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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

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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:

$$SE_E = -20\log\left|\frac{E_t}{E_i}\right| \qquad (1)$$

E_i and E_t are the incident and transmitted electric field strengths. SE performance is evaluated for a plane wave interaction. EMP is described by a double-exponential equation given by[23], [24]

$$E(t) = E_0 \times (e^{-\alpha t} - e^{-\beta t}), \qquad t > 0 \qquad (2)$$

where the parameters $E_0 = 5 \times 10^4$ V/m, $\alpha = 4 \times 10^7$ s^{-1}, $\beta = 6 \times 10^8$ s^{-1}. The waveforms of EMP are shown in Fig. 1 for both time and frequency domains.
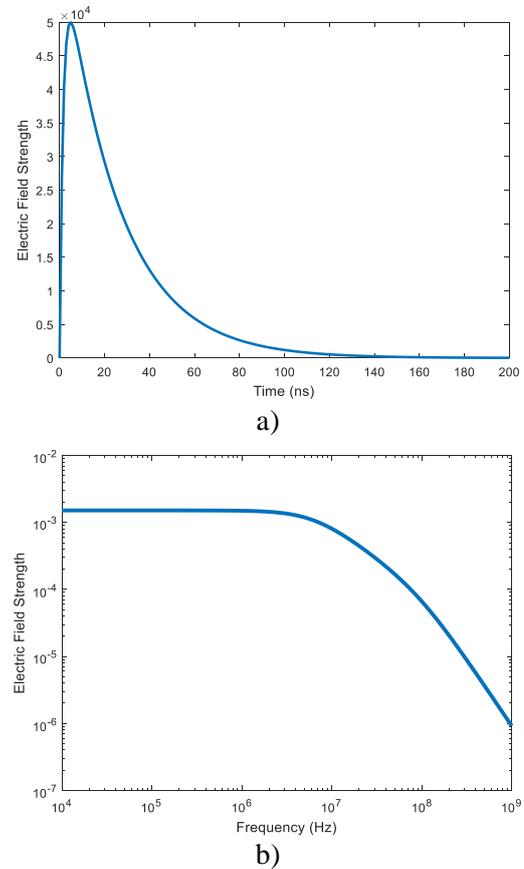

a)

b)

Figure 1 EMP waveform at a) time and b) 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.
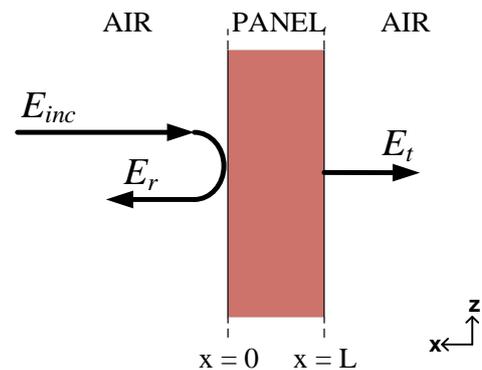
Figure 2 Interaction model of homogeneous panel

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.

$$\begin{bmatrix} E_x \\ H_y \end{bmatrix}_{tr} = \begin{bmatrix} T \end{bmatrix} \begin{bmatrix} E_x \\ H_y \end{bmatrix}_{inc} \tag{3}$$

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

$$\begin{bmatrix} T \end{bmatrix} = \begin{bmatrix} \cos(k_i \cdot d) & jZ \sin(k_i \cdot d) \\ \dfrac{j}{Z} \sin(k_i \cdot d) & \cos(k_i \cdot d) \end{bmatrix} \tag{4}$$

where the thickness of the layer

$$d = y_{l+1} - y_l \tag{5}$$

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

$$Z = \sqrt{\frac{jw\mu}{\sigma + jw\varepsilon}} \tag{6}$$

$$k_i = \sqrt{-jw\mu(\sigma + jw\varepsilon)} \tag{7}$$

$w=2\pi f$ is the angular frequency, σ is the electrical conductivity, ε_0 and μ_0 are the electric permittivity and magnetic permeability of free space, respectively.

