FINDING THE ELECTROMAGNETIC HOMOGENOUS EQUIVALENT OF THE COMPOSITE MATERIAL USING GLOBAL OPTIMIZATION TECHNIQUES TO SOLVE THE INVERSE PROBLEM

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Abstract: The equivalent homogeneous isotropic replacement is computationally efficient way how to enable simulation of the large numeric models of the composite aircrafts for the purpose of precertification electromagnetic compatibility tests to estimate the level of their resistance against the lightning. The paper presents application of two global optimization methods to find an appropriate electromagnetic equivalent of the composite material by homogeneous material to reduce CPU demands of the numeric models of electrically large airplanes for the purpose of electromagnetic compatibility simulations. First, the inverse problem is specified using the already known scattering parameters of the composite material. Afterwards, the global optimization method is applied to find the equivalent with such a value of the complex electromagnetic permittivity to have the impact on the electromagnetic field propagation as close as possible to the original composite material.

1 INTRODUCTION

The demands on the important operational cost reduction of the airplanes by important decrease of the fuel consumption of today's airplanes is nowadays being solved by the aircraft designers replace replacing the fully metallic skin of airplanes with composite materials.

Composite material has by its nature lower shielding effectiveness than the fully metallic skin of airplanes. As the airplanes operate in the environment, which is disturbed by large number of electromagnetic interferences, as nature as artificial, is necessary to know shielding effectiveness of the composite structure.

While the airplanes are frequently used to deliver many people or important cargo, each type of newly designed airplane has to be tested to prove its resistance against lightning. While each testing attempt is very expensive and the whole testing procedure has to be repeated in case of insufficient shielding, the numeric simulation to discover the weak parts is a natural choice. Unfortunately modelling the composite structures directly causes the mesh cells to increase, just at the composite parts. (D'Amore and Sarto, 2000). This is naturally caused by multilayer structure, tiny structure of the composites and high frequency range, on which the EMC values are prescribed by standards.

Composite materials used as construction materials for aircrafts are most often multilayer epoxy or polyester resin reinforced by carbon fibres (carbon fibre reinforced composites CFRC, Von Klemperer, 2009).

To increase the mechanical toughness and the electromagnetic shielding, it is possible to introduce a metallic grid between reinforced epoxy resin layers (see Figure 1). Unfortunately due to the complicated structure of the composite materials and as it contains lossy materials, the numeric models are becoming even more complicated and more CPU-time demanding (Sarto, 2002).

One of the approaches to reduce the computational complexity is to replace the multilayer structure in numerical model with a homogeneous isotropic equivalent providing the same or very close behaviour in electromagnetic field as the original composite structure. The

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homogeneous equivalent in numerical models can be covered by more sparse mesh net leading to the lower CPU demands causing the CPU time of the simulation are reduced. To solve these issues, the global optimization methods were applied to find such a value of the complex permittivity of a homogeneous dielectric layer that exhibits similar frequency responses of scattering parameters as the composite material.

In the first part the 3D model of composite material simulated in commercial full-wave CST Microwave Studio (CST MWS) is described and its scattering parameters are calculated to be used as the input value for the optimization process.

In the second part the principle of the inverse problem used for the determination of complex permittivity of the homogeneous material is described.

In the third part, the design of the global optimization methods is described. The implementation details together with the impact of the selected method using single representative of single-objective and one of the multi-objective approach is discussed.

2 SCATTERING PARAMETERS OF COMPOSITE MATERIAL

The polymer composite supported by carbon fibres is reported to be the most frequently used material for aircraft construction. To increase its mechanical robustness and electromagnetic shielding level the metallic grid is frequently introduced into the composite. From the perspective of electromagnetic parameters, conductive carbon fibres are strongly anisotropic so they have different parameters in various axes. Practically this increases the numeric model complexity even more.

The three-dimensional numeric model of such composite material was created in a commercial modelling program CST Microwave Studio (see Figure 1) consisting of polymer matrix with thickness of 2 mm, with relative permittivity 4 and conductivity 0 S/m and a carbon fibre matrix with 35 μm in diameter, conductivity set to 10^4 S/m along the fibre 50 S/m across fibre and relative permittivity set to 2.

