

Homogenization of the Transversal Conductivity of Unidirectional CFRP Laminas with Coated Filaments

Bálint Pintér^{1,2}, József Pávó¹, Sándor Bilicz¹, Péter Tamás Benkő²,

¹ Budapest University of Technology and Economics, Budapest, H-1111 Hungary, balintpinter@edu.bme.hu

² Robert Bosch Kft., Mobility Electronics, Budapest, Hungary

The aim of this paper is to present a homogenization method that is suitable for obtaining the transversal conductivity of a unidirectional CFRP material made of fibers with a non-metallic coating. This conductivity is dominated by the connection of the fibers; with a fictitious compression of the medium, it can be obtained through the conductance per unit length. The coating, which has a particularly important role in the connections, has a poor conductivity; its modeling is also included in the study.

Index Terms—CFRP, complex transversal conductivity, homogenization, coated fibers

I. INTRODUCTION

In many engineering fields, the importance of lightweight materials is rapidly increasing. A promising one is the carbon fiber reinforced plastic, the CFRP polymer, which is widely used in the aeronautic and automotive industries due to its advantageous characteristics. However, besides the mechanical aspects, the electromagnetic behavior can also be important, one example is its shielding effectiveness in the field of electromagnetic compatibility.

For any electromagnetic design process the homogenized material parameters are required as input. Considering a unidirectional CFRP lamina—which is a basic building block of more complex structures—the purpose is to obtain the homogenized longitudinal and transversal components (along the fibers and perpendicular to them) of its complex conductivity tensor. Assuming that the filaments are along the z axis, the tensor is

$$\underline{\underline{\sigma}} = \begin{bmatrix} \sigma_T^* & 0 & 0 \\ 0 & \sigma_T^* & 0 \\ 0 & 0 & \sigma_L^* \end{bmatrix}, \quad (1)$$

where the entries are complex values, the real part describes conductivity, and the imaginary part describes reactive properties. The value of σ_L^* is dominated by the conductivity of the fibers, σ_f , however, obtaining the transversal equivalent parameters is more challenging. This study is dealing with coated fibers, where the carbon domain is surrounded by a non-metallic conductive polymer [1].

In the literature, several studies describe the media with a 3D equivalent resistor network, e.g., [2]. A different material characterization approach is introduced in [3], where homogenization is based on a 2D simulation method over a unit cell, but it is valid only for the imaginary part (thereby the permittivity). The present paper is an extension of the basic idea presented in [3], in order to improve the accuracy in terms of σ_T^* by taking into account the connections of the elementary filaments.

II. MODEL ASSUMPTIONS

The conduction current flowing transversely through a unidirectional CFRP slab has a zigzag-like current path, as it is depicted in Fig. 1a. This path has two parts: first, when the current flows along the filaments in the longitudinal direction, and second, when it goes through a connection of two fibers. The transversal conductivity to be determined can be done through the conductance per unit length; therefore the method needs the below listed assumptions.

- It can be assumed that the longitudinal term of the path is negligible, due to the high value of σ_f , it causes an imperceptible loss. On the other hand, the connections are important; the small connecting surfaces give a high impedance. Neglecting the longitudinal part, the connection volumes can be shifted freely along the z axis; they can be aligned next to each other.
- With this alignment, a chain of connected fibers can be formed in one row in the transversal direction, but it is compressed due to the lack of resin volumes, which previously separated the filaments. This compression is proportional to the square root of the filling rate $\eta = V_f/V_{\text{total}}$, the ratio of the volume of the filaments to the total, and affects inversely to σ_T^* .
- In the case of coated fibers, it can be assumed that the actual touching components are the coatings and not the carbon domains.
- With this rearranging, a lot of conductive chains can be formed parallel to each other, but they are detached; the fibers are not connected along their entire length. This decreases the conductivity, but from modeling point of view, a longitudinally continuous volume can be considered, and it is sufficient to reduce the obtained conductance per unit length with the ratio of the connected and not connected lengths along neighboring filaments. One can assume that this ratio is somewhat proportional to the filling rate.

This way, the main task is to obtain the conductance per unit length to the transversal direction. A 2D model that unit cell is shown in Fig. 1b is used for the purpose. Here the EM field can be expressed with H_z , the z component of the magnetic

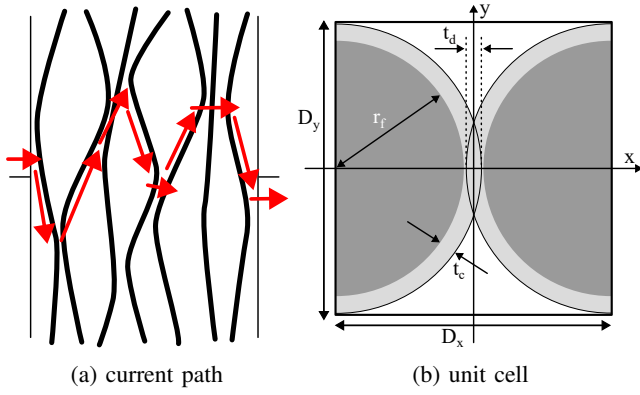


Fig. 1: Path of the transversal conductive current and the unit cell of one connection, where the radius of the fiber is r_f .

