Shielding Effectiveness of a Lossy Metallic Enclosure

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ABSTRACT

In this paper, shielding effectiveness (SE) of a perforated enclosure with imperfectly conducting walls is evaluated. To this end, first, an accurate numerical technique based on method of Moments (MoM) is presented. In this method, lossy metallic walls of the enclosure are replaced by equivalent electric surface current sources. Then, the impedance boundary condition on the imperfectly conducting surfaces is applied and an electric field integral equation is extracted. At the end, the integral equation is solved numerically by Galerkin method. In addition to the mentioned numerical method, an extremely fast analytical technique based on transmission line model(TLM) is proposed which is able to predict the SE with high level of accuracy over a large frequency bandwidth just in a few seconds. For validation of both methods, other commercial softwares (FEKO and CST) are employed and several enclosures with different conductivities are studied. Lossy MoM method shows accurate results for conductivities down to 10S/m, while efficient TLM method proves its accuracy for conductivities down to 250S/m.

KEWORDS

Finite Conductivity, Lossy Metallic Box, Shielding Effectiveness, Shielding Enclosure, Transmission Line Method.

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1- INTRODUCTION

Shielding enclosures are used to protect sensitive systems against radiated disturbance in their environment. Also, using an enclosure is a common way to hinder the produced interfering emission from the equipment. Shielding effectiveness (SE) of an enclosure is mainly affected by the perforations and wall material. SE is defined as the ratio of field strength in present and absence of the enclosure at an observation point inside the enclosure.

In the majority of reported works, in order to simplify the analysis, walls of the enclosure are assumed to be perfect electric conductor (PEC). Various analytic and numerical methods have been introduced to calculate the SE of lossless enclosures with apertures [1-7] Among mentioned methods, transmission line model (TLM) is the fastest technique with high accuracy for rectangular apertures [8-10] However, SE of an enclosure is affected significantly, when a material with low finite conductivity is used.

So far, a few reports have focused on the effect of lossy walls. For example in [11] the authors provide a method based on perturbation theory to analyze the modes of a rectangular waveguide with imperfectly conducting walls. In [12] a power balance method is suggested to estimate the transmitted power into a perforated enclosure, based on the power conservation law. In addition, a perturbation method is introduced for a cavity with good conductive walls in [13] by Collin. In [14] a new method is presented to find the transferred field through allow loss thin infinite wall without any aperture. In the mentioned method, transfer function of the finite conducting thin sheet is found analytically via computing the transmission and reflection coefficients of the sheet. Finally, the desired fields are found by a recursive convolution integral on the impulse response of the system. In [15] a method based on Warne and Chen's transmission line hybrid with local slot antenna model is suggested to evaluate a lossy shielding enclosure. In addition, in [16] a method based on iterative physical optics (IPO) is used to evaluate the field inside the cavity with imperfectly conducting walls. The method is validated for a planar parallel waveguide.

In this work, two approaches are employed to evaluate the SE of a perforated shielding enclosure with imperfectly conducting walls. The first method is a method of Moments (MoM) based on full wave solution, and the second one is a very fast approximate technique based on TLM.

In the first method, the lossy metallic structure of the enclosure is replaced by an unknown physical electric surface current. Next, electric field is calculated by using the free space Green's function. After that, by enforcing the impedance boundary condition, an electric field integral equation (EFIE) is achieved and then is solved by Galerkin method. To solve the EFIE, RWG basis functions are used to expand the unknown electric current. Having the electric current on the surface of the structure, the electromagnetic fields are obtained and consequently SE is calculated. This method is valid at

frequencies where the walls can be considered as good conductors.

The second approach is a TLM in which complex propagation constants and complex characteristic impedances are employed in the conventional model in order to take into account the loss of the walls. This method is extremely fast and can predict SE accurately for the same frequency range studied in the first method. However, its accuracy is decreased more rapidly rather than the first approach as conductivity of the structure is decreased.

