Genetic Homogenization of Composite Materials

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Abstract. *The paper is focused on numerical studies of electromagnetic properties of composite materials used for the construction of small airplanes. Discussions concentrate on the genetic homogenization of composite layers and composite layers with a slot. The homogenization is aimed to reduce CPU-time demands of EMC computational models of electrically large airplanes. First, a methodology of creating a 3-dimensional numerical model of a composite material in CST Microwave Studio is proposed focusing on a sufficient accuracy of the model. Second, a proper implementation of a genetic optimization in Matlab is discussed. Third, an association of the optimization script and a simplified 2-dimensional model of the homogeneous equivalent model in Comsol Multiphysics is proposed considering EMC issues. Results of computations are experimentally verified.*

Keywords

Composite materials, genetic algorithms, complex permittivity.

1. Introduction

The demands on the reduction of the weight and the fuel consumption of today's airplanes enforce designers to replace the fully metallic skin of airplanes by composite materials. Therefore, a very strong research effort is focused on the development of new analytical and numerical techniques for the modeling of these structures in order to efficiently determine their scattering parameters.

In order to provide an efficient characterization of the composite material, a sample of the material is usually placed into a waveguide. As shown in [3], the accuracy of such characterization depends on the position of the sample in case the sample does not occupy the whole cross section of the waveguide.

Dealing with a numerical characterization of composite materials, conventional or hybrid finite-difference time-domain (FDTD) methods are usually used [4], [5]. Due to the relatively complicated structure of the composite materials, CPU-time demands of such an analysis might be relatively high. In order to solve this problem, a genetic algorithm [1] is originally applied to identify such a frequency dependency of the complex permittivity of a homogeneous dielectric layer, which exhibits similar frequency responses of scattering parameters as the composite material.

Section 2 describes a numerical analysis of the composite material in CST Microwave Studio using FDTD which determines scattering parameters of the material. In Section 3, a model of a homogeneous equivalent of the composite material is developed in COMSOL Multiphysics and joined with a genetic algorithm programmed in MATLAB in order to identify the frequency response of the complex permittivity of the equivalent layer; the computed results are compared with experimental data. Section 5 concludes the paper.

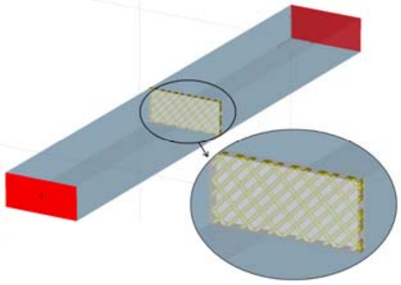

Fig. 1. Three-dimensional model of the continuous composite material in the waveguide R100. Simulated in CST Microwave Studio.

2. Numerical Modeling

The numerical model of the investigated composite material inside a rectangular waveguide was developed in CST Microwave Studio [2]. The waveguide was excited by the transversally electric wave TE_{10} which can model a linearly polarized vertical wave illuminating the layer. The waveguide was terminated by an absorbing layer in order to suppress the reflected wave. Frequency response of the reflection coefficient s_{11} and the transmission coefficient s_{21} are computed for a continuous composite layer (Fig. 1) and for a composite layer with a slot (Fig. 2).

The three-dimensional model of the composite material is created by a lossy metallic grid. The grid is made from the wire of the diameter 0.3 mm. Cells of the grid are of the dimensions 3.0 mm × 1.5 mm. The grid is rotated for 45 degrees. The metallic grid is covered by the lossy laminate dielectrics Taconic RF-35 from both sides. The relative permittivity of the dielectrics is 3.5, and tan $\delta = 0.0018$. The thickness of the dielectric layer is 1 mm on both sides. The slot in the composite layer is 2.5 mm wide.

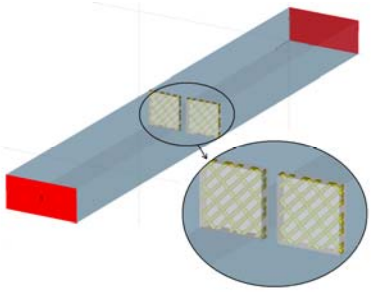

Fig. 2. Three-dimensional model of the composite material with a slot in the waveguide R100. Simulated in CST Microwave Studio.

The structure is discretized by the hexahedral cells. Results of the analysis in the frequency range from 7 GHz to 40 GHz are depicted in Fig. 3 and Fig. 4.

