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**Araştırma Makalesi / *Research Paper***

# Analysis and Simulation of Shielding Effectiveness of a Fiber Reinforced Cylindrical Shell

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**ABSTRACT**

The purpose of the paper is to analyze and simulate the shielding effectiveness (SE) performance of a fiber reinforced cylindrical shell. A matrix model is presented to evaluate the transmitted electromagnetic fields on the axis of cylindrical shell. SE performance of the cylindrical shell is calculated for various parameters such as radius of cylinder, shell thickness and shell conductivity. Also, a 3D model of the cylindrical shell is constructed via Computer Software Technology (CST) program to carry out the analytical results. The analytical calculations and simulations are performed for TM mode excitation. A good agreement is obtained by the comparison of analytical results and CST simulations.

**Keywords:** 3D simulation, cylindrical shell, matrix model, shielding effectiveness

# Fiber Takviyeli Silindirik Kabuğun Ekranlama Etkinliğinin Analizi ve Simülasyonu

**ÖZ**

Bu çalışmanın amacı, fiber takviyeli silindirik bir kabuğun ekranlama etkinliği performansını analiz etmek ve modellemektir. Silindirik kabuğun ekseni üzerinde oluşan elektromanyetik alanları hesaplamak için bir matris modeli sunulmuştur. Silindirik kabuğun ekranlama etkinliği performansı, silindir yarıçapı, kabuğun kalınlığı ve kabuğun elektriksel iletkenliği gibi çeşitli parametreler için hesaplanmıştır. Ayrıca, analitik sonuçları doğrulamak için Elektromanyetik Alan Simülasyon Yazılımı (CST) programı ile silindirik kabuğun 3 boyutlu bir modeli oluşturulmuştur. Analitik hesaplamalar ve simülasyonlar TM modu için gerçekleştirilir. Analitik sonuçların ve CST simülasyonlarının karşılaştırılması sonucunda iyi bir uyum elde edilmiştir.

**Anahtar Kelimeler:** 3 boyutlu simülasyon, silindirik kabuk, matris modeli, ekranlama etkinliği

## INTRODUCTION

The scattering and shielding effectiveness (SE) performance of a cylindrical structure has been studied in literature. Different approaches such as Multifilament Doublet Current Method (MFDCM)(Wang *et al.*, 2019), transfer-matrix method (Chiu and Chen, 1995), reflection and transfer matrices (Chiu and Hsu, 2005) are defined to determine the SE performance of the cylindrical shells. In these studies, the shell of the cylinder is generally considered to be composite materials. The composite material-based cylindrical shell is considered as the fuselage of aircraft (Chiu and Chen, 1995; Hsu and Chiu, 2006; Wang *et al.*, 2019) and SE and scattering performance is analyzed and/or measured.

With the development in technology, reinforced composite materials have been preferred instead of metals with the advantages like low weight, high stiffness, lower corrosion and high strength. Except the anisotropic properties of composite materials, the composite materials and the metals have both very similar electromagnetic properties (Chiu and Chen, 1995; Chiu and Hsu, 2005). Pro-

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tection of electronic equipment from the effects of external sources like High-Intensity Radiated Fields (HIRF), Lighting and High Altitude Electromagnetic Pulse (HEMP) is an important issue against involuntary electromagnetic interference (EMI) (Perala *et al.*, 1991; Cordill *et al.*, 2011; Aziz *et al.*, 2012; Jazzar *et al.*, 2014; Gutiérrez *et al.*, 2014; Vogel, 2014; Bui *et al.*, 2015; Nunes and Schuur, 2015; Cabello *et al.*, 2017; Huang *et al.*, 2017). The aircraft/spacecraft manufacturing industry is one of the areas that reinforced composite materials are widely used as a replacement for metals. The new composite materials like Composite material skin(CMS) (Aziz *et al.*, 2012), Carbon fiber reinforced polymer(CFRP) (Bui *et al.*, 2015; Abdelal, 2018; Munalli *et al.*, 2019), Carbon fiber reinforced composites (CFRC) (De Rosa *et al.*, 2009; Greco *et al.*, 2012) and Graphite-epoxy (GrEp) (Bogorad *et al.*, 2008) are used in aircraft/spacecraft construction. Instead of the physical and chemical advantages of these materials, the electrical conductivity of the composite materials is much lower than those metals (Evans, 1997).

