in order to achieve conductivity, the main problem of this kind of technique is that high levels of fillings are required to guarantee low resistivity (for example 40% carbon); these modify substantially the mechanical properties of the polymer making it brittle and difficult to process [1]. Even with high concentration of conducting particles the conductivity of such fibers remains too low for EM Shielding applications [1 ,3] and for such reason this category will not be deepened.

2.1.2 Coated fibers

The second typology is formed by fibers having a (usually inner) layer of non conducting material and an other (typically outer) of conductive substance. This seems to be the most used technique [2, 4, 5, 6, 8, 10, 11, 12, 13], the coating is usually done with metals or with conductive polymers. The most used metals are silver, copper nickel and combinations for their high conductivity and mechanical properties. Also in this case various techniques to apply the metallic layer to the fiber can be used. The most common ones are:

- Vacuum evaporation decomposition , in [4] K. Lai et al. have shown how to deposit layers of aluminium, copper, silver and titanium on PET filaments through vacuum coating.
- Electro-less plating , in [5], the process is explained thoughtfully from the basics by Mallory et al, and in [6], Sonehara et al. Show the validity of their method for electromagnetic shielding with Nickel based alloy plating.
- Sputtering , [7, 8] is a very well known technique that permits the deposition of thin metallic layers (i.e. Zinc and Titanium [8]) on polymeric compounds.

Many other methods are also available. All these different techniques are widely used and permit to achieve conducting layers of variable thickness, once this is accomplished the electrical behaviour of the overall structure is not influenced by the way used to build it, obviously this is not true for the mechanical properties, which can vary greatly in elements such as the flexibility, durability , weight... .
So far only the coating with metal has been considered, the usage of polymers is also a possibility, conductive organic polymers offer different advantages to metals, first of all they are light and can be used as coatings for fibers normally used in the textile industry, such as cotton [9]. On the other hand they tend to have poor mechanical properties, their processing is also rather difficult due to the high brittleness and high costs [1]. An other sensible difference between metals and organic conductors is that the electrical conductivity of the latter, although being usually much lower that the metals [1], can be modulated by addition of metal and carbon fillers, maintaining the thickness of the layer constant. The most used coatings are Polypyrrol (Ppy) and Polyacrylonitrile (PAN) for their good thermal and electrical behaviour [1, 9 10, 11], also flexibility is usually good. Furthermore the deposition of thin layers of conductive polymers on fabrics or yarns does not noticeably change and sometimes even improves the mechanical properties of the original material [12].Surface resistivities as low as 20 Ω per square have been measured [13].Other kinds of polymers are also appearing on the market, EDOT and PEDOT find increasing interest thanks to their high conductivity [9].Other big issues in organic conductors is their stability and their repeatability, in this case the process of their formation is very relevant.

2.1.3 Purely conductive filaments

The third and final category comprises filaments made by completely conductive materials, being the metals or the polymers discussed above. Copper and Nickel present themselves as good candidates since Silver is mostly used in coatings (for its high price). Combinations are also possible, thin Silver plated Copper wires are in fact a very good example [2]. Interestingly Stainless Steel is also used as a material for conductive fibers in EMC applications, it has very poor conductivity but high EM absorption properties [14]. For the organic conductors the same as above applies with the major difference that the low thickness's used in coatings and the combination with more flexible substrates renders them much less brittle. This main disadvantage limits their use as pure threads [1].

In any case the parameters that have to be taken into consideration when choosing the material are its conductivity and the achievable thickness. Fibers with smaller diameter (and then thinner coating for the coated filaments) will be more efficient in case of high frequency applications because, thanks to the skin effect, only a portion of the available surface will be travelled by the current [17].

2.2 Structure

Before discussing how the yarns are created by weaving or knitting threads, this ones must be defined. Independently of the way the filaments are constructed many combinations are necessary before the final threads can be obtained. Conductive threads can be divided into two categories: monofilament and multifilament [2], the former are composed by a single conductive thread while the latter are composed by numbers of smaller conductors wrapped, for example, around each other forming a spiral-like structure; monofilament threads have usually better electrical properties (such as higher conductivity) than the multifilament ones, this is probably due to the fact their electrical length is lower, multifilament threads, on the other hand,are, possess great mechanical properties but with higher length (per conductor) compared with the monofilament case. Both typologies can then be used by themselves into fabric or be mixed with other non-conductive threads, such as flexible or stretchable polymers or generic fabric to produce lightweight conductive fibers. This combination has the multiple objective of protecting the thin and fragile conductive fiber with the more resistant non-conductive threads and creating complex conductors with adequate mechanical characteristics.

An other interesting factor to keep in consideration is the possibility of having insulated or non-insulated conductors. A layer of non conductive material would provide, first of all resilience to the fiber and have the secondary effect of modifying the electrical behaviour. Independently of the structure used to compose the fabric, in fact, non-insulated fabrics permit conduction of current between different threads (weft and warp for woven structures, see later), contrary to the insulated ones. This causes the latter to have a much lower shielding effectiveness than the former at low frequencies [17]. On the other hand, when the frequency increases, capacitive coupling will be present between the insulated fibers increasing the shielding efficiency to great extent [17]. Figure 2.1 shows some typologies of conductive threads produced by Textile-Wire (ELEKTRISOLA FEINDRAHT AG) [15]

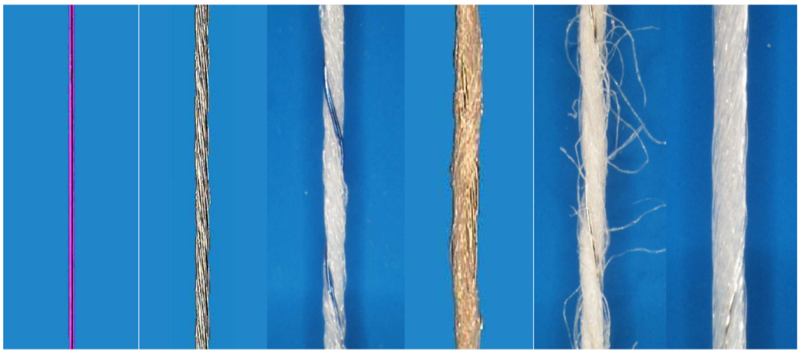


Figure 2.1: Examples of different typologies of conductive yarns

Now that the complex conductive threads are formed, they can incorporated into fabrics in order to form electro-textiles. Before discussing the techniques used to achieve the final textiles a very brief introduction on the internal structure of these is in order. Textiles can be analysed keeping in mind that they have a hierarchical structure, at a microscopic level one can identify fibers as the basic components, going up, combinations of these fibers into repeating cells called yarns (in this case the yarns are the composite conductive threads discussed above) are now visible. Finally, at a macroscopic level, the fabrics, as an overall structure are identified [16]. Yarn geometry is essential knowledge to design highly shielding fabrics;For example the way the conductive fibers are added to the non-conductive ones plays a major role in defining the electrical conductivity of the resulting thread. In fact , the metal or organic conductors, can be applied by covering the non-conducting core with the conductive fibers in an helical fashion, the result is then some sort of ”coated yarn”. Plying is also possible, in this case the conductive filament twists inside the yarn and in the last case, called core, the conductive filaments lie in the inner region of the yarn. Among these these three cases the last one (core) will have the conductors with the least length, the yarns will then have the highest conductivity[14]. Now the yarns need to be combined in order to get to the fabrics, the two most used techniques to build electro-textiles are weaving and knitting, they will now be explained but before that a point has to be stressed; maybe more important than the conductivity of the yarns is the structure this yarns will compose. In fact, from an EM shielding point of view, while the conductivity dictates the behaviour at low frequencies, the structure becomes more and more important as the frequency raises.

2.2.1 Woven Structures

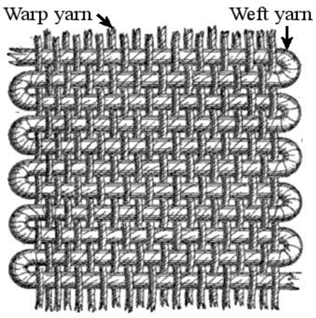


FIGURE 2.2: Warps and Wefts

A woven fabric is produced by interlacing warp and weft yarns [16]. Warps are sets of parallel lengthwise yarns through which the weft is woven, see figure 2.2. They both define the structure of the fabric in the two dimensions. For electromagnetic shielding an ideal case is present when both warp and weft yarns are conductive, this cannot be always the case since mechanical properties of the fabric may require that only one of the two might conduct electricity. It has been shown that, in this case, the shielding is not optimal and becomes polarization dependent, this is due to the currents that can be induced only in one direction [2]; full grids are still the most effective since the currents can follow paths aligned with the source.

Kinds of weaving

Weaves are in general complex, the possibility of raising and lowering the sequence of warp yarns gives rise to three basic kinds of weave structures. These can be then layered in order to achieve full three-dimensionality. These different weaves are the plain, the twill and the satin weaves.

- The plain weave is the simplest kind of weave,obtained by aligning warp and weft yarns perpendicular to each other and parallel to themselves in order to obtain a simple criss-cross pattern, see figure 2.3 [38].
  In the case that all the yarns are conducting the apertures can be kept to minimum size so to obtain good electromagnetic shielding for a mono-layer structure [14, 17].

- The twill weave is obtained when the crossing between warp and weft yarns stops being symmetrical, this creates diagonal lines on the face of the fabric.

See figure B.4 [38].

Compared to plain weave of the same cloth parameters, twills have longer floats, fewer intersections and a more open construction [38].Although this technique may yield to suboptimal shielding it is worthwhile to consider it. If not all the yarns in the weft or warp directions are conductive a plain weave can be considered like a twill one, at least electrically. In this case the apertures are becoming larger the less conducive yarns are present, this will inevitably bring to a decrease of the shielding capabilities of the structure. It is interesting to notice that, by modifying this openings either in the warp or in the weft direction, it is possible to toggle with the resonance characteristics of the structure in order to achieve determined frequency behaviours, for more depth refer to the work of J-S. Roh et al. [17].

- The satin weave , these are structures created in order to have smooth faces free from any twill line, To obtain this the distribution of interception points between yarns has to be as random as possible. See figure 2.5 [38].
  Generally then a satin woven fabric will have two different faces, one will have more warp yarns than weft ones and vice versa. Electrically this can mean that one face will have more conductors than the other. In other words is then possible to create a structure that presents two layers. This is particularly convenient in case the non-conductive fibers are highly dielectric, the insulating layer can then absorb part of the electromagnetic radiation before it reaches the metal shield [14].

2.2.2 Knitted Structures

The second most used technique is knitting. The yarns meander through and create interlocking loops[2]. This can be done either in the warp or in the weft direction[16], figure 2.6 shows an example of weft knitted fabric. Differently from weaving,in which

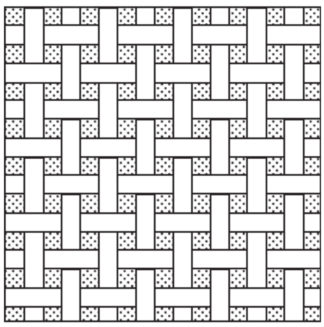


Figure 2.3: Plain weave

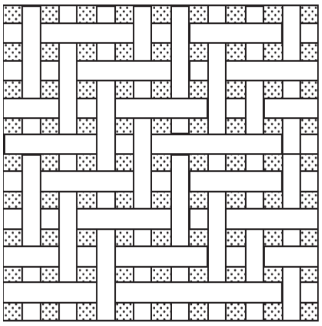


FIGURE 2.4: Twill weave

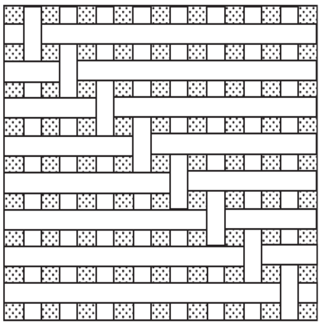


FIGURE 2.5: Satin weave

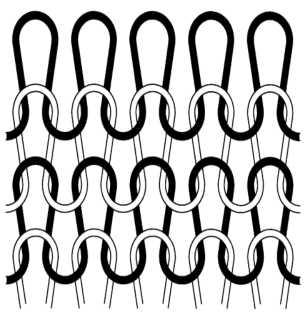


FIGURE 2.6: Knitted structure

the yarns run horizontally and vertically, in knitting there are no straight paths, this leads to more complex structures that offer, to begin with, a much greater elasticity than the woven ones. Strength is usually also greater and can be easily modulated on one or the other direction by using different knitting techniques. The literature presents few works [18, 19] on knitted fabrics used for electromagnetic shielding, the reasons are different. Firstly, knitting doesn't usually allow to achieve such small grid openings as weaving, limiting thus the shielding behaviour of the fabric at high frequencies [18], the thickness is also greater making the realization of multi-layered structures more cumbersome. Furthermore knitted fabrics present yarns that run only in one direction, as seen before for woven structures, this is sub-optimal for shielding since only the field with polarization perpendicular to the running path will be stopped [20]. Metal (or any other conductor) content seems also to play a more important role in knitted fabric [18] than in the woven ones [17].