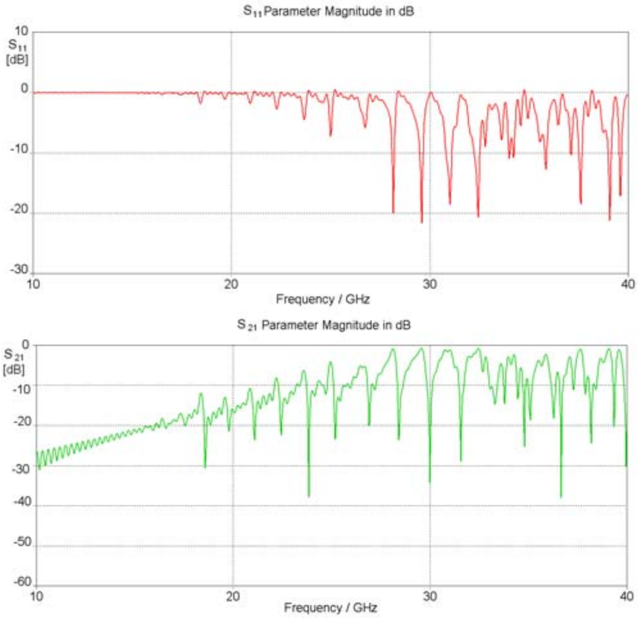

Fig. 3. Reflection coefficient (red line) and transmission coefficient (green line) of the continuous composite material in the waveguide R100. Simulated in CST Microwave Studio.

Simulations of lossy materials within a large frequency range can produce errors (reflection coefficient higher than 0 dB, oscillations in the frequency response of s_{11} and s_{21}, etc.). Documentation of CST Microwave Studio Help explains that an inhomogeneity in the port region decreases the accuracy of the waveguide operator when increasing the distance from the port mode calculation frequency. Depending on the grade of the inhomogeneity and the range of the bandwidth, a broadband error in the simulation results can appear [2].

The described phenomenon can be reduced by narrowing the frequency range of the analysis (Fig. 5), by using locally refined meshes or by combining both the approaches. In 3D models of composite layers, the global mesh density was 30 cells per wave length, and the local mesh density (the composite layer) was 90 cells per wave length.

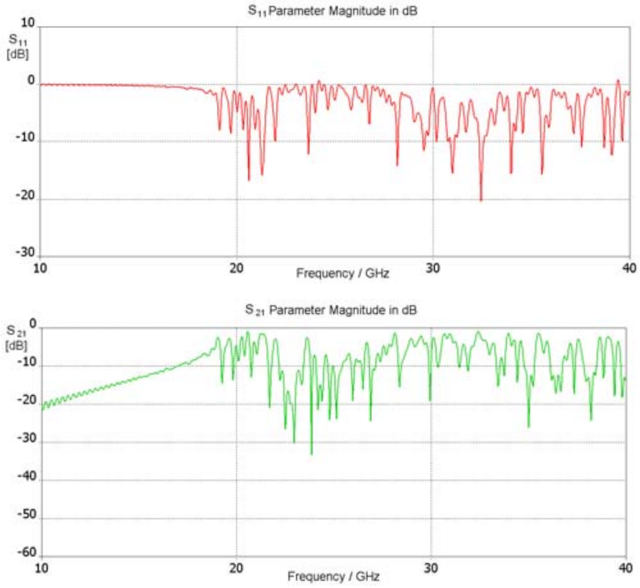

Fig. 4. Reflection coefficient (red line) and transmission coefficient (green line) of the composite material with slot in the waveguide R100. Simulated in CST Microwave Studio.

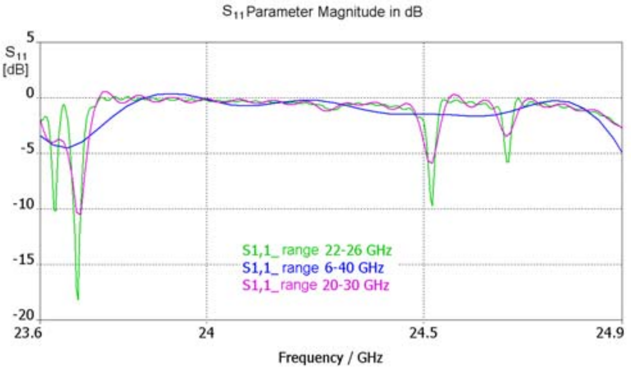

Fig. 5. Frequency response of the reflection coefficient of the composite material in the waveguide R100: frequency range 6 GHz to 40 GHz (blue), 20 GHz to 30 GHz (violet) and 22 GHz to 26 GHz (green).

The frequency range from 7 GHz to 13 GHz was selected for the following simulations and homogenizations.

