Title: Shielding Performance of Composite Materials Used in Air Vehicles

Authors: Baha KANBEROĞLU, Ahmet Yahya TEŞNELİ

Received: 2021-01-28 00:00:00
Accepted: 2021-03-19 12:52:00.995000
Article Type: Research Article
Volume: 25
Issue: 2
Month: April
Year: 2021
Pages: 554-562

How to cite
Baha KANBEROĞLU, Ahmet Yahya TEŞNELİ; (2021), Shielding Performance of Composite Materials Used in Air Vehicles. Sakarya University Journal of Science, 25(2), 554-562, DOI: https://doi.org/10.16984/saufenbilder.869674
Access link
http://www.saujs.sakarya.edu.tr/en/pub/issue/60672/869674

New submission to SAUJS
https://dergipark.org.tr/en/journal/1115/submission/step/manuscript/new
Shielding Performance of Composite Materials Used in Air Vehicles

Baha KANBEROĞLU¹, Ahmet Yahya TEŞNELİ¹

Abstract

The metal skin of air vehicles provides an important shielding effectiveness against the effects of high amplitude electromagnetic waves. In recent years, the composite materials with the advantages such as being lighter, causing lower fuel consumption, are used as a replacement of metals. In this paper, electromagnetic shielding performance of composite materials in air vehicle manufacturing industry is investigated. A panel model is used to obtain the shielding performance of these composite materials. Due to the geometrical similarity of air vehicles with a cylinder, a cylindrical shell model is also considered. Analytical calculations for the interaction of an electromagnetic pulse (EMP) with composite materials are carried out for both panel and cylindrical models. Also, the panel and cylindrical models are constructed via Computer Software Technology (CST) program and analytical and simulation results are compared. There is a good agreement with the results.

Keywords: Composite materials, shielding effectiveness, electromagnetic pulse, analytical calculation, simulation

1. INTRODUCTION

Involuntary electromagnetic interference (EMI) is an important issue for the protection of electronic equipment of aircraft from the effects of external sources like High-Intensity Radiated Fields (HIRF), Lighting (LEMP) and Electromagnetic Pulse (EMP) [1–10]. The aluminum skin of air vehicles provides important level of shielding effectiveness (SE) performance against external EMI sources [1]. With the development of the technology, various studies have been carried out on composite material design that can be used in the manufacture of air vehicles such as aircraft, spacecraft and unmanned aerial vehicle (UAV). In these studies, it has been an important issue to reduce the production cost by reducing the weight of the air vehicles and to prevent the increase of electromagnetic interference [3], [9], [11–16]. With the advantages like lower weight, good mechanical and thermal characteristics, lower maintenance costs, lower corrosion and higher hardness, the use of composite materials such as Composite material skin (CMS) [2], Carbon fiber reinforced polymer (CFRP) [9], [16–17], Carbon fiber reinforced composites (CFRC) [15], [18] and Graphite-epoxy (GrEp) [19] as a replacement of

¹Corresponding author: bkanberoglu@sakarya.edu.tr
¹Sakarya University, Faculty of Engineering, Electrical and Electronic Engineering Department, 54187, Sakarya.
E-Mail: bkanberoglu@sakarya.edu.tr; atesneli@sakarya.edu.tr
ORCID: https://orcid.org/0000-0003-1938-3470; https://orcid.org/0000-0003-0534-5473
metals on aircraft manufacturing industry increases rapidly. Multilayered composite materials show good shielding performance as surface the aircraft (> 20 dB) and can provide protection against EMP and electromagnetic interference [20]. Instead of the advantages of these materials, the electrical conductivity of the composite materials is much lower than metals[21].

The purpose of this paper is to investigate the shielding performance of the composite materials (CFRP, CMS etc.). Firstly, a panel model is considered to calculate the shielding performance of these composite materials. The panel model results are also compared with the model established at CST[22].