In this paper, shielding effectiveness (SE) of an infinitely long fiber reinforced cylindrical shell is considered and a parameter study is performed for various radius of cylinder, various shell thicknesses and conductivity values. Analytical analysis is carried out at cylindrical coordinates via a transfer impedance matrix that is used to determine the relationship between the tangential electric and magnetic fields at the boundaries of the layers. The electromagnetic fields and SE of the cylindrical shell are obtained via calculations on the axis of the cylinder. Simulations of materials can be efficiently performed by CST Microwave Studio (Munalli *et al.*, 2019). Also, the interaction system is modelled via CST Microwave Studio (Computer Simulation Technology, 2019) and analytical results are compared and validated with simulations.

In Section 2, mathematical model of electromagnetic interaction for TM polarized electromagnetic wave is presented. Simulation results of the cylindrical shell are presented for different cases in section 3 and finally, the results are discussed in Section 4.

## MATHEMATICAL MODEL

TM polarized plane wave is considered to interact with a shielded cylinder as shown in Fig. 1. The axis of the cylinder is along the z axis.

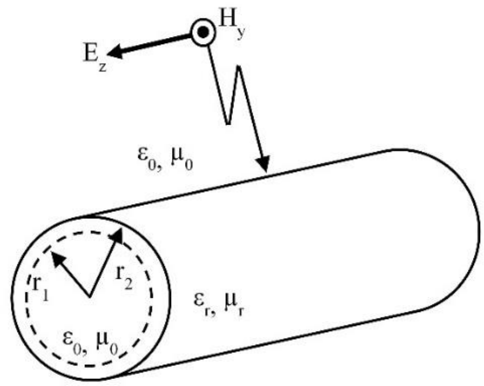


**Figure 1.** Interaction Model

The electric and magnetic fields in cylindrical coordinates are given as

$$\begin{aligned} E^{inc}(r,\phi,z) &= E_z^{inc}(r,\phi)\overrightarrow{a_z} = E_0^{inc}e^{-jk_0 r\cos\phi}\overrightarrow{a_z} \\ H^{inc}(r,\phi,z) &= H_r^{inc}(r,\phi)\overrightarrow{a_r} + H_\phi^{inc}(r,\phi)\overrightarrow{a_\phi} = -\frac{E_0^{inc}}{\eta_0}(\overrightarrow{a_r}\sin\phi + \overrightarrow{a_\phi}\cos\phi)e^{-jk_0 r\cos\phi} \end{aligned} \tag{1}$$

The tangential fields to the cylindrical surface can be shown as (Chiu and Hsu, 2005; Celozzi *et al.*, 2008).

$$\begin{aligned} E_z^{inc}(r,\phi) &= E_0^{inc}\sum_{n=-\infty}^{\infty} j^{-n}J_n(k_0 r)e^{jn\phi} \\ H_\phi^{inc}(r,\phi) &= \frac{1}{jw\varepsilon_0}\frac{\partial E_z^{inc}}{\partial r} = -j\frac{E_0^{inc}}{\eta_0}\sum_{n=-\infty}^{\infty} j^{-n}J_n^{'}(k_0 r)e^{jn\phi} \end{aligned} \tag{2}$$

$J_n(\cdot)$ is the nth order Bessel function of the first kind and $J_n^{'}(\cdot)$ is the derivate of $J_n(\cdot)$. $\eta_0$ and $k_0$ are the characteristic impedance and the wavenumber of the vacuum, respectively (Tesche *et al.*, 1997).

$$\begin{aligned} \eta_0 &= \sqrt{\frac{\mu_0}{\varepsilon_0}} \\ k_0 &= w\sqrt{\varepsilon_0\mu_0} \end{aligned} \tag{3}$$

where ω is the angular frequency, $\varepsilon_0$ is the permittivity and $\mu_0$ is the permeability of free space. 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 (Renaud and Laurin, 1999).

$$\begin{bmatrix} E_{z,n} \\ H_{\phi,n} \end{bmatrix}_b = \sum_{n=-\infty}^{\infty}[Z_n]_{TM}\begin{bmatrix} E_{z,n} \\ H_{\phi,n} \end{bmatrix}_a \tag{4}$$

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

$$[Z_{TM}] = \frac{\pi k_p r}{2}\begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{5}$$

where the related expansion terms are formulated by Wronskian's results on $J_n$ and $Y_n$ (Abramowitz and Stegun, 2003).

