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Analytical model for estimating the shielding effectiveness of cylindrical connectors

A A Ivanov and M E Komnatnov

Tomsk State University of Control Systems and Radioelectronics, 40, Lenina Ave., Tomsk, 634050, Russia

E-mail: anton.ivvv@gmail.com

Abstract. In this paper, an analytical model for evaluating the shielding effectiveness (SE) of cylindrical connectors was proposed. A connector shell may be fully or partially filled with dielectric. The results obtained up to 1 GHz using this model and the finite element method are in good agreement. According to this model, SE of the 2RMDT-connector used in the power bus was calculated and SE of 26 dB was obtained for the worst case.

1. Introduction

In the modern mechanical engineering, serious attention is paid to electromagnetic compatibility, and electromagnetic shielding is widely used to provide it. Shielded connectors, which are often filled with dielectric insulating material, are used to protect cable assembly interconnections from the effects of electromagnetic interference. Dielectric filling and small shell size makes it difficult to measure the shielding effectiveness (SE) of the connectors. Therefore, numerical and analytical methods are used to estimate SE [1]. The SE calculations involving higher-order modes are used in rare cases and can be performed by analytical methods, since the operating frequency range of the connector is often below the resonant frequencies of the shell. Existing analytical models for calculating the SE of rectangular [2] and cylindrical [3] shells don't take into account the effect of dielectric filling. However, the estimation of the shielding effectiveness of connector must be performed with a permittivity, which has a significant effect on the phase velocity of the electromagnetic wave penetrating the shell. The aim of this work is to develop an analytical model for estimating the SE of cylindrical connectors with full or partial dielectric filling.

2. Analytical model of cylindrical connector

Based on the Robinson model [2] , the cylindrical shell of the connector (Figure 1a) can be replaced by an equivalent circuit in which the incident wave is represented by voltage source V_0 with impedance Z_0=120π Ω, the aperture is represented by the coplanar strip transmission line, and the shell is considered as a short-circuited cylindrical waveguide. In the model [2], the shell contains a rectangular aperture. Using the aperture area equivalence, the impedance of a circular aperture can be calculated as:

$$Z_{ap} = jZ_{0s}\frac{r\sqrt{\pi}}{4R}\tan\left(f\frac{r\sqrt{\pi}}{c}\pi\right)$$

where r is aperture radius, R is shell radius, c is speed of light in vacuum, f is source frequency, and Z_{0s} is characteristic impedance of the coplanar strip transmission line, which is defined as [4]:

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$$Z_{0s} = 120\pi^2 \left[\ln\left(2\frac{1+\sqrt[4]{1-(w_e/2R)^2}}{1-\sqrt[4]{1-(w_e/2R)^2}} \right) \right]^{-1}.$$

The effective aperture width can be calculated as:

$$w_e = r\sqrt{\pi} - \frac{5t}{4\pi}\left[1+\ln\left(4\pi r\sqrt{\pi}/t\right)\right]$$

where t is the thickness of the shell wall.

If there is a dielectric ε_r in the shell, characteristic impedance and propagation constant are defined as [5]:

$$Z_g = Z_0 \left[\sqrt{1-\left(\frac{\lambda}{\lambda_c\sqrt{\varepsilon_r}}\right)^2}\sqrt{\varepsilon_r} \right]^{-1},$$

$$k_g = 2\pi\frac{\sqrt{\varepsilon_r}}{\lambda}\sqrt{1-\left(\frac{\lambda}{\lambda_c\sqrt{\varepsilon_r}}\right)^2}$$

where λ is source wavelength, and λ_c is cutoff wavelength equal to $2\pi R/\eta_{mn}$ for the TE_{mn} mode propagation (η_{mn} – n-th root of equation $J'_m(\alpha_{m,n})=0$, and $J_m(\alpha_{m,n})$ – m-th order Bessel function).

The effective complex permittivity, according to [6], can be calculated as:

$$\varepsilon_r = \varepsilon'(1 - j\tan\delta)$$

where ε' is the real part of relative complex permittivity, and $\tan\delta$ is dielectric loss tangent.

The equivalent circuit of a connector is shown in Figure 1b. The shell is partially filled with dielectric from the aperture to point B, where the characteristic impedance and propagation constant are Z_{g1} and k_{g1} respectively. In an air-filled environment, the characteristic impedance and propagation constant are Z_{g2} and k_{g2} respectively. SE calculation can be performed using source transformation to the observation point P. Thevenin's theorem is used for this.