field [3]. Let t_c and t_d denote the thickness of the coating and the average value of the overlap between the coatings of the neighboring filaments, respectively, as it is shown in Fig. 1b. The partial differential equation to be solved is a 2D scalar Helmholtz equation,

$$\frac{1}{\kappa} \frac{\partial^2 H_z}{\partial x^2} + \frac{1}{\kappa} \frac{\partial^2 H_z}{\partial y^2} - j\omega\mu_0 H_z = 0, \quad (2)$$

where $\kappa = \sigma_f$ in the carbon filament and $\kappa = \sigma_{\text{coat}} + j\omega\varepsilon_0\varepsilon_{\text{coat}}$ in the coating region, respectively. The σ_{coat} and the $\varepsilon_{\text{coat}}$ stand for the conductivity and the permittivity of the coating. In the dielectric material $\kappa = j\omega\varepsilon_0\varepsilon_{\text{res}}$, where ε_{res} is the permittivity of the resin. On the top and the bottom edges of the unit cell, the boundary conditions are Dirichlet boundaries with $H_z = \pm H_{z,0}/2$, and on the left and the right edges, homogeneous Neumann conditions can be defined, $\frac{1}{\kappa} \frac{\partial H_z}{\partial x} = 0$ [3]. Once the EM field is calculated, the homogenized complex conductivity can be extracted,

$$\sigma_T^* = j\omega\varepsilon_0\varepsilon_{\text{res}} \frac{D_x}{D_y} \frac{H_{z,0}}{\int_{-D_x/2}^{D_x/2} \frac{\partial H_z}{\partial y} dx}. \quad (3)$$

III. RESULTS

The real and imaginary parts of the distribution of H_z are depicted in Fig. 2. The variation of the conductivity versus the relative overlap, t_d/t_c , is shown in Fig. 3. The conductivity of the carbon was set to $\sigma_f = 62.5 \text{ kS/m}$, and the relative permittivity values of the resin and the coating were $\varepsilon_{\text{res}} = 5$ and $\varepsilon_{\text{coat}} = 5$. The conductivity of typical non-metallic coating material is in a $0.1 \text{ S/m} \dots 100 \text{ S/m}$ range, it is depending on various chemical and mechanical parameters [4], in this study the $1 \text{ S/m} \dots 20 \text{ S/m}$ range was investigated.

At $t_d = 2 \cdot t_c$ overlapping, when the two carbon domains are touching each other, the real part of the conductivity rapidly increases, but this extreme case is out of focus. As well as the non-overlapping case, where σ_T' is negligible, the dominant is the imaginary part that has a positive value, which corresponds to a purely capacitive phenomenon. Excluding the extreme

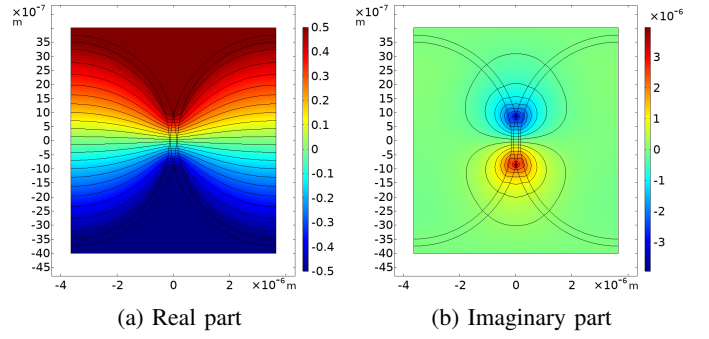


Fig. 2: Distribution of H_z and its contour lines, which gives information about the total current density.

scenarios, the resulting homogenized conductivities compared to measurements show a good agreement; a typical measured value with very similar parameters is $\sigma_T' \approx 7 \text{ S/m}$ [2].

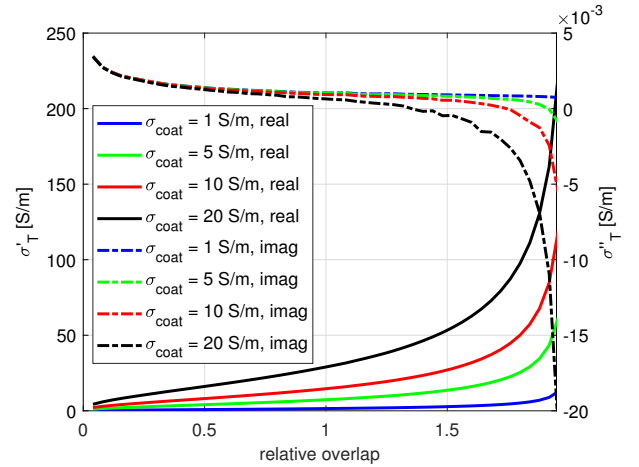


Fig. 3: Real and imaginary parts of the homogenized transversal conductivity versus the relative overlap.

IV. CONCLUSION

With the presented method, the transversal conductivity can be explained of a unidirectional CFRP layer. Using the results in [3] and the ones presented here, the homogenized material parameters can be obtained, which are important inputs for the solution of 3D EM field simulation task, such as calculating the shielding effectiveness of structures made of CFRP.

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