$$\begin{aligned}
A &= J_n(k_p \cdot r_b)\cdot Y_n'(k_p \cdot r_a) - J_n'(k_p \cdot r_a)\cdot Y_n(k_p \cdot r_b) \\
B &= -i\eta_s(J_n(k_p \cdot r_a)\cdot Y_n(k_p \cdot r_b) - J_n(k_p \cdot r_b)\cdot Y_n(k_p \cdot r_a)) \\
C &= \frac{1}{i\eta_s}(J_n'(k_p \cdot r_a)\cdot Y_n'(k_p \cdot r_b) - J_n'(k_p \cdot r_b)\cdot Y_n'(k_p \cdot r_a)) \\
D &= J_n(k_p \cdot r_a)\cdot Y_n'(k_p \cdot r_b) - J_n'(k_p \cdot r_b)\cdot Y_n(k_p \cdot r_a)
\end{aligned} \tag{6}$$

$Y_n(\cdot)$ 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 shell surface (Tesche *et al.*, 1997).

$$\begin{aligned}
\eta_s &= \sqrt{\frac{jw\mu_s}{\sigma_s + jw\varepsilon_s}} \\
k_s &= \sqrt{-jw\mu_s(\sigma_s + jw\varepsilon_s)} \\
k_p &= \sqrt{k_s^{\,2} - k_z^{\,2}}
\end{aligned} \tag{7}$$

where $\varepsilon_s$ is the relative permittivity, $\mu_s$ is the relative permeability and $\sigma_s$ is the conductivity of the shell of cylinder. The electromagnetic SE of the panel can be described as the ratio of the magnitude of the transmitted electric field to incident electric field. SE for electric field is given as:

$$SE_E = -20\log\left|\frac{E_t}{E_i}\right| \tag{8}$$

$E_i$ and $E_t$ are the incident and transmitted electric field strengths. Also, $H_i$ and $H_t$ are the incident and transmitted magnetic field strength.

## RESULTS

A single layer shell is considered for SE performance simulations. The cylinder extends along the z axis and the incident plane wave is propagated normally to the cylinder. A TM polarized wave is assumed to interact with cylinder and propagates along x direction as given in Fig. 1 for all analysis and simulations. Also, to validate the analytical results, a 3D simulation model is established in CST Microwave Studio (Computer Simulation Technology, 2019).

The electrical parameters of Graphite/Epoxy (GrEp) material, widely used in literature, is based on. Electrical parameters of the shell are $\varepsilon_r = 5$, $\mu_r = 1$ and $\sigma_s = 40000$ S/m. The inner radius of the cylinder is selected as $r_a = 20$ cm and the thickness of the shell is d=1 mm.

Three different cases are considered for calculations and simulations. Analytical calculations and CST simulations are performed for various inner radius, shell thicknesses and shell conductivities.

Case 1 is characterized by constant inner radius, shell thickness and electrical permittivity. Analytical analysis and simulations are considered for various shell conductivities ($\sigma_1 = 10^4$ S/m, $\sigma_2 = 2\text{x}10^4$ S/m, $\sigma_3 = 8\text{x}10^4$ S/m). The comparison of analytical and simulation results is given in Fig. 2-4, respectively.