The manuscript is organized as follows. In Section 2, the formulation of two techniques is described. In section 3, results are validated by software simulations. Good agreement between the results shows the applicability of two methods in evaluating the SE of different lossy enclosures. Section 4 includes the conclusion.

2-THEORY

2-1- MoM MATHEMATICAL FORMULATION FOR LOSSY WNCLOSURE

Consider a rectangular metallic enclosure with interior dimensions of a×b×c as in Fig. 1. Wall thickness is assumed to be t and there is a W×L rectangular aperture in the illuminated front wall.
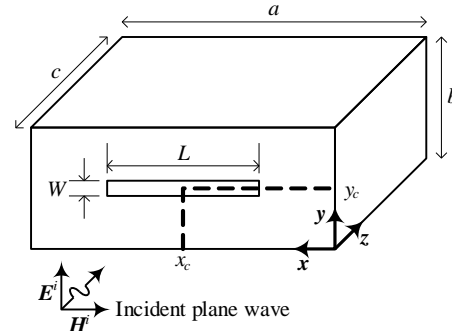

Fig.1. Illuminated lossy enclosure

Since the enclosure is formed by good conductor material, the impedance boundary condition (IBC) can be applied on the surface of the enclosure [17] and [18]. IBC relates the total tangential electric field ($\vec{E}$) to the total magnetic field ($\vec{H}$) at any point on the surface of the a good conductor surface by

$$\hat{n} \times \vec{E} = Z_S \hat{n} \times \hat{n} \times \vec{H}, \tag{1}$$

where is the normal to surface unit vector and, is the surface impedance of the utilized material that is formulated as

$$Z_S = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}} = R_S + jX_S = \sqrt{\frac{\omega\mu}{2\sigma}} + j\sqrt{\frac{\omega\mu}{2\sigma}}, \tag{2}$$

where ε, μ and σ are intrinsic parameters of the lossy conductor. R_S and X_S are surface resistance and reactance, respectively; and ω is the angular speed of the impinging field.

Considering the electric current on the surface of the enclosure as $\vec{J} = -\hat{n} \times \vec{H}$, (1) turns into

$$\hat{n} \times \vec{E}(\vec{r}) = -Z_S\, \hat{n} \times \vec{J}(\vec{r}), \tag{3}$$

On the other hand, total tangential electric field at any point $\vec{r}$ on the surface of the enclosure is

$$\vec{E}(\vec{r})|_{\tan} = \vec{E}_i(\vec{r})|_{\tan} + \vec{E}_s(\vec{r}, \vec{J})|_{\tan}, \tag{4}$$

where, $\vec{E}_i$ is the incident electric field and $\vec{E}_s$ is the scattered electric field due to the induced surface electric current on the enclosure and is calculated by

$$\vec{E}_S(\vec{r}, \vec{J}) = -j\omega\vec{A}(\vec{r}, \vec{J}) - j\frac{1}{\omega\mu_0\varepsilon_0}\nabla\nabla\cdot\vec{A}(\vec{r}, \vec{J}), \tag{5}$$

where ε_0 and μ_0 are intrinsic permittivity and permeability constants of free space, respectively. In addition, $\vec{A}$ is the magnetic vector potential that is obtained by

$$\vec{A}(\vec{r}, \vec{J}) = \frac{\mu_0}{4\pi}\iint\limits_{metallic\ surface}\vec{J}(\vec{r}')G(\vec{r}, \vec{r}')ds', \tag{6}$$

where $G(\vec{r}, \vec{r}') = e^{-jk_0|\vec{r}-\vec{r}'|}/|\vec{r} - \vec{r}'|$ is the free space Green's function and k_0 is the wave number of the impinging field in free space. Replacing (3) and (5) in (4) and doing some mathematical simplifications gives the following EFIE

$$\hat{n} \times (\frac{-j\omega\mu}{4\pi}\iint\limits_{s'}\vec{J}(\vec{r}')G(\vec{r}, \vec{r}')ds'$$
$$-\frac{\mu}{4\pi}\iint\limits_{s'}\nabla'\cdot\vec{J}(\vec{r}')\nabla G(\vec{r}, \vec{r}')ds' + \vec{E}_i(\vec{r})) = -Z_s\hat{n}\times\vec{J}(\vec{r}), \tag{7}$$