Most of the air vehicles such as airplane, UAV can be considered as a cylindrical shell due to their geometry and the surface of the air vehicle is considered to be made of composite materials. Mathematical model of electromagnetic wave interaction with aircraft is carried out at cylindrical coordinates. The electric field on the axis of the cylinder is used to obtain the SE level. Also, a cylindrical shell model is constructed at CST program to validate the analytical results. To reduce the simulation time and mesh number, CST simulations are performed up to 2 GHz for cylindrical model.

2. MODELLING AND ANALYSIS OF COMPOSITE MATERIALS

The electromagnetic SE of the panel can be described as the ratio of the magnitude of the transmitted field to incident field. SE and given as:

\[
SE_E = -20 \log \left( \frac{E_t}{E_i} \right)
\]  

(1)

where the parameters \( E_0=5\times10^4 \) V/m, \( \alpha=4\times10^7 \) s\(^{-1}\), \( \beta=6\times10^8 \) s\(^{-1}\). The waveforms of EMP are shown in Fig. 1 for both time and frequency domains.

Two cases are considered for analytical calculations and simulations. SE is calculated for a panel model in case 1 and for a cylindrical shell model in case 2.

2.1. Case 1: Panel Model Interaction

A three-layer model(Air/Panel/Air) is considered for the SE simulation as shown in Figure 2.
Figure 2 Interaction model of homogeneous panel x polarized TM electromagnetic pulse interacts with the cable channel placed in the ground. Interaction mechanism is shown at Figure 1. A transfer matrix is used to determine the transmitted and reflected electromagnetic waves[25-26]. The matrix model defines the linear connection of electromagnetic field vectors at layer boundaries.

\[
\begin{bmatrix}
E_x \\
H_y
\end{bmatrix}_{\text{inc}} = \begin{bmatrix} T \\ \end{bmatrix} \begin{bmatrix}
E_x \\
H_y
\end{bmatrix}_{\text{inc}}
\]

Transfer matrix T is a 2x2 matrix [25].

\[
[T] = \begin{bmatrix} \cos(k_i \cdot d) & jZ \sin(k_i \cdot d) \\ jZ \sin(k_i \cdot d) & \cos(k_i \cdot d) \end{bmatrix}
\]

where the thickness of the layer

\[d = y_{i+1} - y_i\]  

Wave impedance and wave number of the layers used in transfer matrix are given below, respectively[27].

\[Z = \sqrt{\frac{jw\mu}{\sigma + jw\varepsilon}}\]  

\[k_i = \sqrt{-jw\mu(\sigma + jw\varepsilon)}\]  

w=2πf is the angular frequency, \(\sigma\) is the electrical conductivity, \(\varepsilon_0\) and \(\mu_0\) are the electric permittivity and magnetic permeability of free space, respectively.

### 2.2. Case 2: Cylindrical interaction

TMz polarized EMP is considered to interact with a shielded cylinder as shown in Figure 3.

The electric and magnetic fields in cylindrical coordinates are given as[28]

\[
E^{\text{inc}}(r,\phi,z) = E^\text{inc}_z(r,\phi)z = E^\text{inc}_z(r,\phi)e^{-j\beta_\phi \cos \phi}
\]

\[
H^{\text{inc}}(r,\phi,z) = H^\text{inc}_\phi(r,\phi)\phi = \frac{E^{\text{inc}}}{\eta_0} - (a_s \sin \phi + a_\phi \cos \phi)e^{-j\beta_\phi \cos \phi}
\]

\[
E^{\text{inc}}_z(r,\phi,z) = E^\text{inc}_z(r,\phi)z = E^\text{inc}_z(r,\phi)e^{-j\beta_\phi \cos \phi}
\]

\[
H^{\text{inc}}_\phi(r,\phi,z) = H^\text{inc}_\phi(r,\phi)\phi = \frac{E^{\text{inc}}}{\eta_0} - (a_s \sin \phi + a_\phi \cos \phi)e^{-j\beta_\phi \cos \phi}
\]

\[
J_n(\cdot)\text{ is the nth order Bessel function of the first kind and } J'_n(\cdot)\text{ is the derivate of } J_n(\cdot). \eta_0\text{ and } k_0\text{ are the characteristic impedance and the wavenumber of the air, respectively[27].}
\]

\[
\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}
\]

\[
k_0 = w\sqrt{\varepsilon_0\mu_0}
\]

