Homogeneous Dielectric Equivalents of Composite Material Shields

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Abstract. *The paper deals with the methodology of replacing complicated parts of an airplane skin by simple homogeneous equivalents, which can exhibit similar shielding efficiency. On one hand, the airplane built from the virtual homogeneous equivalents can be analyzed with significantly reduced CPU-time demands and memory requirements. On the other hand, the equivalent model can estimate the internal fields satisfactory enough to evaluate the electromagnetic immunity of the airplane.*

Keywords

Composite material, dielectric layers, electromagnetic immunity, shielding.

1. Introduction

Requirements of the electromagnetic immunity of small airplanes are higher and higher on one hand, and more and more difficult to be fulfilled on the other hand. Several metallic parts of the airplane skin are going to be replaced by composite ones in order to reduce the weight of the airplane, and consequently the jet fuel consumption in order to decrease the operation costs. Unfortunately, the shielding efficiency of composite parts is lower compared to fully metallic parts, which can negatively influence the electromagnetic immunity of the airplane towards the high intensity external fields. For those reasons, small airplanes have to be carefully tested from the viewpoint of electromagnetic aspects.

Numerical analysis of a realistic model of an airplane is extremely complicated, and CPU-time requirements and memory demands are enormous since the electrically large airplane contains very small significant details (a metallic network inside composite parts, several gaps and slots increasing the internal electromagnetic field in the airplane, etc.). Whereas these details have to be covered by a very fine mesh, the continuous parts require a quite rough mesh.

In the paper, the described problem is solved by introducing homogeneous equivalent layers, which exhibit a similar behavior like the realistic structures, but thanks to their homogeneity, can be covered by the usual rough enough mesh.

Shielding efficiency of composite materials belongs to the hot research topics these days. In the last decade, over 100 papers related to this topic were published in IEEE periodicals. On the other hand, papers discussing a proper and efficient numerical modeling of composite layers are quite rare:

- In [1], a model allowing simulation of thin composite multilayered panels in finite-difference time-domain (FDTD) procedure was proposed. The model enabled to overcome the limitations of sub-gridding algorithms, hybrid approaches, and surface impedance boundaries. Each layer of the composite was modeled as a homogeneous medium, characterized by constant effective conductivity and permittivity.
- In [2], an analysis of the lossy periodic multilayer structures consisting of conducting fibers situated in a dielectric matrix was described. In order to discuss the combined effect of fibers and the dielectric matrix, reflection and transmission matrices at the air-matrix, and grating interfaces together with suitable phase correction were incorporated in the model in which the fiber grating was regarded as a thin Floquet layer. In order to reduce the CPU time, an extended filament-current model was examined.
- In [3], a combined magnetic field integral equation and FDTD procedure was developed for the efficient analysis of the transient plane wave penetration inside a metallic-composite box. Suitable boundary conditions were enforced on the composite walls of the enclosure in order to link the methods.
- In [4], a carbon fiber reinforced layer of the composite panel constituted by a braided carbon tissue with weave angle of 90° was analyzed by FDTD. In order to obtain an effective equivalent layer model, effective tensors of conductivity and permittivity were derived in order to represent the composite as a homogeneous anisotropic material.
- In [5], an equivalent circuit of a single-layer homogeneous and anisotropic composite material was calculated considering the diffusion equation.
- In [6], an analytical study in the spectral domain of inhomogeneous layers, which were characterized in terms of transmission matrices, led to an equivalent

circuit representation of the whole multilayered structure.

- In [7], a method to estimate effective permeability of magnetic composite materials for a static field was presented. In the method, the structures of the composite materials were assumed to be periodic. The effective permeability was determined on the basis of magnetic energy balance in the unit cell.
- In [8], a homogenization method was introduced in order to estimate effective permeability of magnetic composite structure for a static field. This method can be applied not only to linear problems but also to nonlinear ones.

The approach presented in this paper adopts the idea of the homogenization of composites [7], [8], and the principle of homogeneous equivalent layers [1], [4]. The presented approach does not tend to develop analytical models of the structure or equivalent circuits [2], [5], [6].

The *blind* global synthesis of equivalent layers by global optimization techniques is the original contribution of the presented paper. Neither the physical configuration of the composite layer is not considered, nor is the physical principles applied. An arbitrary homogeneous layer is used, and its selected parameters are changed to reach the best possible match with the composite layer. If inappropriate parameters are selected, the identification can fail.

