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Analysis Method of Transmission Characterization for Multi-layered Composite Material Based on Homogenization Method

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Abstract

In this paper, the transmission characteristics of the multi-layered composite material with wire mesh and honeycomb core for aircraft applications have been analyzed with the proposed method. The proposed method converts the conductive wire mesh into effective layer, while for the dielectric honeycomb core, effective permittivity has been derived based on volume fraction with the proposed method. The proposed method has been verified through comparison with full-wave simulation and revealed excellent. In addition, the calculation time of the proposed method is a few order of magnitude faster in comparison with the full-wave simulation.

Key Words : Multi-layered Composite, Electromagnetic Interference, Wire Mesh, Honeycomb Core, Homogenization

1. Introduction

Composite materials consist of a few different constituents such as a fiber and a resin to provide high strength and shear stress capability. Use of the composite materials has been steadily expanded in aerospace industry to satisfy low weight, high strength, and low costs simultaneously [1]. Despite the advantages of composite materials compare to the metallic structure, they are penetration path for unintended electromagnetic field due to their dielectric property. Therefore, it is necessary to study the analysis of transmission characteristics for composite material in that aircraft electronic systems are required to have higher reliability compared with the general products.

In order to apply to aircraft components, the composite materials are employed to multi-layered structure which is also combined with arbitrary structures such as a wire mesh and a honeycomb core. For the analysis of these structure, it is difficult to define material properties and analyze the electromagnetic characteristics except for full-wave electromagnetic analysis.

The transmission characteristics of multi-layered dielectric structures can be calculated with analytic methods such as recursive method and boundary value solution [2-5]. Although these methods guarantee accurate results for the dielectric multi-layered dielectric structure, it has limitations to calculate complex structures combined with wire mesh and honeycomb core. Moreover, the estimation of the electromagnetic characteristics for the multi-layered composite material can be performed with the 3-D full-wave numerical methods such as finite-difference time-domain (FDTD) technique, finite element method (FEM), method of moments (MoM); however, the numerical methods are inefficiency applied to the multi-layered structure. The computation resource increases when the layer increase, and one of the layers is changed, meshing process is regenerated for the whole multi-layered structure. Thus, it is necessary to develop an efficient methodology for the electromagnetic analysis of the multi-layered structures including various inhomogeneity and anisotropy.

In this study, the proposed method is based on boundary value solution of the analytic methods combined with homogenization method to better fit to multi-layered composite material with the wire mesh and honeycomb core. The homogenization method can transfer the wire mesh and the honeycomb layer to the equivalent layer with effective permittivity and permeability. The proposed method makes it effective to calculate transmission coefficient of multi-layered

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composite material and reduce calculation time compared to the numerical method.

2. Modeling and Analysis of Multi-layered Composite

Figure 1 illustrates the typical multi-layered composite material with the honeycomb and the wire mesh. The wire mesh composed of conductor provides a shielding effectiveness for impinging lightning strike damage in aircraft and the dielectric honeycomb core is widely used for improving mechanical properties.

The procedure of the proposed method is illustrated in Fig. 2. The wire mesh and the honeycomb layer are replaced to the equivalent layer with effective electromagnetic properties and the transmission coefficient of multi-layered composite material is calculated by the boundary value solution. For the homogenization of wire mesh and honeycomb core, different method is performed to each structure. The multi-layered composite material can be conveniently modeled with equivalent layers which would produce computationally efficient scheme

2.1 Boundary Value Solution

The transmission coefficient for multi-layered dielectric can be analysed by the boundary value solution. It is conveniently used for the multi-layered composite material due to its matrix form. Figure 3 shows the geometry for forward and revers propagating waves, where the solution is given by [2]

$$\begin{bmatrix} E_0^+ \\ E_0^- \end{bmatrix} = \prod_{t=1}^{N} \frac{1}{T_t T_{N-1}} \left[\begin{pmatrix} e^{j\gamma_i t_i} & R_i e^{-j\gamma_i t_i} \\ R_i e^{j\gamma_i t_i} & e^{-j\gamma_i t_i} \end{pmatrix} \right] \begin{bmatrix} 1 & R_{N+1} \\ R_{N+1} & 1 \end{bmatrix} \begin{bmatrix} E_{n+1}^+ \\ 0 \end{bmatrix} \tag{1}$$

Where γ_i is the propagation constant in dielectric, t_i is the thickness of *i-th* layer. R_i and T_i are Fresnel reflection and transmission coefficients, respectively, at the interface. The Fresnel reflection and transmission coefficients of the concrete could be calculated as:

$$R_i = \frac{Z_i - Z_{i-1}}{Z_i + Z_{i-1}}, \qquad T_i = 1 + R_i \tag{2}$$

In the above, Z_i can be calculated as $Z_i = cos\theta / \sqrt{\varepsilon_{r,i} - sin^2\theta}$ while $Z_i = \sqrt{\varepsilon_{r,i} - sin^2\theta} / \varepsilon_{r,i} cos\theta$ parallel polarization.

