Simple Electromagnetic Modeling of Small Airplanes: Neural Network Approach

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Abstract. *The paper deals with the development of simple electromagnetic models of small airplanes, which can contain composite materials in their construction. Electromagnetic waves can penetrate through the surface of the aircraft due to the specific electromagnetic properties of the composite materials, which can increase the intensity of fields inside the airplane and can negatively influence the functionality of the sensitive avionics.*

The airplane is simulated by two parallel dielectric layers (the left-hand side wall and the right-hand side wall of the airplane). The layers are put into a rectangular metallic waveguide terminated by the absorber in order to simulate the illumination of the airplane by the external wave (both of the harmonic nature and pulse one). Thanks to the simplicity of the model, the parametric analysis can be performed, and the results can be used in order to train an artificial neural network. The trained networks excel in further reduction of CPU-time demands of an airplane modeling.

Keywords

Electromagnetic modeling, artificial neural networks, composite materials, small airplanes.

1. Introduction

Composite materials are more and more frequently used in the construction of small airplanes for their good mechanical features and the light weight. On the other hand, electromagnetic parameters of composite materials are closer to dielectrics that to metals, which decreases shielding efficiency of the aircraft skin. Consequently, external electromagnetic fields can penetrate into the airplane with lower attenuation, which can negatively influence the functionality of the sensitive avionics. Therefore, the airplane construction has to be optimized not only from the viewpoint of the mechanical properties, but also from the viewpoint of electromagnetic ones.

Numerical modeling of small aircrafts is an efficient way of revealing critical places inside the airplane where a dangerous intensity of electromagnetic field can appear. Since the development of realistic electromagnetic models is extremely time-consuming, approximate models are going to be developed in the first step. In order to minimize CPU-time demands of simple models, artificial neural networks are applied.

In the open literature, we have not found any paper discussing the exploitation of neural networks for modeling electromagnetic issues of small airplanes. We therefore consider the idea as an original approach to the numerical optimization of small aircrafts from the viewpoint of electromagnetics.

Section 2 of the paper introduces a very simple electromagnetic model of the airplane, and describes the parametric analysis of fields inside the airplane both in the time domain (pulses) and in the frequency domain (harmonic waves). In Section 3, results of the parametric analysis are used to compose a neural network approximating the transfer function of the airplane depending on electric parameters of the airplane skin. Section 4 concludes the paper.

2. Simple Electromagnetic Model

Since the numerical electromagnetic analysis of a realistic airplane is extremely CPU-time consuming, a simplified two-dimensional model of an aircraft is proposed (see Fig. 1):

- The aircraft is modeled by two dielectric layers inside a metallic rectangular waveguide. The layers simulate the left-hand wall and the right-hand wall of the airplane. Electromagnetic properties of dielectric layers can simulate the penetration of external electromagnetic fields into the airplane through composite parts of the skin, through windows and slots.
- Inside the waveguide, transversally electric wave TE_{10} is propagating, which can simulate a vertically polarized wave illuminating the airplane perpendicularly.
- The waveguide is terminated by the absorber, which simulates the open space behind the structure.

The proposed model is very simple on one hand, and is able to involve the basic electromagnetic phenomena on the other hand (penetration of external fields into the aircraft, formation of standing waves inside the aircraft, etc.). Thanks to the simplicity, the model can be used for the parametric analysis of the structure, which is necessary to compose the training set for neural network models [1], [2].

Dielectric walls are of the fixed thickness d = 7 mm, a variable dielectric constant ε_r and a variable loss tangent tan δ. The dielectric constant influences phase conditions inside the structure, and loss tangent determines amplitude conditions inside the structure. Different values of the doublet [ε_r, tan δ] correspond to the different penetration of waves into the airplane. Therefore, a parametric study related to changes in [ε_r, tan δ] is required.

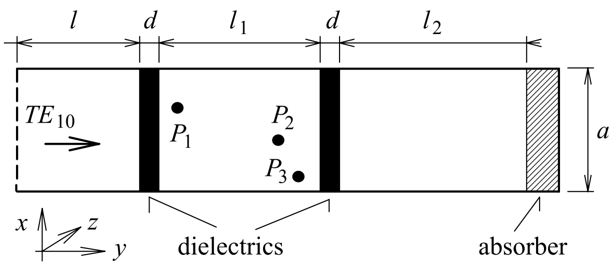

Fig. 1. The simplified aircraft model. In P_1 to P_3, virtual probes are assumed. Dimensions: l = l_1 = 370 mm, l_2 = 180 mm, d = 7 mm, a = 22.86 mm.