In order to solve the integral equation of (7), the enclosure surface is discretized by triangular meshes and is expanded by RWG basis functions [19].Some mathematical considerations should be taken into account. First, singularities in (7) are treated by singularity subtraction technique in [20]. Secondly, to make the integrations fast, barycenteric subdivision of triangle meshes is employed according to [21] to divide each mesh to thirty six sub-meshes. Then, it is assumed that the integrand is constant within each sub-mesh. Therefore, the integral can be evaluated by adding integrand values, all together, at the midpoint of each small triangle.

As a brief overview, here, the required steps in lossy MoM are given:

1- Lossy metallic walls of the enclosure are replaced by the unknown equivalent electric surface current density.
2- An electric field integral equation is extracted by enforcing the impedance boundary condition of (3) on the imperfectly conducting surfaces.
3- The integral equation is solved numerically by Galerkin method to calculate equivalent currents.
4- The electric field is calculated at any observation point.

5- The SE is calculated as the ratio of field strength in present and absence of the enclosure at an observation point inside the enclosure.

2-2- TLM MATHEMATICAL FORMULATION FOR LOSSY ENCLOSURE

Robinson et al. in [9] have proposed an extremely fast and simple to implement circuit model to estimate the shielding effectiveness of a rectangular enclosure with rectangular aperture. Since then the initial model has been generalized to analyze more realistic cases. In this model, the enclosure is represented by a shorted waveguide. In addition, rectangular aperture is assumed to be a coplanar strip transmission line of total width b and separation of W and length L that is shorted at both ends.

In this paper, the circuit model of Robinson is modified to take the losses of the metallic walls into account. Limited conductivity of the walls alters the ideal propagation constant and intrinsic impedance of the representing waveguide and coplanar strip line of Robinson's model. Fig. 2 shows our proposed equivalent circuit model for lossy enclosure of Fig. 1 based on Robinson's TLM.
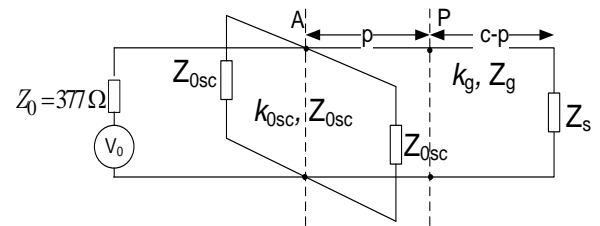

Fig.2. A cavity with imperfectly conducting walls and its proposed circuit model.

According to [9] the propagation constant of a lossy waveguide can be written as $k_g = \alpha_g + j\beta_g$ where α_g is the attenuation constant and β_g is the phase constant as

$$\alpha_g = \frac{R_s}{\eta b}\frac{\left[1 + \frac{2b}{a}\left(\frac{f_c}{f}\right)^2\right]}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}}, \tag{8}$$

and

$$\beta_g = \frac{\omega}{c}\sqrt{1 - \left(\frac{f_c}{f}\right)^2}, \tag{9}$$

where a and b are waveguide cross section dimensions, η is the free space's intrinsic impedance and f_c is the cut-off frequency of the waveguide. The characteristic impedance of the lossy waveguide is obtained using

$$Z_g = j\frac{\omega\mu}{k_g}, \tag{10}$$

For the representing lossy coplanar strip line, here in this paper, we propose using the propagation constant of