2.2. Case 2: Cylindrical interaction

TM_Z 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]

$$E^{inc}(r,\phi,z) = E_z^{inc}(r,\phi)\overrightarrow{a_z} = E_0^{inc}e^{-jk_0 r\cos\phi}\overrightarrow{a_z}$$

$$H^{inc}(r,\phi,z) = H_r^{inc}(r,\phi)\overrightarrow{a_r} + H_\phi^{inc}(r,\phi)\overrightarrow{a_\phi} \tag{8}$$

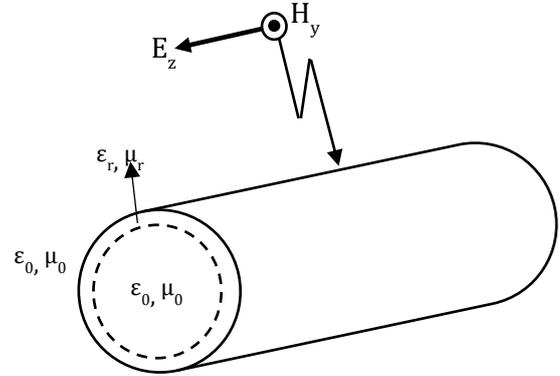$$= -\frac{E_0^{inc}}{\eta_0}(\overrightarrow{a_r}\sin\phi + \overrightarrow{a_\phi}\cos\phi)e^{-jk_0 r\cos\phi}$$

Figure 3 Cylindrical shell interaction model

The tangential fields to the cylindrical surface can be shown as

$$E_z^{inc}(r,\phi) = E_0^{inc}\sum_{n=-\infty}^{\infty} j^{-n}J_n(k_0 r)e^{jn\phi}$$

$$H_\phi^{inc}(r,\phi) = \frac{1}{jw\varepsilon_0}\frac{\partial E_z^{inc}}{\partial r} \tag{9}$$

$$= -j\frac{E_0^{inc}}{\eta_0}\sum_{n=-\infty}^{\infty} j^{-n}J_n'(k_0 r)e^{jn\phi}$$

$J_n(\cdot)$ is the nth order Bessel function of the first kind and $J_n'(\cdot)$ is the derivate of $J_n(\cdot)$. η_0 and k_0 are the characteristic impedance and the wavenumber of the air, respectively[27].

$$\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$$

$$k_0 = w\sqrt{\varepsilon_0\mu_0} \tag{10}$$

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].

$$\begin{bmatrix} E_{z,n} \\ H_{\phi,n} \end{bmatrix}_b = \sum_{n=-\infty}^{\infty} \begin{bmatrix} Z_n \end{bmatrix}_{TM} \begin{bmatrix} E_{z,n} \\ H_{\phi,n} \end{bmatrix}_a \tag{11}$$

$[Z_n]_{TM}$ is the transfer impedance matrix and expressed as

$$[Z_{TM}] = \frac{\pi k_p r_b}{2} \begin{bmatrix} A & B \\ C & D \end{bmatrix} \quad (12)$$

where the related expansion terms are formulated by Wronskian's results on J_n and Y_n [30]

$$
\begin{aligned}
A &= J_n(k_p \cdot r_b) \cdot Y_n{}'(k_p \cdot r_a) - J_n{}'(k_p \cdot r_a) \cdot Y_n(k_p \cdot r_b) \\
B &= -i\eta_s (J_n(k_p \cdot r_a) \cdot Y_n(k_p \cdot r_b) - J_n(k_p \cdot r_b) \cdot Y_n(k_p \cdot r_a)) \\
C &= \frac{1}{i\eta_s}(J_n{}'(k_p \cdot r_a) \cdot Y_n{}'(k_p \cdot r_b) - J_n{}'(k_p \cdot r_b) \cdot Y_n{}'(k_p \cdot r_a)) \\
D &= J_n(k_p \cdot r_a) \cdot Y_n{}'(k_p \cdot r_b) - J_n{}'(k_p \cdot r_b) \cdot Y_n(k_p \cdot r_a)
\end{aligned}
\quad (13)
$$

$Y_n(\cdot)$ is nth order Neumann function of the first kind and $Y_n{}'(\cdot)$ is the derivate of $Y_n(\cdot)$. η_s is the characteristic impedance and k_p is the wavenumber of the surface[31].

$$
\begin{aligned}
\eta_s &= \sqrt{\frac{jw\mu_s}{\sigma_s + jw\varepsilon_s}} \\
k_p &= \sqrt{-jw\mu_s(\sigma_s + jw\varepsilon_s)}
\end{aligned}
\quad (14)
$$

where ε_s is the relative permittivity, μ_s is the relative permeability and σ_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.