Note that Z_i and Z_{i-1} are intrinsic impedance of the materials when wave is transmitted from *(i-1)-th* medium to *i-th* the medium with incident angle θ.

This method can be used to evaluate the transmission coefficient through multi-layered composite material for any incident wave, and the resonant behavior of the multilayer structure can be predicted accurately.

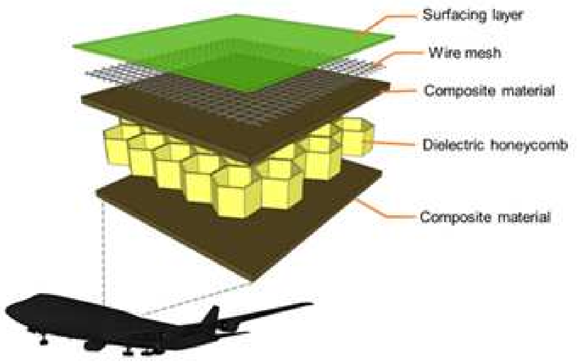


Fig. 1 Typical multi-layered composite material with honeycomb core and wire mesh

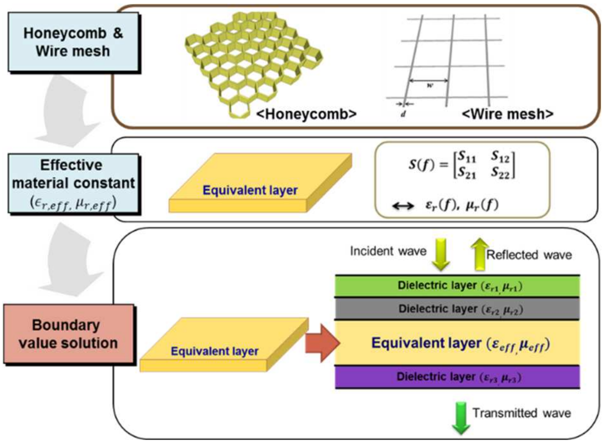


Fig. 2 Procedure of proposed method

2.2 Analysis and Homogenization of Wire Mesh

In this section, the homogenization method is presented to convert conductive wire mesh to effective equivalent layer. In the Fig. 4, the parameters *d* and *w* are wire diameter and center to center wire spacing, respectively. The reflection and transmission coefficient of the wire mesh are calculated using approximated formula, which was summarized from reference [6]. When wire mesh is perfect electric conductor, its equivalent sheet impedance can be written as

$$Z_{s,TE} = j\omega L_s \tag{3}$$

$$Z_{s,TM} = j\omega L_s \left(1 - \frac{sin^2\theta}{2}\right) \tag{4}$$

Note that *TE* and *TM* are defined relative to the plane of incidence formed by the propagation direction, *TE* is directed along the *y* direction that the electric field is

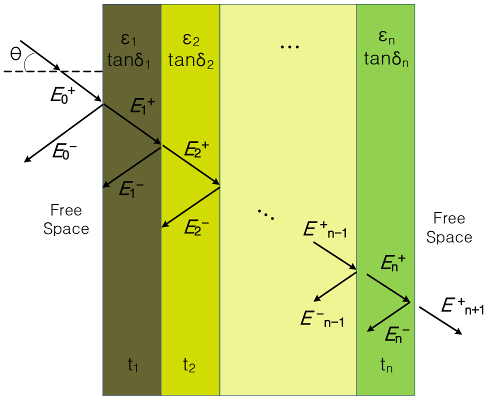


Fig. 3 Boundary value problem for multi-layered dielectric.

perpendicular to the plane of incidence and *TM* is the electric field parallel to it.