$k_{0sc} = \alpha_{0sc} + j\beta_0$ in [22] where β_0 is the free space phase constant and α_{0sc} in Np/m is

$$\alpha_{0sc} = 17.34(\frac{R_s}{Z_{0sc}})\log\left(1 + 4\pi\frac{b-W}{2t} + \frac{2.5t}{\pi(b-W)}\right)$$
$$\times\left(\frac{1.25}{\pi}\right)\frac{P(1+\frac{1+(b-W)}{2W})/(\pi W)}{(1+\frac{b-W}{W}+\frac{1.25t}{\pi W}(1+\log(2\pi\frac{b-W}{t})))^2} \quad (11)$$

and the characteristic impedance of the equivalent coplanar strip line is

$$Z_{0sc} = \frac{120\pi^2}{\log\left(2\frac{1+\kappa_e}{1-\kappa_e}\right)}, \quad (12)$$

where,

$$P = \frac{k(1-k^2)^{3/4}}{1-\sqrt{1-k^2}}\cdot\left(\pi\Big/\log\left(2\frac{1+\sqrt{1-k^2}}{1-\sqrt{1-k^2}}\right)\right)^2 \quad (13)$$

in which

$$\kappa_e = \sqrt[4]{1-\left(\frac{W+\Delta}{b-\Delta}\right)}, \quad (14)$$

$$\Delta = \frac{5t}{4\pi}\left(1+\log\left(4\pi(b-W)/2t\right)\right), \quad (15)$$

and $k = \frac{W}{b}$.

On the other hand, the representing strip line is loaded by the imperfect metallic walls at both ends. Here, in this model, we assume the impedances of these loads be matched and equal to Z_{0sc}. In addition, the representing waveguide at the end of the enclosure is ended to a lossy wall and hence we replace it with the complex surface impedance of (2) in our model (see Fig. 2).

As a brief overview, the following steps are included in the proposed lossy TLM method:

1- The enclosure is represented by an imperfect waveguide which is modeled as a transmission line whose propagation constant and the characteristic impedance are calculated from (8)-(10).

2- It is assumed that the back wall of the enclosure is a lossy load with the given impedance in (2).

3- The rectangular aperture is assumed to be a lossy coplanar strip transmission line of total width b and separation of W and length L. Then, its propagation constant and characteristic impedance are calculated from (11)-(15).

4- Assuming the equivalent coplanar stripline in step 2 is matched at both ends, the representing aperture impedance can be calculated.

5- By replacing the enclosure, the back wall and the aperture with the equivalent circuit model in steps 1 to 4 the equivalent circuit model is obtained.

6- By adding the incident wave as a voltage source with the internal impedance of $Z_0 = 377\ \Omega$ to the circuit model, the equivalent circuit model is completed.

7- By considering the new circuit parameters and using the procedure given in [9], SE is calculated easily at point P at a distance p from the perforated wall.

3- RESULTS

3-1- SE EVALUATION BY LOSSY MoM

Consider a $300\times120\times300$ mm^3 cavity with a central 180×40 mm^2 aperture on the front face. Different materials are considered for the perforated box and the electric field SE (dB) is calculated at the center of the enclosure. In all cases, wall thickness is assumed to be 4mm. The results lossy MoM method is compared with other numerical methods such as finite integration technique (FIT) and MoM in commercial softwares of CST and FEKO, respectively. In addition, for the case of aluminum enclosure, measurements are used to validate the method. The measurements are performed in the anechoic chamber of the Institute of Communications Technology and applied Electromagnetics of Amirkabir University of Technology. The transmitter antenna is a wideband double-ridged horn antenna, while a monopole antenna is connected to the top lid using a SMA connector to measure the electric field. The first port of a network analyzer was connected to the horn antenna and the second port to the monopole. To measure SE, a 30 cm^2 metal plate with the monopole antenna at its center producing a dipole is illuminated and S21 is measured. Then, the enclosure with the probe at the same location of the reference is identically illuminated. The difference between the measured S21 (dB) is SE. The enclosure and the reference plane are placed in the far field of the source antenna.