The developed approach considers a dielectric layer described by state variables (permittivity, losses, thickness, etc.), which unknown values are identified by the particle swarm optimization [9] to meet the frequency response of a modeled composite layer. Exploitation of global optimization techniques to the identification of values of state variables when searching for homogeneous equivalents of composite structures is the original contribution of this paper.

Instead of computing the shielding efficiency, frequency responses of the reflection coefficient are computed in this paper (the more energy is reflected by the composite layer, the better the shielding efficiency is achieved). Whereas the scattering parameters are provided by the CST simulator directly, evaluation of the shielding efficiency requires more CPU time (and slows down the optimization).

2. Homogeneous Equivalents

Composite materials, which are used to build a skin of small airplanes, consist of several dielectric layers and a mesh of metallic wires. Using numerical techniques, the analysis of such a material requires very dense meshing, and therefore, CPU-time demands and memory demands of the analysis are extremely high.

If an electrically large airplane from composite materials is going to be analyzed, the composite skin has to be replaced by homogeneous materials exhibiting equivalent electromagnetic properties. Then, the skin can be discretized by a rough mesh, and the airplane can be analyzed in a reasonable time.

In the paper, the equivalent of the composite layer is built by Particle Swarm Optimization (PSO): frequency response of the reflection coefficient of the composite layer is computed, and parameters of the homogeneous equivalent (complex permittivity, thickness) are identified to reach the same frequency response.

Therefore, the complex permittivity and the thickness are state variables of the optimization, and the difference between the frequency response of the reflection coefficient of the composite layer and the equivalent one is the objective function. PSO searches for such permittivity and thickness to minimize the differences between frequency responses.

In PSO language, the equivalent layer is a particle which coordinates correspond to the permittivity and the thickness of the equivalent. The particle is attracted to the optimum. The optimum is represented by the particle with the minimum error (the difference between the frequency response of the reflection coefficient of the composite layer and the equivalent one).

The velocity vector of the particle consists of three components. The first component corresponds to the inertia of the particle. The second component expresses the attraction to the optimum, which has been revealed by the particle personally (the personal best position). The third component is given by the attraction to the optimum, which has been revealed by the whole swarm of particles (the global best position).

The swarm of particles iteratively moves to the optima until the value of error function does not fall below the required threshold, or until the number of iterations does not exceed the prescribed number of iterations.

The ability of the particle swarm optimizer (PSO) to identify parameters of homogeneous equivalents of gaps (the width of the gap is 3 mm) in dielectric walls and gaps in composite materials was tested on structures shown in Fig. 1.

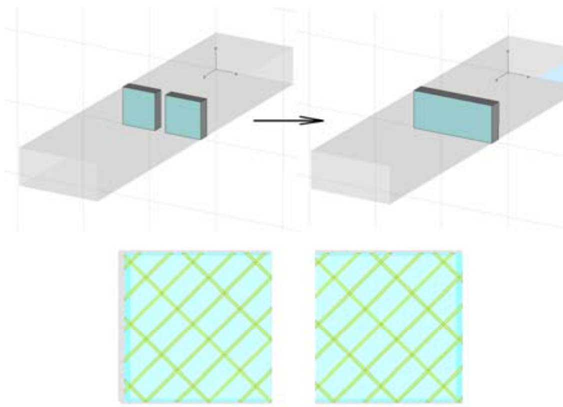

Fig. 1. Slot in the dielectric wall (top) and in the composite one (bottom).

The upper figure shows the slot in a dielectric wall which is being substituted by a homogeneous layer. The lower figure displays the front view of the slotted dielectrics with a metallic grid.

In order to minimize CPU-time demands of the electromagnetic analysis during the synthesis of homogeneous equivalents, the structure was placed inside the R100 waveguide. The waveguide was excited by the dominant TE_{10} mode in the frequency range from 7.0 GHz to 13.0 GHz. That way, the incidence of the horizontally polarized wave was simulated.

Obviously, the characteristic impedance of free space and of the waveguide can differ. Different characteristic impedances result in different values of reflection coefficients of both the composite layer and the homogeneous equivalent. That way, the influence of the waveguide on the properties of the homogeneous equivalent is compensated.

Finally, the dielectric constant, the conductivity and the thickness of a homogeneous dielectric layer are changed in order to obtain the frequency response of the reflection coefficient, which is identical to the composite structure.