The model consisted of two such layers of polymer-carbon composite surrounding a copper grid with wire 0.3 mm in diameter and eye size 3x1.5 mm.

The whole structure was placed to the standard R100 waveguide and simulated for normal incidence of TM_{01} wave. This arrangement was particularly selected so that the model could have been easily verified experimentally by direct measurement.

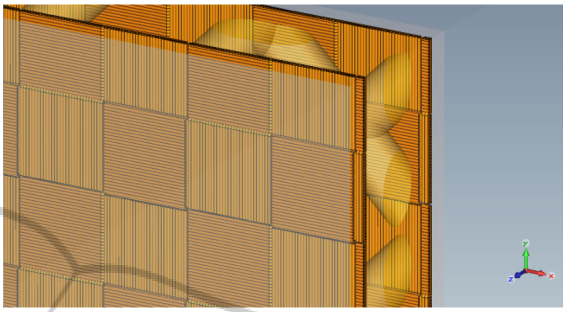

Figure 1: Detailed three dimensional model of carbon fibre reinforced composite (CFRC) simulated in CST Microwave Studio.

The high computational demands (from 3 day up to one week depending on the hardware) on the simulation solver are not only caused by the multilayer thin structure of the model, small eye size of metallic grid and carbon fibres matrix or by anisotropic nature of the carbon fibres but also by quite huge frequency range, required for the precertification test.

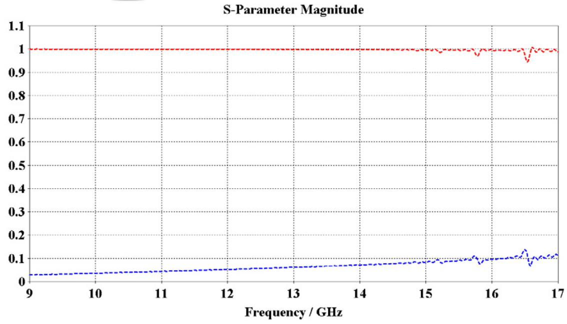

Figure 2: Scattering parameters of composite material: red line – reflection coefficient, blue line – transmission coefficient (simulated in CST MWS).

This wide frequency range also has a negative impact to the overall error of the numeric model. This challenge was described in the paper (Jilková and Raida, 2009). The output of the simulation – set of so called scattering parameters of scattering parameters (see Figure 2) – served as the input values to the optimization process.

3 PRINCIPLE OF INVERSE PROBLEM

To find the homogeneous equivalent material two particular members of the global optimization methods was used. The inverse problem is specified as finding such a frequency dependency of the complex permittivity of a homogeneous dielectric layer that exhibits similar frequency responses of both scattering parameters as the composite material (s_{11} reflection coefficient and s_{21} transmission coefficient). Replacement principle is shown on Figure 3.

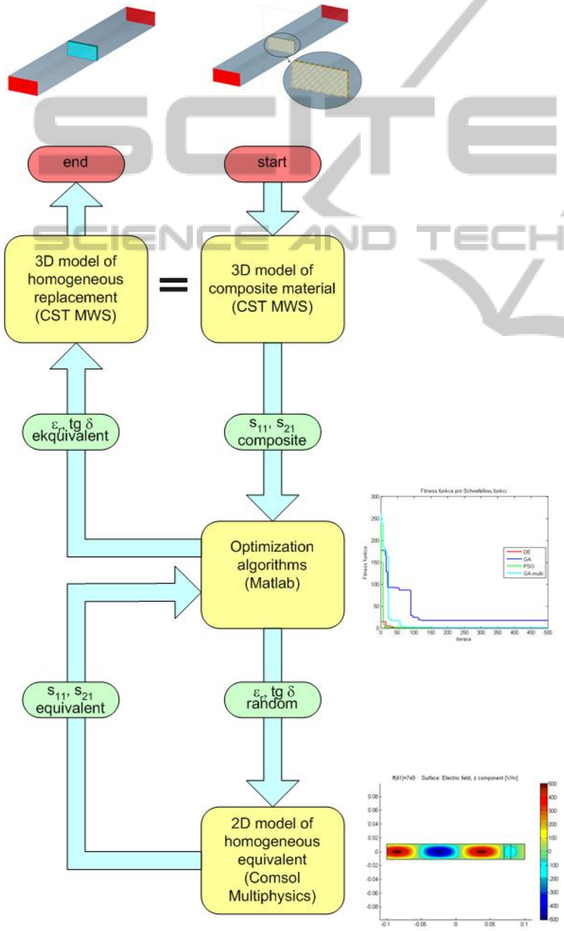

Figure 3: Principle of inverse problem.

