A finite element tool for the electromagnetic analysis of braided cable shields

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Abstract

In this work we present a finite element tool for the electromagnetic analysis of braided cable shields. This tool is able to calculate the transfer impedance of a cable shield and it can be applied to a wide variety of situations where complex geometries and materials may be present. Also, it can help in the development, validation and improvement of novel, or existent, analytical models. These analytical models are computationally less expensive than a numerical approach but, they may be not available for some types of cable shields and, when available, they may be hard to compare directly against measurements. On the other hand, we can easily compare the analytical results against the numerical tool because all the parameters involved in the comparative are exactly known. Therefore, our computer tool offers a new extra criterion to assess whether a model is correct or not. Moreover, it allows studying in great detail the behavior of the fields and currents in and around the shield. This feature makes the tool very useful for gaining new
insights into the physics behind the shielding process.

Keywords: Braided shields, cable shielding, electromagnetic analysis, finite element method, numerical modeling, transfer impedance.

1. Introduction

The shielding quality of a braided cable shield can be characterized by a parameter $Z_t$ called surface transfer impedance, or just transfer impedance. This parameter was initially introduced by Schelkunoff [1] and is defined as

$$Z_t = \frac{1}{I_0} \frac{\partial V}{\partial z}$$

(1)

where $I_0$ is the current flowing through the shield induced on its outer surface and $\partial V/\partial z$ is the voltage per unit length on the inside of the shield. The value of $Z_t$ is independent of external factors and depends only on the geometry and materials of the shield. It allows to estimate the effect produced by an external field in the wires inside the cable or, reciprocally, the radiation leaked from inside the cable to the environment. A low value of $Z_t$ indicates a good shielding against interfering electromagnetic fields.

Although it is possible to measure the transfer impedance [2, 3], it is always advantageous to have an electromagnetic model able to predict its value before the actual manufacturing of the shield. This not only saves time and money, also improves the quality of the final product by allowing the virtual test of many more design possibilities. One of the objectives of this paper is to help in the development of electromagnetic models for cable shields. For that, we have developed a finite element (FEM) tool which is able to calculate the transfer impedance of a cable shield and that it can be applied
systematically to a wide variety of situations where complex geometries and materials may be present. This tool can help in the improvement of existing analytical models [4, 5, 6, 7, 8, 9, 10, 11] or in the development of new ones. Also, it allows to study in great detail the behavior of the fields and currents in and around the shield, which makes the tool very useful for gaining new insights into the physics behind the shielding process.

Analytical models are usually computationally less expensive than a numerical approach but, they may be not available for some types of cable shields and, when available, they may be hard to compare directly against measurements. The difficulties in the validation of the theoretical models are due to inaccuracies in the measurement process [3] and/or uncertainties in the input data produced by manufacturing tolerances [12] or changes in the properties caused by aging and handling [13]. On the other hand, we can easily compare analytical results against the FEM tool presented here because all the parameters involved in the comparative are exactly known. Therefore, our computer tool offers a new extra criteria to assess whether a model is correct or not.

Two of the points described above (validation of analytical models and improvement of the understanding of the underlying physics) were the main motivations for the development of the numerical tool presented here. We found some discrepancies between analytical models and measurements and we did not know if such discrepancies were caused by poor modeling or by measurements uncertainties. This work tries to answer this question.

In the next section we describe the parameters that characterize a braided cable shield and how we generate its computer aided design (CAD) model. In
section 3 is explained how to calculate $Z_t$ on this CAD model with the finite element method. In section 4 this numerical approach is compared against an analytical model and against measurements. Finally, in sections 5 and 6, we analyze the results and reach to conclusions.

2. CAD model

A previous step before starting with the numerical analysis is to generate a CAD geometry representing the braided wire shield. In our case, this task is performed with a Tcl/Tk plug-in integrated in the pre-processor software GiD [14, 15]. The geometry of the shield is automatically generated from the data introduced in the user-friendly window of Fig. 1. This plug-in generates only cable shields of the type shown in Fig. 2. More general geometries can also be computed with our numerical tool (see, for instance, references [16, 17, 18, 19, 20]) but they must generated from scratch or imported from another CAD environment.