First, it is assumed the enclosure is formed by Aluminum plates with conductivity of $\sigma = 3.5\times10^7$S/m. The results of the lossy MoM method are compared with results of CST, FEKO and measurements in Fig. 3, at 500 to 1000MHz. As observed, there is good agreement between different methods. As it is observed in the Fig. 3, at around 600 to 950 MHz, the SE becomes negative. Negative SE means that the enclosure along with the aperture no longer act as protective box against the external electromagnetic field. In fact at these frequencies the enclosure acts as a resonator which produces very large values for the fields at some points inside it. Large negative SE bandwidth is due to the close resonant frequencies of the enclosure itself and the aperture.

In the next step, the conductivity is assumed to be about one hundred times lower (10^5S/m). The SE of the cavity is calculated and compared in Fig. 3 up to 1000 MHz. Again, Fig. 4 shows good agreement between the results. In the next three cases, conductivity is assumed to be 1000S/m, 110S/m for Milliken and 10S/m. The proposed MoM method is compared with softwares in Figs. 5-7. As CST and FEKO show similar results, only one of them is used for verification in a number of figures. Please note that, since the proposed method forces the IBC (that is only valid for good conductors) it shows accurate results

for the assumed conductivity values at the considered frequency range. However, it is obvious that for conductivity of 10S/m in Fig. 7, our MoM results show little difference with CST. On the other hand, all the results confirm the fact that as the conductivity of the structure decreases, due to decreased Q factor of the shield, SE improves.

3-2- SE EVALUATION BY LOSSY TLM

Fig. 8 compares the results of the circuit model with measurements for the same enclosure of Fig. 3. As observed good accordance can be inferred for the Aluminum enclosure case. In addition, Figs. 9-12 shows the calculated SE by lossy TLM method for the same enclosure with different conductivities of 10^5, 1000, 500 and 250S/m. The figures confirm the accuracy of the approximate lossy TLM technique in predicting SE of lossy enclosures. In each figure, one or two numerical method is considered for validation. Please note that lossy TLM method gives the results in less than a few seconds, while numerical methods last a few hours. Also, the method is very simple to implement. These properties highlight the power of this approximate method.

Please note that as conductivity decreases the accuracy decreases too, especially at higher frequencies. However, this method can still be referred when a very fast SE prediction is needed for highly lossy cases.

4- CONCLUSION

To evaluate the SE of a lossy perforated enclosure two different methods are introduced. The first one is a MoM based numerical method that assumes an electric current on the enclosure and forces IBC on the surface of the enclosure. The results of these methods can be used as a way to choose proper material at the considered frequency range for the shielding purposes. Each conducting material has a finite conductivity and skin depth which may change with the frequency.

