



**HAL**  
open science

# Comparative Study of Thin Layers Modeling in Electromagnetism: Application to Multilayer Magnetic Shielding

Kokouvi Etse, Paul Clérico, Laurent Prevond, Anne-Laure Helbert, Thierry Baudin, Xavier Mininger

► **To cite this version:**

Kokouvi Etse, Paul Clérico, Laurent Prevond, Anne-Laure Helbert, Thierry Baudin, et al.. Comparative Study of Thin Layers Modeling in Electromagnetism: Application to Multilayer Magnetic Shielding. IEEE Transactions on Electromagnetic Compatibility, 2023, 65 (5), pp.1351-1359. 10.1109/TEMC.2023.3286010 . hal-04245327

**HAL Id: hal-04245327**

**<https://hal.science/hal-04245327v1>**

Submitted on 17 Oct 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Comparative Study of Thin Layers Modeling in Electromagnetism: Application to Multilayer Magnetic Shielding

Kokouvi Etse<sup>1,2,3</sup>, Paul Clerico<sup>1,3</sup>, Laurent Prevond<sup>3</sup>, Anne-Laure Helbert<sup>2</sup>, Thierry Baudin<sup>2</sup>, Xavier Mininger<sup>1</sup>

<sup>1</sup> Université Paris Saclay, CentraleSupélec, CNRS, Laboratoire de Génie Electrique et Electronique de Paris, 91192, Gif-sur-Yvette, France.

Sorbonne Université, CNRS, Laboratoire de Génie Electrique et Electronique de Paris, 75252, Paris, France

<sup>2</sup> Université Paris-Saclay, CNRS, Institut de Chimie Moléculaire et des Matériaux d'Orsay, 91405 Orsay, France

<sup>3</sup> Université Paris Saclay, ENS Paris Saclay, UMR CNRS 8029, SATIE - Cnam 91190 Gif sur Yvette

Simulation of devices including thin electromagnetic shields is nowadays a significant challenge because of the fine mesh required and the associated computation time. Recently, the transmission line theory used to model field propagation through thin conductive layers has been revised to solve shielding problems leading to the development of the Artificial Material Single Layer (AMSL) method. Initially developed for single-layer materials, this method has been extended to multilayer configurations. This paper presents an approach combining the homogenization of multilayer shields through energetic consideration and the second order AMSL method to accurately model metal composite for magnetic shielding applications. A comparison between the proposed approach and that of AMSL method for multilayers is proposed in terms of accuracy and computational time. These two discretization methods are also compared to the Impedance Network Boundary Conditions (INBCs) approach. On the frequency range of validity of the proposed method, the maximum relative error compared to experimental results is lower than 8.5%.

*Index Terms*— Artificial material single-layer, Finite element modeling, Homogenization, Multilayer shields

## I. INTRODUCTION

Electromagnetic pollution, the result of the massive integration of electronics in all areas of human activity, is not only potentially dangerous for living beings [1], [2] but it can also affect the integrity of sensitive devices. Generally, the shielding of electric field and plane wave is provided by a thin layer of a very good conductor material such as copper or aluminum. For low-frequency magnetic shielding, magnetic materials with high relative magnetic permeability are used to ensure good attenuation of the disturbing field. Several research efforts have shown interest in using multilayers instead of single layer materials [3]-[5]. These authors generally use the finite element method (FEM) for the modeling and study of their systems. There arises the problem of discretizing the thin multilayer shields (MS) domain, considering the skin effect and the heterogeneity of the shield in the case of a MS made of good electric conductive materials and/or soft magnetic materials.

Considering the skin depth and the effect of each layer in a model requires a very fine mesh which is costly in terms of computation time and memory required and practically impossible in 3D for some configurations. To overcome these difficulties, several methods of meshing adapted to thin layers of conductive materials have been developed [6]-[10]. One of the oldest methods that have been proposed is called Impedance Network Boundary Condition (INBCs) [6].

The INBCs method consists in replacing the shield layer with an equivalent boundary element allowing the discontinuity of the electromagnetic field that the shield would have created. This method is based on the lossy transmission line theory. It has been integrated into some software such as COMSOL under the name of Transition Boundary Condition (TBC) [11]. It is very useful for modeling problems in which the shielding layer can be eliminated without affecting the system configuration. However, for applications where a study of a multiphysics coupling is envisaged or when the shield geometry cannot be

neglected, this method is hardly applicable. Moreover, the use of this method is not trivial when it is not directly integrated in the software. To maintain the geometry of the shield while reducing the mesh size, the first order AMSL [7] and second order AMSL methods [8] have been developed.

The AMSL method consists in keeping the geometry of the shield but replacing its electric and magnetic properties with artificial properties. It requires to mesh it with only a single layer of finite element and maintains the same electromagnetic performance. In [9], the AMSL method is extended to the anisotropic materials and later to multilayers [10].

The above-mentioned methods are not applicable to MS that are subjected to stress or fragmentation. The objective of this paper is to propose a multilayer domain discretization technique combining homogenization by an energetic approach associated in a second step to the second order AMSL method, leading to an accurate and easy to implement thin conductive multilayer domain discretization method. The homogenization makes it possible to determine the effective permeability, conductivity, and permittivity of the fictitious homogenized layer that is electrically equivalent to the multilayer. Several homogenization techniques have been developed to predict the effective electromagnetic properties of composite materials. These techniques include analytical, numerical, and experimental models [12-17]. Achkar et al. [12] introduced a homogenization method that relies on finite element computations and inverse problem solving to estimate the effective properties of woven composites, but it was restricted to high frequencies ( $f > 0.1$  GHz) where only electrical conductivity and dielectric permittivity are unknown parameters. Préault et al. [13] extended the dynamic homogenization method [14] by considering the skin effect in the homogenization of composites. Their approach is based on the resolution of the inclusion problems, where the infinite medium surrounding the inclusions plays a key parameter. The

method is quite complex and suited to high frequency applications. For low frequency magnetic shielding applications, a simple method based on near field shielding effectiveness measurements has been proposed for the homogenization of composite panels [15]. The proposed method consists in matching the SE evaluated using Moser formula [18] to that measured over the frequency range of 1 Hz to 1 MHz. This method is only applicable for the determination of the equivalent electrical conductivity of the composite material. In addition, Moser formula considers an infinite plate as shield whereas measurements consider a finite plate. Therefore, the conductivity resulting from the proposed method may not be very accurate for high frequency fields. In [16], an analytical homogenization method based on surface impedance and effective media theory for composite materials containing metallic wire grid has been proposed. This work was limited to low volume fractions of inclusions.

It can be noticed that the above-mentioned homogenization methods are not suitable to multilayer conductive shields subjected to necking or fragmentations. The homogenization based on energetic approach is here proposed and coupled to AMSL to deduce the artificial properties of the equivalent single layer allowing the multilayer conductive shield domain to be meshed with a single finite element over the thickness. This work is structured as follows: first, the proposed homogenization method in case of both planar and non-planar multilayer conductive shields is described in section II. Then, the application of the second order AMSL method to the homogenized layer is presented in section III. In section IV, the validity of the proposed method is studied. Finally, a comparison between the different conductive thin layer meshing methods in terms of accuracy and computational time is revealed in section V.