In between the dielectric layers, three virtual probes P_1 to P_3 are situated. At the coordinates of these probes, intensity of the internal electric field is computed.

For the normalized external electromagnetic field, the transfer function of the structure is composed

$$E_i = E_i(\varepsilon_r, \operatorname{tg}\delta) \tag{1}$$

where i is the number of the probe, and [ε_r, tan δ] are parameters of layers (both the layers are assumed to be of the same electromagnetic properties). Numerical computations produce discrete values of the transfer function; trained neural networks can provide continuous approximations. Using neural models of the transfer function, internal fields can be estimated for different walls and different external fields. External fields can be of the harmonic nature or the pulse one.

2.1 Harmonic Analysis

Illumination of the aircraft model by a harmonic wave simulates the influence of strong radio transmitters. The harmonic model was developed in COMSOL Multiphysics [3].

Parameters of dielectric layers [ε_r, tan δ] vary in the intervals $\varepsilon_r \in$ <3; 30> and tan $\delta \in$ <0.01; 1> with steps $\Delta\varepsilon_r$ = 0.25 and Δtg δ = 0.025. Fig. 2 shows two extremes of the amplitude for $\varepsilon_r \approx 16$ and $\varepsilon_r \approx 9.5$ and small losses. For higher losses, waves are attenuated and no significant standing waves are formed.

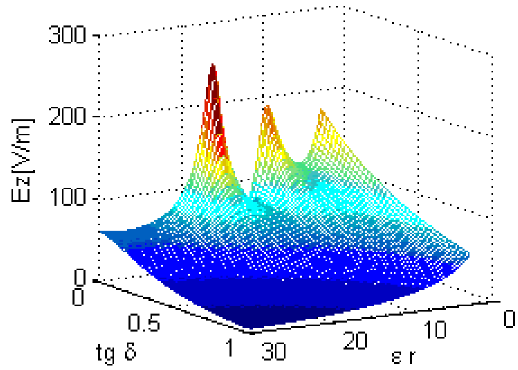

Fig. 2. Amplitude of electric field intensity in the virtual probe P_3 [5 mm; 743 mm] depending on parameters of dielectric layers [ε_r, tan δ] at f = 7 GHz.

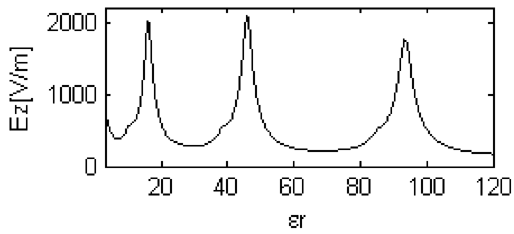

Fig. 3. Amplitude of electric field intensity depending on the relative permittivity for tan δ = 0.01 at f = 7 GHz.

The dependency depicted in Fig. 2 creates the training set for teaching the neural network.

2.2 Transient Analysis

The incident wave can be of the pulse nature simulating the effects of a lightning, for example. Therefore, a transient analysis with a Gaussian pulse wave is performed.

Using the transient solver in COMSOL Multiphysics, the field in the time domain is calculated. Parameters of the excitation signal are chosen to maintain the dominant mode in the waveguide. The evaluation is stopped when the steady state energy in the structure is small enough (20 ns).

In the probes, we evaluate maximum values of the field for doublets [ε_r, tan δ], which corresponds with the maximum current induced by the field into the wires oriented in z-direction in the location of virtual probes P_1 to P_3. Also, the effective value of field is evaluated

$$E_{zef} = \sqrt{\frac{\int_0^T E_z^2(t)dt}{T}} \tag{2}$$

Time of the simulation is T and E_z is the vertical component of the electric field intensity.

Fig. 4 shows that the highest field appears at $\varepsilon_r \approx 16$, which is the same as in case of the harmonic analysis. Unfortunately, the highest and effective values depend on the longitudinal coordinate y there.