2.1. Geometric parameters

The parameters required to generate the braided wire geometry can be divided into two groups. The first group includes the parameters which give a general description of the braid:

- diameter of a single wire ($d$),
- inner diameter of the shield ($D$),
- number of carriers (i.e. belts of wires) in the braid ($C$),
- number of wires in a carrier ($N$), and
Figure 1: Graphical user interface integrated in the software GiD [14, 15].
Figure 2: Different weaving modes for a braided cable shield. On the left pictures are the unit cells for each weaving mode. On the right pictures are the braided wire geometries generated from the unit cells on the left. The full braided geometry is generated after rotating the unit cells in the transversal planes and translate them along the longitudinal axes.
Figure 3: Geometric parameters description. $D_{FE}$: diameter of the external contour, $D$: inner diameter of the shield, $D_J$: diameter of the central core, $d$: diameter of a single wire, $\lambda_w$: separation between wires inside the same carrier, $\lambda_e$: distance between the braid and the longitudinal surface located in the outer part of the shield, $\lambda_C$: distance between carriers, $\lambda_D$: distance between the braid and the longitudinal surface located in the inner part of the shield.
• weave angle of the braid ($\alpha$).

These parameters are usually the only input data required by analytical models for the full description of a braided cable shield geometry (see, for instance, reference [11]). The second group of parameters are specific of the plug-in described at the beginning of this section. They allow us to generate more general geometries and to test different configurations. They are optional and can be let fixed for a given type of shields. These parameters are (see figures 2 and 3):

• weaving mode (one-step/two-step),

• distance between carriers ($\lambda_C$),

• separation between wires inside the same carrier ($\lambda_w$),

• distance between the braid and the longitudinal surface located in the inner part of the shield ($\lambda_D$),

• distance between the braid and the longitudinal surface located in the outer part of the shield ($\lambda_e$),

• diameter of the central core ($D_J$),

• diameter of the external contour ($D_{FF}$), and

• shape of the function describing a smoother or steeper ascent/descent of the wires ($\Omega$, $\Gamma$).

The geometry generated with the above parameters is the unit cell from which a full braid geometry can be obtained (see Fig. 2). We only have to
rotate the unit cell in the transversal plane (XY-plane) and translate it along the longitudinal axis (Z-axis) to create a complete braided cable shield.

2.2. Plug-in parameters description

The two different weaving modes (one-step/two-step) were implemented because the braiding machines weave the shield wires in these two modes. The two-step mode is the most common in real braids. We calculated $Z_t$ in both modes for some braid samples, but we did not observe any relevant differences between the results. Then, we have selected the one-step mode for the simulations of this paper because the computational cost is lower.

The parameter $\lambda_C$ determines the maximum vertical (transversal) distance between carriers. This distance is not exactly known in a real braided shield and it is also not known by which production parameters it is influenced and what are the tolerances. Moreover, it is even difficult to measure this distance afterwards. Therefore, an estimation of this parameter has to be made based on the other braid parameters such as weave angle, strand diameter and braid diameter (see equations (13) and (14) of section 4.1). This parameter has a big effect on $Z_t$ and is the main responsible of the differences between theoretical models and measurements [11].

The parameter $\lambda_w$ determines the separation between wires inside the same carrier. Variations in the value of $\lambda_w$ have some effect on $Z_t$ and it can be a useful parameter when modeling loose braids or shields in which the wires are separated between them for some reason (e.g. wires covered with an insulated layer). Although visually the wires in the braid seem to be in contact, this connection is poor. For instance, the transfer impedance does not change after a salt spray test where the skin of the wires is corroded.
Also, in [21], it is shown experimentally that a braided shield has the same behavior as a shield consisting of insulated wires. Moreover, corrosion in aged cables tend to accentuate this behavior. If the numerical tool used for computing electromagnetic fields has implemented contact elements then, we can model the insulation between wires by imposing an infinite electrical resistance between them and setting $\lambda_w = 0$. In this work we use a finite element tool which does not have implemented this type of element (see section 3.4). Therefore, we have to model the wire insulation by embedding the wires in a non-conductive media and imposing a finite separation between them ($\lambda_w > 0$). For the simulations of section 4 the separation was set to $\lambda_w = 0.02\,\text{mm}$. This value of $\lambda_w$ is determined by a compromise between the real geometry ($\lambda_w \approx 0$) and the computational cost of the simulations. The minimum separation between wires determines the minimum size of the mesh elements and, consequently, the size of FEM matrix and the hardware resources required for a simulation. Therefore, the shorter is the separation, the larger are the computational needs (see section 3.4). The $\lambda_w$ selected was the minimum distance we could afford with our available computational resources.

