Modelling of Pyramid Absorbers Used in EMC Facilities

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***Abstract*—In this work we show some numerical aspects related to the full-wave 3D simulations of absorber wall properties. Two problems are discussed: (i) characterization of the dielectric properties of the absorber medium and (ii) modelling of the absorber wall geometry terminating the EMC facility. It is shown that approximation of the constitutive properties of the absorber medium by Debye models with several relaxation terms can lead to a better accuracy than for a single term based Debye formula description. Regarding absorber wall geometry: multilayer models characterized by anisotropic permittivity distribution offer better approximation properties than isotropic multilayer models.**

***Index Terms*—TEM waveguide, pyramid absorber, Debye model, multilayer absorber model, numerical field simulation**

I. Introduction

The transverse electromagnetic (TEM) waveguide is commonly used in electromagnetic compatibility (EMC) tests where it is applied e.g. to test immunity of the devices over a broadband frequency range. The geometry of an asymmetric, open, TEM waveguide consists of three metallic planes, with the input of the waveguide connected to a signal generator and the output terminated by a combination of a resistor network and a wall of polyurethane pyramid absorbers (Fig. 1) [1].

Fig. 1. TEM waveguide for EMC tests in Fraunhofer INT

A proper model of the absorbing wall is a key factor to a successful simulation of the electromagnetic behaviour of the EMC facility. There are two issues that have to be addressed: (i) identification of the dielectric properties of the absorber medium and (ii) modelling of the geometry of the absorbing wall loading the waveguide.

The permittivity of the absorber material can be extracted from measurements [2], e.g. by application of transmission-line techniques [3]. Alternatively, the dielectric properties of the absorber medium can be approximated by tabulated data reported for graphite-impregnated absorber foams with various carbon loading [4], [5], or by parameterized Debye formula [6]. When the electric permittivity of the absorber medium is known, absorber wall can be modelled either by the direct implementation of the pyramids lattice in the numerical solver, or by application of the multilayer model with a permittivity profile matching the free-space to the bulk absorber medium properties [7]. The regular geometry of the multilayer models allows to reduce numerical costs related to the required mesh density that should resolve the pyramid shape of the absorber wall [8]–[10].

The subject of this paper is numerical modelling of the absorber loading the experimental facility shown in Fig. 1. Preliminary results of this work published in [11] presented measured values of electric permittivity for the absorber material and a simple multilayer model based on isotropic description of the permittivity profile. This paper extends the previous work by application of Debye relaxation formula to approximate the measured permittivity [6] and multilayer models of the absorber wall geometry based on anisotropic description of the permittivity profile [7]. We review the possible approaches to the numerical modelling of the absorber medium as well as the numerical aspects related to the representation of the absorber wall. The results of this work will be applied in the numerical simulations of the experimental EMC facility shown in Fig. 1.

This paper is organized as follows. Section II describes the approximation of the dielectric properties of the absorber medium with Debye models, Section III presents the multilayer approach based on anisotropic permittivity profile applied to the modelling of the absorber wall geometry and finally Section IV closes the paper with conclusions and a brief outlook.

II. Description of absorber material

The electric permittivity of the absorber material is extracted from the measurements of the absorber loaded coaxial line and the corresponding results are shown in Fig. 7 of [11]. Typically, the commonly encountered absorber materials based on carbon loaded foams display dielectric response that can be approximated by the first-order Debye relaxation equation

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TABLE I
DEBYE MODEL WITH K RELAXATION TERMS FITTED TO THE MEASURED ABSORBER PERMITTIVITY IN THE FREQUENCY RANGE 10 MHZ - 1 GHZ.

K		1	2	3
ε_{s1}		7.59	8.29	7.88
ε_{s2}		-	3.63	3.71
ε_{s3}		-	-	2.44
ε_{∞}		2.23	1.86	1.47
f_{e1}	[MHz]	91.2	34.5	23.8
f_{e2}	[MHz]	-	353.2	146.0
f_{e3}	[MHz]	-	-	1217.4
σ_e	[mS/m]	5.31	3.74	3.26

with additional DC conductivity term [6]:

$$\varepsilon_r(\omega)=\left(\varepsilon_\infty+\frac{\varepsilon_s-\varepsilon_\infty}{1+\omega^2\tau_e^2}\right)-j\left(\frac{\sigma_e}{\omega\varepsilon_0}+\frac{(\varepsilon_s-\varepsilon_\infty)\omega\tau_e}{1+\omega^2\tau_e^2}\right) \quad (1)$$

where ε_∞ is the relative optical permittivity, ε_s is the relative static permittivity, ε_0 is the free-space permittivity, τ_e represents the dielectric relaxation time (related to the frequency $f_e = 1/(2\pi\tau_e)$), σ_e is the static electric conductivity and $\omega = 2\pi f$ is the angular frequency.