For TM wave incidence, the relation between the tangential electric and magnetic fields can be characterized by given equation at the boundaries of the layers[29].

\[
\begin{bmatrix}
E_{z,n} \\
H_{\phi,n}
\end{bmatrix} = \sum_{n=\infty}^{\infty} [Z_n]_{TM} \begin{bmatrix}
E_{z,n} \\
H_{\phi,n}
\end{bmatrix}
\]
\[ [Z_{TM}] = \frac{\pi k_p r_b}{2} \begin{bmatrix} A & B \\ C & D \end{bmatrix} \]  \tag{12}

where the related expansion terms are formulated by Wronskian’s results on \( J_n \) and \( Y_n \) [30]

\[ A = J_n(k_p \cdot r_e) \cdot Y_n(k_s \cdot r_e) - J_n(k_s \cdot r_e) \cdot Y_n(k_p \cdot r_e) \]
\[ B = -i \eta_s (J_n(k_p \cdot r_e) \cdot Y_n(k_s \cdot r_e) - J_n(k_s \cdot r_e) \cdot Y_n(k_p \cdot r_e)) \]
\[ C = \frac{1}{i \eta_s} (J_n(k_p \cdot r_e) \cdot Y_n(k_s \cdot r_e) - J_n(k_s \cdot r_e) \cdot Y_n(k_p \cdot r_e)) \]
\[ D = J_n(k_p \cdot r_e) \cdot Y_n(k_s \cdot r_e) - J_n(k_s \cdot r_e) \cdot Y_n(k_p \cdot r_e) \]  \tag{13}

\( Y_n(\cdot) \) is nth order Neumann function of the first kind and \( Y'_n(\cdot) \) is the derivate of \( Y_n(\cdot) \). \( \eta_s \) is the characteristic impedance and \( k_p \) is the wavenumber of the surface [31].

\[ \eta_s = \sqrt{\frac{j \omega \mu_s}{\sigma_s + j \omega \varepsilon_s}} \]
\[ k_p = \sqrt{-j \omega \mu_s (\sigma_s + j \omega \varepsilon_s)} \]  \tag{14}

where \( \varepsilon_s \) is the relative permittivity, \( \mu_s \) is the relative permeability and \( \sigma_s \) is the conductivity of the surface layer of cylinder.

### 3. RESULTS

Firstly, SE of composite panel exposed to EMP is investigated. Electrical parameters of the composite materials used in air vehicles manufacturing are given in Table 1. These parameters are used at analytical calculations and construction of a panel model at CST program.

| Material | Relative Permittivity | Electrical conductivity(S/m) |
|----------|-----------------------|-----------------------------|
| CMS[1]   | 14.5                  | 500                         |
| CFC[8]   | 1                     | 10^4                        |
| CFRP[6]  | 6.4                   | 1.5x10^4                    |
| GrEp[19] | 1                     | 4x10^4                      |

Analytical calculation results are given in Figure 4. Simulations performed for 0.5 mm thickness panel at frequency range between 1 MHz to 10 GHz.

It is clear from Figure 4 that GrEp shows the best shielding performance among 4 composite materials. 0.5 mm thick GrEp panel provides SE between 70 and 220 dB at selected frequency spectrum. CFC and CFRP have similar shielding performances and a notable increase occurs with frequency. SE performance of all composite materials remain constant up to 100 MHz and shielding efficiency in the range of 40–80 dB up to material. With increasing frequency, SE performance of composite materials increase dramatically.

![Figure 4 SE Comparison of Composite Materials](image)

The panel is constructed for CMS and CFC materials at CST and simulation results are compared with analytical results in Figure 5. Frequency Domain Solver is preferred for CST simulations. According to Figure 5, there is an excellent agreement between analytical and simulation results.
A cylinder can be considered as a small model of aircrafts. A cylindrical shell model is considered to analyze the cylindrical SE performance of composite materials against EMP. The shell of the cylinder is assumed to be constructed by composite materials and electric field along the axis of cylinder and cylindrical SE performance of materials is analyzed.