## II. HOMOGENIZATION OF THE MULTILAYER

### A. Case of stacked plane layers

First, the physical properties of the equivalent single layer having the same electromagnetic properties as the multilayer are derived. Let us consider a MS composed by  $p$  isotropic conductive layers and  $q$  electric insulator layers where  $p \geq 2$  and  $q \geq 0$ . The conductivity, permeability, and permittivity of the  $i^{\text{th}}$  layer of thickness  $e_i$  are respectively given by:  $\sigma_i$ ;  $\mu_i = \mu_0 \mu_{r_i}$ ;  $\epsilon_i = \epsilon_0 \epsilon_{r_i}$ . The total thickness of the MS is:  $e = \sum_{i=1}^n e_i$  where  $n = p + q$  is the number of layers. Considering the MS geometry shown in Fig. 1, the equivalent electromagnetic properties of the homogenized layer of the MS is derived in equations (1). These equations are obtained by considering plane stacked layers as serial or parallel electrical resistances, magnetic reluctances, or capacitors.

Non-zero conductivity must be attributed to non-conducting materials to ensure a good accuracy and convergence of the computation. The equivalent single-layer electrical and magnetic properties of the MS are derived in electrostatic and magnetostatic conditions. Therefore, these properties are valid if the total thickness  $e$  is assumed to be lower than the penetration depth. Considering Fig. 1, the necessary condition for validating the homogenized layer properties is given in equation (2).

$$\begin{aligned}\sigma_{eqx} &= \sigma_{eqy} = \frac{\sum_{i=1}^n \sigma_i e_i}{e} \\ \sigma_{eqz} &= \frac{e}{\sum_{i=1}^n \frac{e_i}{\sigma_i}} \\ \mu_{reqx} &= \mu_{reqy} = \frac{\sum_{i=1}^n \mu_{r_i} e_i}{e} \\ \mu_{reqz} &= \frac{e}{\sum_{i=1}^n \frac{e_i}{\mu_{r_i}}} \\ \epsilon_{reqx} &= \epsilon_{reqy} = \sum_{j=1}^q e_j * \sum_{j=1}^q \frac{\epsilon_{r_j}}{e_j} \\ \epsilon_{reqz} &= \frac{\sum_{j=1}^q e_j}{\sum_{j=1}^q \frac{e_j}{\epsilon_{r_j}}}\end{aligned}\quad (1)$$

If  $q = 0$  then  $\epsilon_{reqx} = \epsilon_{reqz} = 1$

$\sigma_{eqx}$ ,  $\sigma_{eqy}$ ,  $\sigma_{eqz}$  are respectively the conductivity in the x, y, and z directions of the resulting homogenized layer. The same applies to the relative permeability and relative permittivity.

$$\delta_{eqxy} = \frac{1}{\sqrt{\pi f \mu_{eqxy} \sigma_{eqxy}}} \geq e \quad (2)$$

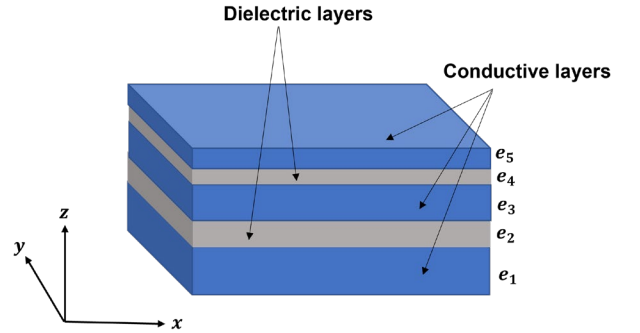


Fig. 1. Multilayer shield configuration: case of five layers

### B. Case of non-planar layers

In the case of MS obtained by process such as roll bonding with high reduction rates [19], the different layers are not flat (Fig. 2) due to necking and fragmentation along rolling direction (RD) and/or transverse direction (TD). Therefore, the multilayer AMSL method as developed in [10] cannot be directly applied. Let us consider a multilayer whose longitudinal section is presented in Fig 2. It is elaborated by cold roll bonding of aluminum (EN AW-8011) and steel (DC01 (1.0330)) with a reduction rate of 69.2%. A 2.2kW-3HP rolling mill has been used to elaborate the multilayer and an optical microscope is used to observe the structure of the longitudinal section. The notation ND means the normal direction to the rolling plane (RD, TD). In such configuration, equation (1) cannot be applied. The equivalent electromagnetic properties of the homogenized single-layer of same total thickness can nevertheless still be numerically determined by applying an electrical or magnetic potential difference on the multilayer external faces. Whatever the chosen homogenization

approach, in a second step, AMSL method is used on the obtained homogenized layer. The next paragraph describes the approach proposed to deduce the equivalent electric conductivity and magnetic permeability of the homogenized single-layer in case of the non-planar MS.

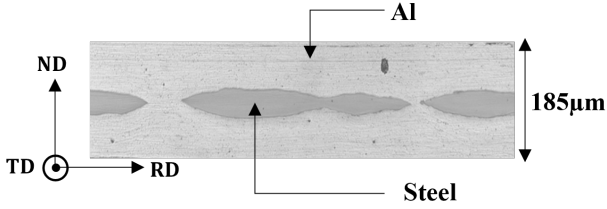


Fig. 2. Longitudinal section of the MS obtained by cold-roll bonding of Al/Steel/Al

First, the 2D geometry of the shield is imported into COMSOL Multiphysics and an extrusion is applied to obtain the 3D geometry. Next, a magnetostatic computation of the 3D finite element model of the shield is done to determine the equivalent magnetic permeability. Considering the trilayer structure shown in figure 3a, the equivalent magnetic permeability along RD is determined by applying some boundary conditions to the shield boundaries, enumerated in figure 3b, as follow:

$$\left\{ \begin{array}{l} \text{On boundary 1: } \vec{A}_0 = \begin{pmatrix} 0 \\ a_0 \\ 0 \end{pmatrix} \text{ Wb/m with } a_0 \neq 0; \\ \text{On boundary 2: } \vec{A}_0 = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \text{ Wb/m} \\ \text{On boundary 3 \& 4: } \vec{n} \times \vec{H} = \vec{0} \\ \text{On boundaries 5 \& 6: } \vec{n} \times \vec{A} = \vec{0} \end{array} \right. \quad (3)$$

This led to the flow of magnetic field  $\vec{H}$  along RD. The total magnetic energy stored can be obtained from the finite element tool from B and H quantities. This value is then compared to the analytical expression of the magnetic energy depending on the reluctance ( $\mathcal{R}_{RD}$ ):

$$W_{magRD} = \int_{V_C} \int_0^B (H_{RD} \cdot dB) dV_C = \frac{1}{2} (\mathcal{R}_{RD} \Phi_{RD}^2) \quad (4)$$

where  $\Phi_{RD} = a_0 \times w$  is the magnetic flux, and  $dV_C$  is the volume element of the MS. The relative permeability along RD is finally obtained through equation (5):

$$\mathcal{R}_{RD} = \frac{1}{\mu_{RD}} * \frac{L}{e \cdot w} \quad (5)$$

With a similar approach, the equivalent electric conductivity along RD is determined by applying to the shield boundaries enumerated in Fig. 3b the following boundary conditions:

$$\left\{ \begin{array}{l} \text{On boundary 3: } V = 0 \\ \text{Boundary 4: } V = V_0 \text{ with } V_0 \neq 0 \\ \text{On boundary 1,2,5 and 6: } \vec{n} \cdot \vec{j} = 0 \end{array} \right. \quad (6)$$

where  $J$  is the electric current density flowing through the MS,  $V_0$  the applied electric potential.