The investigated composite material exhibits good shielding efficiency for frequencies up to 20 GHz (cells of the wire grid are much smaller compared to the wavelength). For higher frequencies, bands of very small reflections and very high ones can be observed.

3. Homogeneous Equivalent

In order to develop a homogeneous equivalent of the composite material, a simple dielectric layer of the thickness 2 mm in the waveguide is modeled in COMSOL Multiphysics, and frequency response of the complex permittivity is computed by genetic algorithm to obtain the same characteristics as provided by the composite material.

f [GHz]	ε_r	tan δ
7.0	110.5	0.979
7.5	138.6	0.337
8.0	435.5	0.091
8.5	228.6	0.349
9.0	540.0	0.024
9.5	77.5	0.989
10.0	106.6	0.247
10.5	55.9	0.802
11.0	571.2	0.030
11.5	111.6	0.176
12.0	7.2	0.902
12.5	107.4	0.167
13.0	651.9	0.162

Tab. 1. Frequency response of the relative permittivity and the loss-factor of the continuous composite layer produced by the genetic optimization in MATLAB.

The global algorithm for the synthesis of a homogeneous equivalent of the composite layer can consider the thickness of the equivalent layer as the state variable of the procedure. Nevertheless, the computed thickness has to be constant at all the frequencies of the model validity interval.

The population consisted of 30 individuals. The length of the binary coded individual was 40 bits, the maximum number of iterations equaled to 100. In order to evaluate the fitness function, the COMSOL model was simulated to compute values of the reflection coefficient and the transmission one for the randomly generated complex permittivity. The dielectric constant could vary within the interval $\varepsilon_r = [2; 1000]$ and the loss tangent can change within the interval tan $\delta = [0.000001; 1]$. Individuals for the next population were selected by the tournament. Probability of the multipoint crossover was set to 70 % and probability of the multipoint mutation was assumed to be 6 %. In the optimization, the elitist strategy was applied.

The identification procedure produces frequency response of the relative permittivity and the loss-factor (see Tab. 1 and Tab. 2). The computed response is imported back to the CST Microwave Studio to verify the agreement between the frequency responses of scattering parameters of the original composite material and the equivalent homogeneous dielectric layer (see Fig. 6 and 7).

The comparisons of both the models show the deviations between the original structures and the equivalent materials. The deviations can be caused by the different representation of lossy materials in COMSOL Multiphysics (used for identification properties) and CST Microwave Studio (used for simulation properties). The reflection coefficient achieves good agreement in both the cases. In the first model, the transmission coefficient is higher ranging from 5 dB to 10 dB (see Fig. 6). In the second model, the agreement is better, and the maximal difference is about 5 dB (see Fig. 7). In case of EMC problems, the agreement is of the satisfactory accuracy.

f [GHz]	ε_r	tan δ
7.0	2.0	0.750
7.5	95.6	0.884
8.0	151.1	0.929
8.5	194.9	0.391
9.0	25.6	0.252
9.5	290.6	0.299
10.0	154.3	0.257
10.5	63.1	0.240
11.0	158.3	0.970
11.5	34.5	0.313
12.0	258.4	0.744
12.5	37.9	0.306
13.0	108.5	0.894

Tab. 2. Frequency response of the relative permittivity and the loss-factor of the composite layer with slot produced by the genetic optimization in MATLAB.

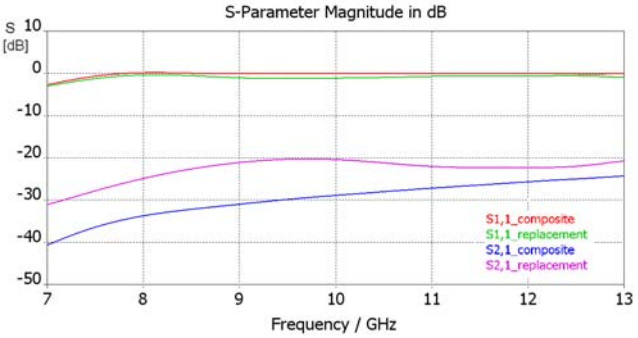

Fig. 6. Comparison of the reflection coefficient and transmission coefficient of the original continuous composite (red, blue) and the homogeneous equivalent one (green, violet). Simulated in CST Microwave Studio.