As in the panel model, the analytical calculations and CST simulations are performed for a cylindrical shell model. To reduce the simulation time and mesh number in CST simulations, the highest frequency is limited to 2 GHz, the radius of cylinder is selected as \( R = 20 \text{ cm} \) and the thickness of composite panel \( d = 0.5 \text{ mm} \). The analytical results are given in Figure 6.

All composite materials show the same characteristics except the SE magnitudes. There is a significant increase at SE values up to 100 MHz. After 100 MHz, resonances occur, and SE values decrease sharply at resonance frequencies. GrEp material provides the highest SE performance about 80 dB and the CMS the lowest about 30 dB.

Except resonance frequencies, there isn’t a notable change at SE values with increasing frequency. It is clear from the Figure 6 that the electrical properties of the materials don’t have a significant effect on resonance frequencies. First resonance frequency is 574.65 MHz and second is 1.315 GHz. These frequency values are related to the radius of the cylinder and roots of the Bessel function.

\[
f_{\text{res}} = \frac{c}{2\pi\sqrt{\frac{\varepsilon_r \mu_r}{R}}} \sqrt{\left(\frac{x_{mn}}{R}\right)^2 + \left(\frac{p\pi}{l}\right)^2}
\]

where \( m \)th root of \( n \)th order of Bessel function is denoted by \( x_{mn} \). \( R \) is the radius, \( l \) is the length, \( \varepsilon_r \) is the relative permittivity and \( \mu_r \) is the relative permeability of the cylinder. Due to Figure 6 and Equation 9, the radius of the cylinder is more decisive on resonance frequencies than electrical parameters of composite materials.

Then, the cylindrical shell model is constructed in the CST program. GrEp material is selected as the shell of the cylinder. Time domain solver is used for simulation. The result of the model is compared with analytical results in Figure 7.
Analytical and simulation results show the same characteristics and there is a good agreement between the resonance frequencies and magnitude values.

Due to the good agreement between analytical and simulation results, it is considered to perform some additional simulations to obtain E-field distributions at 935 MHz that is the central frequency of resonances of cylindrical interaction given in Figures 6 and 7. Field monitors are used to evaluate E-field distributions. E-field distribution for plane wave interaction with CFC material is given in Figure 8.

It is clear from Figure 8 that the E-field distribution behind the panel has similar results as given in Figure 5. The majority of incident E-field is reflected through the CFC panel and CFC panel provides a notable SE.

E-field distribution for plane wave interaction with cylindrical shell model is also given in Figure 9. Simulations are performed for GrEp material as in Figure 7. Incident, transmitted and reflected E-fields are given in Figure 9. Due to inner reflections, the major part of the incident E-field is reflected and transmitted from the cylindrical shell model. A good SE performance is achieved.

4. CONCLUSIONS

In this paper, the composite materials used in air vehicle manufacturing industry are investigated. The analytical calculations and simulations are performed for composite materials. A panel model is considered to obtain the SE level of materials. Due to geometric similarity of air vehicles and cylinder except the wings, a cylindrical shell model is constructed and SE level on the axis of the cylinder is calculated. CST models are constructed for both panel and cylindrical model. There is a good agreement between analytical results and simulations for panel and cylindrical shell models. CFC, CFRP and GrEp materials obtain 60dB shielding
performance at least for 0.5 mm thickness. GrEp provides the highest shielding effect for panel and cylindrical models. Except resonance frequencies, 75 dB shielding is achieved by GrEp for cylindrical shell application. Based on the agreement, E-field distributions are evaluated at central frequency of resonances at 935 MHz for planar and cylindrical models. The results are compatible with analytical and simulation results. Also, it is noticed that the analytical model has an advantage of solving the problem in a brief, simple and fast way.

**Funding**

“This study is supported by Sakarya University Scientific Research Projects Coordination Unit. Project Number: 2011-50-02-028.”