Table 1 Electrical Properties of Composite Materials

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

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.
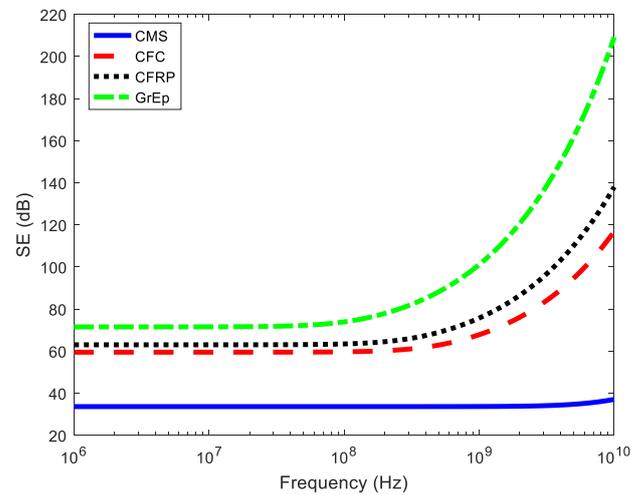

Figure 4 SE Comparison of Composite Materials

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.
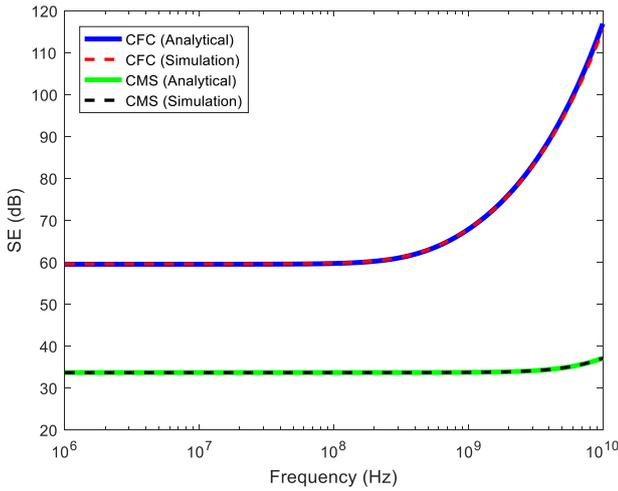
Figure 5 SE Comparison of Composite Materials

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 cm and the thickness of composite panel d= 0.5 mm. The analytical results are given in Figure 6.
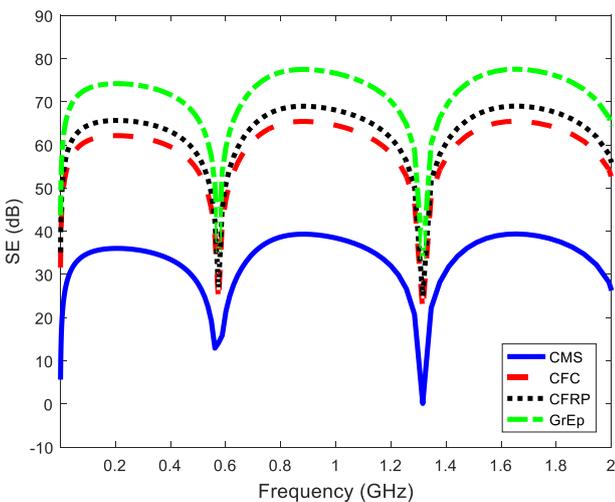

Figure 6 SE Comparison of Composite Materials

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.