This led to the flow of electric field  $\vec{E}$  along RD. The total electrical energy loss due to Joule effect can be directly evaluated in the finite element model from E and J quantities. The corresponding analytical expression is given in equation (7). Finally, the electric conductivity along RD is obtained through equation (8).

$$W_{jRD} = \int_{V_C} (E_{RD} \cdot J) dV_C = \frac{V_0^2}{R_{RD}} \quad (7)$$

$$R_{RD} = \frac{1}{\sigma_{RD}} * \frac{L}{e \cdot w} \quad (8)$$

This step is repeated considering the appropriate boundary conditions to find the relative magnetic permeability and the electric conductivity along the two remaining directions.

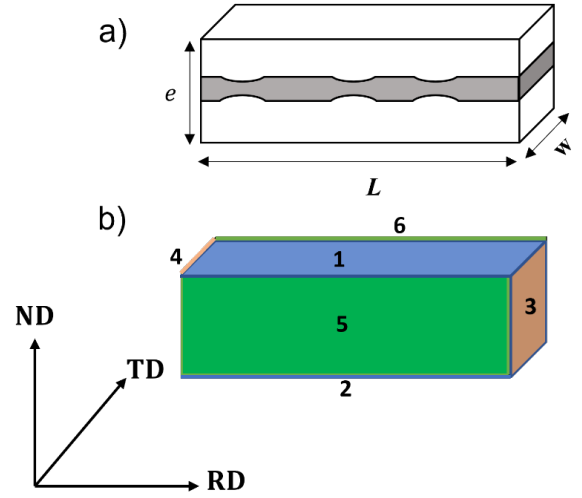


Fig.3: 3D model of non-planar trilayer shield

### III. APPLICATION OF THE AMSL SECOND ORDER METHOD TO THE HOMOGENIZED LAYER

AMSL method presents the interesting advantage that only one mesh layer is needed over the shield thickness. This part briefly summarizes the main steps of this approach. From the AMSL method developed in [8], the artificial properties of the shield are given by:

$$\sigma_{AMSL} = Re\{\chi\} \quad (7)$$

$$\epsilon_{rAMSL} = \frac{Im\{\chi\}}{\omega \epsilon_0} \quad (8)$$

$$\mu_{rAMSL} = \frac{1}{j\omega \mu_0 \xi} \quad (9)$$

where  $\chi$  is the solution of equation (10):

$$e^2 \chi^2 + e(8Y_{TL,m} - 7Y_{TL,0})\chi + 15(Y_{TL,0}^2 - Y_{TL,m}^2) = 0 \quad (10)$$

$Y_{TL,0}$  and  $Y_{TL,m}$  are the self-admittance and mutual admittance of the shield. Between the two solutions of equation (10), the solution with the larger real part is, from self-experience, the one suitable for the calculation of the properties of the artificial material. This later AMSL method where, the solution with the larger real part is considered will be designated in this paper as AMSL2P.

The expression of  $\xi$  is given in [8] as:

$$\xi = \frac{-e^3 \chi^2 + 12e^2(Y_{TL,0} + Y_{TL,m})\chi}{60e\chi - 120(Y_{TL,m} + Y_{TL,0})} \quad (11)$$

As this method is based on the lossy transmission line equations that described the propagation of the tangential field components inside the shield [20], [21], only the properties of the homogenized layer in the plane (RD, TD) are considered to calculate the equivalent admittance matrix. Therefore, the anisotropy of the homogenized layer over the direction perpendicular to the plane (RD, TD) can be neglected. In the example illustrated in Fig. 2, the anisotropy along ND can be neglected since the magnetic flux is channeled along the (RD, TD) plane and the eddy currents are also in the same plane. The self-admittance and mutual admittance of the equivalent circuit model of the shield in the case of Fig. 2 are respectively given in equations (12) and (13).

$$Y_{TL,0} = \frac{\cosh(\gamma_{RD}e)}{\eta_{RD} \sin(\gamma_{RD}e)} \quad (12)$$

$$Y_{TL,m} = -\frac{1}{\eta_{RD} \sinh(\gamma_{RD}e)} \quad (13)$$

$\eta_{RD}$  and  $\gamma_{RD}$  are the intrinsic impedance and propagation constant along RD and are described in equations (14) and (15).

$$\eta_{RD} = \sqrt{\frac{j\omega\mu_{RD}}{\sigma_{RD} + j\omega\epsilon_{RD}}} \quad (14)$$

$$\gamma_{RD} = \sqrt{j\omega\mu_{RD}(\sigma_{RD} + j\omega\epsilon_{RD})} \quad (15)$$

#### IV. APPLICATIONS

The analysis of the validity of the proposed method is performed by comparing the simulation results of a finite element model based on the proposed approach and experimental data. The simulation results of the proposed approach are also compared to the ones of the finite element model with a conventional mesh. For that, the magnetic shielding effectiveness (SE) of different multilayer materials are compared. The test bench used for measuring the SE of the samples is shown in Fig. 4. It consists of a signal generator supplying a coil which generates a sinusoidal disturbing magnetic field whose attenuation by the material defines its SE according to the relationship:

$$SE(dB) = 20 \log_{10} \frac{B_{unshield}}{B_{shield}} \quad (16)$$

where  $B_{unshield}$  is the magnetic flux density measured by the probe in the absence of the shield and  $B_{shield}$  the magnetic flux density measured in the presence of the shield.

##### A. Planar multilayer shield

The structure of the planar multilayer considered is as presented in Fig. 1. It is obtained by gluing 2 layers of aluminum and one layer of steel. The multilayer obtained is considered as a 5 layers shield (Al/Glue/Steel/Glue/Al). The Al sheets have a thickness of 500  $\mu\text{m}$  and the layer of steel 200  $\mu\text{m}$ . The total thickness of the multilayer is 1.36 mm. It means the glue has a total thickness of 160  $\mu\text{m}$  i.e., 80  $\mu\text{m}$  per interface. The glue is a non-conducting and non-magnetic material. The dimension of the shield is 10 cm\*10 cm\*1.36 mm. The material properties are given in Table 1.