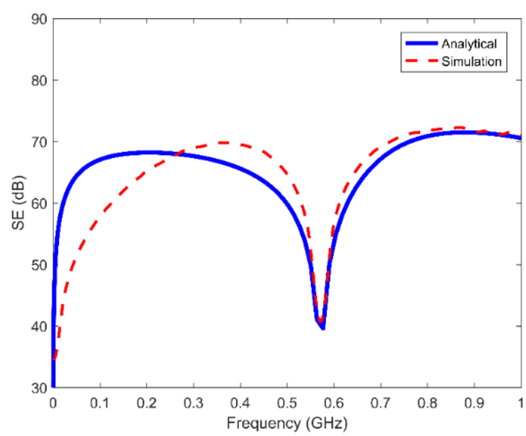

**Figure 2.** SE of cylindrical shell ($\sigma_1$= $10^4$ S/m)

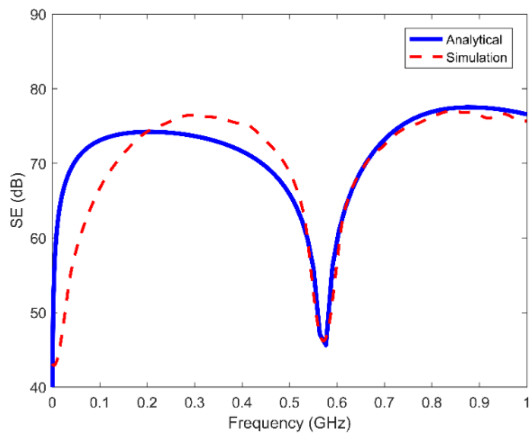


**Figure 3.** SE of cylindrical shell ($\sigma_2$= $2x10^4$ S/m)

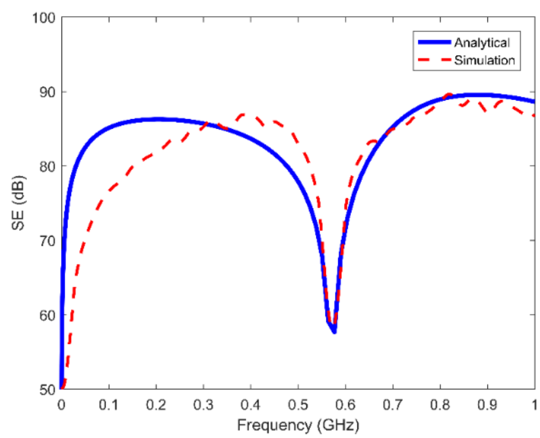


**Figure 4.** SE of cylindrical shell ($\sigma_3$= $8x10^4$ S/m)

The analytical results agree very well with the 3D simulation results for both conductivity values. The SE of the cylindrical shell increase with the conductivity. The amplitude of the SE is about 70 dB for $\sigma_1$= $10^4$ S/m and 87 dB for $\sigma_3$= $8x10^4$ S/m. Also, resonance frequency of the cylindrical shell doesn't change with conductivity and $f_{res}$ = 574.65 MHz for analytical calculations. The resonance frequency depends on the radius of the cylinder and roots of the Bessel function.

$$f_{rez} = \frac{c}{2\pi\sqrt{\varepsilon_r \mu_r}} \sqrt{\left(\frac{x_{mn}}{R}\right)^2 + \left(\frac{p\pi}{l}\right)^2} \quad (9)$$

where mth root of nth 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. The calculated resonance frequency of the Case 1 is $f_{res}$ = 574.15 MHz and there is a good agreement with analytical calculations and 3D simulations.

Case 2 is characterized by different inner radius values. Shell conductivity, shell thickness and electrical permittivity are constant parameters. The SE of the cylindrical shell is considered for three inner radius values ($R_1$= 10 cm, $R_2$=40 cm, $R_3$=1 m). The comparison of analytical and simulation results is given in Fig. 5-7, respectively.

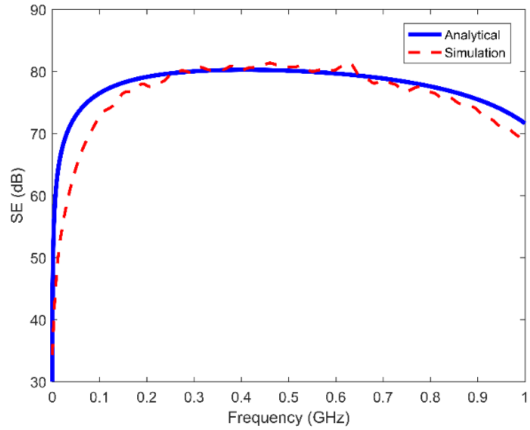


**Figure 5.** SE of cylindrical shell ($R_1$=10 cm)

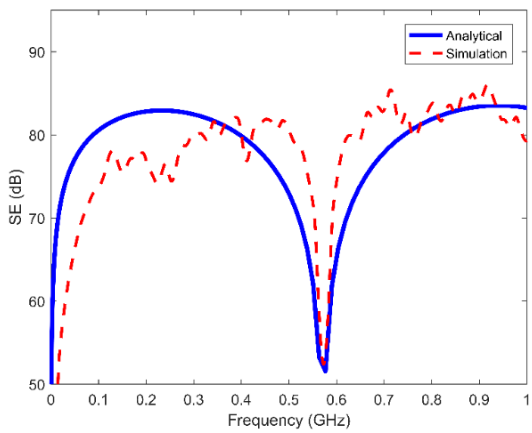


**Figure 6.** SE of cylindrical shell ($R_2$=40 cm)

There is a good agreement between the analytical and simulation results. The resonance frequencies and amplitude of SE show the same characteristics and have close values for all inner radius values. It is clear from the figures that the number of resonance frequencies changes with the inner radius. There is a direct proportion between the inner radius and the number of resonance frequencies. For $R_1$= 10 cm, there isn't any resonance frequency at 0-1 GHz frequency range but for $R_1$= 100 cm, the number of resonances increases up to 6 as it is given in Fig. 7. Despite the increase at number of resonance frequencies, the amplitude of the SE does not change and about 80 dB.

In Case 3, SE of the cylindrical shell is considered for various shell thicknesses ($d_1$= 0.6mm, $d_2$=0.8mm, $d_3$=1.2mm) while other electrical and physical parameters are constant. The analytical and simulation results are given in Fig. 8-10, respectively.