Ls the sheet inductance is

$$L_s = \frac{\mu_0 w}{2\pi}\ln(1-e^{-\pi r/w})^{-1} \tag{5}$$

Where *r* is the radius of the wire and ω is the angular frequency. Using the sheet impedance for each polarization, the reflection R_m and transmission T_m can be calculated by [6]

$$R_{m,TE} = \frac{-1}{1+2(Z_{s,TE}/Z_0)cos\theta} \tag{6}$$

$$T_{m,TE} = \frac{2(Z_{s,TE}/Z_0)cos\theta}{1+2(Z_{s,TE}/Z_0)cos\theta} \tag{7}$$

for perpendicular polarization, and

$$R_{m,TM} = \frac{cos\theta}{2(Z_{s,TM}/Z_0)+cos\theta} \tag{8}$$

$$T_{m,TM} = \frac{2(Z_{s,TM}/Z_0)}{2(Z_{s,TM}/Z_0)+cos\theta} \tag{9}$$

for parallel polarization.

To define effective layer of the wire mesh, the effective permittivity and permeability are obtained from reflection coefficient R_m and transmission coefficient T_m of the wire mesh. From obtained reflection and transmission coefficient, the wire mesh can be characterized by wave number k_m and impedance η_m [7]:

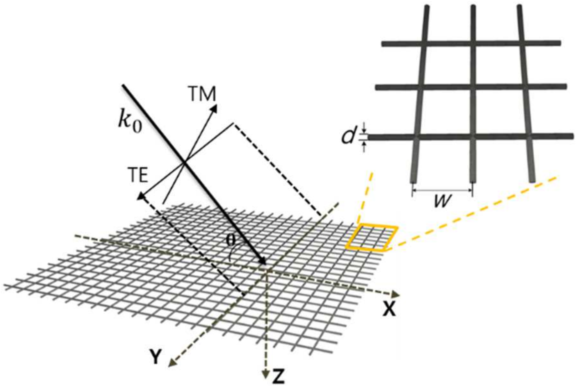


Fig. 4 Configuration of wire mesh

$$k_m t_m = \pm \arccos\left(\frac{k_0(R_m-1)^2+k_0 T_m{}^2}{T[k_0(1-R_m)+k_0(1+R)]}\right) \tag{10}$$

$$\eta_m = \pm\sqrt{\frac{k_0{}^2(R_m-1)^2-k_0{}^2 T_m{}^2}{(R_m+1)^2-T_m{}^2}} \tag{11}$$

The parameter t_m is thickness of the wire mesh layer. The effective permittivity and permeability of the wire mesh can be determined through the following relations. For perpendicular polarization,

$$\mu_{eff,m} = \frac{km}{\eta_m} \tag{12}$$

$$\varepsilon_{eff,m} = \frac{kx2+km2}{\mu}\cdot\frac{c2}{\omega 2} \tag{13}$$

and for parallel polarization,

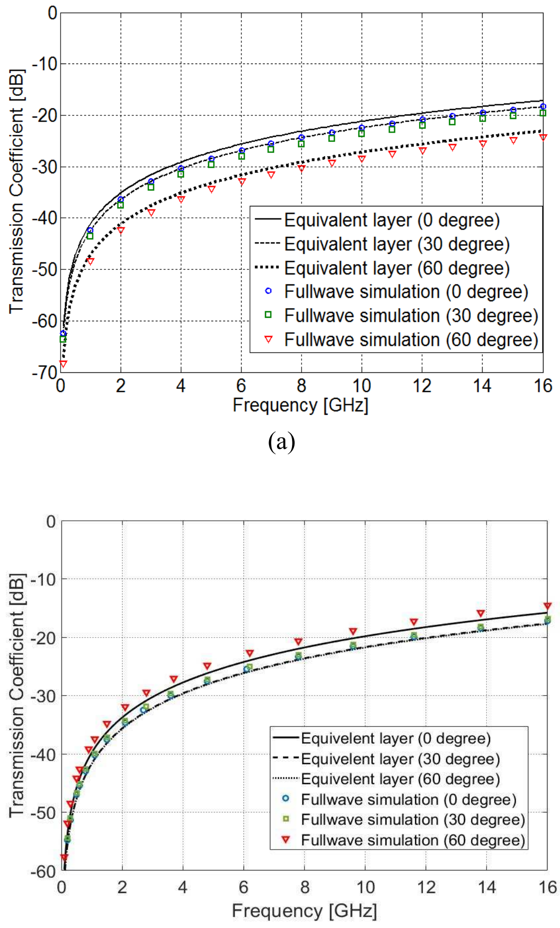
$$\varepsilon_{eff,m} = \frac{km}{\eta_m} \tag{14}$$

$$\mu_{eff,m} = \frac{kx2+km2}{\varepsilon}\cdot\frac{c2}{\omega 2} \tag{15}$$

Where k_x the tangential component of wave number k_0 is defined as

$$k_x = k_0 \sin\theta \tag{16}$$

In Fig. 5, the calculated transmission coefficient results of equivalent layer using effective properties $\varepsilon_{eff,m}$ and $\mu_{eff,m}$ is compared to the result from full-wave simulation tool (HFSS), when the parameters of the wire mesh are diameter d = 0.1 mm, wire spacing w = 1 mm, and each polarization at incident angle of 0°, 30°, and 60°.