Tab. 1 shows results of the search for a homogeneous equivalent of the slot in the dielectric wall. For the search, PSO and a gradient algorithm were used.

	equivalent 1	equivalent 2	equivalent 3
optimization	**gradient**	PSO	gradient
thickness [mm]	**10.00**	4.00	7.00
conductivity [mS/m]	**18.89**	26.36	0.00
permittivity [-]	**1.84**	9.71	12.56

Tab. 1. Parameters of the homogeneous equivalent of the slot in the dielectric wall. Equivalent 1 exhibits the best match.

The dielectric layer in a waveguide reflects the electromagnetic wave at the boundaries air – dielectrics and dielectrics – air. If the reflected waves are of the opposite phase at a given frequency, the reflected waves can vanish, which causes the minimum of the reflection coefficient (Fig. 2).

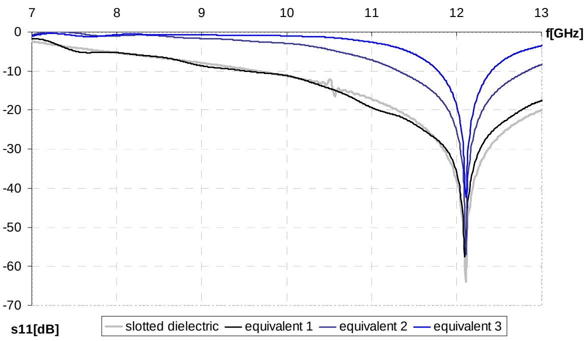

Fig. 2. Frequency response of the magnitude of the reflection coefficient for the slot in dielectric layer and for homogeneous equivalents specified in Tab. 1.

Amplitude and phase of reflected waves depend on the dielectric constant of the dielectric layer, on its thickness and losses. If the slot in the wall is much smaller compared to the wavelength, the effective permittivity of the wall is decreased causing changes of amplitudes and phases in the structure. If the dielectric constant, thickness and losses in the layer are changed, the required position of the minimum of the reflection coefficient can be obtained.

Tab. 2 shows results of the search for a homogeneous equivalent of the slot in the composite material. The composite material contains a metallic grid made from the wire of the radius 0.1 mm. A cell of the grid is of the dimensions 1.5 mm × 3.0 mm. The grid is rotated for 45°. For searching parameters of a homogeneous equivalent, PSO is used.

Numerical analysis of the slot in the composite wall shows that the reflection coefficient of the structure is nearly constant in the frequency band of interest $s_{11} \sim -1$ dB (see Fig. 3) since the size of cells is much smaller than the wavelength.

Searching for a homogeneous equivalent structure, a significant increase of the conductivity of the structure can be expected. This assumption is confirmed by the results shown in Tab. 2. Tab. 2 shows that the increase of the dielectric constant of the equivalent layer causes the decrease of its thickness. A higher dielectric constant is related to a shorter wavelength. The thickness of the layer has to be therefore reduced to keep the identical phase shift between both reflected waves.

	equivalent 1	equivalent 2	equivalent 3
optimization	PSO	PSO	PSO
thickness [mm]	0.55	2.00	1.77
conductivity [S/m]	0.10	0.10	0.10
permittivity [-]	39.29	10.00	19.79

Tab. 2. Parameters of the homogeneous equivalent of the slot in the composite wall.

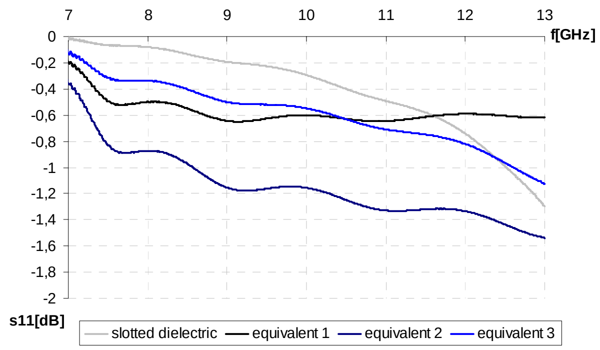

Fig. 3. Frequency response of the magnitude of the reflection coefficient for the slot in the composite material and for homogeneous equivalents specified in Tab. 2.

In the next Section, the developed homogeneous equivalents are used in a very simple model of an airplane when computing internal electromagnetic fields.

3. Simple Airplane Model

The simplified model of an airplane is depicted in Fig. 4. In the significant distance of the excitation wall, a layer simulating the left-hand wall of an airplane is modeled. In several wavelengths, the second layer is assumed simulating the right-hand wall of the airplane.