Chapter 3

Modeling of shielding fabrics

The characterization of shielding textiles is not an easy task. Their inhomogeneous structure makes it quite difficult to embrace them in a simple and comprehensive theory, approximations need to be used to level down the order of the problem. This section will present the methods used in literature to model conductive textiles but first a basic introduction on the parameters used to determine the shielding quality of a structure is in order.

3.1 Basic Shielding Principles

Following Scheulknoff's theory, beautifully expressed and adjourned by Shultz et al. [21], three phenomena concur when an object is placed on the trajectory of an electromagnetic field. Part of the radiation is reflected by the surface of the shield and goes back to the source, this is usually called REFLECTION, the bit that is actually passing through the barrier is then attenuated (i.e. converted into heat), nominally ABSORPTION, then the last effect happens at the end of the shield, parts of the EM waves that successfully entered the structure are then reflected back and forth in the structure, this last phenomenon is then called MULTIPLE REFLECTIONS.
Without going too deep in details, lets define these three effects and the characteristics a fabric surface must have in order to be a good electromagnetic shield. The definition of shielding effectiveness is given in formula 3.1 [21,22]:

$$\begin{aligned} SE = 20\log_{10}|p^{-1}| + 20\log_{10}|e^{\gamma l}| + 20\log_{10}|1 - qe^{-2\gamma l}| \\ = R + A + B; \end{aligned} \tag{3.1}$$

where

$$p = \frac{4k}{(1+k)^2}; \quad \text{with} \quad k = \frac{Z(l)}{\eta_0};$$

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)};$$

$$q = -\frac{(1-k)^2}{(1+k)^2};$$

- The first term, R, in the previous equation represents the reflection. It depends only on the transmission coefficient p, which is itself only dependent on the free-space impedance η_0 and the impedance $Z(l = 0)$ of the shield at the surface invested by the EM radiation. If these two are not identical then part of the waves will be reflected in function of the ratio k of these two impedances. The higher the conductivity then the lower $Z(l)$ will be and therefore the greater the portion of radiation that will be rejected.

- The second term A, on the other hand, represents how much of the EM energy that managed to pass into the shield is actually absorbed (converted into thermal energy). This term is function of the propagation constant γ, which is itself function of the permittivity ϵ, permeability μ and conductivity σ of the shield only. If the latter is fixed to enhance reflective behavior then the first two must be maximized in order to achieve high absorption. The choice of the non conductive fibers becomes now very important.

- The last term B is indicative of a phenomenon that occurs when the waves leave the shield on the opposite end. Parts of these are reflected back to the beginning of the shield and then, either exit from there or keep being attenuated from one side to the other of the screen; this is way B is called the multiple reflections coefficient.

The first term is usually the one that influences the shielding effectiveness the most [21, 22]. High absorbtion can also be achieved with the implementation of specific materials but it is usually limited by the low thickness of fabric shields. B is usually neglected but it has to be noted that in case of materials with low absorbing properties, the term B should be taken into consideration and eventually corrected [21].

This was all valid in the hypothesis that the screen is made of continuous (more or less) conductive material. Thus is also true for conducting textiles given that the wavelength of the incident radiation is big compared to the grid openings in the woven or knitted structures [24]. If not the problem shifts from being a basic planar shield study to the much more complex aperture theory. Since the structure of these fabrics is so complex, a rigorous mathematical characterization of the shielding effectiveness of these structures is a very demanding task[20], most of the works in literature that attempt an analytical solution make use of heavy simplifications and semi-empirical methods [23, 24 ,25, 27]; the others reach a solution with the use of modeling software tools [20].Some examples of both categories are now going to be presented.

3.2 Modeling attempts

3.2.1 Semi - Empirical models

Historically parts of the approximations were based on the periodic structure of the fabrics, instead of considering the overall surface, only a basic cell composed by two warp and weft's yarns would be considered and then repeated. With the advancing of technology and therefore the increase of frequency this approach became outdated [20]. So, as expressed above, now the problem is usually divided in two separate parts, a “low frequency approach” and a “high frequency approach”.

3.2.1.1 Low frequencies

In this case the basic shielding theory expressed above is usable, In case of the thin shield approximation an other parameter can be used in order to predict the shielding effectiveness of the screen. With the assumption that the thickness of the fabrics is very low (it is usually a safe assumption) the absorption term A and the multiple reflections B become negligible and the shielding is then mostly due to the reflection term R. The shielding effectiveness if then some what proportional to the conductivity of the material through a coefficient called $surface\ resistivity\ R_s$ [22]:

$$R_s = \frac{1}{\sigma t}; \qquad \text{expressed in} \quad \frac{\Omega}{sq} \tag{3.2}$$

Avery high conductivity σ is then need to compensate for the low thickness t. If the yarn geometry and the electrical properties of the conductive fibers are known (such as density of coating, weight of the non conductive fabric, ratio of conductive fabrics to non-conductive), an approximate value of the surface resistivity can be easily computed geometrically following the procedure explained by Sandrolini and Reggiani in [24]. This method is subject to the accuracy of the knowledge of the materials composing the yarn and it is at least good enough to provide the order of magnitude of the surface resistivity in a fast and computationally inexpensive way.

3.2.1.2 High frequencies

Sadly as the frequency increases the apertures become more and more important and cannot be ignored any more. The shielding will then be a function of the ratio between the wavelength of the incident radiation and the aperture area, specifically the maximum aperture size will determine the quality of the shield [24].Henn and Cribb show a very interesting semi-empirical model in which the Shielding effectiveness is determined on that principle.

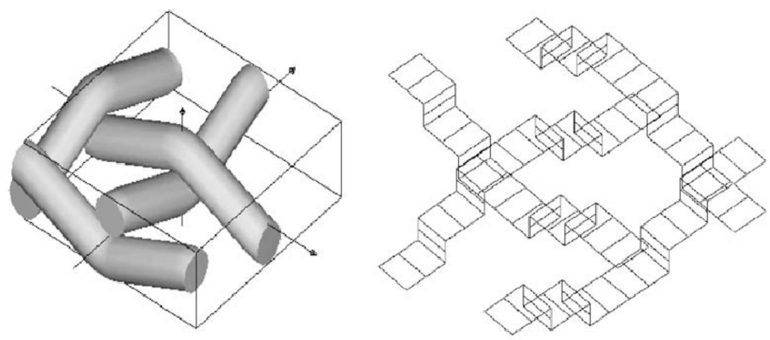
$$SE = e^{(-fcn[\frac{L}{\lambda}])} + (1 - e^{-fcn[\frac{L}{\lambda}]}) \tag{3.3}$$

where λ is the wavelenth of the incident radiation, L is the maximimum aperture size in the fabric and $fcn[\frac{L}{\lambda}]$ is the function that needs to be developed from fabric geometry and measurements.
The major problem is the reproducibility of such method, in which the needed parameters are computed from the geometry of a given fabric and thus need to be recalculated for any different case [24]. The vast majority of methods to find the SE are (semi-)empirical, they rely heavily on measurements [23,24,25,26]. Usually some experimental results are obtained and then a theoretical model is built. A very impressive work on semi-experimental techniques (not only for the shielding effectiveness) was developed by Shaw et al. [26] in which the scattering parameters measured through a test cell are being used to determine

a transmission loss which is then recomputed in the form of resistance per unit length, this quantity is then adjusted to take into account the non uniform current distribution and in the end a surface impedance formulation is employed to derive an equivalent conductivity suitable to express the yarn with a method of moments.

3.2.2 Software modeling

The other approach to the characterization of these shielding fabrics is the usage of specific software tools capable of using highly optimized mathematical methods such as Finite-Difference Time Domain (FDTD) [28], Finite Elements Methods (FEM) [29] and Integral Equations Methods (IEM) [20]. These software techniques are yes very powerful but suffer of some drawbacks, to begin with, the differential methods (FDTD and FEM) are capable of handling arbitrary structures and they are usually applied in the design of well known antenna structures and relay mainly on Approximate Boundary Conditions (ABC) [20]. To apply them to a new generation of problems and applications might not be so straightforward.An other difficult point is the determination of the conductivity of the yarns in these tools, as today most of the works do not regard the problem [28, 29] or assume it infinite [20], while others relay on an empirical way to determine the value and then place it into the software [25]. It is obvious that any value of conductivity different from infinite will increase dramatically the computational complexity of the problem.
This said, the only real attempt to model rigorously the behaviour of conductive textiles for shielding applications, based on the geometrical properties of these at a mesoscopic scale,proposed by Volski et al. in [20], will now be discussed. This technique is based on the equivalence theorem: each conducting yarn is replaced by an equivalent current. The boundary conditions for electric field lead then to integral equations (IEM) that are solved using the methods of moments (MoM). The fabrics are then shaped in a tool for mechanical design and imported into the IEM electromagnetic tool (in [20] these are WiseTex [30] for the mechanical part and MAGMAS [31], see figure 3.1), in this transition the yarns are approximated in horizontal and vertical flat conductive strips or walls (namely these are the staircase approximation and the equivalent wire approximation). The electromagnetic properties of the yarns are then maintained and all the overhead given by the mechanical characteristics is discarded. This method seem to be very effective and relatively simple, for more insight on the actual implementation of this technique please read [20].



(a) Yarns in WiseTex (b) Yarns in MAGMAS

Figure 3.1: Example of topology transfer between the mechanical and electromagnetic tool

Chapter 4

Measurents

4.1 Literature

Literature provides an extensive list of experiments and attempts made in order to measure the electromagnetic properties of these advanced textiles. In this section some of the most used techniques will be listed and discussed and some new approaches developed in this department will also be examined.

The measuring techniques used for textiles are usually the same used on flat, thin materials, this approach is obvious considering that shielding materials are mostly of rigid structures and fabrics come naturally in sheets but it is also a limiting factor for textiles have their strong points in flexibility and in daily applications these materials will have bends and corners. This said, measurements for flat samples will be used throughout this work for the sake of comparison. The two most used standards in SE measurements of flat samples are the ASTM D4935-99 [32] and the IEEE 299 [33], the former makes use of a flanged circular coaxial transmission-line holder and the latter uses a shield enclosure with a hatch[24, 34, 39]. An other method to measure SE of flat, thin materials, is gaining more popularity thanks to its simplicity; it's the free space transmission technique [35, 36, 37]. This setup allows to assess the EM properties of the sample without the need of expensive anechoic rooms or flanged transmission-line holders.
From all these techniques the SE is computed as an insertion loss (IL), the power transmitted is then measured before and after the placing of the sample and the difference is then proportional to the shielding qualities of the fabric.

$$SE = 10\log_{10}(\frac{Power_{received}}{Power_{transmitted}}); \quad (4.1)$$

4.1.1 Flanged Coaxial Cell

In this case the measuring apparatus is composed of a network analyzer which feeds a flanged coaxial transmission-line holder, figure 4.1, in which plane waves are reproduced and thus the far field shielding effectiveness of a flat material can be computed from the S21 parameter. The coaxial holder has an interrupted inner

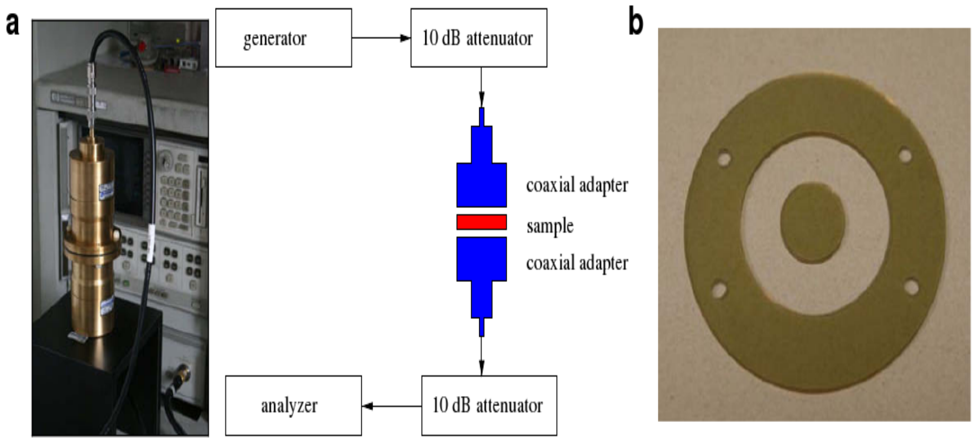


Figure 4.1: Flanged coaxial cell at the TELEMIC Lab (a) with relative calibration sample (b)

conductor and a flanged outer one that permits the position of the sample between the two parts of the device. For a firm fixation either heavy holders or insulating screws may be used, this point is particularly important for non woven structures which tend to be thicker and less compressible that their woven counterparts [24, 34]. An other important factor to remember when applying this method to textiles is that in the best of the hypothesis they posses a periodic structure (see satin-weave and embroideries as counter examples) but inhomogeneities are still present and thus the response is polarization dependent and this cannot be measured with the setup since the result is an average over every polarization [20]. The system is firstly calibrated with a sample of known characteristics and then a measurement of empty space is performed. The sample can now be interposed and measured. The insertion loss introduced by the presence of the sample will determine its shielding capabilities. The standard ASTM D4935 is used to quantify measurements in the range 30 MHz to 1.5 GHz.