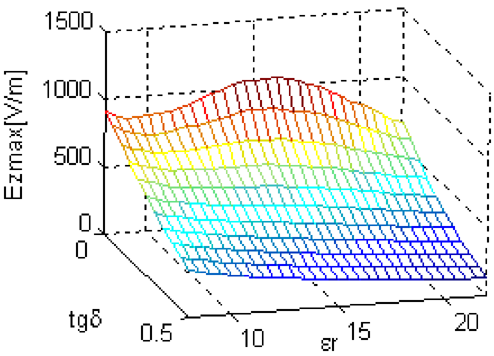

Fig. 4. Maximum values of electric field intensity in the point P_1[0 mm; 0.358 mm] depending on parameters of dielectric layers [ε_r, tan δ].

Results presented in Fig. 4 and Fig. 5 show different tendencies of the highest and effective values above the plane of parameters [ε_r, tan δ]. This means that small average intensity does not denote small maximum field and vice versa.

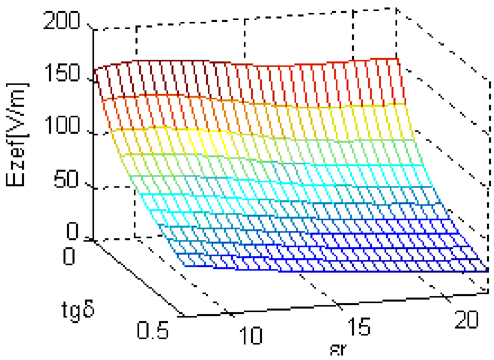

Fig. 5. Effective values of electric field intensity in the point P_1[0 mm; 0.358 mm] depending on parameters of dielectric layers [ε_r, tan δ].

The data presented in Fig.4 and Fig. 5 were computed by COMSOL Multiphysics. However, we observe a small portion of energy reflected by the excitation boundary on the left (the dashed line in Fig. 1). In order to ensure correctness of results, the same analysis was performed in CST Microwave Studio [4]. Results produced by both programs exhibited good correspondence.

The dependencies depicted in Fig. 4 and Fig. 5 form the training sets for teaching the neural network.

3. Neural Approximations

An artificial neural network maps the input patterns into the output ones. The output response is formed by multiplying and summing input signals and by processing the result by a non-linear activation function [6], [7]. A simple structure of the neural network is shown in Fig. 6.

During the training process, the neural network is learned to behave the same way as the numeric model of the airplane: considering permittivities and loss tangents of the analyzed structure as input parameters, the neural model provides field intensities inside the structure as the output patterns.

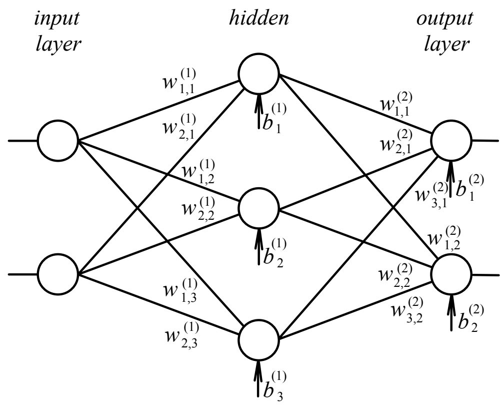

Fig. 6. Artificial neural network: $w_{i,j}^{(n)}$ denotes the weight between the output of i-th neuron in the layer (n–1) and the j-th neuron in the layer n, $b_i^{(n)}$ is the threshold of the i-th neuron in the layer n.

The neural network trained on discrete results of the numerical analysis is able to provide a continuous approximation of a given dependency over the plane of input parameters. Since the dependency of the maximum values of field intensity (Fig. 4) and the dependency of the effective values of field intensity are similar, the neural approximation of effective intensities (Fig. 5) and amplitudes (Fig. 4) are shown in this paper only.

Two different structures of the neural network were proposed:

- The network consisting of two input neurons (dielectric constant, loss tangent) and three output neurons (field intensity in points P_1, P_2 and P_3).
- The networks consisting of three input neurons (dielectric constant, loss tangent, the number of the virtual probe i) and a single output (field intensity in the point P_i).

The distribution of the approximation error of the developed neural networks is shown in Fig. 7. For the comparison, the error related to the approximation by the multi-dimensional cubic spline is also provided.

The approximation error in Fig. 7a (harmonic wave) and Fig. 7b (pulse wave) is related to the networks consisting of two input neurons and one output neuron. The approximation error in Fig. 7c (pulse wave) is related to the network consisting of three input neurons and three output neurons.