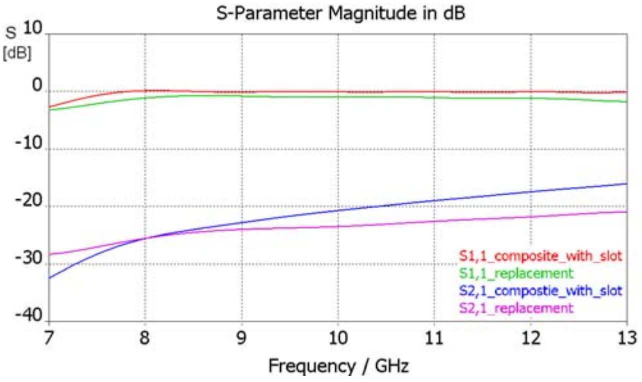

Fig. 7. Comparison of the reflection coefficient and the transmission coefficient of the original composite layer with a slot (red, blue) and the homogeneous equivalent one (green, violet). Simulated in CST Microwave Studio.

Results of measurements were adopted from [6]; only frequency responses of the transmission coefficient were available. Comparisons between the computed values and measured ones are depicted in Fig. 8. Obviously, deviations can be observed both for the simulation of the original composite and for the simulation of the homogeneous equivalent. The measurement results are of the approximate nature only: the measurement was accomplished in a metallic box, and the simulation was performed for the layer in the waveguide R100 in CST Microwave Studio.

Minimum deviations can be observed for the frequency response of the measured transmission line and the simulations of the realistic composite material in the frequency range from 8.5 GHz to 10.5 GHz (the difference is below 3 dB). The maximum difference between the transmission coefficient of the homogeneous equivalent and measured data is about 10 dB. Such accuracy is acceptable for EMC purposes.

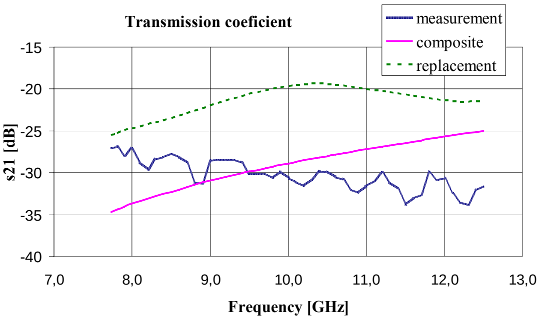

Fig. 8. Frequency response of the transmission coefficient of the composite layer computed in CST Microwave Studio (pink) and measured (zig-zag). Comparison with the homogeneous equivalent computed in CST Microwave Studio (dotted).

4. Conclusions

The paper describes an original method of a genetic synthesis of an equivalent homogenous substitute for a realistic composite material. The method is aimed to reduce CPU-time demands of the analysis of complicated objects consisting of composite materials. First, numerical models of two the composite structures were developed in CST Microwave Studio to produce the frequency response of scattering parameters as the optimum state to be reached by the genetic synthesis of a homogeneous equivalent. The genetic synthesis of a homogeneous equivalent results in a frequency response of complex permittivity of a dielectric layer exhibiting the same properties as the realistic model of the composite material. The proposed method proved the functionality of the synthesis of homogeneous equivalents of composite layers. On the other hand, accuracy of the proposed method is not sufficient, and therefore, a local tuning of the optimum parameters is going to be implemented. Accuracy of the genetic synthesis can be improved by exploiting a multi-objective optimization approach to the homogenization process (the required frequency response of the reflection coefficient is the first objective, and the required frequency response of the transmission coefficient is the second objective). The multi-objective synthesis procedure is intensively investigated.

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References

[1] RAHMAT-SAMII, Y., MICHIELSSEN, E. *Electromagnetic Optimization by Genetic Algorithms*. New York: J. Wiley&Sons, 1999.

[2] *CST Microwave Studio Users' Guide*. Available: www.cst.com

[3] MIYAGAWA, H., HIROSE, K., NISHIKAWA, T., WAKINO, K., KITAZAWA, T. Determination of complex permittivity and permeability of materials in rectangular waveguide using accurate hybrid numerical calculation. In *Proceedings of the International Microwave Symposium 2005*, vol. 1, p. 4–8.

[4] SARTO, M. S. Sub-cell model of multilayer composite materials for full FDTD and hybrid MFIE/FDTD analyses. In *Proc. of the IEEE International Symposium on Electromagnetic Compatibility 2002*, vol. 2, p. 737–742.

[5] REQUENA-PEREZ, M.E., DIAZ-MORCILLIO, A., MONZO-CABRERA, J. Accurate permitivity measurement by means of inverse calculation based on genetic algorithms. In *Proc. of the Int. Symp. on Antennas and Propagation IPS 2004*, vol. 1. p. 511–514.

[6] GOŇA, S., KŘESÁLEK, V. *Measurement of reflection and transmission properties of composite samples no. 1 to 8, and synthesis of equivalent models of those samples*. Research report. Zlín: University of Tomáš Baťa, 2008.

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