The proposed extremely simple model is appropriate for substituting the composite layer by the homogeneous equivalent. On the other hand, such a simplification it is not acceptable for the EMC simulation of the whole airplane. Nevertheless, the paper is aimed to develop the methodology of substituting composite layers by homogeneous equivalents.

Parameters of walls correspond to the parameters of the developed homogeneous equivalents. Field intensity inside the model is computed in the internal points P_1 [–7 mm; 400 mm], P_2 [0 mm; 600 mm] and P_3 [5 mm; 743 mm]. The simplified model is tested depending on the type of the excitation (a harmonic planar wave versus a Gaussian planar wave) and on the angle of incidence (0°, 30° and 60°).

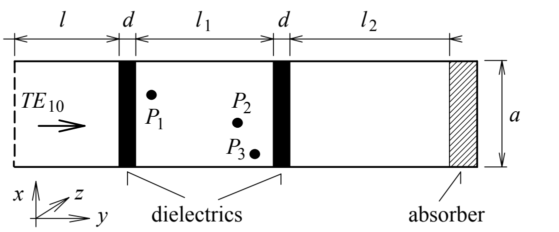

Fig. 4. The simplified airplane model. In P_1 to P_3, virtual probes are assumed. Dimensions: l = l_1 = 370 mm, l_2 = 180 mm, d = 7 mm, a = 22.86 mm.

For the harmonic waves, the accuracy of the homogeneous equivalent of the slot in the dielectric layer is given in Tab. 3, and the accuracy of the homogeneous equivalent of the slot in the composite layer is given in Tab. 4. The accuracy is compared from the viewpoint of the electric field deviation related to the original structure and the homogeneous equivalent. Deviations are averaged at all the frequencies of the analysis.

Angle of incidence [°]	0	30	60
$d\|E\|_{P1}$ [dBV/m]	3.95	2.61	2.63
$d\|E\|_{P2}$ [dBV/m]	3.82	2.37	1.94
$d\|E\|_{P3}$ [dBV/m]	3.73	2.48	1.91

Tab. 3. The average deviation of the field intensity in testing points for the homogeneous equivalent of the slot in the homogeneous dielectrics.

Angle of incidence [°]	0	30	60
$d\|E\|_{P1}$ [dBV/m]	6.02	6.18	10.44
$d\|E\|_{P2}$ [dBV/m]	6.16	6.87	12.15
$d\|E\|_{P3}$ [dBV/m]	6.70	6.84	12.74

Tab. 4. The average deviation of the field intensity in testing points for the homogeneous equivalent of the slot in the composite layer.

In case of the slot in the homogeneous dielectric layer, the accuracy of the equivalent rises with increasing angle of incidence (the increasing angle of incidence decreases the electric width of the slot).

In case of the slot in the composite layer, the tendencies are opposite. Reasons for this behavior are going to be investigated.

For the worst case (the slot in the composite, the angle of incidence α = 60°), the frequency response and the time response of the electric field intensity in testing points is shown in Fig. 5 and Fig. 6, for the harmonic wave illumination.