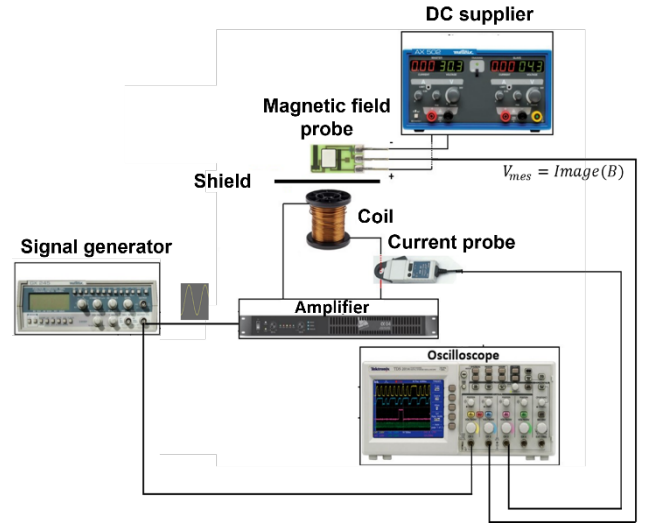


Fig. 4. Illustration of the test bench used for the magnetic shielding effectiveness measurement.

The SE calculated using the conventional FEM mesh and the proposed Homog+AMSL2P approach is compared to the SE measured using Hall effect probe SS94A1 with a sensitivity of 5.0+0.1 mV/G. 3D simulations are carried out under COMSOL Multiphysics. Fig. 5 shows the reduced model considered for simulations. The symmetries of the geometry of the SE measurement bench allow to consider only a quarter of the entire geometry to reduce computation time.

TABLE 1: MATERIALS PROPERTIES

Material	Electrical Conductivity (MS/m)	Relative magnetic permeability	Relative electrical permittivity
Al (EN AW-8011)	28	1	1
Steel (DC01)	10	160	1
Glue (Loctite 435)	$10^{-6}$	1	1
Homogenized layer	21.74	24.04	1

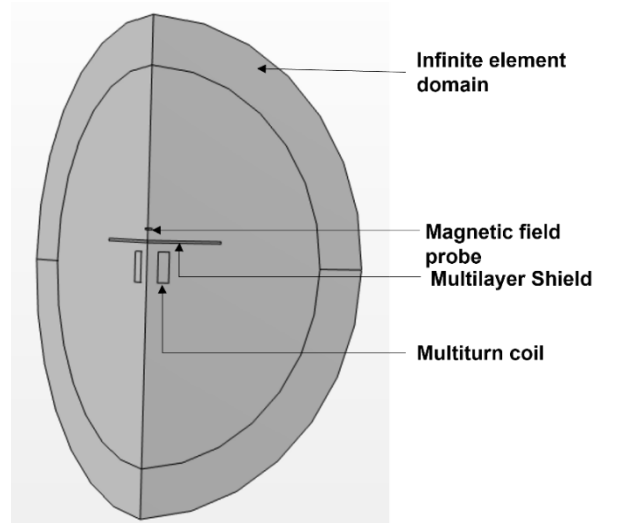


Fig. 5. 3D model considered for simulations.

All simulations are carried out on a computer having the following characteristics: “CPU: Intel(R) Xeon(R) W-1270P CPU 3.80GHz, number of core: 16, active Memory: 128 Go”. The number of finite element layers over the thickness of the shield in the case of classical mesh was varied until an increase of the number of layers resulted in a variation of shielding effectiveness lower than  $10^{-3}$  dB. This leads to 21 finite element layers for the MS domain discretization in the case of the classical mesh. Considering the material properties and equation (2), the proposed method should be valid till  $f = 255$  Hz.

The comparison shown in Fig. 6 reveals that, for  $f < 255$  Hz, the mean error of the proposed Homog+AMSL2P compared to the Classic FEM is 7.3%. The comparison of the proposed Homog+AMSL2P with the experimental data reveals a mean error of 8.4%. The computation time using classic FEM is 936 seconds and that of Homog+AMSL2P is 136 seconds. Therefore, the proposed method reduces the computation time by 85.5% compared to the classic FEM mesh.

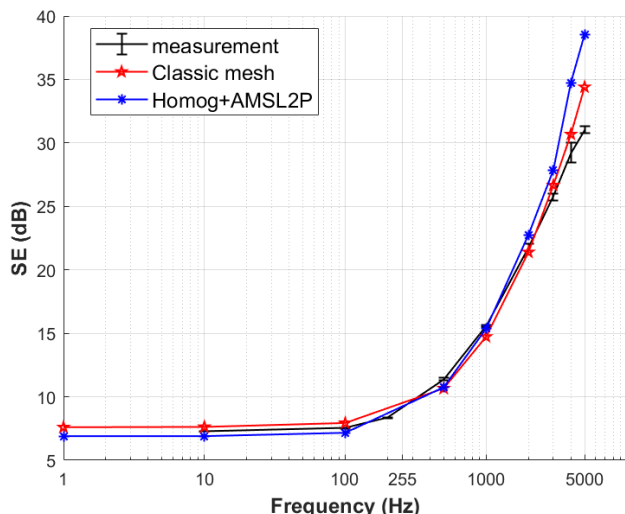


Fig. 6. Computed and measured magnetic shielding effectiveness of the planar multilayer

For  $255 \text{ Hz} < f < 5000 \text{ Hz}$ , the trend of the shielding effectiveness remains correct but only allows a qualitative assessment because the error increases as the skin depth becomes smaller than the shield thickness.

### B. Case of non-planar multilayers

To validate the application of the proposed Homog+AMSL2P approach in case of non-planar multilayers, let us consider the metal composite elaborated by cold roll bonding process presented in Fig. 2. The dimension of the shield is  $3 \text{ cm} \times 3 \text{ cm} \times 0.185 \text{ mm}$ . The steel used to elaborate this metal composite is the one described in Table 1. Due to the material availability, the properties of the aluminum used to elaborate the metal composite is different from the one presented in Table 1. The aluminum used is EN AW-1200. Its properties are as follows:  $\sigma = 33.61 \text{ MS/m}$ ,  $\mu_r = 1$ ,  $\epsilon_r = 1$ . The metal composite obtained by cold roll bonding has anisotropic properties due to the presence of fragmentation. The physical properties of the homogenized layer of the metal composite obtained by energetic approach are given in Table 2.

As previously explained, its physical properties along ND direction are negligible for SE applications.

TABLE 2: HOMOGENIZED LAYER PROPERTIES

	Electrical conductivity (MS/m)		Relative magnetic permeability	
	RD	TD	RD	TD
Homogenized layer	29.5	29.5	31.5	42

For Homog+AMSL2P approach, only the influential material parameters are retained, i.e. RD component of the conductivity and permeability, leading to a new fictive isotropic material. Table 3 gives the results of the simulated SE obtained with Homog+AMSL2P approach, compared to the ones obtained with a conventional mesh applied to homogenized layer with anisotropic properties (Homog+conventional mesh). A comparison is also made with experimental data considered as reference.