Both proposed methods calculate the SE of the lossy enclosure for different levels of conductivity. Lossy MoM has good accuracy even at small conductivities such as 10 S/m. In comparison with the full-wave methods where the body volume of the lossy walls is discretized, lossy MoM discretizes only the surface of the enclosure and owes fewer meshes and consequently more efficiency. Lossy TLM is not as accurate as lossy MoM, and it lost its accuracy at small conductivity values (up to 250 S/m) where lossy MoM is still an accurate solution. However, lossy TLM is extremely fast and the total calculation time is in less than just one second while lossy MoM calculation lasts a few hours. Since lossy TLM's implementation is very easy, for a fast SE prediction, lossy TLM is a very useful and accessible tool.
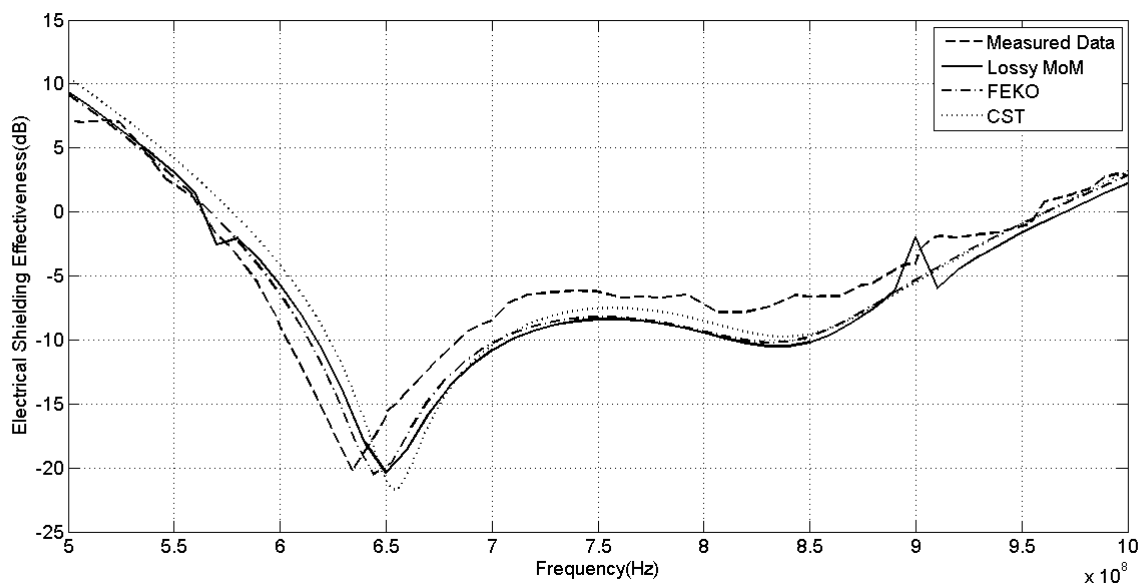

Fig.3. SE of a 300×120×300mm cavity with one 180×40mm aperture, 4mm wall thickness and conductivity of 3.5×10⁷S/m at its center.
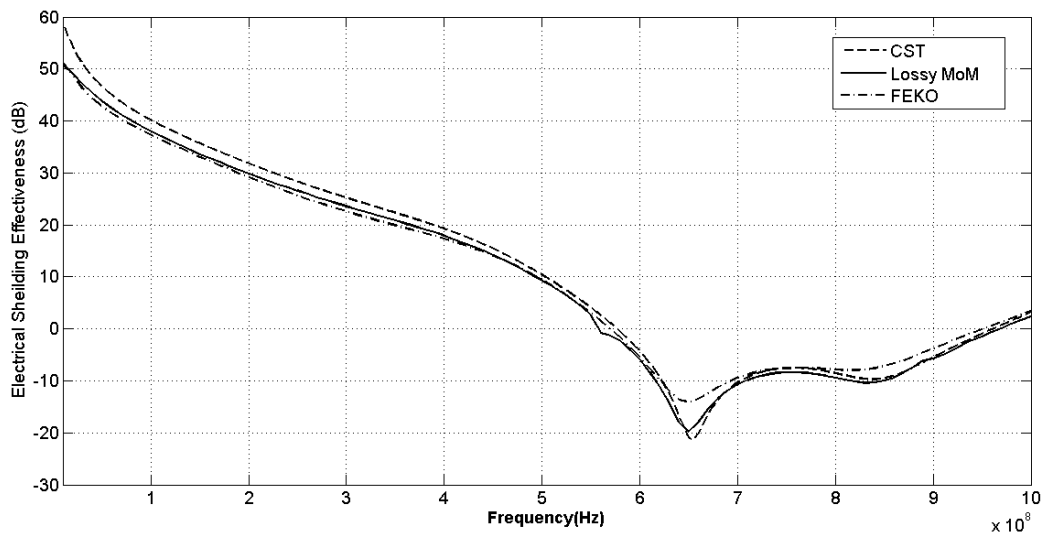
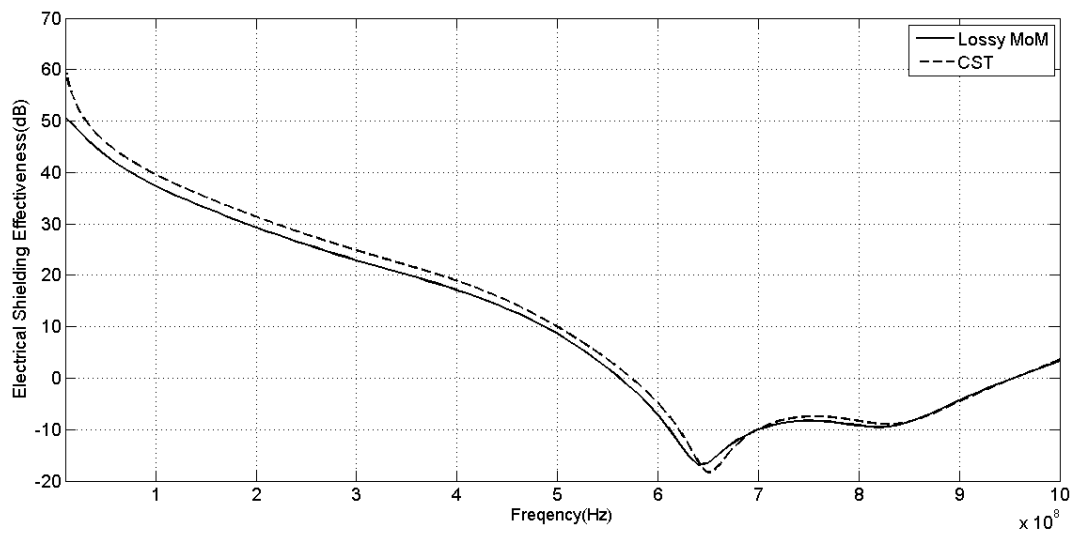**Fig.4. SE of the enclosure in Fig. 3 with conductivity of 105S/m.**