The parameters $\lambda_D$ and $\lambda_e$ determine, respectively, the distances between the braid and the lower and upper longitudinal surfaces (see Fig. 3). These parameters are used to define the surfaces where the fields are integrated to obtain $Z_t$ (see section 3.3). They can also be useful for defining the limiting surface of materials or sources in and/or around the shield. They are set to $\lambda_D = \lambda_e = 0.02\,\text{mm}$ for similar reasons to that given in the case of $\lambda_w$. We also tested with $\lambda_e = 0.01\,\text{mm}$ and $\lambda_e = 0.005\,\text{mm}$, but not relevant changes
in $Z_t$ were observed.

The parameter $D_J$ defines the diameter of a central coaxial cylinder. This cylinder is used to apply the driven current density $J$ (see section 3.2). It can also be useful for modeling, for instance, cables located inside the shield. The parameter $D_{FF}$ defines the distance from the center of the shield to the surface where the far field condition is applied (see section 3.1). Thanks to the properties of the transfer impedance ($Z_t$ is independent of external factors and depends only on the geometry and materials of the shield) the parameters $D_J$ and $D_{FF}$ have little or no effect on $Z_t$. Then, we can select any reasonable value for them. For the simulations of section 4, we set its values to $D_J = D/2$ and $D_{FF} = 3D$, being $D$ the inner diameter of the shield.

The parameters $\Omega$ and $\Gamma$ define the shape of the function describing the ascent (or descent) of the wires when going from the inner to the outer surface of the shield (or vice versa). Their values are in the interval $\Omega, \Gamma \in [0, 1]$. They were set to $\Omega = 0.2$, $\Gamma = 1.0$ in this work. We selected these values to avoid contacts between carriers. We tested several different values of $\Omega$ and $\Gamma$ (always avoiding contact between carriers) but, we did not observe any effect on $Z_t$. Nevertheless, these parameters can be useful for testing different configurations of the braid if the available FEM software has implemented contact elements.

3. Numerical model

Once the CAD geometry is ready, we apply the finite element method to the unit cell (see Fig. 4). The FEM model employed here is based on the
Figure 4: Finite element model. Left: FEM boundary conditions on the unit cell and imposed current density $\mathbf{J}$. Periodic boundary conditions (PBC) are applied on the transversal planes. Cyclic boundary conditions (CBC) are applied on the longitudinal planes. First order absorbing boundary condition (1st ABC) is applied on the upper boundary surface (colored in blue). Right: Surfaces where the electric field $\mathbf{E}$ is integrated to obtain $Z_t$. $S_E$ is the surface located just above the shield (colored in blue). $S_E$ is where the longitudinal component of the electric field $E_z$ is integrated. $S_I$ is the sum of the transversal surfaces of the shield wires (colored in red). $S_I$ is where the current density $J_z = \sigma E_z$ is integrated.
model presented in [16], which was developed for perforated tubes. In this section we adapt the approach of reference [16] to the case of braided wire geometries.

3.1. Boundary conditions

The boundary conditions we must employ for braided wire shields are different to the conditions used in [16] for perforated tubes. We must apply periodic boundary conditions (PBC) and cyclic boundary conditions (CBC) instead of perfect electric conductor (PEC) and perfect magnetic conductor (PMC) boundary conditions (see Fig. 4).

The PBC is applied on the transversal planes of the unit cell. In those planes we impose that $\mathbf{E}(\mathbf{r}) = \mathbf{E}(\mathbf{r} + \mathbf{p})$, being $\mathbf{p}$ a vector pointing in the Z-direction with a modulus equal to the longitudinal length of the unit cell. This condition is equivalent to consider that the shield has an infinite length and that is periodic with a periodicity $|\mathbf{p}|$. We are also assuming that the phase of the electric field does not change along the longitudinal direction.
(Z-axis), it only changes in the transversal direction (XY-planes). We assume that because the problem is excited by a longitudinal current source placed along the Z-axis which generates a cylindrical wave with a constant phase along the Z direction and the frequency of this wave is much larger than the dimensions of the shield sample.

The CBC is applied on the longitudinal planes showed in Fig. 4. On the CBC planes we impose that \( E(r) = \Re\phi_z\{\Re\phi_z\{E\{r\}\}\} \), being \( \Re\phi_z\{\cdot\} \) a rotation about the Z-axis with an angle of \( \varphi = 4\pi/C \) rad for the one-step weaving mode unit cell and \( \varphi = 8\pi/C \) rad for the two-step weaving mode unit cell. This condition imposes a rotational symmetry about the longitudinal Z-axis with an angle \( \varphi \).