To achieve be able to apply the global optimization method on this problem, the 2D problem of the homogeneous dielectrics was created which was further easier to simulate because of lower computational demands being therefore convenient for the optimization. As for the 3D model, the output of the 2D model consisted of both scattering parameters that were afterwards compared with those obtained from 3D model. The input to the 2D model was formed by the the real part of the relative permittivity and a loss tangent parameter. These two can be used to calculate so called complex permittivity that completely characterizes any lossy dielectric material. The model was created in COMSOL Multiphysics. For the purpose of the global optimization, the dielectric constant was permitted to vary within the interval [1; 1000] and the loss tangent was set to vary within [0; 1000].

The complex permittivity acquired from the optimization of the 2D model was finally verified in the 3D model of the equivalent in CST MWS to see if the scattering parameters match in the whole frequency spectra.

4 GLOBAL OPTIMIZATION

Why should the global optimization methods be used to find an equivalent homogeneous material? An usual way how to find properties of equivalent material is to derive its properties using the analytical description of its electromagnetic properties.

This involves expressing the characteristics of the material in Maxwell equations which may become very complicated when it comes for complex multilayer lossy anisotropic structure. The usual way how to cope with it is to introduce some approximation and simplifications which can be limiting in many ways.

Also the analytic solution may change heavily if some parameters of the model change (eg. introducing nonzero conductivity of the dielectric to take into account its non-zero loss). On the other hand using the optimization methods in connection with numerical models enables finding equivalent material of much broader range of composite structures since the only requirement for the structure is that it has to be possible to reliably simulate.

The principle stays the same for simple layer composite, for multilayer composite structure, for single carbon fibres or for knitted carbon armature. The method is even convenient for composite structures with metallic grid.

For the entire frequency range, a single evaluation of the relative permittivity and a single evaluation of the loss tangent are required (see Table 1). The fitness function is of the form:

$$F_1(x) = [\ S_{11,ref} - S_{11,opt}(x)]^{-1/2} \qquad (1)$$

$$F_2(x) = [\, S_{21,\mathrm{ref}} - S_{21,\mathrm{opt}}(x)]^{-1/2} \qquad (2)$$

Here, $S_{11,ref}$ is the computed value of the reflection coefficient of the realistic model of the composite material at the frequency range. Then, $S_{11,opt}(\mathbf{x})$ is the reflection coefficient of the equivalent homogeneous material computed in COMSOL Multiphysics for the vector of state variables $\mathbf{x} = [\varepsilon_r, \tan\delta]$.

Similarly, $S_{21,ref}$ is the computed transmission coefficient of the realistic model of the composite material, $S_{21,opt}(\mathbf{x})$ is the transmission coefficient of the equivalent homogeneous material computed in COMSOLl Multiphysics for the state vector $\mathbf{x} = [\varepsilon_r, \tan\delta]^T$.

The equivalent material was searched for one particular composite material using two different optimization approaches – a singleobjective and a multiobjective. For the single-objective solution, the fitness functions (1) and (2) are weighted by weighting coefficients $w_1 = 1$ and $w_2 = 1$ and summed:

$$F(x) = w_1F_1(x) + w_2F_2(x) \qquad (3)$$

4.1 Single-objective Optimization

For single-objective optimization a classical global optimization representative – a genetic algorithm – was selected. Genetic Algorithms (GA) are members of stochastic global optimization methods and are based on the Darwinian Theory of the evolution of species. The values of the control parameters were chosen according to recommendations published in (Rahmat-Samii and Michielssen, 1999).

The population consisted of 50 individuals, the accuracy of binary coding was set to 0.001. Individuals for the next population were selected by the tournament operator. Probability of the multi-point crossover was set to 70 % and probability of the multi-point mutation was set to 6 %. The elitist strategy was applied. The optimization was set to minimize the optimized problem.