TABLE 3: SE OF THE NON-PLANAR MULTILAYER VERSUS FREQUENCY

f (Hz)	Experimental SE (dB)	Homog + conventional mesh SE (dB)	Homog + AMSL2P SE (dB)
10	2.20	2.18	2.08
100	2.22	2.18	2.09
500	2.25	2.21	2.13
1000	2.30	2.28	2.19
5000	3.40	3.96	3.90

The difference between the Homog+AMSL2P approach and Homog. + Conventional mesh results reveal the error made by neglecting the anisotropy of the material in the (RD, TD) plane. This error remains lower than 4%. The anisotropy of the material in (RD, TD) could be considered by applying the AMSL for anisotropic shield [9] to the homogenized layer at the cost of a more complex implementation. Compared to the experimental results, the mean error committed with the Homog+AMSL2P approach is lower than 7.8% on the studied frequency range. A good agreement between proposed approach and experimental results is then observed. The next section compares the accuracy of the Homog+AMSL2P approach to some other existing methods.

## V. COMPARISON OF THE PROPOSED HOMOG+AMSL2P APPROACH TO SOME EXISTING METHODS

To compare different approaches of meshing thin conductive multilayer domain in a finite element model, a simple 2D axisymmetric model as shown in Fig. 7.a is considered. It consists of a coil generating a magnetic field shielded by a multilayer plate located 1cm upper that coil. The simulations are again carried out under COMSOL Multiphysics. The model is bounded by an infinite element domain as shown in Fig. 7b.

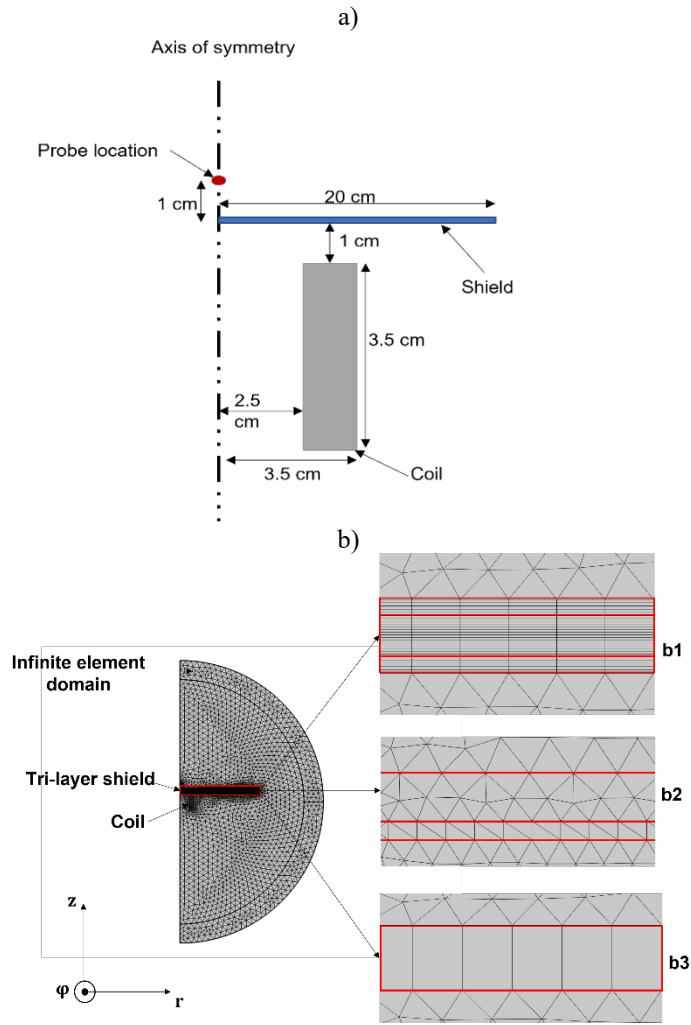


Fig. 7. 2D axisymmetric model considered for simulations: a) model geometry; b) zoom of the shield domain meshed with b1) structured quadrilateral mesh (SQM); b2) INBC/TBC approach; b3) AMSL approach.

#### A. Case of stacked plane layers

Five discretizing approaches based on three meshing methods are considered for the shield domain: structured quadrilateral mesh (SQM) shown in figure 7b1; meshing with the INBC/TBC approach (Figure 7b2); meshing with the multilayer AMSL method (Figure 7b3) and the energetic homogenization approach associated either directly with the SQM or to the AMSL2P method. To compare these different approaches, the following three-layer shield structures are considered.

- MS 1: Al(242.5 $\mu$ m)/Steel(515 $\mu$ m)/Al(242.5 $\mu$ m),  
 $e_{tot} = 1$  mm
- MS 2: Al(150 $\mu$ m)/Steel(100 $\mu$ m)/Al(150 $\mu$ m),  $e_{tot} = 0.4$  mm
- MS 3: Steel(150 $\mu$ m)/Cu(100 $\mu$ m)/Steel(150 $\mu$ m),  
 $e_{tot} = 0.4$  mm

As in 3D, the number of finite element layers used to discretize the MS considered over their thicknesses in the case of the SQM has been increased until this increase had no longer significant influence on the computed shielding effectiveness. The computational results with this discretization approach are then considered as a reference for the comparison of the

accuracy of the different discretization approaches. The results are presented in figures 8 to 10.

Figures 8a 9a and 10a show respectively the SE of the multilayers MS1, MS2 and MS3 depending on the considered discretization approach. A good consistency between the SE obtained by the different approaches is observed for frequencies below 10 kHz. Figures 8b, 9b and 10b give a more detailed analysis of the accuracy of the considered approaches. The ones based on the transmission line method show a good accuracy with an error lower than 5% on the frequency range of 1Hz to 100 kHz. At very low frequencies, the new proposed approach shows on average the best accuracy with a maximum error below 4%. The error committed using the INBC and multilayer AMSL methods decreases with an increase of frequency because these methods are more suitable for high frequencies and good conducting materials. Conversely, the further away from the frequency of validity of the proposed method, the greater the error committed. This limit is explained by the fact that the homogenization by energetic approach is limited to low frequencies as it is only valid in quasi-static conditions. Therefore, applying AMSL2P to the homogenized layer is valid and accurate for low frequencies as long as  $\delta > e$ . Nevertheless, the different simulations show that the method remains applicable up to 4 times the theoretical validity frequency.

The difference between the homogenized layer shielding effectiveness and that of the real structure in high frequency is related to the difference in the distribution of the induced current in the layers (eddy current) with the appearance of the skin effect and therefore to the difference in electromagnetic losses created by the shield.

The simulation time and the maximum relative error of the considered discretization methods over 1 Hz to 100 kHz are presented in Table 4. The relative error of the Homog+AMSL2P approach is determined only on its frequency range of validity.