Fig.5 .SE of the enclosure in Fig. 3 with conductivity of 10^3S/m
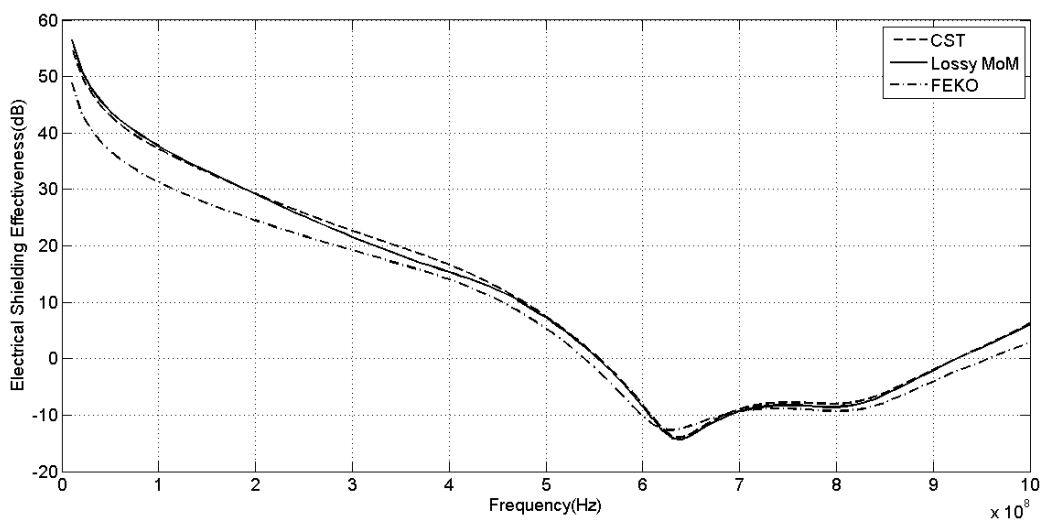
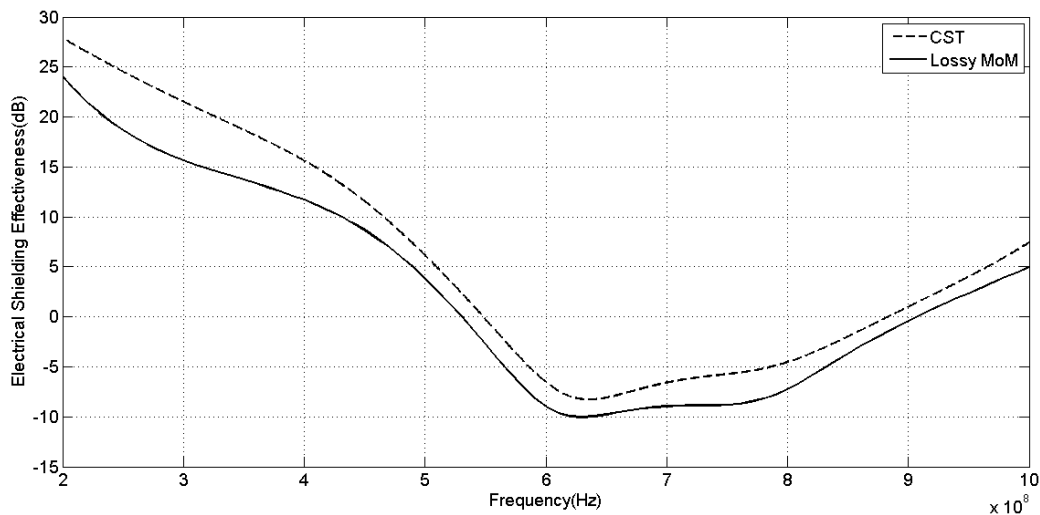**Fig.6 .SE of the enclosure in Fig. 3 with conductivity of 110S/m**