**The Declaration of Conflict of Interest/ Common Interest**

This study was produced from the Baha KANBEROĞLU's PhD thesis entitled "Electromagnetic pulse shielding effectiveness analysis of multilayered cylindrical structures", which was accepted in 2020.

**Authors' Contribution**

The authors contributed equally to the study.

**The Declaration of Ethics Committee Approval**

This study does not require ethics committee permission or any special permission.

**The Declaration of Research and Publication Ethics**

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

**REFERENCES**

[1] B. D. Cordill, S. A. Seguin, and M. S. Ewing, “Shielding effectiveness of composite and aluminum aircraft, model and measurement comparison,” *Conf. Rec. - IEEE Instrum. Meas. Technol. Conf.*, pp. 1408–1413, 2011.

[2] M. A. Aziz et al., “Shielding effectiveness of composite aircraft: A reverberation chamber and virtual measurement study,” 2012 *IEEE I2MTC - Int. Instrum. Meas. Technol. Conf. Proc.*, pp. 2775–2779, 2012.

[3] G. G. Gutiérrez et al., “HIRF virtual testing on the C-295 aircraft: On the application of a pass/fail criterion and the FSV method,” *IEEE Trans. Electromagn. Compat.*, vol. 56, no. 4, pp. 854–863, 2014.

[4] M. H. Vogel, “Impact of lightning and high-intensity radiated fields on cables in aircraft,” *IEEE Electromagn. Compat. Mag.*, vol. 3, no. 2, pp. 56–61, 2014.

[5] A. Jazzar, E. Clavel, G. Meunier, and E. Vialardi, “Study of lightning effects on aircraft with predominately composite structures,” *IEEE Trans. Electromagn. Compat.*, vol. 56, no. 3, pp. 675–682, 2014.

[6] L. Huang, C. Gao, F. Guo, and C. Sun, “Lightning Indirect Effects on Helicopter: Numerical Simulation and Experiment Validation,” *IEEE Trans. Electromagn. Compat.*, vol. 59, no. 4, pp. 1171–1179, 2017.

[7] R. R. Nunes and J. Schuur, “Investigation on the propagation and coupling in aircraft using absorbing films,” *IEEE Int. Symp. Electromagn. Compat.*, vol. 2015-Septm, pp. 322–327, 2015.

[8] M. R. Cabello et al., “SIVA UAV: A Case Study for the EMC Analysis of Composite Air Vehicles,” *IEEE Trans. Electromagn. Compat.*, vol. 59, no. 4, pp. 1103–1113, 2017.
[9] V. P. Bui, W. Thitsartarn, E. X. Liu, J. Y. C. Chuan, and E. K. Chua, “EM Performance of Conductive Composite Laminate Made of Nanostructured Materials for Aerospace Application,” *IEEE Trans. Electromagn. Compat.*, vol. 57, no. 5, pp. 1139–1148, 2015.

[10] B. Kanberoglu, M. . Hilmi Nişanci, and A. Şükran Demirkiran, “Electromagnetic characterization of ceramic material produced with natural zeolite,” *Mater. Sci. Semicond. Process.*, vol. 38, pp. 352–356, 2015.

[11] M. D’Amore, D. A. Lampasi, M. S. Sarto, A. Tamburrano, V. De Santis, and M. Feliziani, “Optimal design of multifunctional transparent shields against radio frequency electromagnetic fields,” *Electromagn. Compat. Symp. Adelaide 2009, EMCSA 2009 - Symp. Proc.*, pp. 81–86, 2009.

[12] Y. Corredores, P. Besnier, X. Castel, J. Sol, C. Dupeyrat, and P. Foutrel, “Adjustment of Shielding Effectiveness, Optical Transmission, and Sheet Resistance of Conducting Films Deposited on Glass Substrates,” *IEEE Trans. Electromagn. Compat.*, vol. 59, no. 4, pp. 1070–1078, 2017.

[13] L. Guadagno et al., “Development of epoxy mixtures for application in aeronautics and aerospace,” *RSC Adv.*, vol. 4, no. 30, pp. 15474–15488, 2014.