According to Table 4, the best discretization method for planar multilayer shields in terms of accuracy and computation time is the AMSL method for multilayers developed in [10]. However, this method can not be used in case of non-planar multilayers as detailed in section II-B.

#### B. Case of non-planar multilayers

To highlight the interest of the proposed approach over existing ones, let us consider the metal composite obtained by cold roll bonding of aluminum (EN AW-8011) and steel (DC01). It has a total thickness of 210 $\mu$ m as shown in Fig. 11a and has been meshed as shown in Fig. 11b. A reduction rate of 65% was applied to the initial stacked multilayer sheet to obtain this metal composite. In this case, the methods based on transmission line theory are not applicable as the layers are not flat. To avoid conventional fine discretization leading to a very long computation time, the proposed approach can be accurately applied. The homogenized single layer material properties obtained by the proposed energetic approach are as follows:  $\sigma_{eq} = 28.9$  MS/m,  $\mu_{req} = 39.98$  along RD.

The SE of this metal composite is computed using both a classical fine triangles mesh and the proposed approach. For the mesh with triangles, the maximum element size has been varied

until the variation in the computed SE becomes lower than  $10^{-3}$  dB. This results in a minimum element size of  $10\mu\text{m}$  and a maximum element size of  $40\mu\text{m}$ . Fig. 12a. reveals a good agreement between the SE computed using conventional mesh and SE computed using either Homog + conventional mesh or Homog+AMSL2P approach. Fig. 12b reveals the error committed using both homogenized approaches.

The maximum error with the proposed approach (Homog. +AMSL2P) instead of classical mesh is lower than 3.3% over its frequency range of validity. As shown in Table 5 using the proposed approach reduces the computation time by a factor 13 and leads to very short computation times compared to the use of the classical mesh. Triangles mesh (Homog. + classic mesh) is also applied to the homogenized material to validate the applicability of the AMSL method to the homogenized layer. Fig. 12b reveals that the error committed using AMSL2P on homogenized layer is negligible.

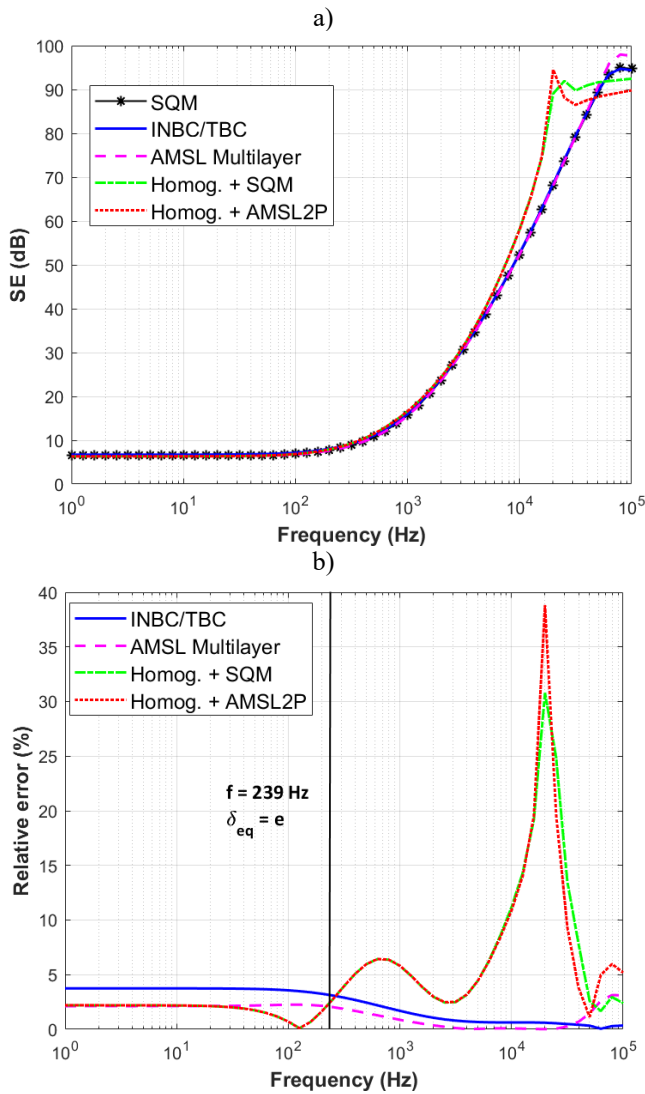


Fig. 8: a) Impact of shield domain discretization approach on shielding effectiveness of MS 1 and b) relative error of the considered approaches

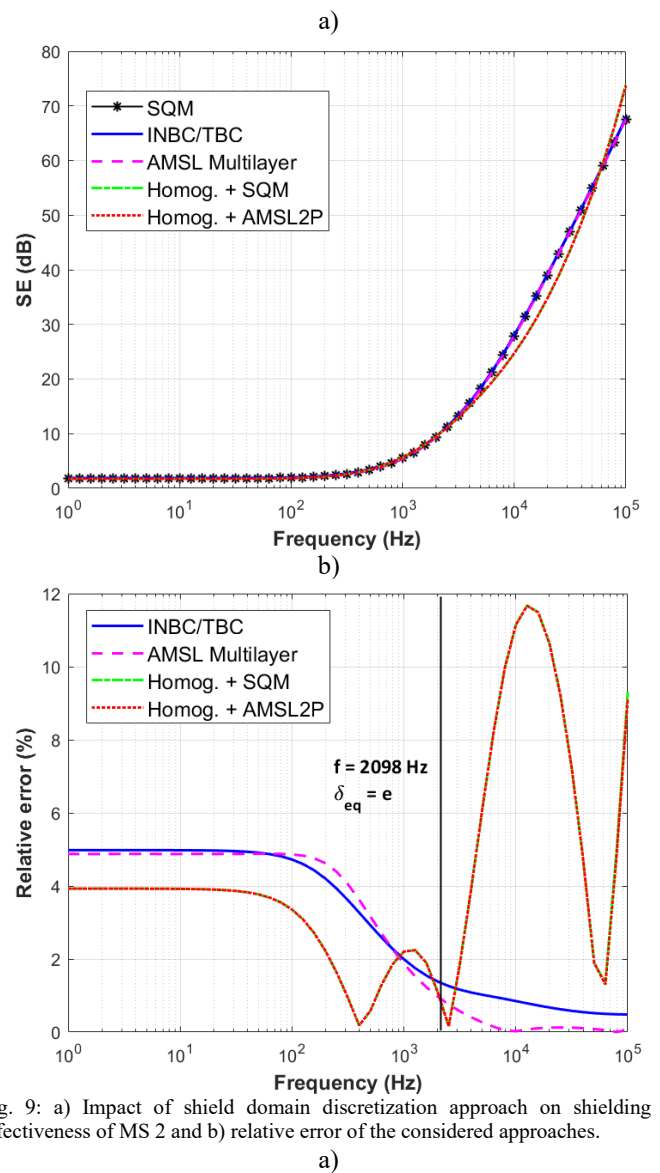
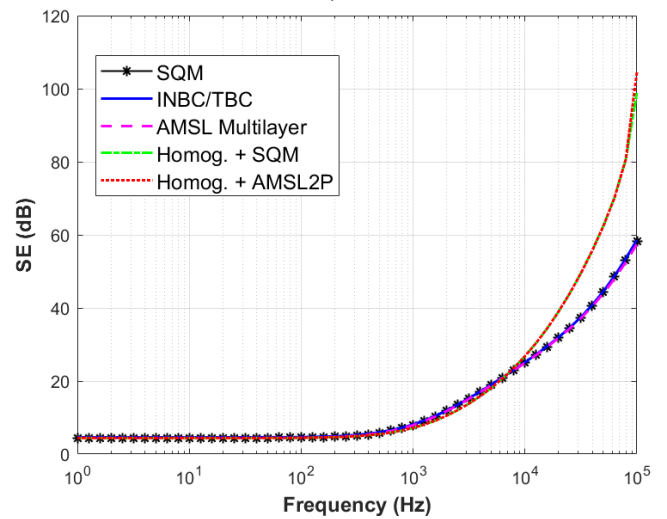