Time needed for a single simulation run and then calculation of the complex permittivity value using single-objective genetic algorithm was approximately 12 hours (see Table 1). Because of time needed for the calculation of the criteria function, the entire optimization cycle was repeated only one hundred times.

The values of complex permittivity obtained from the optimization run were then set to 3D model to compare the reflection parameters with the model of the original composite. The error of calculation was at maximum 0.45% on the whole frequency range of 15-40 GHz.

In Table 1 one chosen value of complex permittivity from the set of the optimization run is shown. On Figure 4, the scattering parameters for this value of the complex permittivity of the homogeneous replacement are shown in comparison with scattering parameters of the original composite. As it can be seen on Figure 4 good match was achieved.

4.2 Multi-objective Optimization

Niched-Pareto Genetic Algorithms, by Horn et al., is a multi-objective GA based on the non-domination concept. NPGA uses the binary tournament selection (Deb, 2001).

The population consisted of 50 individuals, mutation probability was set to 6%, the crossover probability was 70% and the selected accuracy of coding is 0.001.

The result of a single optimization run is formed by a set of results corresponding to all the criterions (Pareto front). The calculation needed to evaluate one Pareto front was about half of the time needed for single-objective optimization (see Table 1), the optimization run was repeated hundred times.

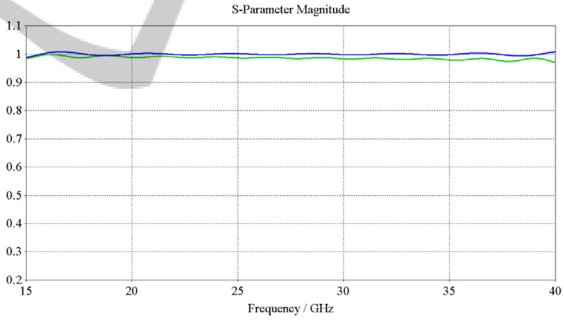

Figure 4: Reflection coefficients of replacements achieved by single-objective genetic algorithms (blue) in comparison with the detailed 3D composite model (green).

After an inverse implementation of the values of complex permittivity of replacements from all simulation runs to the 3D model, all the optimized results were simulated to do the comparison with the original composite material results.

In Table 1 it is shown, that maximal error of the replacement on frequency range 15 – 40 GHz is less then 0.45 %.

On Figure 5 a single choice value of the complex permittivity of the replacement compared with reflection coefficient of the original composite material is shown.

Table 1: Comparison of optimization methods, minimum and maximum accuracy reached for frequency range 15-40 GHz.

Optimization	ε_r [-]	tg δ [-]	time [h]	Accuracy [%]
GA	36.64	549.34	12	0.16-0.45
NPGA	80.27	726.73	6	0.06-0.45

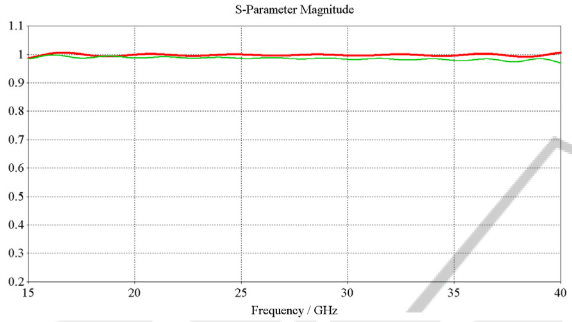

Figure 5: Reflection coefficients of replacements achieved by multi-objective NPGA in comparison with originally reflection coefficient of composite material. Green linie: composite material, red linie: NPGA replacement. Simulated in CST MWS.

5 CONCLUSIONS

For the comparison, the single-objective optimization (reflection coefficient considered) and the multi-objective optimization (both the reflection coefficient and the transmission one) were tested.

In order to compute the minima of objective functions, genetic algorithms and Niched-Pareto genetic algorithm were applied to the problem. First, the single-objective approach exhibits a very good functionality. Second, the substitute synthesized by the multi-objective approach shows a very good agreement too.

The most significant advantage of the multi-objective approach is the speed of the simulation. Time needed to one simulation for NPGA was one half compared to single-objective approaches.

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