This model can be extended by using multiple Debye relaxation terms, i.e. a sum of K first-order Debye rational functions [8], [12], [13]:

$$\varepsilon_r(\omega)=\left(\varepsilon_\infty+\sum_{i=1}^{K}\frac{\varepsilon_{si}-\varepsilon_\infty}{1+\omega^2\tau_{e\,i}^2}\right)-j\left(\frac{\sigma_e}{\omega\varepsilon_0}+\sum_{i=1}^{K}\frac{(\varepsilon_{si}-\varepsilon_\infty)\omega\tau_{ei}}{1+\omega^2\tau_{e\,i}^2}\right) \quad (2)$$

where ε_{si} is the relative permittivity at the low-frequency limit of the i-th relaxation, τ_{ei} is the time constant of the i-th relaxation term and ε_∞ is the relative permittivity at the high-frequency limit of the model.

The first question that arises is: how many relaxation terms are needed in order to approximate absorber permittivity? Most often a single Debye term is used [6], [9], [10], although other works show that two to three relaxation terms are required to accurately represent the dispersive behaviour of the electric permittivity [8], [12].

We approximated absorber permittivity obtained from experiments by Debye models with one, two and three relaxation terms. For fitting purposes least-squares regression procedures available in Matlab [14] and differential evolution algorithm [15] are used. The parameters of Debye models are given in Tab. I, whereas the corresponding fitted permittivity characteristics are shown in Fig. 2-3. It can be noticed that the two- and the third-order Debye model offers better approximation of the dielectric absorber properties than Debye model with a single relaxation term.

It is interesting to compare reflection of a single pyramid characterized by permittivity extracted from measurements to a pyramid modelled by the K-th order Debye formula (2). This case is numerically simulated with full-wave 3D electromagnetic solver [16] and the corresponding S_{11} curves are

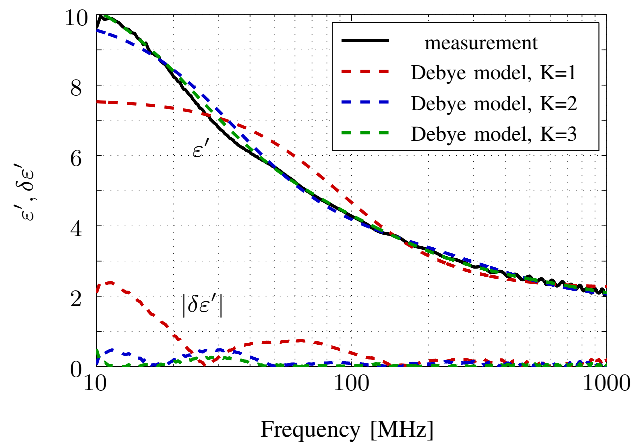

Fig. 2. Absorber permittivity ε' extracted from measurements and fitted by Debye model with K relaxation terms in the frequency range 10 MHz - 1 GHz. $\delta\varepsilon'$ describes the difference between the measured data and Debye model.

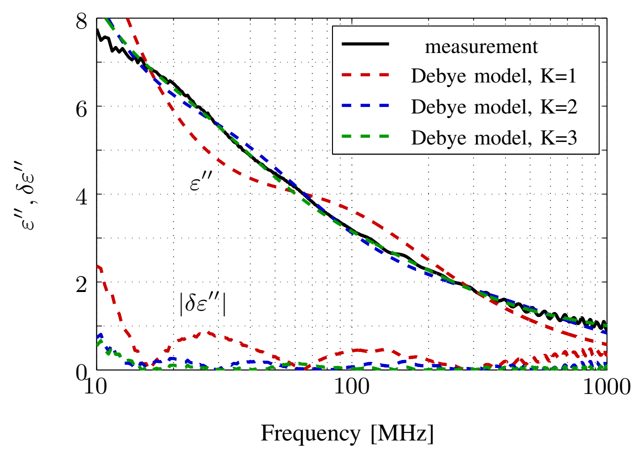

Fig. 3. Absorber permittivity ε'' extracted from measurements and fitted by Debye model with K relaxation terms in the frequency range 10 MHz - 1 GHz. $\delta\varepsilon''$ describes the difference between the measured data and Debye model.

shown in Fig. 4. There is virtually no difference in the pyramid reflection for ε described by Debye models with two or three relaxation terms and the pyramid characterized by measured permittivity data. However, characterization of the pyramid properties by Debye model with single relaxation term results in the limited quality of the approximated reflection curve.