4.1.2 Shielded enclosure

An other widely spread method consists in placing an antenna, typically a horn, inside a metal enclosure directed towards a hole on which the material to test is placed. Outside and disconnected from the enclosure a receiving element is positioned in order to measure the variation in the EM signal with and without sample in between the antennas. Figure 4.2 shows a typical setup. The scope of the enclosure is to minimize unwanted diffractions and reflections. Typically this kind of setups

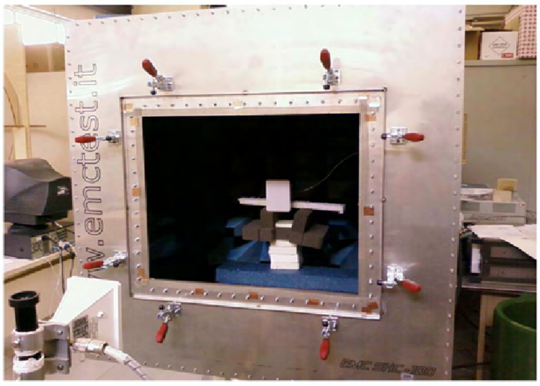


FIGURE 4.2: Shielded enclosure setup used in [24]

can be used for wide frequency ranges such as 2 - 18 GHz. The major drawback of this technique is that only samples with a wide surface can be measured but new systems based on small enclosures will be presented with the new standard IEEE 299-2.

4.1.3 Free space measurement

Two directive antennas, typically horns, are used in a free space environment and a mathematical method is then applied to remove diffraction. This method is applicable to flexible materials thanks to the high degrees of freedom in the geometry of the setup and the measurements are highly reproducible [35]. Figure 4.3 shows a scheme of the setup [35]. Also in this case SE is computed by the scattering parameters, there's to notice here that, being in free space, the variations in sample and environment geometry will sadly bring a certain degree of inaccuracy coming from diffraction around the sample and reflections from the working area surrounding the setup[36, 37]. Particularly, if the distance between the antennas is low enough to minimize reflections the power measured with the presence of a sample might be of the same order of magnitude than the one recorded without sample due to diffraction around the object. Some arrangements can still be taken in order to minimize such problems:

- the reflection parameter S_{11} is much more sensible to ambient and sample conditions than the transmission parameter S_{21} which should therefore be used [35].
- an enclosure of absorbing material can be placed around the receiving horn antenna in order to shield it from diffracted and reflected waves, see figure 4.4 [36].

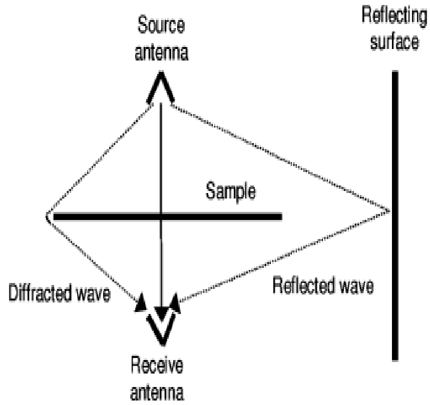


Figure 4.3: Scheme of the elements of the free space method

- a software based solution is also used, since diffracted and reflected waves will go through a longer path than the transmitted ones they will show up shifted in time with respect to the direct ones, they can then be removed by applying a time-gating technique, more information can be found in [35, 36]. The range of frequencies at which this system is applicable varies in function of the size of the horns and the distance between them (that will determine whether or not the sample is in far field), typically values between 1GHz and 18GHz have been reported.

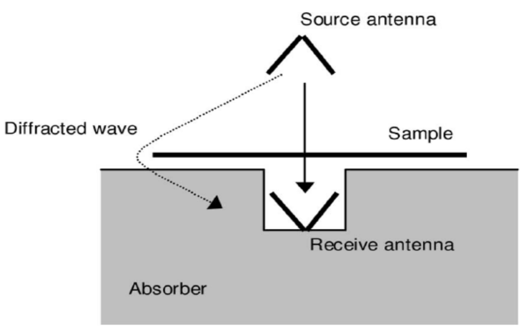


Figure 4.4: absorbing box

4.2 Measurements in Loco

Here, at the Telemic Lab some measurements were done on samples received by Bekaert, these are woven fabrics composed by polymeric and stainless-steel fibers. The steel is spun on the polymer to obtain fibers with diameter of $6.5\mu m$ [10]. Of the three samples we received, two (sample 1 and 3) are plain woven and the last one (sample 2) is double layer, the quantities of metal vary in each of them as seen from table 4.1

TABLE 4.1: Samples'compostion

Sample	% metal	% polymer	structure
1	87	13	plain weave $200g/m^2$
2	90	10	double layer $270g/m^2$
3	70	30	plain weave

Two of the aforementioned measurements techniques have been used: the flanged coaxial holders and the free space method. They work on different frequencies ranges which makes their complementarity ideal to check the results of the setups and analyze the samples on a wider spectrum.

4.2.1 Flanged coaxial cell

This measurement set-up is shown in figure 4.1. It consists of 2 coaxial adapters (ElectroMetrics, EM-2701A), two 10 dB attenuators, and a network analyzer, (HP8510C). The measurement followed a calibration procedure in which the power transmitted (P_{cal}) is measured when a sample,built in accordance with the specifications given in the manual of the coaxial holder, is used. In the second step the power transmitted when the fabric is placed between the holders is measured. All the measurements were performed between 100 MHz and 1.5 GHz. Figure 4.5 shows the SE, computed as in equation 4.1 for the three samples, they demonstrate interesting shielding capabilities leading for the relative maxima.

Since the samples received have rather wide surface,an other set of measurements has been done, in which the fabric sheets where bent in order to acheive a double layer.

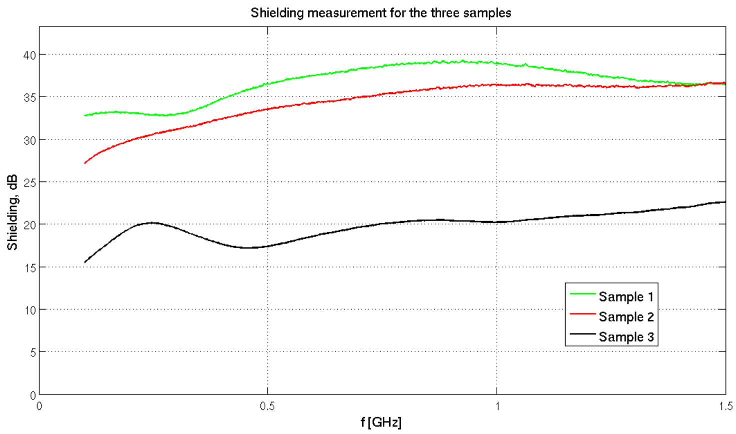


Figure 4.5: SE for flanged coaxial hoders

Table 4.2: Maximum values of SE

Sample	MaxSE [dB]	Freq. [GHz]
1	39.3063	0.8295
2	36.7178	1.3720
3	22.6085	1.4035

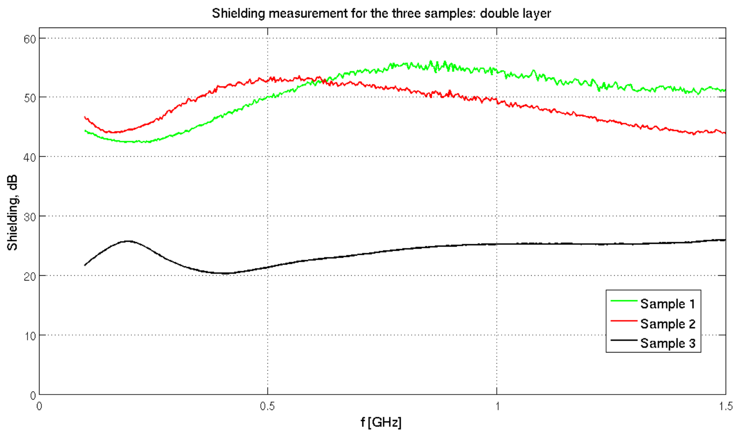


Figure 4.6: SE for flanged coaxial hoders and two layers of fabric

Table 4.3: Maximum values of SE

Sample	MaxSE [dB]	Freq. [GHz]	increase [dB]
1	56.1558	0.7595	+ 16.8495
2	53.5907	0.4725	+ 16.8729
3	25.9344	1.3895	+ 3.3259

4.2.2 Free space method

The setup is here composed by two antennas (both Dorado GH1-18N) facing each other at short distance. As before the measurement procedure consists of two consecutive steps with and without the material under test in position. The difference in the power transmission between the two cases can be attributed to the shielding by the material. The distance between the two horns can be reduced in an attempt of minimizing unwanted diffraction and reflection [37], but without falling into the near field zone, in which (formula 3.1) wouldn't be valid anymore. Like expressed before, the finiteness of the sample has to be taken into consideration, diffraction will always be present and since an absorbing enclosure, as proposed by Marvin et al. in [36] was not available just the time-gating technique was used. In short a diffracted ray will reach the receiving antenna with the same amplitude as a direct one (in absence of shield) but with a phase difference. By analyzing the time domain then, this delay can be found and the relative peaks removed through an envelope. Figures 4.7, 4.8 and 4.9 show finally the results for sample 2 for variable distances of 20, 50 and 100 mm respectively.

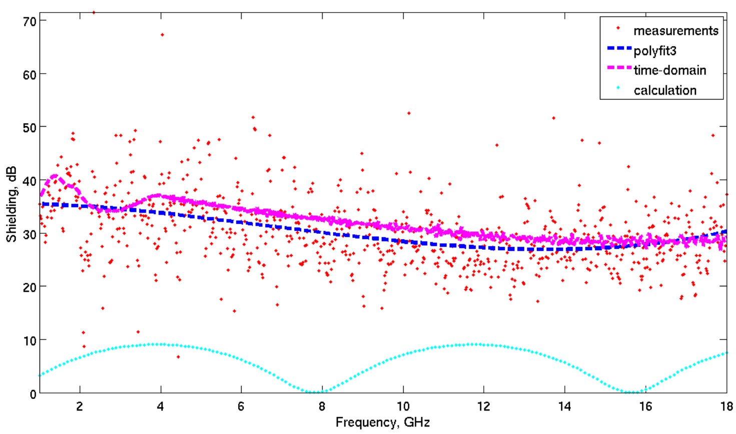


FIGURE 4.7: SE for free space at 20 mm

There seems to be good agreement between the two setups,in fact, in the overlapping interval, 1-1.5 GHz, the measured values are of the same order of magnitude.

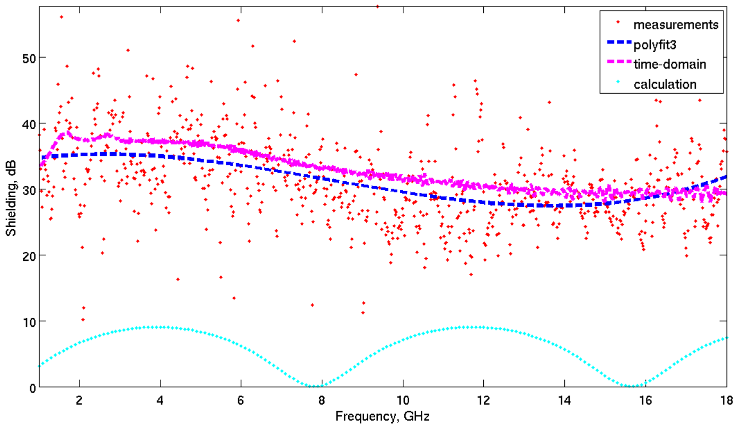


Figure 4.8: SE for free space at 50 mm

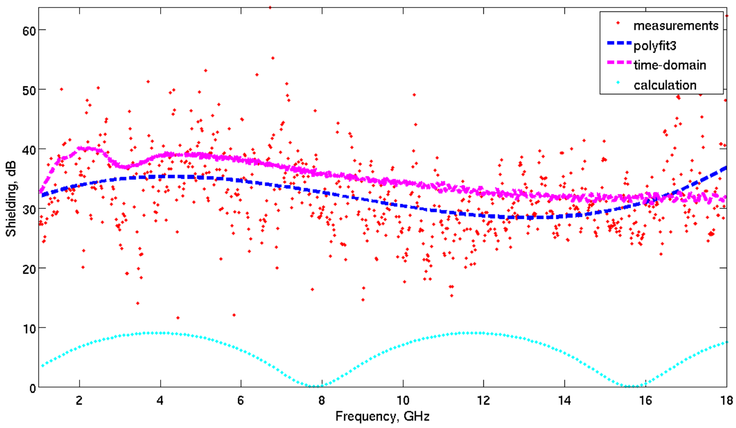


Figure 4.9: SE for free space at 100 mm

Chapter 5

Simulations

This chapter deals with the analysis of the different textile structures described before. Firstly the process through which these pass from their physycal design to the electromagnetic tool is presented then the approximation choices and the steps performed in order to model the behaviour of the different morphologies are explained.