Finally, as in [16], we apply a first order absorbing boundary condition (1st ABC) on a longitudinal surface sufficiently separated from the braid (see Fig. 4). The distance used in this work was given in the previous section (\( D_{FF} = 3D \)). As it is mentioned there, this boundary conditions has little effect on \( Z_t \). We can even obtain the same value of \( Z_t \) after replacing the 1st ABC for a PEC boundary condition.

3.2. Sources

The problem is driven by a time-harmonic current source \( J \) oscillating at a frequency \( \omega \). The current \( J \) is placed in a coaxial cylinder inside the shield (see Fig. 4). This longitudinal source \( J = J_z\hat{z} \) generates a cylindrical wave with its axis in the Z-direction. The electromagnetic wave generated by \( J \) induces eddy currents in the braid. The modulus of the current density is set to \( |J| = J_z = 1 \text{ MA/m}^2 \) in this work. Variations in the value of \( |J| \) have not effect on \( Z_t \) because the problems solved here are linear. Also, as mentioned
in section 2.2, variations in the size of the inner cylinder have not effect on $Z_t$. In this work we set $D_J = D/2$.

3.3. Transfer impedance

Once the electromagnetic fields are calculated in the unit cell with the above boundary conditions and sources, we use the following equations to obtain $Z_t$ (see equation (1) and Fig. 4):

$$\frac{\partial V}{\partial z} = \frac{1}{A_E} \iint_{S_E} E_z \, dS_E$$  \hspace{1cm} (2)

and

$$I_0 = \frac{C}{2} \iint_{S_I} \sigma E_z \, dS_I,$$  \hspace{1cm} (3)

where $E_z$ is a complex function representing the longitudinal component of the electric field, $S_E$ is a surface located just above the braid, $C$ is the number of carriers, $S_I$ is the transversal surface of the wires, $A_E$ is the area of $S_E$ and $\sigma$ is the electrical conductivity of the wires. Equation (2) represents the transversal electric field averaged over $S_E$. Equation (3) represents the induced current going through the shield. In the two-step weaving mode we must multiply the integral of equation (3) by $C/4$ instead of by $C/2$.

Although $Z_t$ was originally defined as the ratio between the voltage per unit length on the inner surface of the shield and the induced current flowing through its outer surface (see the beginning of section 1), it can also be defined, by reciprocity, as the ratio between the voltage per unit length on the outer surface of the shield and the current flowing through the shield induced on its inner surface [13]. This last definition is the one adopted here (as in [16]). This is why we impose the source $J$ in a coaxial cylinder inside the shield (which induces eddy currents from inside the shield in the shield’s
inner surface) and calculate the voltage per unit length on the exterior surface of the shield.

The transfer impedance can also be obtained by applying the original definition. To do that, we use the same boundary conditions as the ones detailed above. But, instead of defining an inner $J$, we impose the current source in a coaxial hollow cylinder placed outside the shield. Besides, the voltage per unit length must be computed on the inner surface of the shield instead of in its exterior surface. The results obtained with this approach and the approach of the previous paragraph are identical.

3.4. Numerical tool

Once the boundary conditions, material properties and sources are defined, we can proceed to mesh and calculate. We have to mesh the unit cells of the braids taking special care of the surface of the wires and its interspaces (see Fig. 5). We must mesh carefully the surface of the wires to model accurately the induced currents at high frequencies because of its small skin depth. Also, as indicated in section 2.2, we must mesh properly the space between geometrical objects (almost two FEM mesh elements between objects is recommended), which largely determines the computational cost of the simulation.