Fig. 9: a) Impact of shield domain discretization approach on shielding effectiveness of MS 2 and b) relative error of the considered approaches.





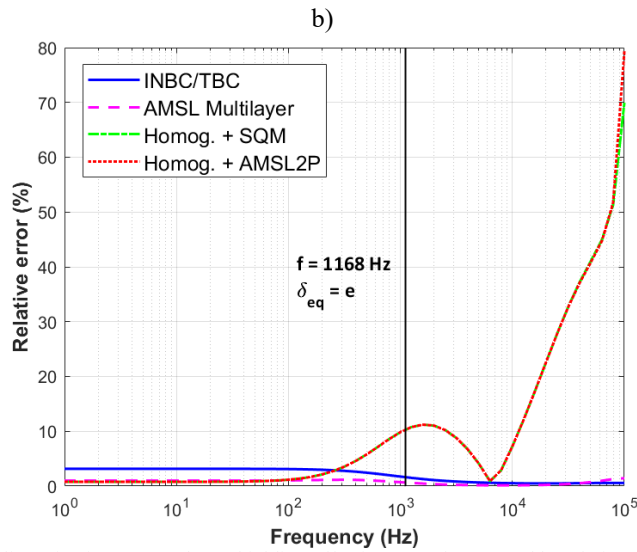


Fig. 10: a) Impact of shield domain discretization approach on shielding effectiveness of MS 3 and b) relative error of the considered approaches

TABLE 4: PERFORMANCE OF THE DIFFERENT MESHING METHODS

Discretization approach	SQM	INBC/TBC	AMSL Multilayer	Homog + SQM	Homog + AMSL2P
Simulation time (s)	8	5	2	7	4
Maximum relative error (%) MS 1	--	3.7	2.1	2.7	2.7
Maximum relative error (%) MS 2	--	4.9	4.8	3.9	3.9
Maximum relative error (%) MS 3	--	3.2	1.0	9.8	9.8

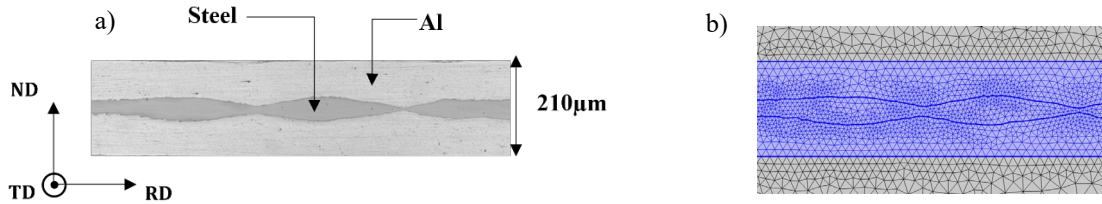


Fig. 11. Metal composite Al/Steel/Al obtained by cold roll bonding.

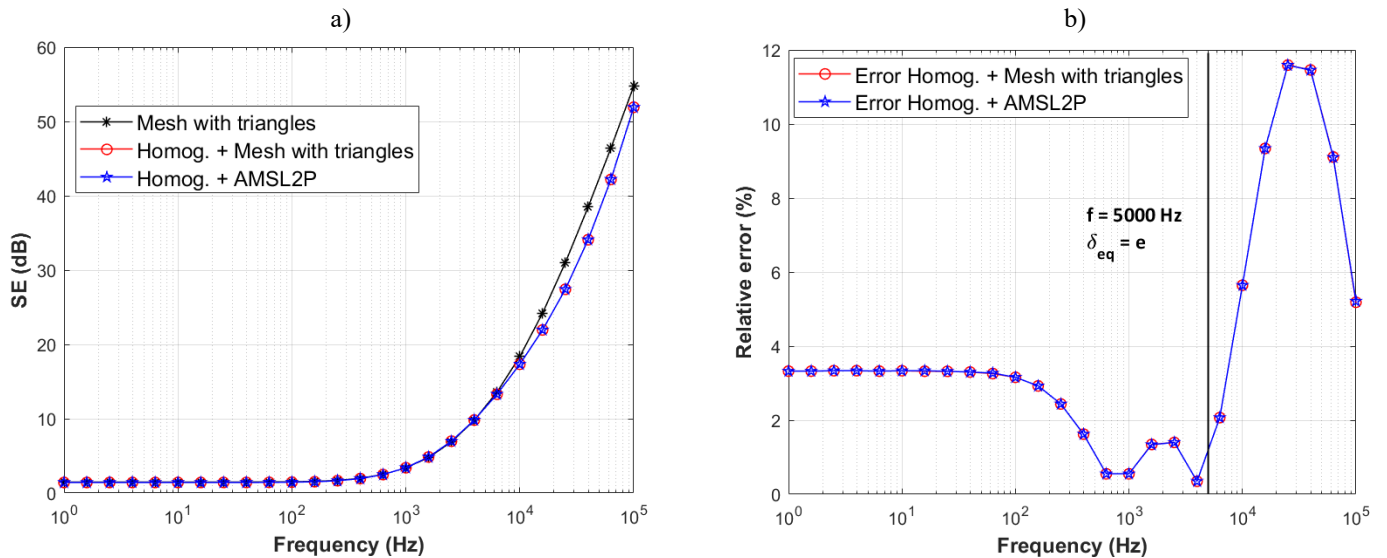


Fig. 12: a) Shielding effectiveness versus frequency of the metal composite; b) relative error of homogenization approaches

TABLE 4: PERFORMANCE OF THE PROPOSED METHOD

Mesh	Mesh with triangles	Homog+Mesh with triangles	Homog + AMSL2
Simulation time (s)	229	78	18
Maximum relative error (%)	--	3.32	3.32