5.1 Notes

5.1.1 Conversion from WiseTex to MAGMAS

As explained in chapter 3 the mechanical structure of the fabric is firstly designed in WiseTex, in this tool the fibers are defined as a concatenation of ellipses, their width, the distance between them and the kind of weaving are defined. The resulting file is then imported, as is, into a converter that will create the input file for MAGMAS. This conversion is done in 5 steps [20], 1) firstly the ellipses are parametrised then 2) the unit cell is meshed into a 3D grid and the centres of the ellipses are mapped onto the nearest centre of each 3D grid cube, the mesh will then always be symmetrical into the unit cell. 3) Strips and walls are introduced by analysing the ellipses centre. 4) The topology just created is meshed into the strips and walls and 5) the output file for MAGMAS is generated. In order to perform these steps some elements need to be defined, such as the minimal grid step or the subdivisions in x,y and z directions that will define the adherence of the new topology to the old one. At this point is possible to choose between a fully 3D mesh (strips and walls) and a 2D (only strips). The width of the yarn is also redefined, during the conversion only the centre of the yarns is passed to the new mesh, the width is then added giving the possibility of being modulated without the necessity of redrawing the structure. Now that the mesh is ready the necessary information in order to compute the shielding are added such as the electrical conductivity, the dielectric permittivity, the number of points taken to compute each Green's function.

5.1.2 Design Choices

As explained MAGMAS permits different degrees of approximation of the morphology, as a first attempt the yarns are modelled as bi-dimensional metal strips, this should give an upper limit on the shielding capabilities of such structures. The fully three-dimensional structure comes next, the designed yarns now resemble more the physical ones. The original hypothesis is that the two cases differ greatly in the approach to the problem but should lead to very close results since the elongations in the propagation direction are much smaller compared to the length of the yarns. Once the validity of the method is shown for the plain weave typology the other two, namely twill and satin, are also going to be implemented in the attempt to analyse their electromagnetic properties. For this set of simulations the electrical conductivity is set to infinity, this is surely a limiting factor at low frequencies but at smaller wavelengths the topology plays a much bigger role, an optimistic shielding behaviour can then be obtained; also the computational complexity is greatly reduced. The dielectric permittivity is also supposed equal to free space, this value can be changed in future to take into account the presence of polymeric material in the mesh. The witdh of the strips is 0.35 mm if not specified.

The obtained simulations are also compared with a lumped model obtained by literature[40], in this case infinitely conductive strips are assumed, these give rise to some (mainly) inductive and capacitive grating from which is possible to compute the transmission and reflection coefficients. The first inconvenience about a numerical tool applied to EM analysis of complex structures is the " low-frequency catastrophe" as very efficiently stated by Vecchi in [42]. In this case is numerically very difficult to define properly a geometrically complex structure in quasi static conditions, different methods have been proposed to circumnavigate the problem but they could not be implemented in the short term and are not in the scope of this project

5.2 Bidimensional structure

At first a plain weave structure with unit cell of 2mm by 2mm has been analysed, figure 5.1 shows an example of the structure while in figure 5.2 the S12 parameter, obtained by simulating, is presented; it is here noticeable that the transmission coefficient increases, as predicted, with frequency.

In a second set of simulation the spacing between parallel vertical (and horizontal) yarns is increased exponentially from 2mm to 8mm. The shielding is now function of this spacing. The curves are rather smooth and agree quite well with the ones obtained following the analytical method (figure 5.3).

If the spacing is allowed to increase more some discrepancies with respect to the predicted behaviour are visible towards the end for the 16mm spacing curve and from the middle on the 32mm in figure 5.4. These abnormalities occur at 9.3GHz for the 16mm case and start at 4.7GHz for the 32mm one. These two frequencies correspond to wavelengths of 32 and 64 mm respectively, which are exactly twice the size of the unit cell for the respective curves. After rigorous analysis it has been

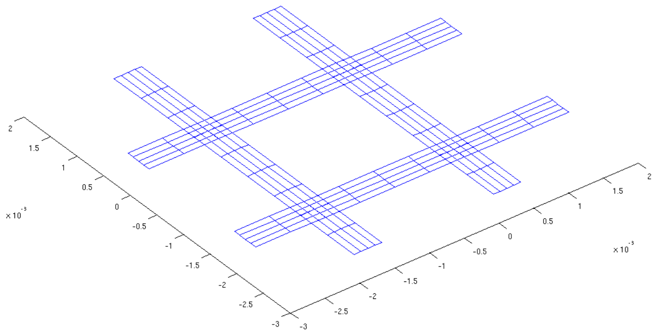


FIGURE 5.1: Mesh of 2D plain weave structure

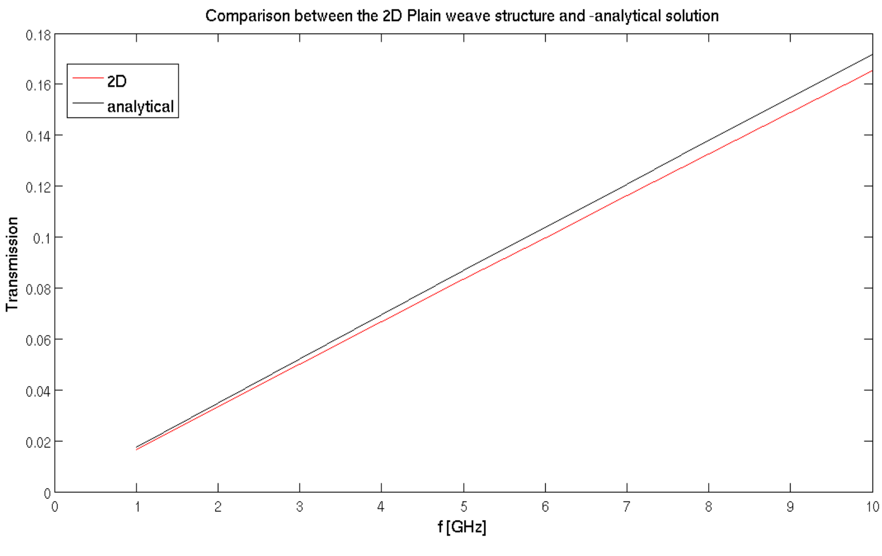


FIGURE 5.2: Transmission for 2mm by 2mm woven structure

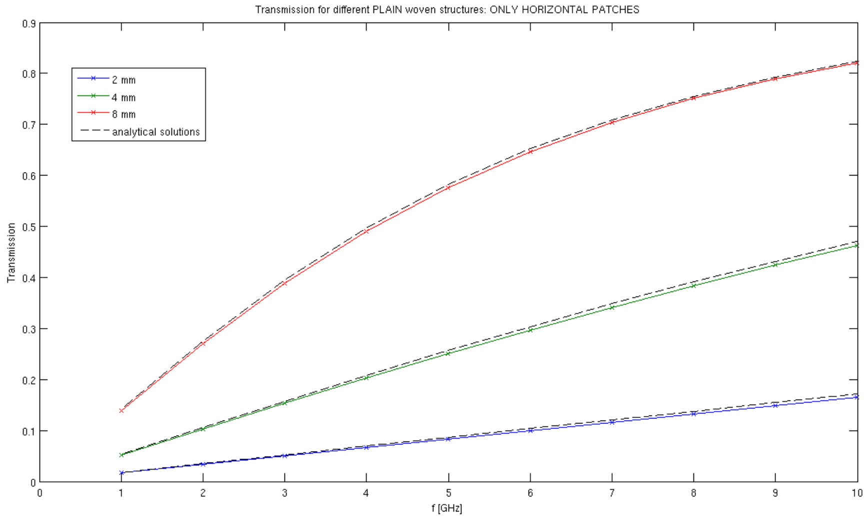


Figure 5.3: Transmission for 2mm by 2mm woven structure

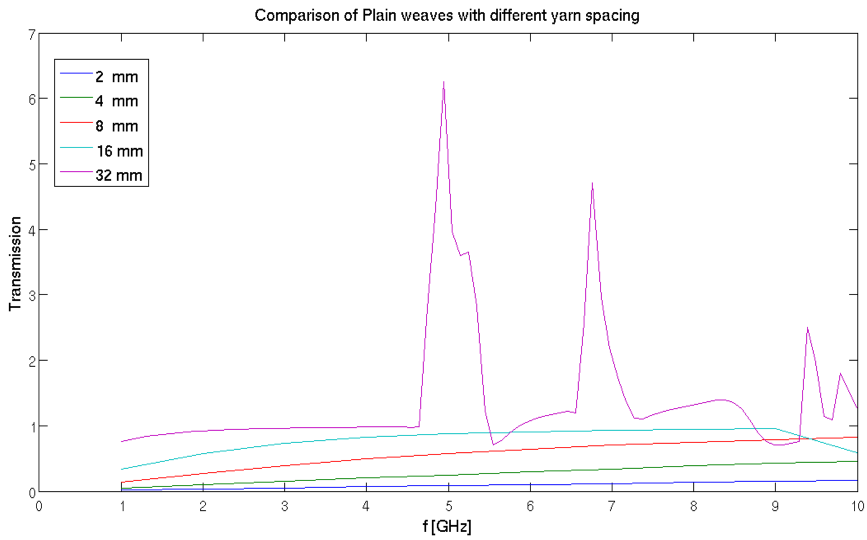


Figure 5.4: Comparison of 2D structure for different spacing

inferred that from the moment the wavelength becomes as small as two unit cells multi-modal propagation occurs and therefore the presence of grating lobes becomes dominant. The system was not developed to operate in such conditions and thus the results are not to be taken valid from these points onward.

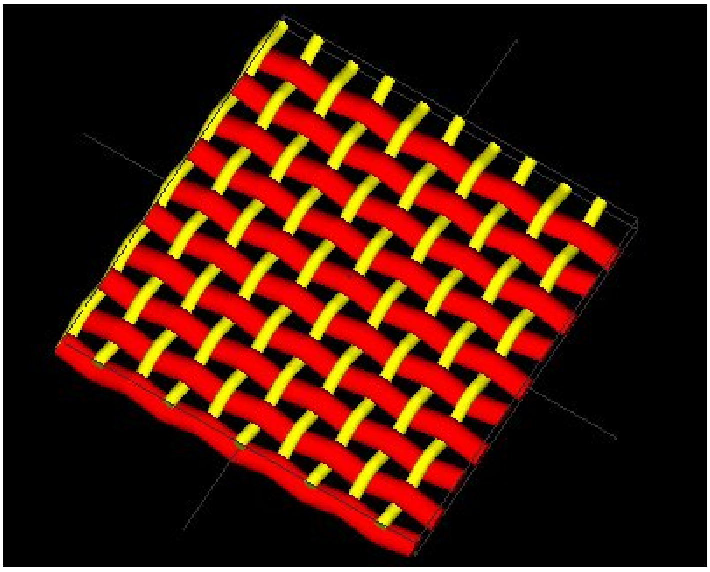


Figure 5.5: WiseTex designed Plain weave

5.3 Three-dimensional structure

For all the 3D simualtions the interfaces that define the depth in the z direction are 1mm apart. This value is given directly by WiseTex and parametrized during the conversion to the MAGMAS mesh.

5.3.1 Plain weave

Vertical walls are now introduced in the attempt of reproducing the physical structure, figure 5.5 shows the structure designed with WiseTex and figure 5.6 shows the resulting MAGMAS mesh with only two positions in the propagation direction. As visible from figure 5.7 when this more realistic morphology is compared to the simple strip case, although following the same trend,presents worst EM shielding capabilities; this is most likely due to larger apertures, the propagating wave coming sideways sees a wider open surface.

It was explained before that the models differ greatly in the cases, the fully three-dimensional one requires a much higher precision. MAGMAS calculates the number of Green's functions differently for patches and walls and as the period increases (above 4mm spacing) these need to be incremented. Figure 5.8 shows the difference between the transmission coefficient S12 obtained with a plain weave with 4mm spacing between yarns when 20 or 60 points are taken to solve the Green's functions in the unit cell. The precision is therefore fundamental, especially at low frequency as discussed above.At high frequencies the curves converge.