The FEM software used for computing the electromagnetic fields was an in-house code called ERMES [17]. This software solves the time-harmonic Maxwell’s equations with the FEM formulation explained in [18, 22, 19]. ERMES has been implemented in C++ and has a graphical user interface integrated in GiD. ERMES is open source and it can be downloaded freely from [17]. For the examples of section 4 we used around $2.5 \times 10^6$ isoparamet-
Table 1: Braided cable shield samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>D (mm)</th>
<th>d (mm)</th>
<th>C</th>
<th>N</th>
<th>α (°)</th>
<th>K</th>
<th>⟨h⟩/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.00</td>
<td>0.202</td>
<td>24</td>
<td>5</td>
<td>38.00</td>
<td>0.97</td>
<td>0.64</td>
</tr>
<tr>
<td>2</td>
<td>6.00</td>
<td>0.160</td>
<td>24</td>
<td>7</td>
<td>32.20</td>
<td>0.97</td>
<td>0.72</td>
</tr>
<tr>
<td>3</td>
<td>12.0</td>
<td>0.160</td>
<td>48</td>
<td>6</td>
<td>35.60</td>
<td>0.94</td>
<td>0.91</td>
</tr>
<tr>
<td>4</td>
<td>2.95</td>
<td>0.101</td>
<td>16</td>
<td>6</td>
<td>30.08</td>
<td>0.84</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td>1.50</td>
<td>0.100</td>
<td>16</td>
<td>3</td>
<td>21.44</td>
<td>0.79</td>
<td>1.00</td>
</tr>
</tbody>
</table>

D: inner diameter of the braid, d: diameter of a single wire, C: number of carriers, N: number of wires in a carrier, α: weave angle of the braid, K: optical coverage, ⟨h⟩: average distance between carriers by equation (14), h: average distance between carriers by equation (13). For all the samples, the value of the electrical conductivity is \( \sigma = 4.12 \times 10^7 \, \text{S/m} \) and the values of the electric permittivity \( \epsilon \) and the magnetic permeability \( \mu \) were assumed to be the same as vacuum \( (\epsilon = \epsilon_0, \mu = \mu_0) \).

ric 2nd order elements. The symmetric FEM matrix generated by ERMES occupied around 20 GB of RAM memory. ERMES needed between 2-3 hours (depending on the frequency range) to solve a single frequency in a computer with a CPU at 2.5 GHz and the operative system Microsoft Windows XP x64. We must remind that ERMES is a research code, better computational performance can be achieved with better tools. The numerical method explained in this section can be used with any FEM software able to solve the time-harmonic Maxwell’s equations. Moreover, the CAD geometry described in section 2 can be exported from GiD to any other FEM software.
Figure 6: Average distance between carriers. (a) For dense braids, the wires at the border of a carrier are closer to the adjacent carriers than the wires in the middle ($\kappa_C < h$). (b) For loose braids, all the wires in a carrier are at the same minimum distance of the adjacent carriers ($h$).
4. Results

As it was mentioned in the introduction of this paper, the main motivation for developing a numerical tool was to improve our understanding of the discrepancies between measurements and analytical models. In this section, we compare the numerical approach described above with the analytical model of reference [11] and against measurements. Our intention is to see if both mathematical approaches give similar results or, on the other hand, they also present discrepancies between them. The advantage of comparing the model [11] against the CAD tool instead of only against measurements is that all the parameters involved in the computation of $Z_t$ are well-known and thus, we eliminate uncertainties from the comparative.

4.1. Analytical model

The analytical model presented in [11] is based on the models of Vance [23, 4], Kley [8] and Tyni [6]. Its original contribution is a correction factor added to the hole inductance formula that improves the prediction of $Z_t$. This model is summarized next to make the article more self-contained.

In reference [11] is solved the following equation:

$$Z_t = Z_d + j \omega (L_h + L_b)$$

(4)

where $Z_d$ represents the diffusion of electromagnetic energy through the metal braid, $j = \sqrt{-1}$ is the imaginary unit, $\omega = 2\pi f$ is the angular frequency of the incident fields, $L_h$ is the hole inductance and $L_b$ is the braid inductance. The input data required to obtain $Z_t$ with equation (4) are: inner diameter of the braid ($D$), number of carriers ($C$), number of wires in a carrier ($N$), diameter
of a single wire \((d)\), conductivity of the wires \((\sigma)\), magnetic permeability of the wires \((\mu)\) and weave angle of the braid \((\alpha)\).

The diffusion component \(Z_d\) is computed using the following expression [23, 4]:

\[
Z_d = \frac{4 \gamma d}{\pi d^2 NC \sigma \cos(\alpha) \sinh(\gamma d)}
\]  

(5)

where \(\gamma = (1 + j)/\delta\) is the complex propagation constant of the wires and \(\delta = \sqrt{2/\omega \mu \sigma}\) is the skin depth of the wire.