The required order of the Debye model depends on the frequency range in which absorber properties are approximated - for larger bandwidths more relaxation terms are needed. In the presented case second order Debye model offers good approximation of the absorber permittivity for frequencies between 10 MHz and 1 GHz.

A practical advantage of the approach based on approximation of absorber properties by Debye models is reduced

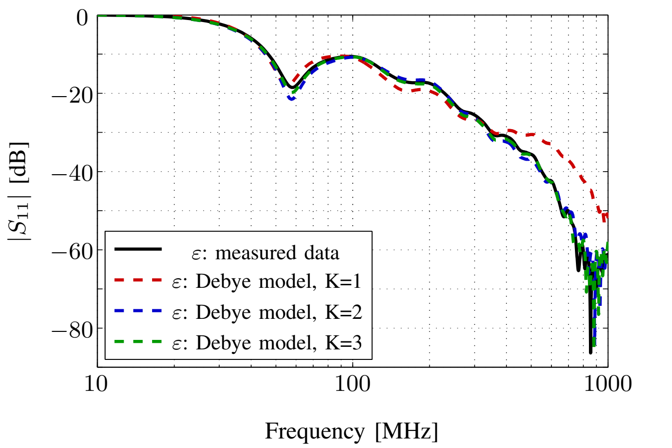

Fig. 4. Simulated S_{11} of a single pyramid. Absorber permittivity is extracted from measurements or fitted by Debye model with K relaxation terms in the frequency range 10 MHz - 1 GHz.

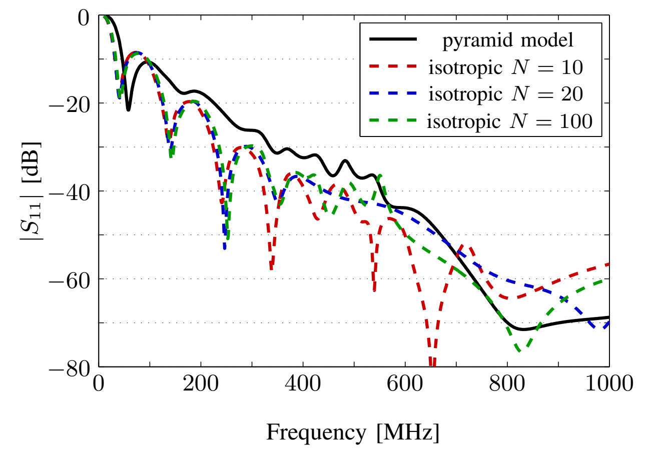

Fig. 5. Simulated S_{11} of a single pyramid modelled by the isotropic N-layer model in the frequency range 10 MHz - 1 GHz.

TABLE II
SIMULATION TIME OF THE PYRAMID ABSORBER CHARACTERIZED BY PERMITTIVITY EXTRACTED FROM MEASUREMENTS OR DESCRIBED BY DEBYE MODEL WITH K RELAXATION TERMS.

Absorber permittivity	10 MHz - 1 GHz	
	Simulation time	
Measured data	7min25s	1.00
Debye model, K=1	2min53s	0.39
Debye model, K=2	2min53s	0.39
Debye model, K=3	3min11s	0.43

simulation time with time-domain solver. The simulation time of the pyramid absorber described by Debye model can be reduced to ca. 40% of the simulation time required for the structure modelled by user defined permittivity list based on the experimental data and implemented in tabulated form in the electromagnetic solver (Tab. II). The numerical cost saving is related to the order of the general dispersive model used internally by the solver to approximate permittivity data given by the user. The numerical cost reduction might be of particular advantage in simulation of large structures, e.g. a TEM waveguide including absorber wall.

III. Modelling of Absorber Wall

In order to limit the numerical requirements related to the simulation of the TEM waveguide its absorber wall geometry is modelled by a multilayer approach [7]. Generally, the layers in the model can be described by isotropic or anisotropic electric permittivity [5]. In this section some numerical aspects related to the application of the multilayer approach are discussed.