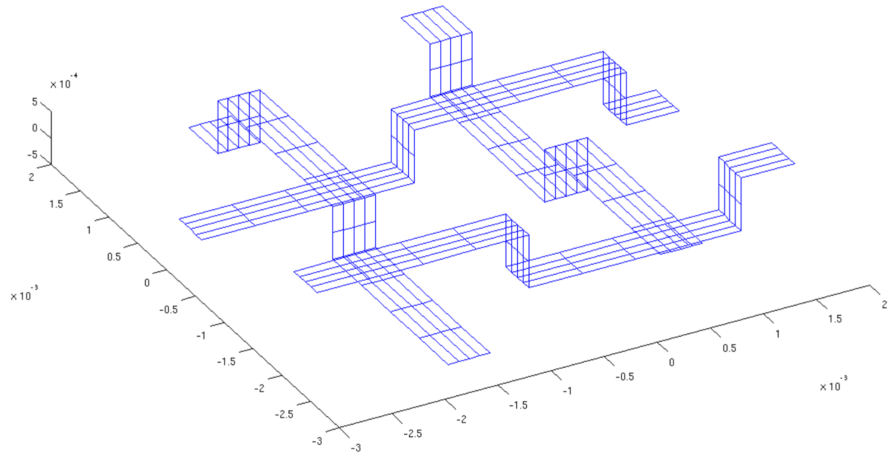


Figure 5.6: Mesh of 3D Plain weave structure

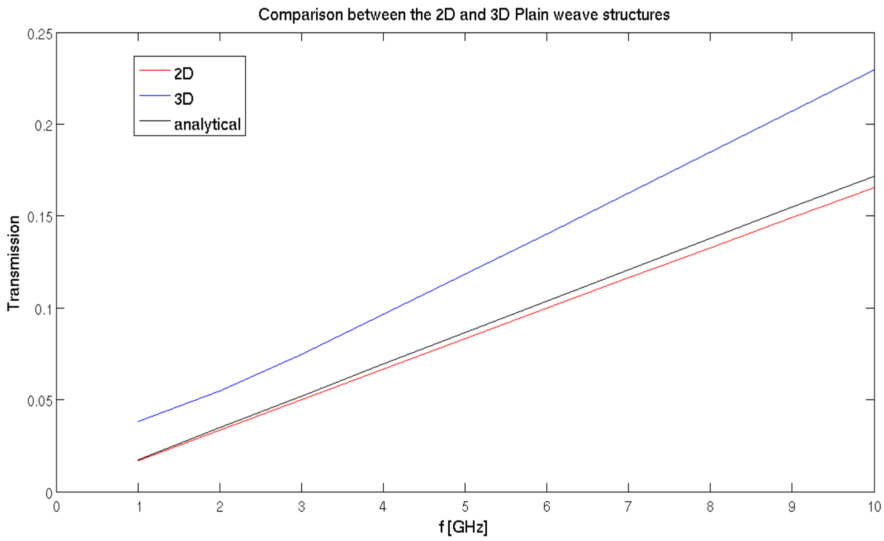


Figure 5.7: Comparison between 2D and 3D plain weave structures

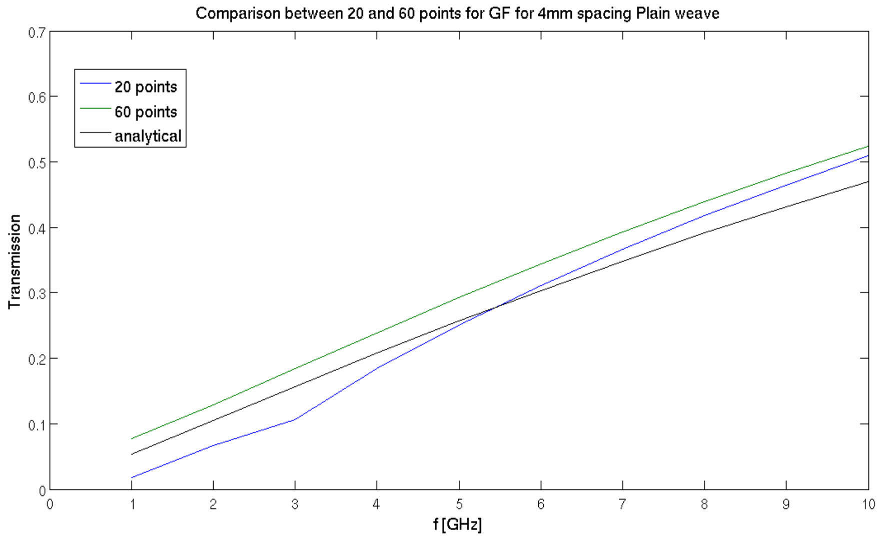


FIGURE 5.8: Difference in precision

Figure 5.9 shows that the trend is then the same as in the simple 2D case, this can be considered an initial proof of the validity of the software. In the same image the analytical solutions are also shown, these are the same for the 2D case, it makes then sense that their transmission is lower.

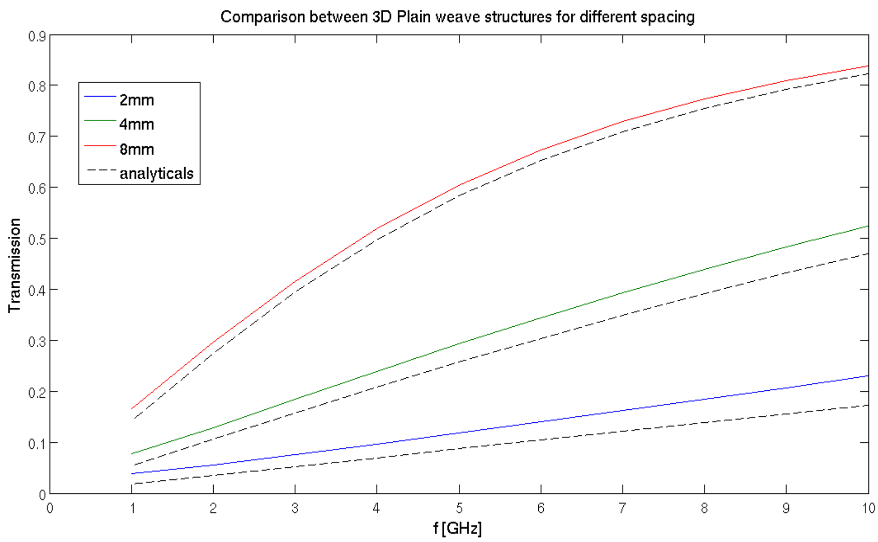


FIGURE 5.9: Comparison for different 3D Plain weave strucures

It is also interesting to see the behaviour of such topology when the diameter of the yarns is varied, figure 5.10 presents the results for a varying width between 0.25 and 1 mm, the trend is as expected, the wider the strips the less radiation passes trough.

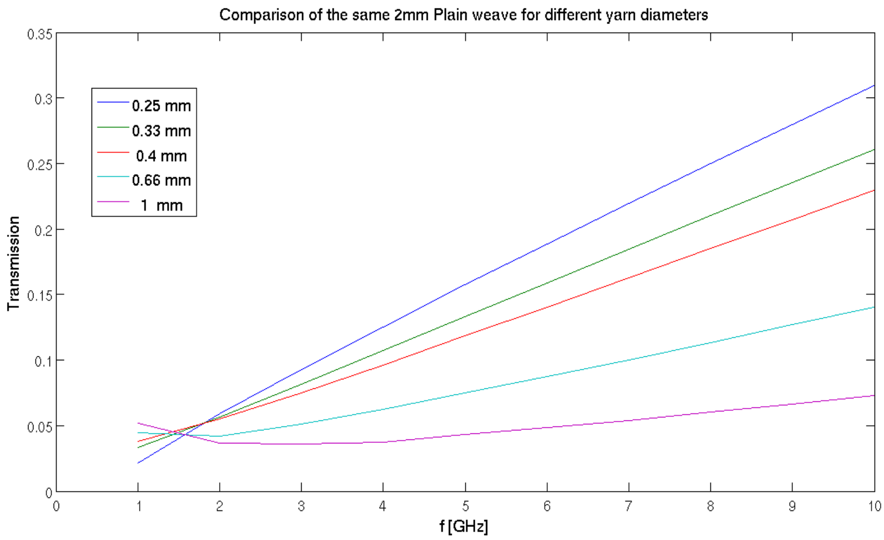


Figure 5.10: Comparison of the same 2mm Plain weave for different yarn diameters

5.3.2 Twill weave

Now the same proceedings for a twill structure are presented, the weave is shown in figure 5.11 as designed in WiseTex and in figure 5.12 as imported by MAGMAS (only the warp yarns are shown for simplicity), as explained before the symmetry at a microscopic level is lost, in practice the period here is three yarns instead of two and the overall structure is not symmetric anymore. The original hypothesis we formulated stated that the difference between the plain and twill weaves should be negligible since the distance between parallel yarns is actually the same; but as visible from figure 5.13, which shows the behavior for 2mm spacing, this is not the case.

The difference in shielding is probably due to grouping of warp yarns present in the twill weave, these run exactly parallel to each other except for the crossing points with the weft ones which are much less than in the plain case. The total structure results so less porous, this is in accordance with the experiments conducted by Perumalraj et al.[41].

Again the same is replicated for the 4mm and 8mm spacing in figures 5.14 and 5.15. The last figure of this section presents the three twill simulations all on the same graph, also in this case the usual trend is followed. The low level symmetry loss is

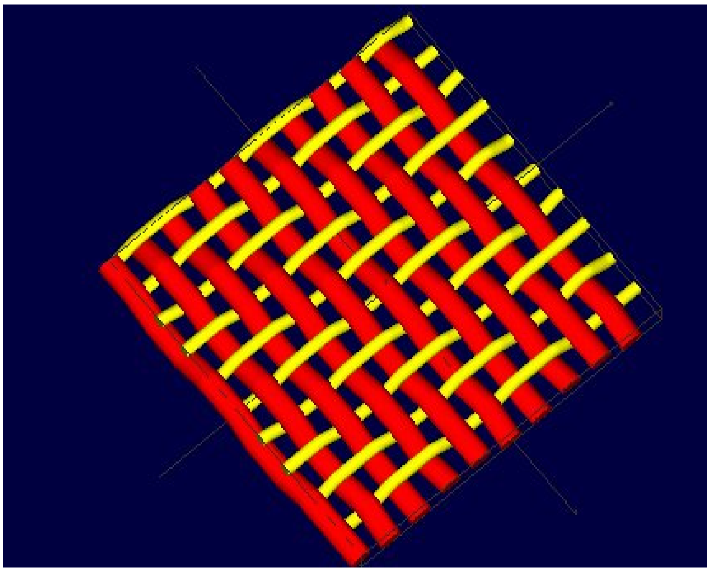


FIGURE 5.11: WiseTex designed Twill weave

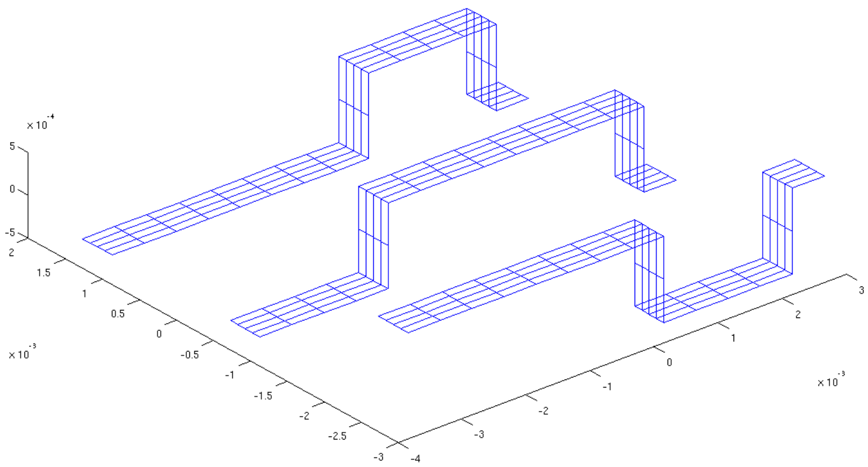


FIGURE 5.12: Mesh of 3D Twill weave structure

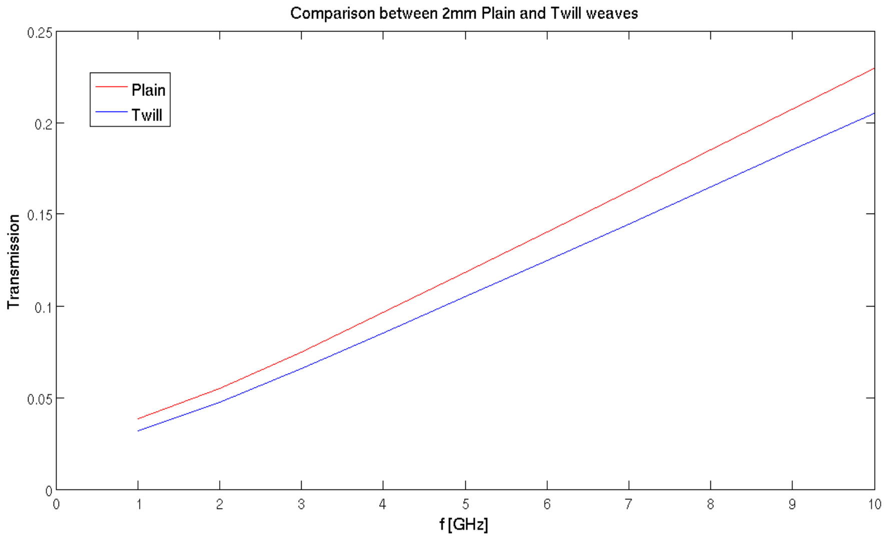


FIGURE 5.13: Comparison between Plain and Twill for 2mm spacing

visible here, in fact the three curves seem to diverge at low frequencies.