$$f_{rez} = \frac{c}{2\pi\sqrt{\varepsilon_r \mu_r}} \sqrt{\left(\frac{x_{mn}}{R}\right)^2 + \left(\frac{p\pi}{l}\right)^2} \qquad (15)$$

where mth root of nth order of Bessel function is denoted by x_{mn}. R is the radius, l is the length, ε_r is the relative permittivity and μ_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.
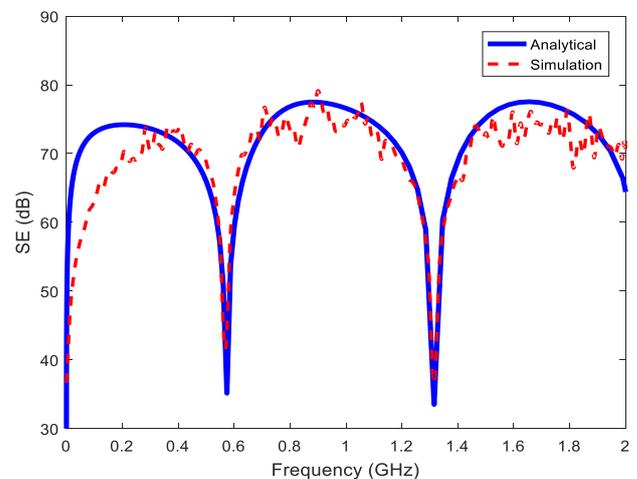

Figure 7 SE performance of cylindrical shell with single layer AML (d=0.5 mm, r= 20 cm)
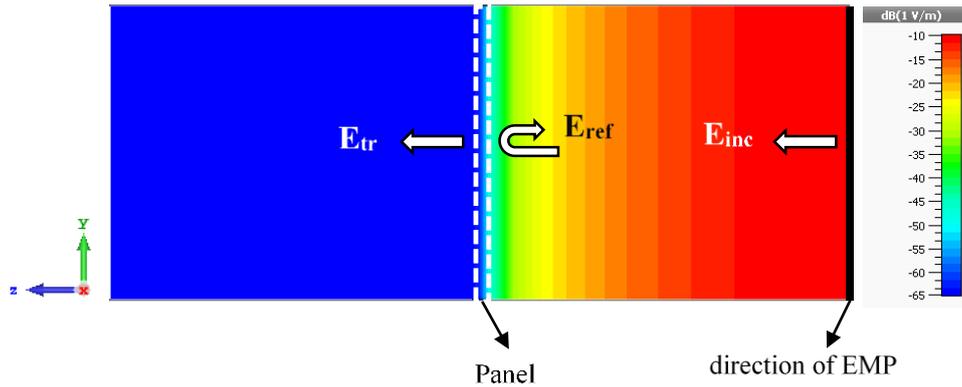
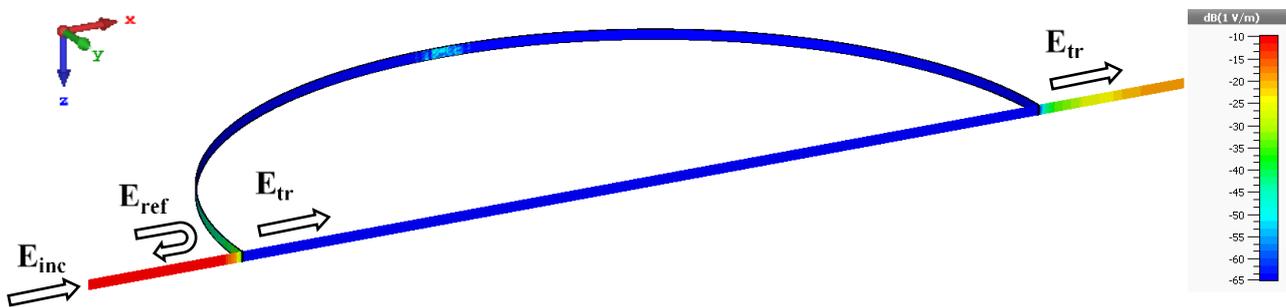Figure 8 E-Field distribution of panel model interaction

Figure 9 E-Field distribution of cylindrical model interaction

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.

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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.

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