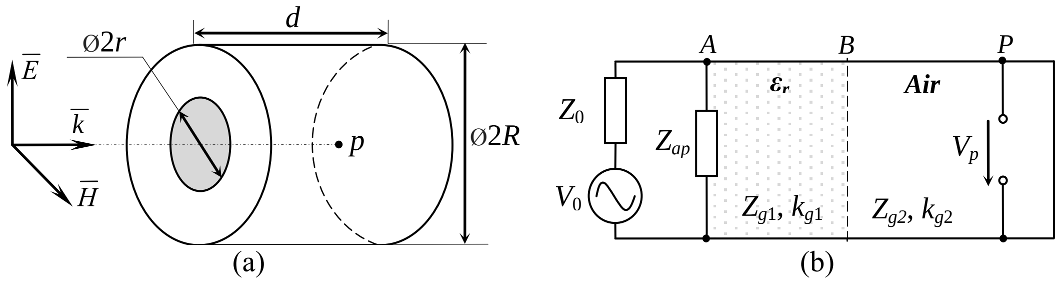

Figure 1. Cylindrical shell with aperture (a) and equivalent circuit for calculating the SE of connector (b).

Voltage and source impedance in the aperture (point A) can be calculated as $V_1=V_0Z_{ap}/(Z_0+Z_{ap})$ and $Z_1=Z_0Z_{ap}/(Z_0+Z_{ap})$. To transform the source to the air-dielectric interface region (point B), the input impedance of the transmission line is used. Voltage and impedance at the point B are defined as:

$$V_2 = V_1\left[\cos(k_{g1}b) + j\frac{Z_1}{Z_{g1}}\sin(k_{g1}b)\right]^{-1},$$

$$Z_2 = Z_{g1}\frac{Z_1 + jZ_{g1}\tan(k_{g1}b)}{Z_{g1} + jZ_1\tan(k_{g1}b)}$$

where b is distance from the aperture to the dielectric-air interface.

For the equivalent circuit in Figure 1b, the voltage and source impedance at the observation point P can be calculated as:

$$V_3 = V_2 \left[\cos\left(k_{g2}(p-b)\right) + j\frac{Z_2}{Z_{g2}} \sin\left(k_{g2}(p-b)\right) \right]^{-1},$$

$$Z_3 = Z_{g2} \frac{Z_2 + jZ_{g2}\tan\left(k_{g2}(p-b)\right)}{Z_{g2} + jZ_2 \tan\left(k_{g2}(p-b)\right)}.$$

Load impedance is defined as:

$$Z_4 = jZ_{g2}\tan\left(k_{g2}(d-p)\right).$$

The resulting voltage at the observation point P can be calculated as $V_p=V_3Z_4/(Z_3+Z_4)$. Then the SE at point P inside the connector is defined as:

$$SE = -20\log_{10}\left|2V_p/V_0\right|.$$

Using the presented analytical expressions, SE can be calculated as a function of frequency at any observation point located on the axis passing through the center of the shell, perpendicular to the aperture. This corresponds to the worst case for SE. The method of transforming the source to the observation point can also be easily changed for the arbitrary location of the dielectric inside the shell. To do this, it is enough to change the arguments of trigonometric functions and the characteristic impedance.

3. Validation of the analytical model

To validate the analytical model, calculations of the SE of the shell with R=150 mm and d=300 mm were performed. Two cases were considered: the shell with full opening (r=R) and full dielectric filling (ε'=3.72), and the shell with r=40 mm and partial dielectric filling (b=100 мм). The calculations were performed for p=150 mm in the frequency range of 1–1000 MHz. Only TE_{11} modes were considered. SE results were also obtained using the numerical finite element method (FEM). The resulting frequency dependences are shown in Figures 2a and 2b.

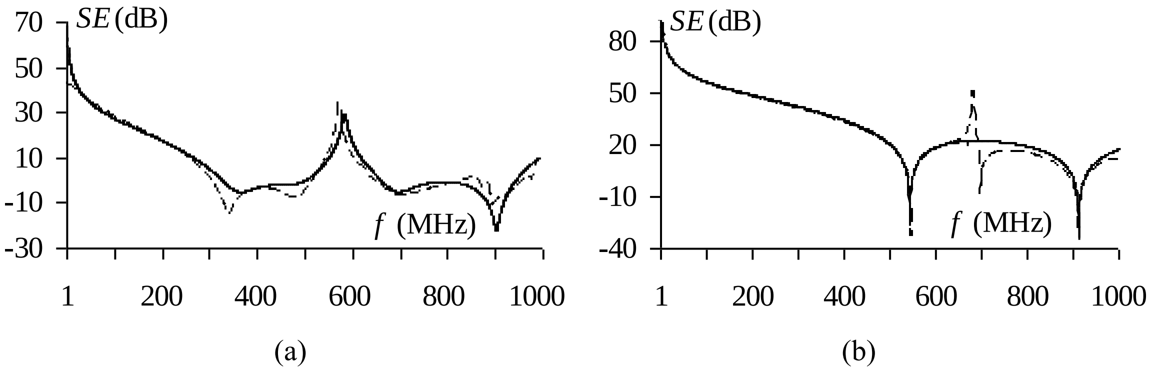

Figure 2. Results of calculating the SE by the analytical model (—) and FEM (– –) for a cylindrical shell with full (a) and partial (b) dielectric filling.