(a)

(b)

Fig. 5 Comparison of transmission coefficient between equivalent sheet impedance method and equivalent layer (a) perpendicular pol., ($\theta = 0°$, 30°, 60°), (b) parallel pol., ($\theta = 0°$, 30°, 60°)

Thus, it is clear that the conductive wire mesh can be replaced by equivalent layer with effective parameters.

In order to confirm the connection between boundary value solution and equivalent layer of the wire mesh, the verification has been performed. As shown in Fig 6, the wire mesh is embedded in the dielectric layer. The parameters of dielectric layer are t = 3mm and $\varepsilon_r = 4$, and the wire mesh diameter and the spacing are 0.1 and 1 mm, respectively.

In Fig. 7, the results using boundary value solution with homogenization method and HFSS are shown. It is clear that the proposed method is applicable to the multi-layered composite material including conductive wire mesh.

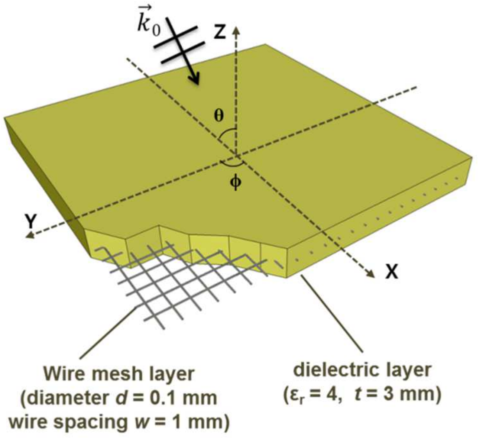
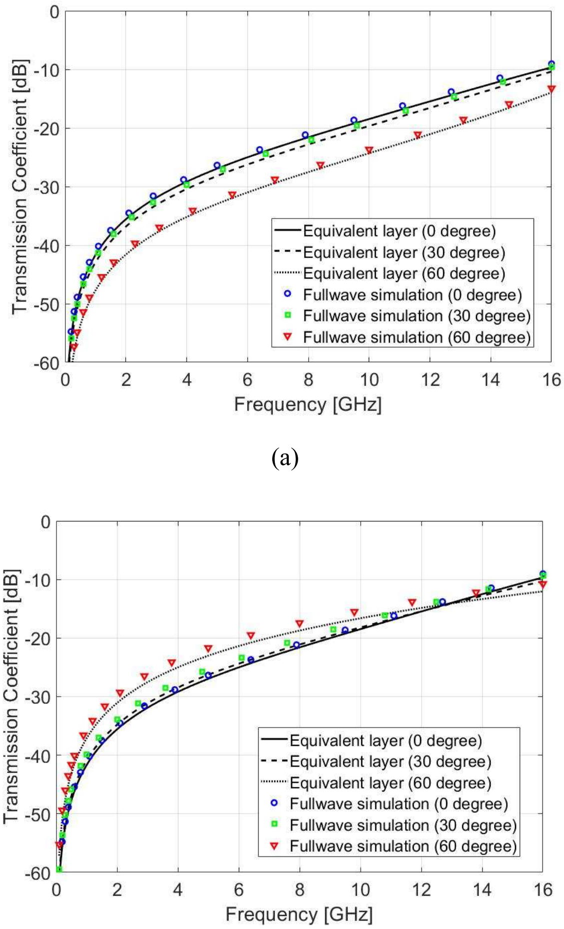


Fig. 6 Geometry for verification of boundary value solution with homogenization method



(a)

(b)

Fig. 7 Comparison of transmission coefficients between proposed method and full-wave simulation for dielectric layer with embedded the wire mesh (a) perpendicular pol., ($\theta = 0°$, 30°, 60°), (b) parallel pol. ($\theta = 0°$, 30°, 60°)