The basic implementation of the multilayer approach is the isotropic model for effective electric permittivity:

$$\varepsilon(n) = [1 - g(n)]\varepsilon_h + g(n)\varepsilon_g \quad (3)$$

where $\varepsilon(n)$ is the permittivity of the n-th layer ($n = 1, \ldots, N$), ε_h is the free-space (host medium) permittivity, ε_g represents absorber (guest medium) permittivity and $g(n) = (n/N)^2$ is the permittivity distribution. The multilayer isotropic model offers limited approximation quality as it is shown in Fig. 5, where simulated S_{11} parameter of the multilayer isotropic model is compared with S_{11} of the pyramid absorber. Introduction of a larger number of layers does not improve the quality of this approximation.

The anisotropic model improves the pyramid representation by introducing different effective permittivity components in the transversal (x, y) and longitudinal (z) directions [7]:

$$\varepsilon_t(n) = \varepsilon_h \left(1 + g(n)\frac{2(\varepsilon_g - \varepsilon_h)}{[1 + g(n)]\varepsilon_h + [1 - g(n)]\varepsilon_g}\right) \quad (4)$$

$$\varepsilon_z(n) = [1 - g(n)]\varepsilon_h + g(n)\varepsilon_g \quad (5)$$

where longitudinal component $\varepsilon_z(n)$ is equal to permittivity distribution in the isotropic model (3). From Fig. 6 it can be noticed that application of the anisotropic description significantly improves quality of approximation of pyramid reflection properties when compared with the results of the isotropic model shown in Fig. 5. On the other hand, there is no improvement in the approximation quality for the number of layers larger than 20. N=10 is a good choice for the multilayer absorber representation in this case.

The minimal number of layers modelling the absorber structure is related to the electrical length of the pyramid. At 1 GHz, the pyramid's length (0.94m) is equivalent to ca. $3\lambda_0$ so there should be at least 6 layers in the model. The thickness of a single layer should be smaller than $\lambda_0/2$ in order to avoid the response originating from the periodicity of the multilayer structure.

The multilayer absorber wall representation is expected to work well for pyramid array periods smaller than $\lambda_0/2$ and reasonably well for periods between $\lambda_0/2$ and λ_0 [8]. Once period of the absorber array is larger than the wavelength

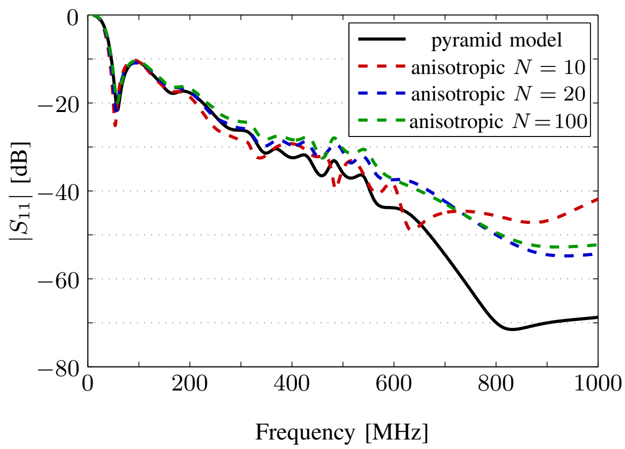

Fig. 6. Simulated S_{11} of a single pyramid modelled by the anisotropic N-layer model in the frequency range 10 MHz - 1 GHz.

the grating lobes may appear and the effective layer model becomes inadequate [8], [17], [18]. In our case the pyramid absorbers arranged in the absorber wall (see Fig. 1) constitute a square array with the lattice constant (the distance between the tips of the neighbouring pyramids) equal to $a = 30.5$ cm. Consequently, the homogenized multilayer model is expected to work well for frequencies up to 0.5 GHz and reasonably well in the range $0.5 - 1$ GHz. This is confirmed by the simulated S_{11} parameter of the multilayer models (Fig. 6). The S_{11} frequency characteristic of these models is very well fitted to the pyramid reflection curve up to 400 MHz with the deviation of several dB between 400 and 600 MHz and of $10 - 15$ dB in the frequency range $600 - 1000$ MHz.

IV. Conclusion and Outlook

In this work we show numerical aspects related to full-wave 3D simulations of absorber wall terminating EMC facilities. It is shown that approximation of absorber medium properties by Debye models can lead to numerical cost saving in terms of required CPU time, whereas anisotropic multilayer model offers significantly better approximation quality of the absorber wall properties than its isotropic counterpart. The problem of choice of the number of layers and the working frequency range of the multilayer absorber representation is also addressed in this paper.

The developed absorber models will be applied in the numerical simulations of the in-house TEM waveguide used for EMC tests.

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