[14] I. M. De Rosa, F. Sarasini, M. S. Sarto, and S. Member, “EMC Impact of Advanced Carbon Fiber / Carbon Nanotube Reinforced Composites for Next-Generation Aerospace Applications,” vol. 50, no. 3, pp. 556–563, 2008.

[15] S. Greco, A. Tamburrano, A. D’Aloia, R. Mufatti, and M. S. Sarto, “Shielding effectiveness properties of carbon-fiber reinforced composite for HIRF applications,” *IEEE Int. Symp. Electromagn. Compat.*, pp. 1–6, 2012.

[16] N. Abdelal, “Electromagnetic interference shielding of stitched carbon fiber composites,” *J. Ind. Text.*, pp. 1–18, 2018.

[17] D. Munalli, G. Dimitrakis, D. Chronopoulos, S. Greedy, and A. Long, “Electromagnetic shielding effectiveness of carbon fibre reinforced composites,” *Compos. Part B Eng.*, vol. 173, no. December 2018, p. 106906, 2019.

[18] I. M. De Rosa, R. Mancinelli, F. Sarasini, M. S. Sarto, and A. Tamburrano, “Electromagnetic Design and Realization of Innovative Fiber-Reinforced Broad-Band Absorbing Screens,” *IEEE Trans. Electromagn. Compat.*, vol. 51, no. 3, pp. 700–707, Aug. 2009.

[19] A. L. Bogorad, M. P. Deeter, K. A. August, G. Doorley, J. J. Likar, and R. Herschitz, “Shielding Effectiveness and Closeout Methods for Composite Spacecraft Structural Panels,” *IEEE Trans. Electromagn. Compat.*, vol. 50, no. 3, pp. 547–555, Aug. 2008.

[20] J. Wang, B. Zhou, L. Shi, C. Gao, and B. Chen, “Analyzing the electromagnetic performances of composite materials with the FDTD method,” *IEEE Trans. Antennas Propag.*, vol. 61, no. 5, pp. 2646–2654, 2013.

[21] R. W. Evans, “Design Guidelines for Shielding Effectiveness, Current Carrying Capability, and the Enhancement of Conductivity of Composite Materials,” *NASA Contract. Rep.*, no. 4784, 1997.

[22] CST, “Computer Simulation Technology, CST Studio Suite 2015, User Guide,” Darmstadt, Germany, 2019.

[23] US Department Of Defence, “MIL-STD-464C Electromagnetic environmental effects requirements for systems,” Washington, 2010.

[24] IEC 61000-2-9, “IEC 61000-2-9 Electromagnetic compatibility (EMC) –
Part 2: Environment – Section 9: Description of HEMP environment – Radiated disturbance Basic EMC publication Compatibilité,” *International Organization*. 2009.

[25] H. Oraizi and A. Abdolali, “Several theorems for reflection and transmission coefficients of plane wave incidence on planar multilayer metamaterial structures,” *IET Microwaves, Antennas Propag.*, vol. 4, no. 11, pp. 1870–1879, 2010.

[26] B. Kanberoğlu and A. Şükran Demirkıran, “Shielding Effectiveness of Ceramic Bodies Produced with Natural Zeolite,” *Acta Phys. Pol. A*, vol. 125, no. 2, pp. 642–644, Jan. 2014.

[27] K. Zhang and D. Li, *Electromagnetic Theory for Microwaves and Optoelectronics*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008.

[28] S. Celozzi, R. Araneo, and G. Lovat, *Electromagnetic Shielding*. 2008.

[29] P. R. Renaud and J. J. Laurin, “Shielding and scattering analysis of lossy cylindrical shells using an extended multifilament current approach,” *IEEE Trans. Electromagn. Compat.*, vol. 41, no. 4 PART 1, pp. 320–334, 1999.

[30] M. Abramowitz and I. A. Stegun, *Handbook of Mathematical Functions*. New York: Dover, 2003.

[31] F. M. Tesche, M. Ianoz, and T. Karlsson, *EMC Analysis Methods and Computational Models*. Canada: John Wiley & Sons, 1997.