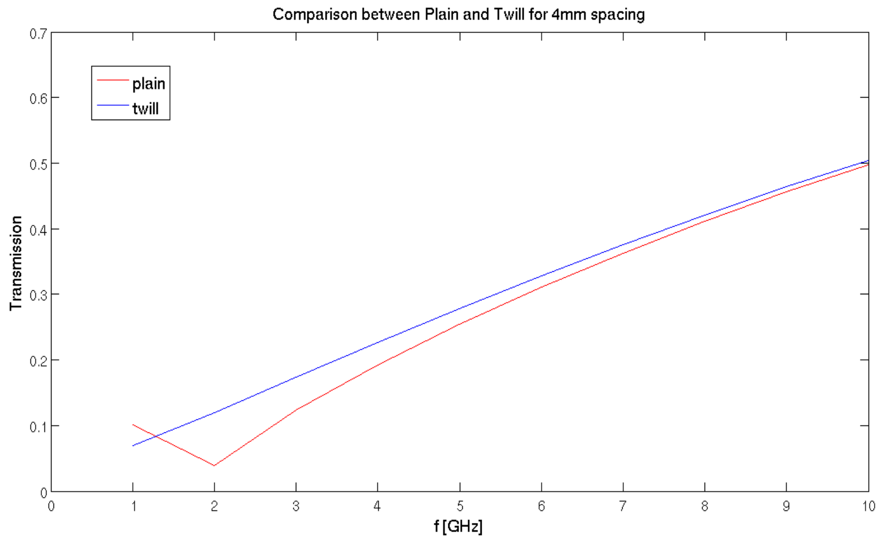


FIGURE 5.14: Comparison between Plain and Twill for 4mm spacing

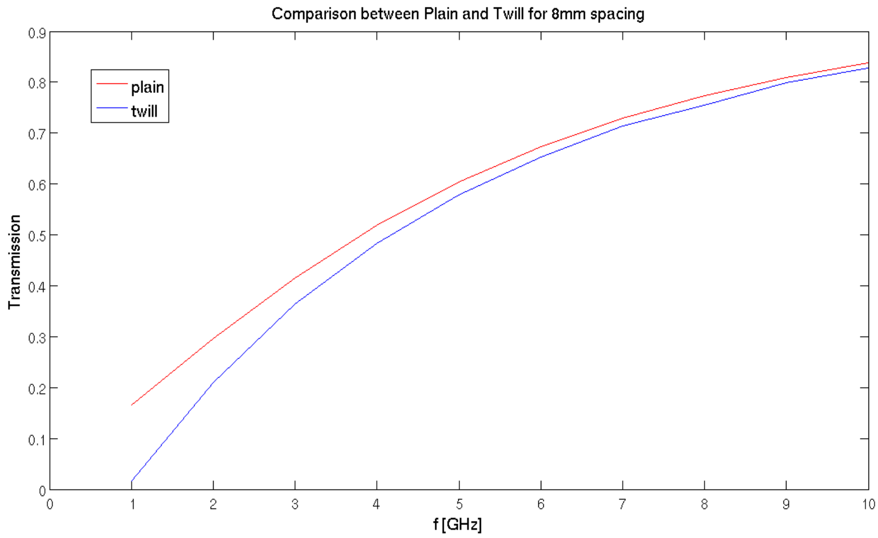


FIGURE 5.15: Comparison between Plain and Twill for 8mm spacing

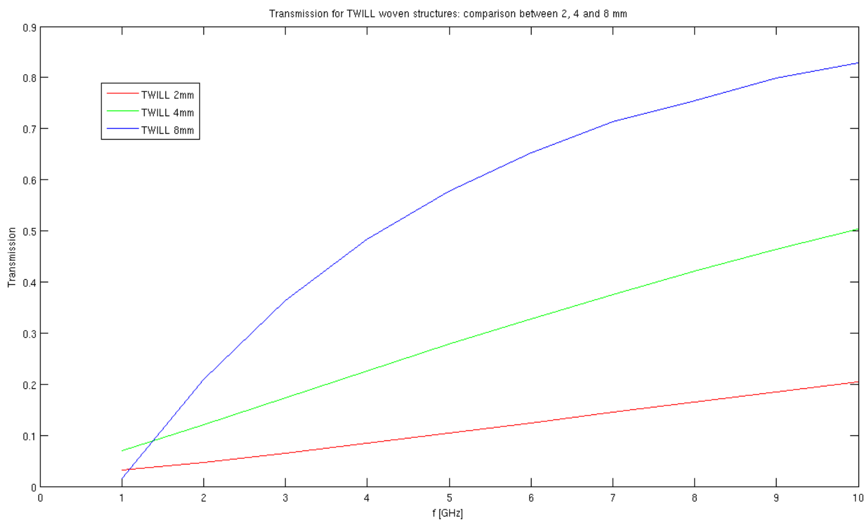


FIGURE 5.16: Comparison between the different Twill weaves

5.3.3 Satin weave

As explained before satin is a type of weaving in which warp and weft yarns are arranged in such a way to minimize the crossovers, the symmetry in the ”unit cell” is lost completely. In fact the smallest form of satin was implemented, this is called 5-harness and is constructed by having a crossover every 5 yarns in the warp direction with a step of 2 in the weft direction (see figure 5.17).Figure5.18 shows the mesh used for this set of simulations (as for the twill case only the warp yarns are shown for simplicity), exactly as for the previous case the behaviour of a satin structure with 2mm spacing between yarns has been compared with the one of identically spaced twill and plain weaves; this can be seen in figure 5.19.

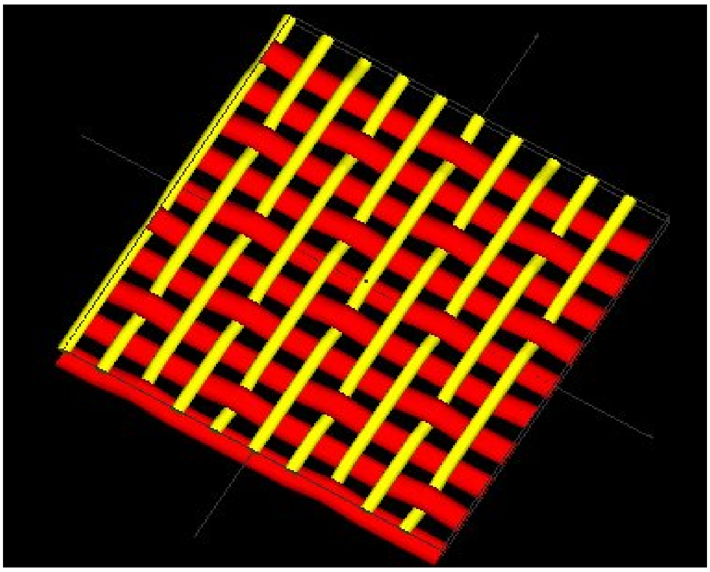


Figure 5.17: WiseTex designed Satin weave

The satin structure seems to have an overall lower transmission than the other two types, this can be explained by extending the yarn grouping effect discussed for the twill case. The intersection between warp and weft yarns happen now only once every 5, this permits to obtain island of homogeneous yarns closely placed to each other. The same goes for the 4mm and 8mm spacing cases as shown in figures 5.20 and 5.21.

Figure 5.20 shows some discrepancy at lower frequency, this is entirely due to the already explained limit of the MoM. The interesting discovery is however in figure 5.21, apparently a ditch appears at 7.5 GHz, wavelength of 40 mm; this is not physical behaviour of the structure. In fact 5 yarns spaced by 8mm each create a 40mm wide structure, this is then taken by MAGMAS to calculate the coupling between the dipoles, since the basic element seen by the antennas is a 5 yarn structure MAGMAS excites the dipoles with higher order modes. At this point when the wavelength becomes smaller than the periodicity (in MAGMAS, the 40mm, not the

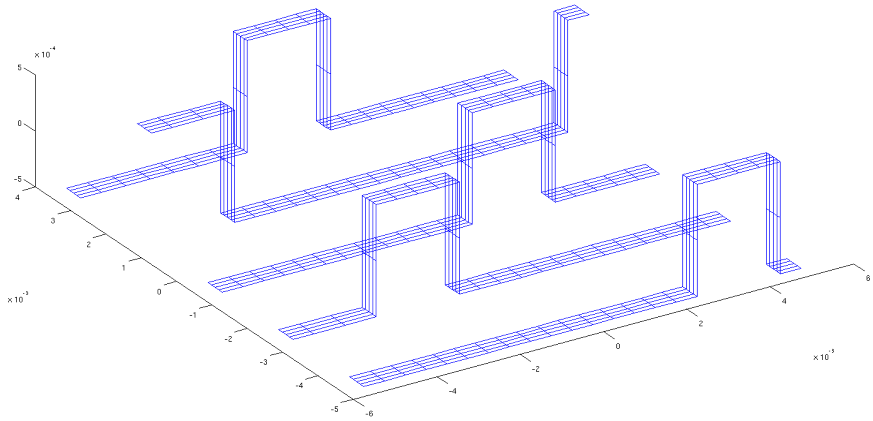


Figure 5.18: Mesh of 3D Satin weave structure

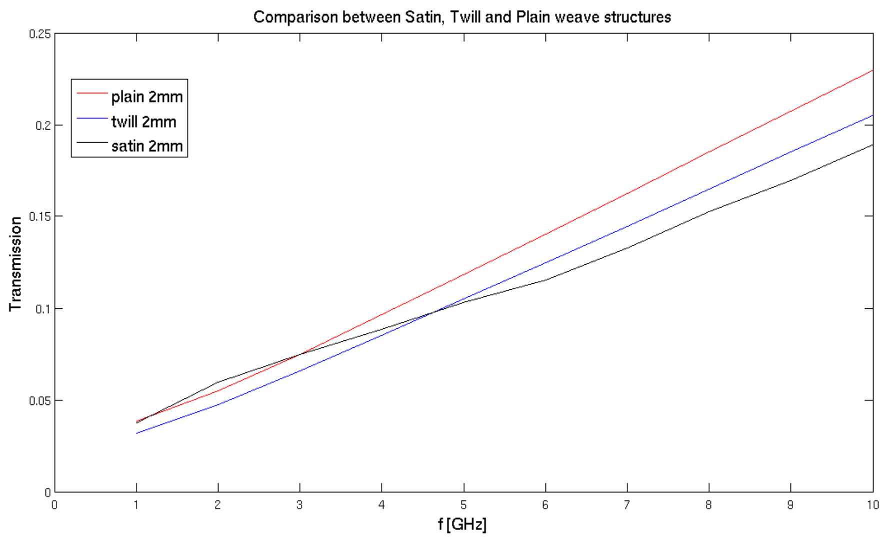


Figure 5.19: Comparison between Plain, Twill and Satin weaves for 2mm spacing

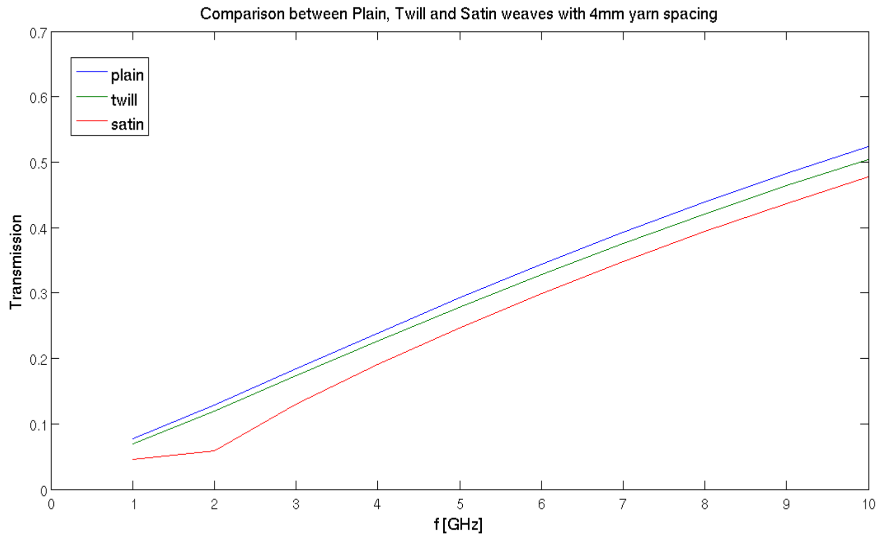


FIGURE 5.20: Comparison between Plain, Twill and Satin weaves for 4mm spacing

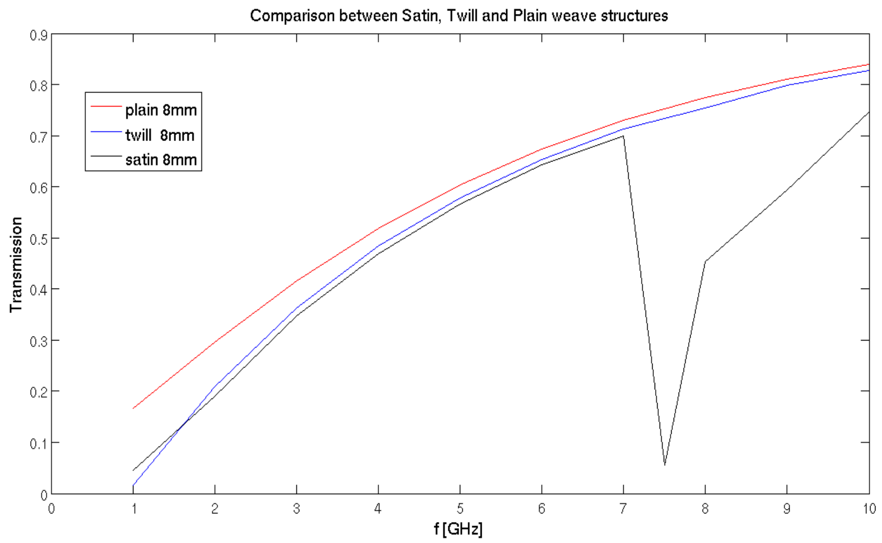


FIGURE 5.21: Comparison between Plain, Twill and Satin weaves for 8mm spacing

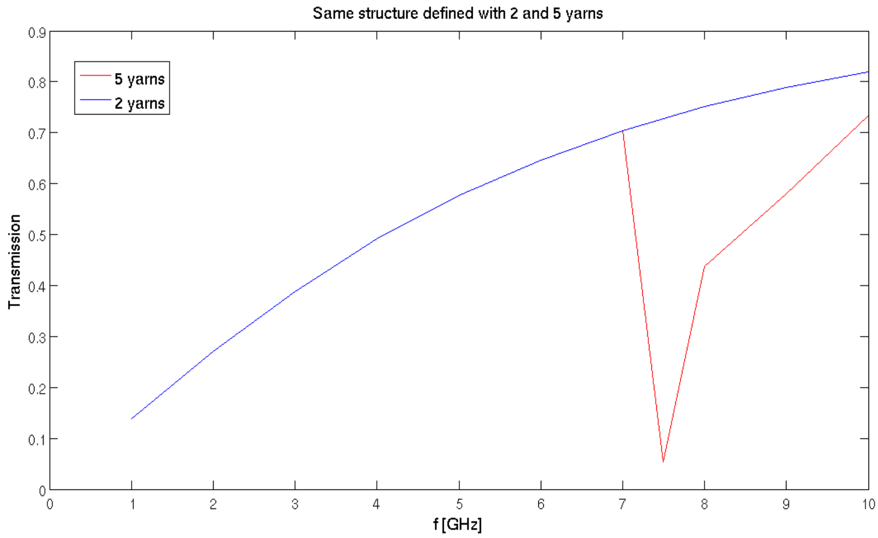


FIGURE 5.22: Comparison same structure defined with 2 and 5 yarns

physical one) high order modes are initiated. To further evaluate this limit of the software and validate the results obtained when the frequency does not reach the aforementioned values the same structure, comprised of yarns spaced by 8mm, was designed in Wisetex with 2yarns (minimum number to define the period) and using 5yarns (redundancy in information). The result shown in figure 5.22 proves that the behaviour is not physical but a product of the method used in computing the coupling.