The hole inductance \(L_h\) represents the penetration of the fields through the apertures and it is calculated by [8, 11]

\[
L_h = 0.875 \Gamma \exp(-\tau) M_V
\]  

(6)

where the factor 0.875 takes into account the curvature of the braid, \(\Gamma = 0.5079\) is a correction factor for rhombic holes [11], \(\exp(-\tau)\) represents the attenuation produced by the so called "chimney" effect and \(M_V\) is a term that includes the magnetic polarizability of the holes. The exponent \(\tau\) is given by the expression [8]

\[
\tau = 9.6 F \sqrt{\frac{F^2 (2 - F)^2 d}{D_m}}
\]  

(7)

being \(F\) the filling factor and \(D_m = D + 2.5d\) the average diameter of the braid. The filling factor \(F\) is defined as

\[
F = \frac{N d C}{2\pi D_m \cos(\alpha)}.
\]  

(8)

The term \(M_V\) is computed for \(\alpha \leq 45^\circ\) using

\[
M_V = \mu \frac{\pi}{6C} (1 - K)^{3/2} \left( \frac{e^2}{E(e) - (1 - e^2) K(e)} \right)
\]  

(9)
and for $\alpha > 45^\circ$ using
\[
M_V = \mu \frac{\pi}{6C} (1 - K)^{3/2} \left( \frac{e^2}{(K(e) - E(e)) \sqrt{1 - e^2}} \right)
\]  \hspace{1cm} (10)

where $K = F(2 - F)$ is the optical coverage and $e$ is the eccentricity. If $\alpha \leq 45^\circ$ then $e = \sqrt{1 - \tan^2(\alpha)}$ and if $\alpha > 45^\circ$ then $e = \sqrt{1 - \cot^2(\alpha)}$. The functions $K(e)$ and $E(e)$ are the complete elliptic integrals of the first and the second kind, respectively, defined by
\[
K(e) = \int_0^{\pi/2} \frac{1}{\sqrt{1 - e^2 \sin^2(\varphi)}} \, d\varphi,
\]
\[
E(e) = \int_0^{\pi/2} \sqrt{1 - e^2 \sin^2(\varphi)} \, d\varphi.
\]  \hspace{1cm} (11)

The braid inductance $L_b$ represents the coupling between carriers and is obtained from the expression [6]
\[
L_b = -\mu \frac{h}{4\pi D_m} \left( 1 - \tan^2(\alpha) \right)
\]  \hspace{1cm} (12)

where $h$ is the average distance between carriers. In [11], this average distance is calculated with the formula [6]:
\[
h = \frac{2 \, d^2}{b + d}
\]  \hspace{1cm} (13)

where $b = Nd(1 - F)/F$. This equation must be corrected when comparing the analytical model [11] with the CAD models of this work. We must use, instead of (13), the following equation (see Fig. 6):
\[
\langle h \rangle = \begin{cases} h & \text{if } \kappa_C \geq h \\ \frac{N-2}{N} h + \frac{2}{N} \kappa_C & \text{if } \kappa_C < h \end{cases}
\]  \hspace{1cm} (14)

where $N$ is the number of wires per carrier, $h$ is the distance of equation (13) and $\kappa_C$ is the distance showed in Fig. 6. The values of $\kappa_C$ are obtained from
the CAD model by measuring them directly on the geometry. The average distance given by equation (14) takes into account that, for dense braids, the 2 wires at the border of a carrier are closer to the adjacent carriers than the \( N - 2 \) wires in the middle (see Fig. 6). On the other hand, for loose braids, all the wires in a carrier are at the same minimum distance of the adjacent carriers \( (h) \).

4.2. Simulations

The analytical model of section 4.1 and the numerical model of section 3 were applied to more than twenty different braided cable shield samples during the EU project HIRF-SE (High Intensity Radiated Fields Synthetic En-
Figure 8: Sample 2. Modulus of the electric field $E$ (normalized to its maximum value) at $f = 100$ MHz. Left: Surface located 0.02 mm under the inside side of the braid. Right: Surface located 0.02 mm above the outer side of the braid.
Figure 9: Sample 5. Modulus of the current density $\mathbf{J}$ (normalized to its maximum value) at $f = 100\,\text{MHz}$. Left: Inside view of the braid. Right: Outer view of the braid.
Figure 10: Sample 5. Modulus of the electric field $E$ (normalized to its maximum value) at $f = 100$ MHz. Left: Surface located 0.02 mm under the inside side of the braid. Right: Surface located 0.02 mm above the outer side of the braid.
Figure 11: Sample 1. Modulus and phase of $Z_t$. 
Figure 12: Sample 2. Modulus and phase of $Z_t$. 