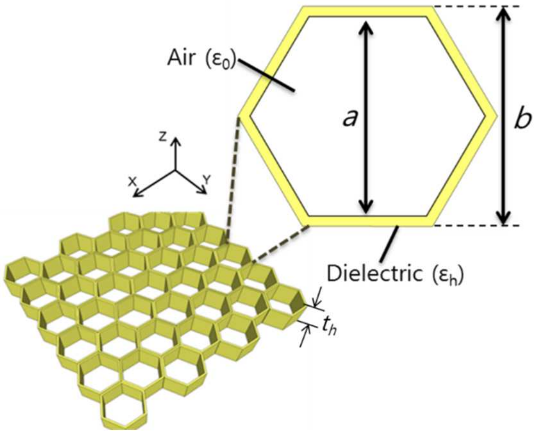


Fig. 8 Geometry of dielectric honeycomb core and unit cell

2.3 Homogenization for Honeycomb Core

In this section, the homogenization of dielectric honeycomb core layer is discussed. For the dielectric honeycomb core, effective permittivity and permeability can be easily obtained. In this study, it is assumed that hexagonal lattice of the honeycomb core is relatively small in comparison with a wavelength in medium and the property of honeycomb core is non-magnetic.

Figure 8 depicts the geometry of the honeycomb core and its unit cell. The honeycomb core behaves as an uniaxially anisotropic medium which can be expressed by diagonal effective permittivity tensor $\varepsilon_{eff,h}$

$$\varepsilon_{eff,h} = \begin{pmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & \varepsilon_z \end{pmatrix} \tag{17}$$

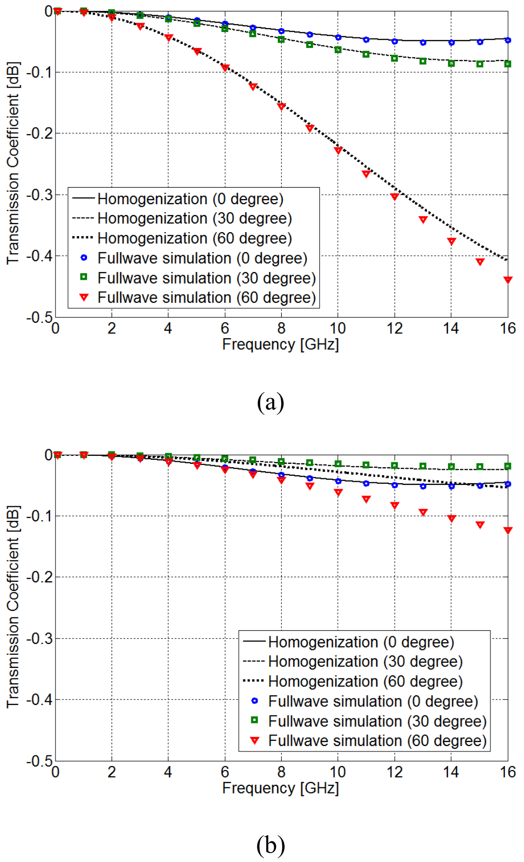
To simplify the calculation of the effective permittivity, it is assumed that the radial direction (*x-y* plane) is symmetric ($\varepsilon_x = \varepsilon_y = \varepsilon_t$). The radial permittivity ε_t which is given by [8],

$$\varepsilon_t = \varepsilon_h \frac{(2-g)\varepsilon_0 + g\varepsilon_h}{g\varepsilon_0 + (2-g)\varepsilon_h} \tag{18}$$

and the axial permittivity ε_z can be obtained [9];

$$\varepsilon_z = g\varepsilon_0 + (1-g)\varepsilon_h \tag{19}$$

where the parameter $g = 1 - a^2/b^2$ is the volume fraction of the honeycomb core with the dimensional parameters *a* and *b*. For two different polarizations, Fig. 9 shows the transmission coefficient as a function of frequency for three different incident angles. *a* and *b* are 6 and 6.4 mm, respectively, while the thickness of the honeycomb is 5 mm.



(a)

(b)

Fig. 9 Transmission coefficients of dielectric honeycomb core using the effective permittivity and permeability (a) perpendicular pol. (θ = 0°, 30°, 60°) (b) parallel pol. (θ = 0°, 30°, 60°)

transmission coefficient as a function of frequency for three different incident angles. *a* and *b* are 6 and 6.4 mm, respectively, while the thickness of the honeycomb is 5 mm.