## VI. CONCLUSION

In order to overcome some limitations of the AMSL approach that prevent the method from being used in a number of actual magnetic shielding applications, this paper has introduced an additional step for the finite element modelling of non-planar thin multilayers or composites. The domain of the heterogeneous composite is first homogenized, and the 2<sup>nd</sup> order AMSL method is next applied to this single layer. The homogenized layer properties are obtained either by analogy with electric and magnetic circuit theory in case of plane layers or from an energetic approach in case of non-planar multilayers such as the ones with fragmentations. It has been shown that the proposed approach is easy to be implemented in commercial software. It inherits the advantages of the AMSL method. Therefore, the computation time and required memory are significantly reduced. However, since the properties of the homogenized layer are obtained by static considerations, the proposed method is valid up to four times the frequency at which  $\delta_{eq}$  equals the shield thickness. The proposed method is then particularly useful for low frequency applications such as non-planar multilayer magnetic shields obtained by roll bonding or the ones containing inclusions. In these later cases, there is no well-known and easy to implement method to lighten the mesh. Studies based on the consideration of the total electromagnetic losses including reflection losses are underway to extend this homogenization approach to higher frequencies and to some other composites. Ongoing works will also focus on the modelling of heterogeneous thin electromagnetic shields subjected to multi-physics constraints such as thermal and mechanical phenomenon.

## REFERENCES

- [1] A. Karimi, F.G. Moghaddam, and M. Valipour (2020). Insights in the biology of extremely low-frequency magnetic fields exposure on human health. In *Molecular Biology Reports* (Vol. 47, Issue 7).
- [2] A. Ahlbom, E. Cardis, A. Green, M. Linet, D. Savitz, and A. Swerdlow (2001). Review of the epidemiologic literature on EMF and health. *Environmental Health Perspectives*, 109(SUPPL. 6), 911–933.
- [3] X. Ma, Q. Zhang, Z. Luo, X. Lin and G. Wu (2016). A novel structure of Ferro - Aluminum based sandwich composite for magnetic and electromagnetic interference shielding. *Materials and Design*, 89, 71–77. <https://doi.org/10.1016/j.matdes.2015.09.137>
- [4] S. -Y. Lee, Y. -S. Lim, I. -H. Choi, D. -I. Lee and S. -B. Kim (2012). Effective Combination of Soft Magnetic Materials for Magnetic Shielding. *IEEE Transactions on Magnetics*, vol. 48, no. 11, pp. 4550–4553, doi: 10.1109/TMAG.2012.2196682.
- [5] P. Clérico (2019). Development of a bimetallic Al/Steel/Al composite fabric for electromagnetic shielding. PhD dissertation, Université Paris Saclay, France.
- [6] M. Feliziani and F. Maradei (1998). Fast computation of quasi-static magnetic fields around non perfectly conductive shields. *IEEE Transactions on Magnetics*, 34(5 PART 1)
- [7] M. Feliziani, S. Cruciani, T. Campi and F. Maradei (2018). Artificial Material Single Layer to Model the Field Penetration through Thin Shields in Finite-Elements Analysis. *IEEE Transactions on Microwave Theory and Techniques*, 66(1). <https://doi.org/10.1109/TMTT.2017.2737994>
- [8] S. Cruciani, T. Campi, F. Maradei and M. Feliziani (2018). Conductive Layer Modeling by Improved Second-Order Artificial Material Single-Layer Method. *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 10, pp. 5646–5650. doi: 10.1109/TAP.2018.2854413.
- [9] S. Cruciani, T. Campi, F. Maradei and M. Feliziani (2018). Artificial Material Single-Layer Method Applied to Model the Electromagnetic Field Propagation Through Anisotropic Shields. *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 8, pp. 3756–3763. doi: 10.1109/TMTT.2018.2840975.
- [10] S. Cruciani, T. Campi, F. Maradei and M. Feliziani (2020). Finite-Element Modeling of Conductive Multilayer Shields by Artificial Material Single-Layer Method. *IEEE Transactions on Magnetics*, vol. 56, no. 1, pp. 1–4. Art no. 7502504, doi: 10.1109/TMAG.2019.2949737.
- [11] AC/DC Module User's Guide, pp. 286–287 (2020). COMSOL Multiphysics® v. 5.6. COMSOL AB, Stockholm, Sweden.
- [12] G. Al Achkar, L. Pichon, L. Daniel and N. Benjelloun (2020). Effective Electromagnetic Properties of Woven Fiber Composites for Shielding Applications. *IEEE Transactions on Electromagnetic Compatibility*, 62(4), 1082–1089. <https://doi.org/10.1109/TEMC.2019.2931764>
- [13] V. Prévault, R. Corcolle, L. Daniel, L. Pichon (2014). Influence of skin effect on the effective shielding effectiveness of composite materials. *Journal of Applied Physics*, 115 (15), pp.154904. 10.1063/1.4871197
- [14] V. Prévault, R. Corcolle, L. Daniel and L. Pichon (2013). Effective permittivity of shielding composite materials for microwave frequencies. *IEEE Transactions on Electromagnetic Compatibility*, 55(6), 1178–1186. <https://doi.org/10.1109/TEMC.2013.2265173>
- [15] G. Andrieu, J. Panh, A. Reineix, P. Péliouss, C. Girard, X. Romeuf and D. Schmitt (2012). Homogenization of composite panels from a near-field magnetic shielding effectiveness measurement. *IEEE Transactions on Electromagnetic Compatibility*, 54(3), 700–703. <https://doi.org/10.1109/TEMC.2012.2186455>
- [16] G. Al Achkar, L. Pichon, M. Bensetti and L. Daniel (2021). Homogenization of metal grid reinforced composites for near-field low frequency magnetic shielding. *Progress In Electromagnetics Research M*, 99, 153–163. <https://doi.org/10.2528/PIERM20052402>
- [17] A. Shivola (2000). Mixing rules with complex dielectric coefficients. I. *Appl. 1* (4):393–415. doi: 10.1023/A:1026511515005. *Subsurf. Sens. Technol. Appl.*, 1(4), 393–415.
- [18] J. R. Moser (1988). Low-Frequency Low-Impedance Electromagnetic Shielding. *IEEE Transactions on Electromagnetic Compatibility*, 30(3), 202–210. <https://doi.org/10.1109/15.3298>
- [19] P. Clérico, X. Mininger, L. Prévond, T. Baudin, and A.L. Helbert (2019). Compromise between magnetic shielding and mechanical strength of thin Al/Steel/Al sandwiches produced by cold roll bonding: Experimental and numerical approaches. *Journal of Alloys and Compounds*, 798, 67–81.
- [20] S. A. Schelkunoff (1943). *Electromagnetic Waves*. New York, NY, USA: Van Nostrand.
- [21] R. B. Schulz, V.C. Plantz, and D.R. Brush (1988). Shielding Theory and Practice. *IEEE Transactions on Electromagnetic Compatibility*, 30(3), 187–201.