5.4 Modeling of real structures

Some additional samples have been received during the drawing of this work, these two plain woven structures, produced by GKD, are both made of solely conductive yarns (stainless steel). They are therefore the most appropriate choice to check the validity of the modelling tool since parameters like the permittivity of the non metallic elements is non-existent, differently from the samples presented in chapter 4. In table 5.1 the data relative to the mesh of these samples is presented and figure 5.23 shows the shielding obtained through the same procedure for the coaxial flanged cell holder presented in chapter4. The samples where to small to use any other measuring technique, the results are therefore limited to a 30MHz to 1.5GHz range.

As expected the better performance of sample A if given by the smaller spacing between yarns and the larger width of each of these. Sadly, both the structures are too small, or more accurately their characterization is very difficult due to frequency range in relation to the spacing, another ”low frequency problem” has been

Table 5.1: Samples'details

Sample	spacing [mm]	width [mm]
A	0.196	0.056
B	0.223	0.031

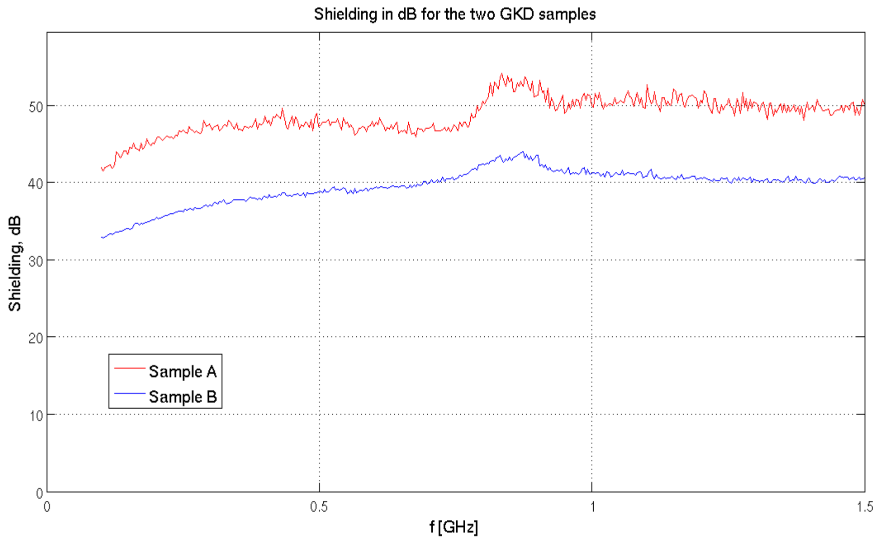


Figure 5.23: Shielding in dB for the two samples

encountered. As explained above the tool cannot handle this yet but an approximate result might still be reachable. It has been noticed that some proportionality in the results for the same topology and different spacings is present in the analytical method, especially for small structures (with respect to the wavelength) where the transmission is linear; furthermore the validity of the analytical method is guaranteed for lower frequencies. A plain weave 10 times bigger than sample A has been designed and simulated, following this proportional property the resulting curve has been scaled appropriately, figure 5.24 shows this operation.

The new curve has then been converted in decibels and compared for the overlapping part of the spectrum with the measured response, as shown in figure 5.25. Although this surely an approximation the results seem to agree quite well.

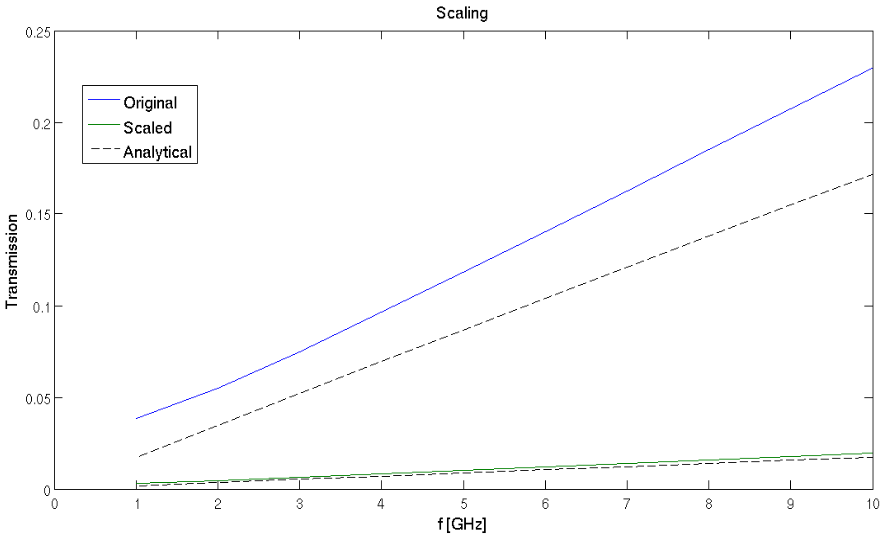


FIGURE 5.24: Shielding in dB for the two samples

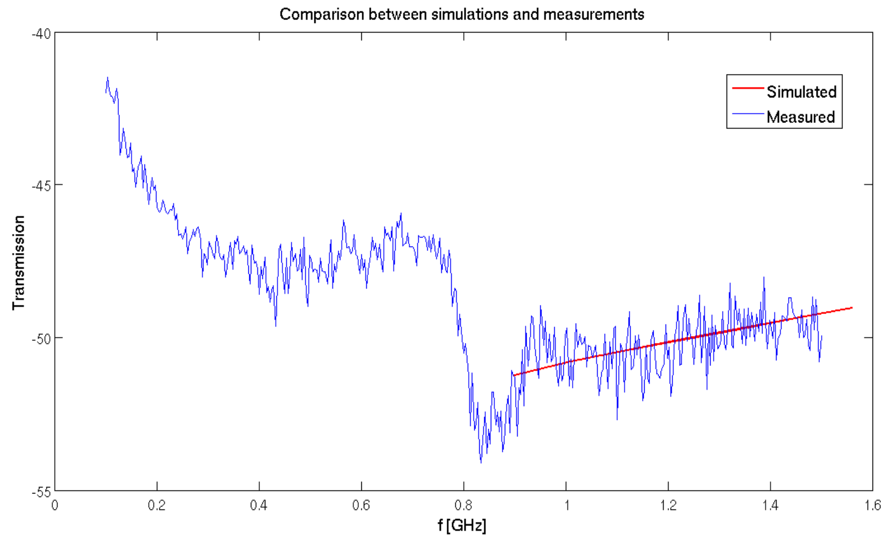


FIGURE 5.25: Shielding in dB for the two samples

5.5 Conclusion

In this chapter different morphologies have been simulated with a set of varying parameters and then compared with each other giving very interesting results. A set of bi-dimensional strips has been simulated in order to test the numeric tool with analytical solutions, this has been proven efficient. Then fully three-dimensional structures were introduced and analysed one by one and compared with each other, the comparative showed that satin weaves place first for shielding followed by the twill and lastly by the simplest plain weaves. While the comparison between twill and plain has already be done in literature [41] the addition of the satin is believed to be a novelty. In the process the validity of the tool has been confirmed by comparison of different structures, its shortcomings have also been exposed. The numerical software used could be thus confirmed as a solid tool to design and study these structures. In the end an approximated solution for the design of weaves with very small periodicity had also been proposed and analysed and showed good accordance between the simulated and measured result.

Chapter 6

Conclusion

The world of shielding textiles has been introduced and analysed, the production techniques, the different planar structures present today and the works currently done in the community relative to the modelling and the measurements of these fabrics are presented thoughtfully. Some of these aforementioned structures, such as Plain, Twill and Satin weaves, have then been simulated and compared. These show that the shielding behaviour is strongly dependent on the morphology and in particular of:

- Yarn spacing:the distance between the filaments determines the aperture size.
- Yarn diameter:the width of the modelled strips determines the amount of conductive surface the wave encounters.
- Morphology:more specifically the symmetry at yarn level, if more yarns are allowed to group together the shielding behaviour improves

A comparison between a measured sample and a simulated one is also included, although this represents only an early attempt for the limit of the software it still is an encouraging result.

The next necessary step would be to fix this ”low-frequency catastrophe”, by separating the induced current in the yarns in solenoidal and not-solenoidal in a loop-star fashion as done in [42] and optimize the software to take into account parameters like a finite conductivity.

Appendices

Appendix A

Conversion files and routine

This appendix shows the conversion files used to generate the MAGMAS input from WiseTex and the script used to obtain the final result from the former. Tables from A.2 to A.6 show the files for the plain weave cases. The twill ones are shown in tables A.7, A.8 and A.9; finally the satin ones are in tables A.10, A.11 and A.12. As a final note, it is reminded that the 2D structure were obtained from tables A.2 to A.6 by replacing the element on the fourth row T (as in true for walls) with F (as in false for only strips). The first Table A.1 explains how the design parameters are inserted into these conversion files.

Table A.1: explanation of a conversion file

WiseTexfile.cfl ds mdx mdy mdz nsel
nPs nPz nPw nWidth
nFibres
Wall nHor-Int
nFreq Freq1 Freq2
MAGMASfilename
nRx nRy
nSA nRA
nCOpa COpa
Fbma
eps
re1 re2

Where :
WiseTexfile.cfl - is the name of the WiseTex cfl output file
nsel - indicates how the grid is built
1 means: (ds is used)
2 means (mdx,mdy,mdz are used)
ds - minimal grid step in the x,y and z direction (mm)
mdx, mdy, mdz - number of subdivisions in the x, y and z direction.
nPs - number of segments on a small patch defined by mdx,mdy

nPz - number of segments on a small wall defined by mdz
nPw - number of segments across the fibre
nWidth indicates how the width of an yarn is calculated
1 means: w=pi*(a1+a2)/4
2 means: w=(a1+a2)/2
>2 means w=(a1+a2)/ nWidth
<0 means: w=(a1+a2)*abs(nWidth)
Note: a1 and a2 are the radii of the ellipses defining the yarns
nFibres - maximal number of yarns that will be taken into consideration. This option is used for a test purpose to reduce a structure to 1 yarn.
Wall indicates how fibres are modeled
T means fibres are modeled using walls and patches
F means. Fibres are modeled using only horizontal patches.
nHor-Int - number of horizontal interfaces (used if Wall = .false.)
nFreq - number of Frequency points
Freq1 - the first point in GHz
Freq2 - the last point in GHz
nRx, nRy - number of points in the x and y direction to calculate GF
nSA,nRA - number of terms used in acceleration procedures in the spectral and spatial domain
nCOpa - conductivity of patches
0 means: Copa=10E+30
1 means: Copa=59.6E+6 (Copper)
Fbma (default: 1) allows to use different asymptotes by using different Fbma.
Eps - means dielectric permittivities
re1 re2 - tolerated errors for acceleration routines in the spectral and the spatial domain respectively.