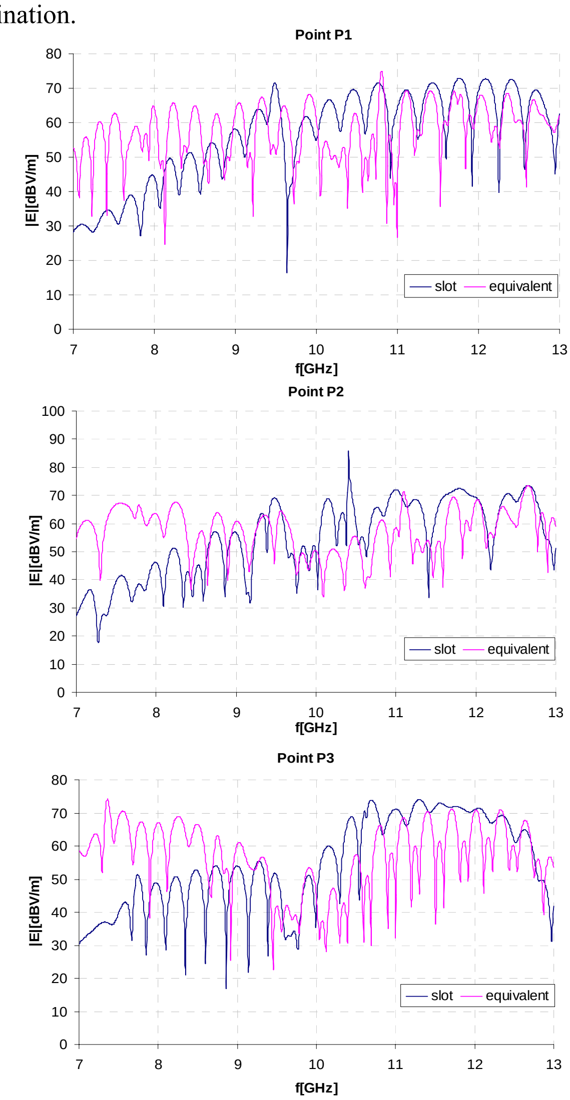

Fig. 5. Frequency response of field intensity in testing points for the angle of incidence 60°: the slot in composite (blue), the homogeneous equivalent (magenta).

The overall accuracy of the substitution is given by the number of frequency points, in which the frequency response of the reflection coefficient was observed and from which the fitness function was evaluated. We used four frequency points since the responses had rather linear shape with one dominant resonance when substituting the slotted dielectrics (Fig. 2), and without any resonance when substituting the slotted composite layer (Fig. 3).

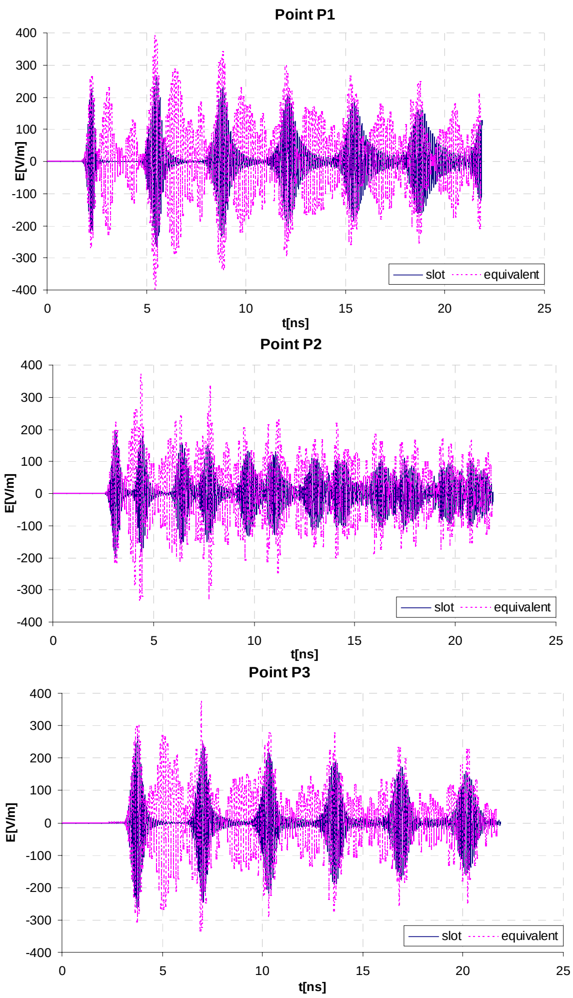

Fig. 6. Time response of field intensity in testing points for the angle of incidence 60°: the slot in composite (blue), the homogeneous equivalent (magenta).

The substitution was developed for the normal incidence of the wave. If the angle of incidence is increased, the dimensions of the grid are apparently changing (decreasing in the horizontal direction) causing the increasing differences in the frequency range from 7 GHz to 9 GHz. Since the frequency responses are derived from the time responses (using Fourier transformation), the accuracy of the frequency responses is the same as time responses.

4. Conclusions

In the paper, a novel approach to the development of homogeneous equivalents of complicated composite structures was presented. The approach uses particle swarm optimization in order to identify values of state variables of homogeneous dielectric layers those exhibit the same frequency response of the reflection coefficient like the original structure.

The developed equivalents were tested in a simple model of an airplane consisting of a left-hand wall and a right-hand wall. Field intensities in the internal testing points were compared for the harmonic excitation wave and the pulse one.

Even in case of the worst accuracy, the estimated field intensities are of the comparable value, which might be sufficient for studying electromagnetic immunity issues. Nevertheless, further development is performed to increase the accuracy of models (e.g., layered equivalents or anisotropic equivalents are considered to obtain more degrees of freedom). Moreover, multi-objective techniques are going to be developed in order to optimize the behavior of equivalents from the different viewpoints.

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