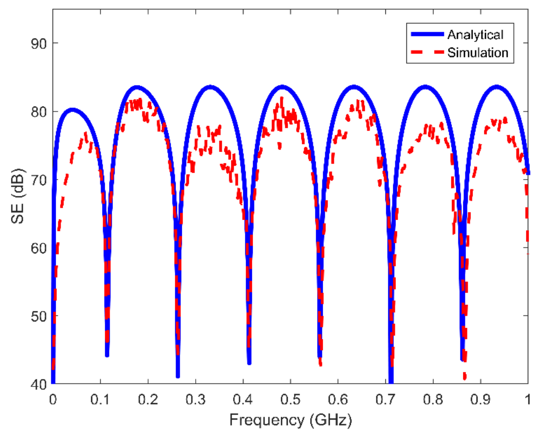


**Figure. 7.** SE of cylindrical shell ($R_3$=100 cm)

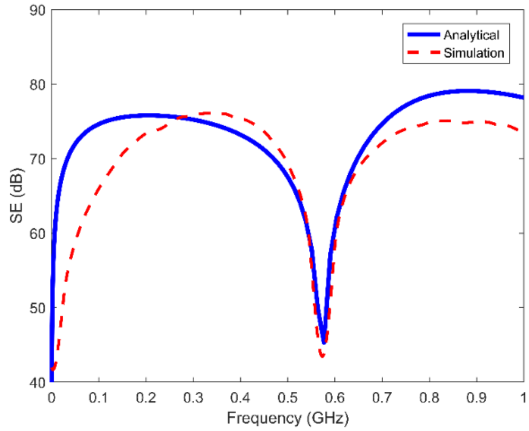


**Figure 8.** SE of cylindrical shell ($d_1$=0.6 mm)

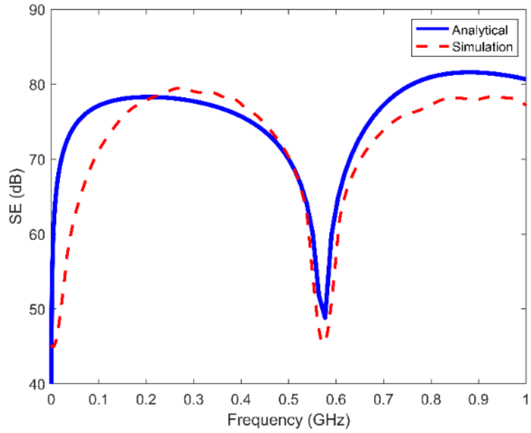


**Figure 9.** SE of cylindrical shell ($d_2$=0.8 mm)

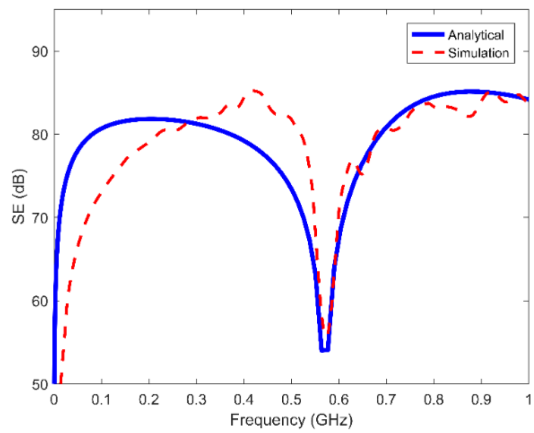


**Figure 10.** SE of cylindrical shell ($d_3$=1.2 mm)

There is a good agreement between analytical results and CST simulations. It is clear from the figures that increasing shell thickness provides more SE. Also, the shell thickness doesn't affect the resonance frequency. The resonance frequency has the same value in Case 1 and $f_{res}$ = 574.65 MHz.

The results of comparison of analytical and 3D simulation results for three cases are very similar. Analytical results show the same characteristic as the simulation results and the amplitude of SE and resonance frequencies show good agreement.

## CONCLUSIONS

SE performance of a single layer cylindrical shell for TM wave incidence is evaluated via a 2x2 matrix model. Shielding performance of the cylindrical shell is studied in terms of conductivity and thickness of the shell as well as inner radius of cylinder. Then, the interaction model of cylindrical shell is modelled via 3D simulation software to validate the analytical results. The results of analytical calculations and 3D simulations are compared up to 1 GHz and the analytical results are in a good agreement with 3D simulation results. The analytical method can approximately be used to evaluate the SE level of cylindrical structures. Also, the computation time for analytical formulas is negligible against the computation time of 3D simulations.

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