Table A.2: plain weave 2mm spacing

```
plain02.cfl 1 20 20 2 2
2 2 1 2
2
T 1
10 1 10
PlainModel
40 40
20 20
0 1.000000000000000E+30
4.0
1.0
1e-6 1.e-6
```

Table A.3: plain weave 4mm spacing

```
plain04.cfl 1 20 20 2 2
2 2 1 2
2
T 1
10 1 10
PlainModel
60 60
20 20
0 1.000000000000000E+30
4.0
1.0
1e-6 1.e-6
```

Table A.4: plain weave 8mm spacing

```
plain08.cfl 1 20 20 2 2
2 2 1 2
2
T 1
10 1 10
PlainModel
80 80
20 20
0 1.000000000000000E+30
4.0
1.0
1e-6 1.e-6
```

Table A.5: plain weave 16mm spacing

```
plain16.cfl 1 20 20 2 2
2 2 1 2
2
T 1
10 1 10
PlainModel
80 80
20 20
0 1.000000000000000E+30
4.0
1.0
1e-6 1.e-6
```

Table A.6: plain weave 32mm spacing

```
plain32.cfl 1 20 20 2 2
2 2 1 2
2
T 1
10 1 10
PlainModel
80 80
20 20
0 1.000000000000000E+30
4.0
1.0
1e-6 1.e-6
```

Table A.7: twill weave 2mm spacing

```
twill02.cfl 1 20 20 2 2
2 2 1 2
3
T 1
10 1 10
PlainModel
40 40
20 20
0 1.000000000000000E+30
4.0
1.0
1e-6 1.e-6
```

Table A.8: twill weave 4mm spacing

```
twill04.cfl 1 20 20 2 2
2 2 1 2
3
T 1
10 1 10
PlainModel
60 60
20 20
0 1.000000000000000E+30
4.0
1.0
1e-6 1.e-6
```

Table A.9: twill weave 8mm spacing

```
twill08.cfl 1 20 20 2 2
2 2 1 2
3
T 1
10 1 10
PlainModel
80 80
20 20
0 1.000000000000000E+30
4.0
1.0
1e-6 1.e-6
```

Table A.10: satin weave 2mm spacing

```
satin02.cfl 1 20 20 2 2
2 2 1 2
5
T 1
10 1 10
PlainModel
80 80
20 20
0 1.000000000000000E+30
4.0
1.0
1e-6 1.e-6
```

Table A.11: satin weave 4mm spacing

```
satin04.cfl 1 20 20 2 2
2 2 1 2
5
T 1
10 1 10
PlainModel
100 100
20 20
0 1.000000000000000E+30
4.0
1.0
1e-6 1.e-6
```

Table A.12: satin weave 8mm spacing

```
satin08.cfl 1 20 20 2 2
2 2 1 2
5
T 1
10 1 10
PlainModel
100 100
20 20
0 1.000000000000000E+30
4.0
1.0
1e-6 1.e-6
```

Here follows now the routine script that performs the calculations.

```
alias corr= mod_cfl_file.exe
alias conv= convertWiseTexL.exe
alias creat= create_magmas_inputL.exe
alias magmasV= magmas3D.esat.Linux.i686.debug
alias s11L= make_resultsL.exe

cp WiseTex.dta WiseTex2.dta
corr
rm *.phy

cp WiseTexT.dta WiseTex.dta
rm Hor_Patches.dat
rm Ver_Walls.dat
conv
creat

rm *Z.out
magmasV PlainModel
magmasV PlainModelF
magmasV PlainModelR

s11L

cp WiseTex2.dta WiseTex.dta
```

The script is here explained:
The conversion file WiseTex.dta is copied into a dummy file WiseTex2.dta

The algorithm corr generates the mesh and checks if all the entries are valid numbers (Mesh is saved in test.cfl).
The physical structures generated in the past are removed
The resulting corrected mesh (from test.cfl) is now in WiseTexT.dta which is going to be used
The previous files containing data on walls and patches are removed
The algorithm conv creates the new staircase topology for MAGMAS from the mechanical one with all the relevant information
The algorithm creat gives three MAGMAS files:

- PlainModel - in which the total structure is now comprised of the yarns and two active dipoles

- PlainModelF - creates the two dipoles

- PlainModelR - corresponds to a conductive screen faced on an active dipole

Old output files are now removed
MAGMAS calculates now the coupling between dipole in the previous three PlainModel files

S11L will combine the previous three results in order to obtain the transmission and reflection parameters of the fabric.
In the end the original WiseTex.dta file is restored.

Special thanks for these instructions go to Dr. Voslki who developed them in the first place.

Appendix B

WiseTex

This appendix shows some screenshots of the mechanical design tools for textiles developed by MTM KULeuven. Figure B.1 shows a new woven structure file in WiseTex.

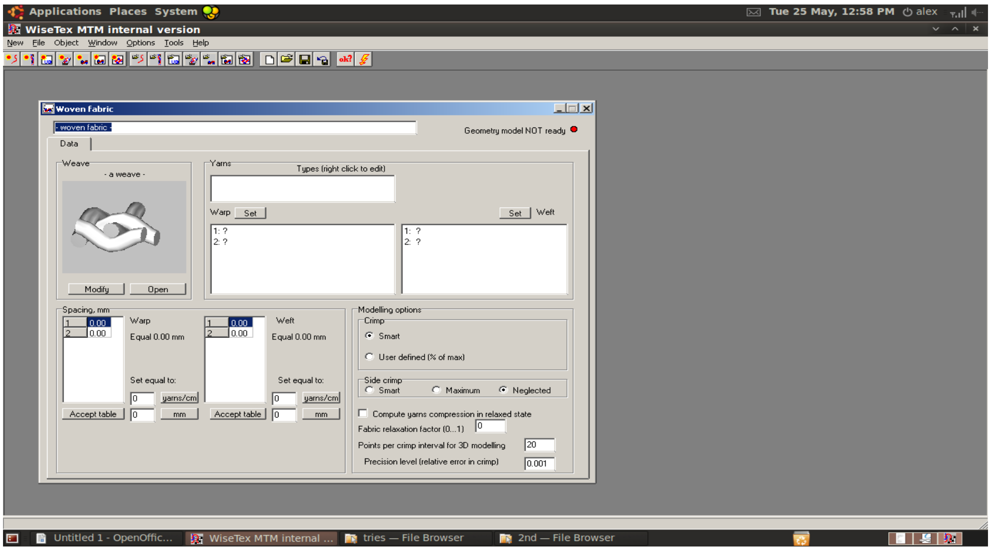


FIGURE B.1: Create a new weave

Figure B.2 shows a the panel in which the yarns are designed.

Figure B.3 shows a the weave design interface in which the yarn positioning is decided.

Figure B.4 shows the resulting structure (in this case twill).At this stage the spacing between yarns is selected.

Figure B.5 shows the final 3D structure.

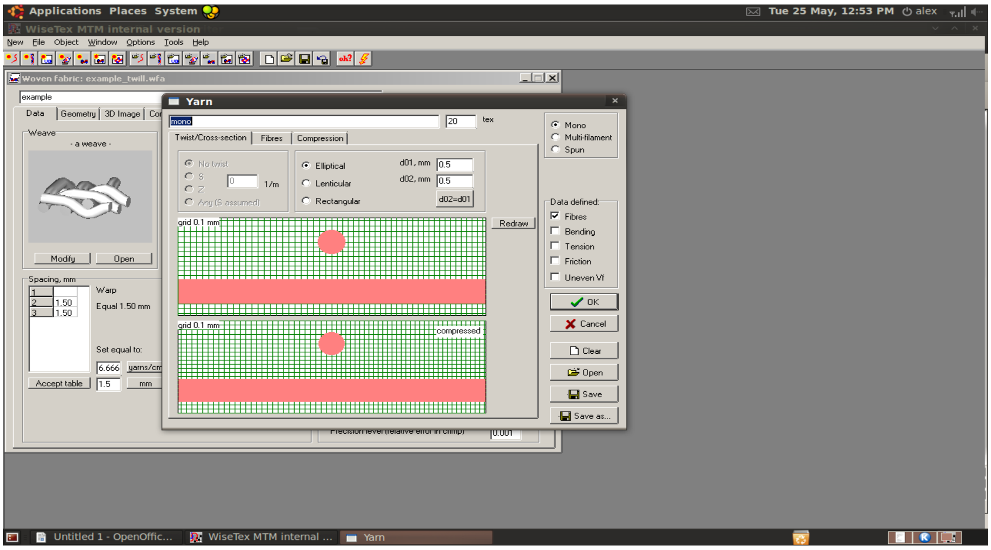


Figure B.2: Design the yarns

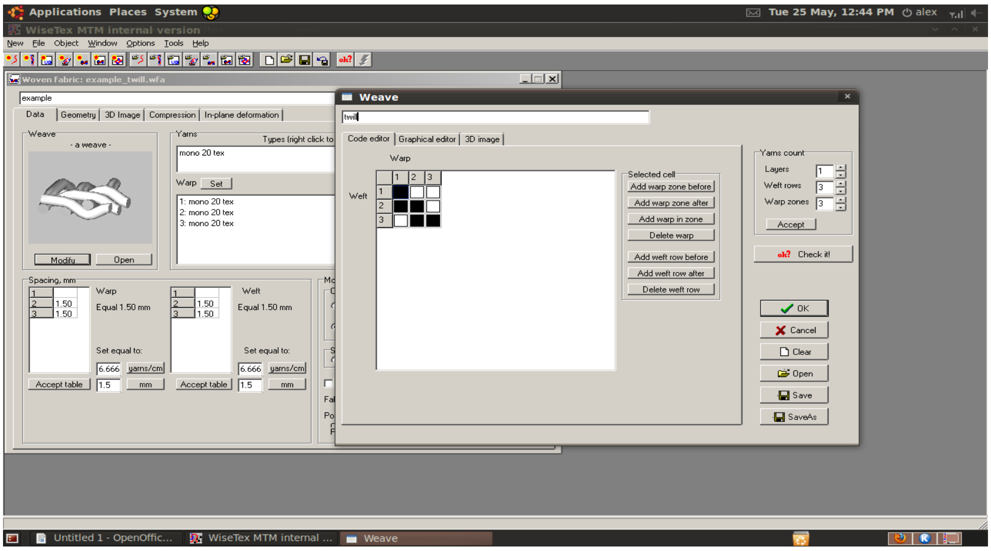


Figure B.3: Design a new weave

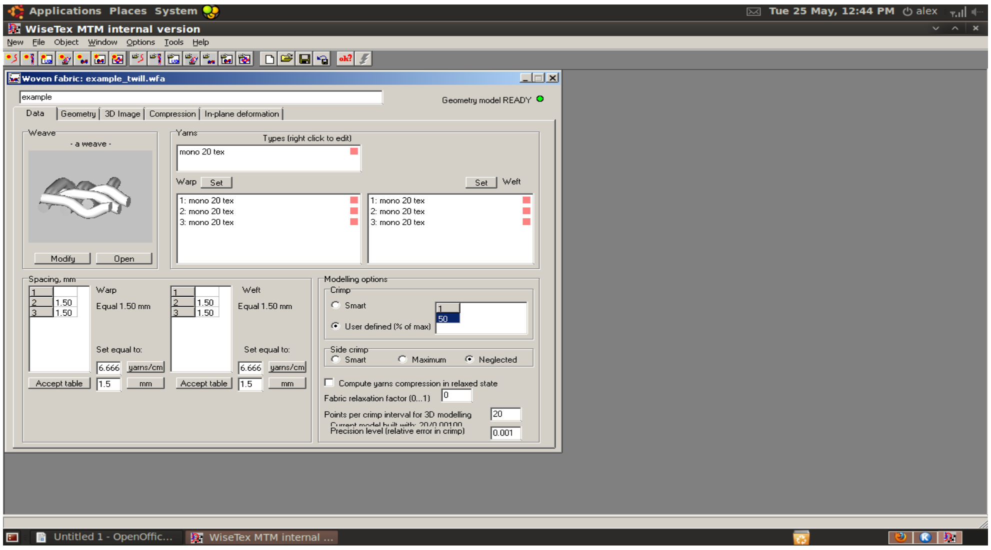


FIGURE B.4: Define cell properties

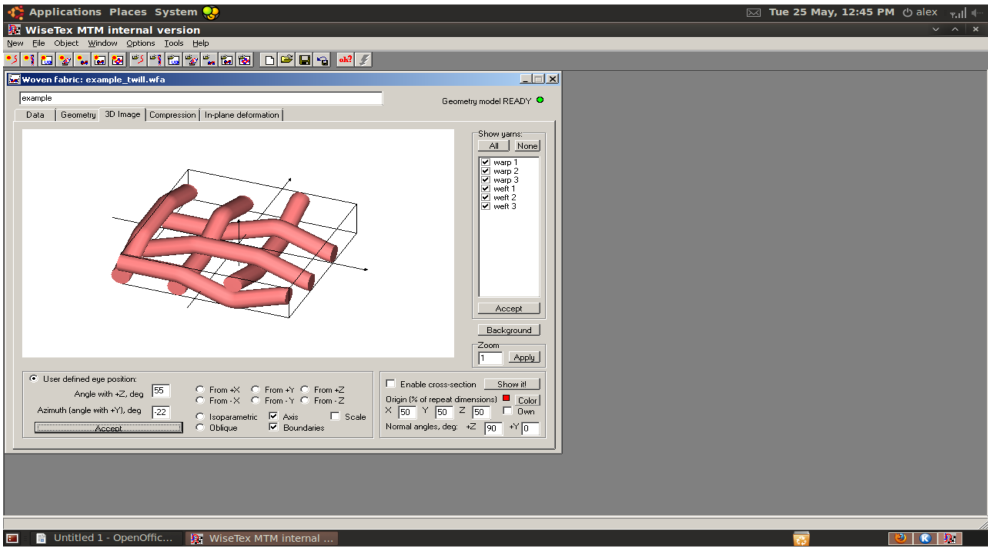


FIGURE B.5: 3D topology

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