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27
Figure 13: Sample 3. Modulus and phase of $Z_t$. 
Figure 14: Sample 4. Modulus and phase of $Z_t$. 
Figure 15: Sample 5. Modulus and phase of $Z_t$. 
vironment, European Community’s 7th Framework Programme FP7/2007-
2013, ref.: 205294). These samples were manufactured and the transfer
impedance of each braid was measured according to the line injection method
[24, 2]. The geometrical parameters of five representative samples are given
in table 1.

In figures 7 to 10 are shown the current density and the electric field
distribution at $f = 100$ MHz of samples 2 and 5. In these pictures we can see
that the electric field and the current density are higher in the inside part of
the shield than in the outer part. This is because we induce currents in the
shield from its inside (see sections 3.2 and 3.3) and the field is attenuated
after going through the shield. We can also observe in figures 7 and 9 that
the current density is slightly higher in the exterior wires of the carriers than
in the ones placed in the middle. This effect may be useful for the design of
new braids which could take advantage of this uneven distribution.

In figures 11 to 15 it is shown the measured modulus of $Z_t$ and the phase
and modulus of $Z_t$ calculated with the numerical model of section 3 and the
analytical model of section 4.1. These results are analyzed in the following
section.

5. Analysis of results

We can see in figures 11 to 15 that both approaches provide equivalent
values of $Z_t$ (in phase and modulus) after correcting the average distance
between carriers with equation (14). The small differences observed are as-
sociated to computational constraints and to the assumptions made by each
model about the geometry of the braids. For instance, the differences in the

31
medium frequency range are due to the fact that the analytical approach does not model properly fine geometric details like the curvature of the wires or the gaps between wires in the same carrier. As it is shown in the last example of reference [16], it is precisely at the medium frequency range where the fine geometric details produce a more noticeable effects on $Z_t$. The small disagreements at higher frequencies can also be explained by differences in the geometric modeling. In this case, the small disagreements are caused by differences in the dimensions of the shield holes. These holes size differences are due to the inclusion in the numerical tool of a finite separation between braid wires ($\lambda_0 > 0$, see section 2.2) that is not included in the analytical model.

On the other hand, we can see in figures 11 to 15 that there are some differences between the mathematical models and the measured $Z_t$. These discrepancies can be attributed to resonances and uncertainties in the input data. The resonances appear due to small impedance mismatches between the test sample and the measurement equipment and due to the fact that, at high frequencies, the sample length is large in terms of wavelength. The uncertainties comes from the large sensitivity of the results to inaccuracies in the knowledge of the input parameters. For instance, the transversal sections of samples 4 and 5 were not circular and the diameters (D) shown in table 1 are an approximation. Moreover, the electrical conductivities of samples 4 and 5 were not exactly known. Nevertheless, the main source of error is, by far, the average distance between carriers $h$ (see sections 2.2 and 4.1). This distance is not exactly known and it is even difficult to measure it after the actual manufacturing of the shield. Therefore, $h$ is only known
approximately. This parameter has a big effect on \( Z_t \) (see reference [11]) and it can account for most of the disagreements between simulations and measurements.

6. Conclusion

As it is clear from the results of section 4, the numerical approach presented in this work and the analytical model of section 4.1 provide equivalent values of \( Z_t \). As it is explained in section 5, their small disagreements can be attributed to computational constraints and to differences in the geometric modeling. On the other hand, the discrepancies between measurements and theoretical models can be attributed to resonances and uncertainties in the input data. Therefore, we can consider the analytical approach [11] as cross-validated against a numerical method which solves the full set of Maxwell’s equations in an infinite periodic braided shield with all its wires isolated from each other.

The numerical model presented in this work, although computationally more expensive than the analytical approach, has proven to be a useful tool for the improvement and validation (or cross-validation) of analytical models. Also, it can be useful to compute \( Z_t \) on complex cable geometries and materials that do not have an analytical solution available. Although in this work we have shown only shields with an analytical solution, it is clear from the references [16, 17, 18, 19, 20] that the same FEM approach can be applied to more general configurations. Moreover, the detailed visualization of the fields and currents provides a more complete description of the shield behavior and can be very helpful for improving our understanding of the physics.
behind the shielding process.

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