The network for harmonic waves exhibits the higher approximation error $Z \approx 9.2$ % due to the oscillatory nature of the approximated function. In order to decrease the error, techniques described in [2] have to be applied.

Accuracy of both the networks for pulse waves is similar. The approximation error $Z \approx 1.1$ % is much lower due to the smooth nature of the approximated function.

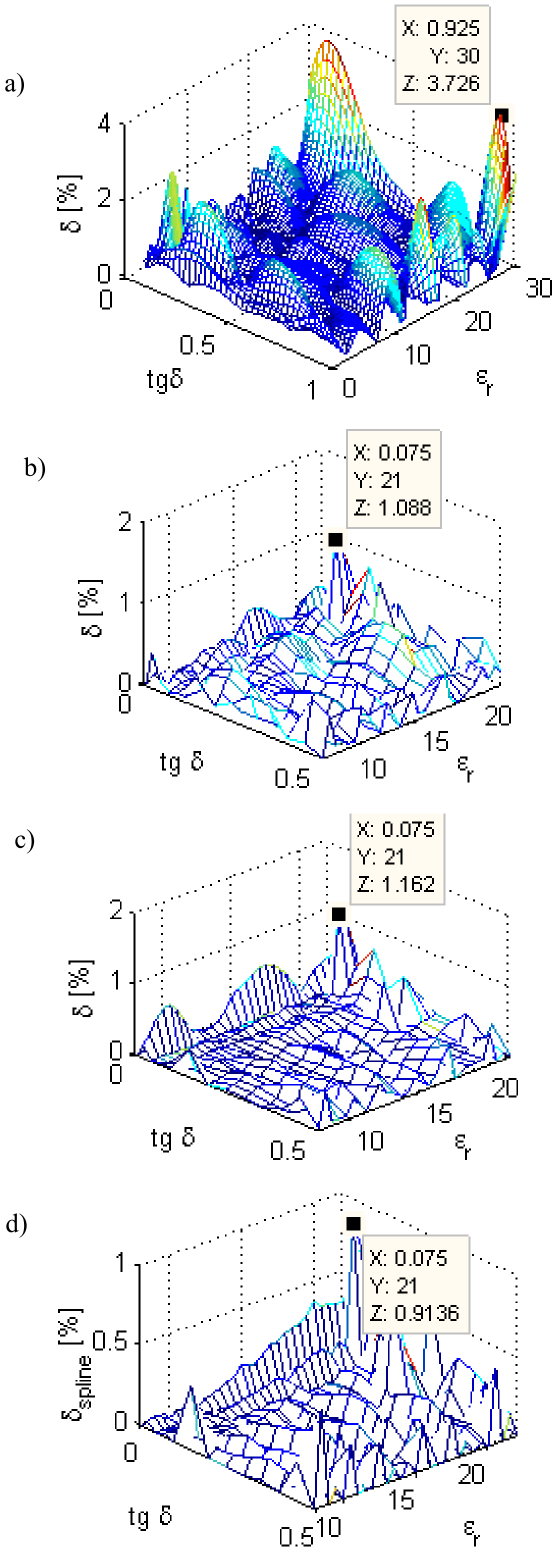

Fig. 7. Approximation error of continuous models of the transfer function of the simplified model of the aircraft in the point P_2: a) neural model for harmonic wave, b), c) neural models for effective value of pulse excitation, d) spline model for effective value of pulse excitation.

The cubic spline provides the approximation error $Z \approx 0.9$ %. Whereas the accuracy of the neural models can be increased, the accuracy of the spline approximation is final.

4. Conclusions

In the paper, a simple electromagnetic model of a small aircraft was proposed. Relations between the distribution of the electromagnetic field inside the aircraft and electric parameters of model walls were investigated both for the external harmonic waves and pulse ones.

Exploiting discrete results of the numerical analysis, continuous neural and spline models of the transfer function of the aircraft were developed. Approximation abilities of neural networks were verified by the comparisons with numerical results.

Accuracy of rough neural models was better than 10 %. The error can be reduced by refining the training set. On the other hand, the achieved error is satisfactory from the viewpoint of electromagnetic compatibility tests.

Further development will be aimed to the application of the approaches described in this paper to modeling more complex airplane models.

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