From Figures 2a and 2b it can be seen that the results are consistent. The average value of absolute error for the frequency dependences was 3.12 dB (Figure 2a) and 2.88 dB (Figure 2b). The frequency dependence obtained by FEM (Figure 2b) has a resonance at the frequency about 700 MHz, which corresponds to the first resonance for the TE_{21} mode. The presented model doesn't take into account higher-order modes. However, it can be improved using the approach proposed in the paper [7].

4. Analysis of the connector shielding effectiveness

Using the proposed model, SE calculations of the 2RMDT-connector were performed. This low-frequency industrial connector is used in DC and AC circuits (up to 3 MHz). In accordance with the MIL-STD-461G, such calculations must be performed up to the frequency of 18 GHz, but this is not required when the connector is used in a power bus. Therefore, a frequency range of 0–1 GHz was chosen to calculate the SE. The geometrical model of the connector is shown in Figure 3. The shell has an internal diameter of 28 mm and a total length of 64 mm. The body is partially filled with a dielectric (ε'=6) by the length of b=26.5 mm.

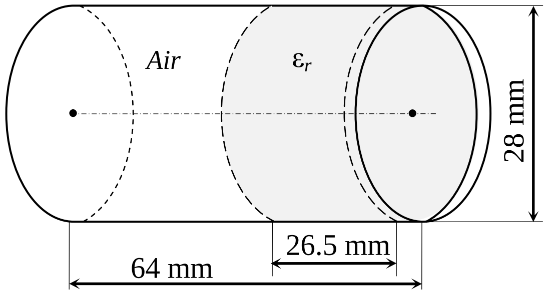

Figure 3. Geometrical model of the cylindrical 2RMDT-connector shell with partial dielectric filling.

The calculations were performed for r=R=28 mm and the end wall thickness t=2.5 mm when the observation point P changed from 8 mm to 54 mm from the aperture. For observation points located inside the dielectric, the load impedance was defined as:

$$Z_4 = Z_{g1} \frac{Z_5 + jZ_{g1} \tan\left(k_{g1}(b-p)\right)}{Z_{g1} + jZ_5 \tan\left(k_{g1}(b-p)\right)}$$

where Z_5=jZ_{g2}tan(k_{g2}(d – b)). The results are shown in Figure 4.

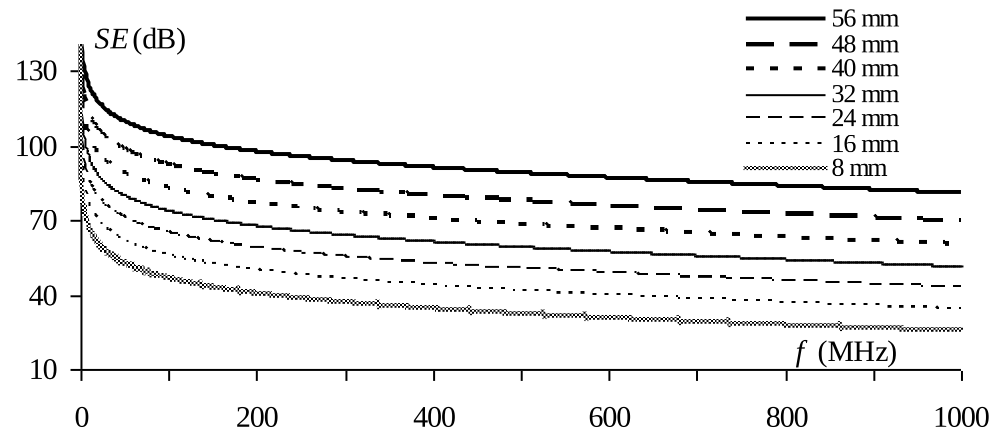

Figure 4. Frequency dependencies of the 2RMDT-connector SE at various observation points.

As can be seen from Figure 4, the dependencies monotonously decrease with increasing frequency. When the observation point is shifted from the aperture, the SE increases in the entire frequency range by approximately 10 dB for each subsequent point P. At the observation points located inside the dielectric, the SE dependencies don't undergo visible changes. The worst SE value was obtained at the point p=8 mm at the frequency of 1 GHz and was 26 dB.

5. Conclusion

A new analytical model has been developed for estimating the SE of cylindrical connectors. Its results are in good agreement with the results obtained by FEM. The model can be applied to connectors and cylindrical shells with full or partial dielectric filling. Also it can be used if the dielectric consists of many layers with different permittivity, which is important because of the wide use of composite shielding materials. SE calculation by the analytical model, as compared to the FEM, takes significantly less time. The proposed model can be useful for the design of shielding structures used in mechanical engineering.

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The results of this work will be used in the future to study the effect of permittivity and dielectric loss on SE of shells. This is a serious problem for shielding, because dielectric filling can significantly influence the SE.

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