2.4 Analysis of Multi-Layered Composite Material

The description of the 5-layer composite material with the wire mesh and the honeycomb core are illustrated in Fig. 10. The wire mesh and dielectric cover layer are located on top of the composite material. The diameter and spacing of the wire mesh are fixed to 0.1 and 1 mm, respectively, and thickness of the dielectric cover is 0.1 mm with and ε_r= 4. The honeycomb core is placed between two composite materials. The composite material has permittivity of 23 and loss tangent of 0.4 with 2.3 mm thickness. Figure 11 shows the transmission coefficients calculated with the proposed method as well as full-wave simulation as a function of the frequency

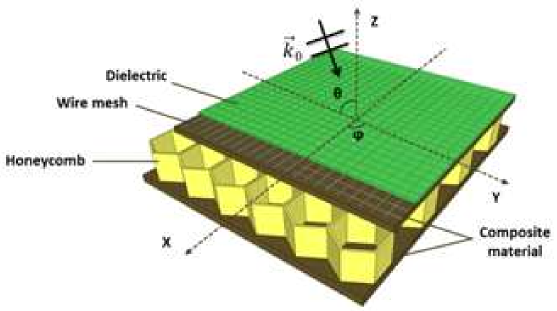
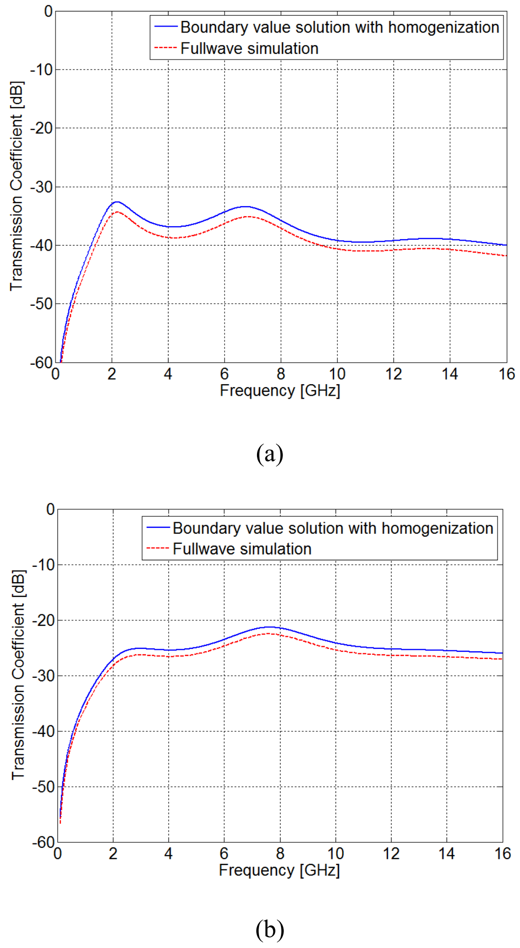


Fig. 10 Description of multi-layered composite material with wire mesh and honeycomb core



(a)

(b)

Fig. 11 Comparison of transmission coefficients between proposed method and full-wave simulation, θ = 60° (a) perpendicular pol., (b) parallel pol.

with incident angle $\theta = 60°$. The results of boundary value solution with homogenization method agree very well with the full-wave simulation. The calculation time of the proposed method is defined by MATLAB [10]. All calculations are performed by desktop computer with Intel Core i7-2600 CPU at 3.4 GHz and 8 GB RAM. Maximum frequency is 16 GHz and 160 counts are computed using two methods. Calculation time is about 0.23 seconds for the proposed method and about 269 seconds in case of using full-wave simulation. These results show that the boundary value solution with homogenization method is an efficient method for multi-layered composite material with the wire mesh and the honeycomb core. It is clear that the proposed method is suitable for optimization and design of arbitrary multilayer composite structure under given specifications.

3. Conclusions

In this paper, the transmission characteristics of the multi-layered composite material with wire mesh and honeycomb core for aircraft applications have been analyzed with the proposed method. The multi-layered composite materials are usually combined with conductive wire mesh and honeycomb core. This structure is difficult to define its material properties and analyze the electromagnetic characteristics due to the complicated shape.

The proposed method is based on boundary value solution and homogenization method is utilized to transform the wire mesh and honeycomb core into equivalent layers with the effective permittivity and permeability. In order to derive the equivalent layers, different homogenization methods are applied for the metallic mesh and the honeycomb core. The proposed method has been verified through comparison with full-wave simulation and revealed excellent. In addition, the calculation time of the proposed method is a few order of magnitude faster in comparison with the full-wave simulation. The boundary value solution with the homogenization method makes it possible to calculate transmission coefficient of multi-layered composite material. Therefore, it is possible to be used for the analysis of variety of multi-layered structures.

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