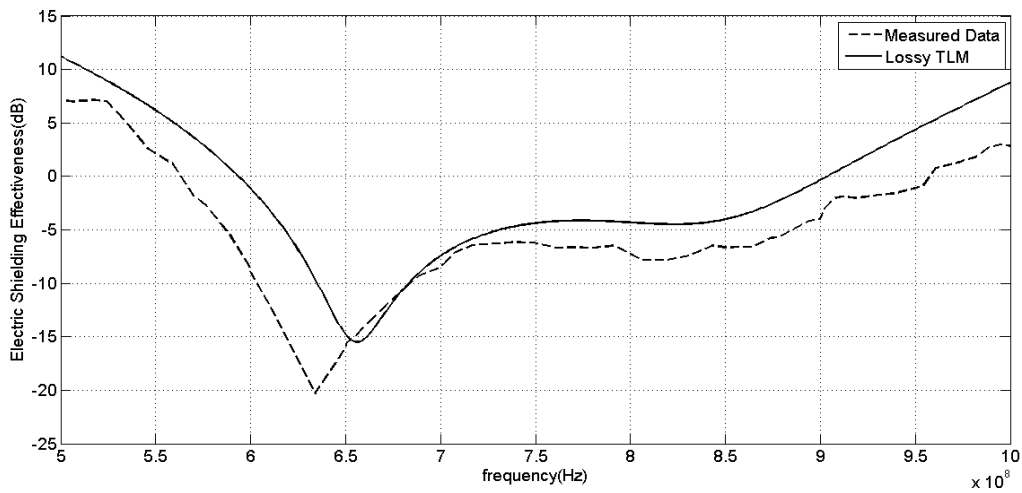**Fig.7 .SE of the enclosure in Fig. 3 with conductivity of 10S/m**

Fig.8.SE comparison for the enclosure in Fig. 3 with conductivity of 3.5×10^{7}S/m for lossy TLM technique
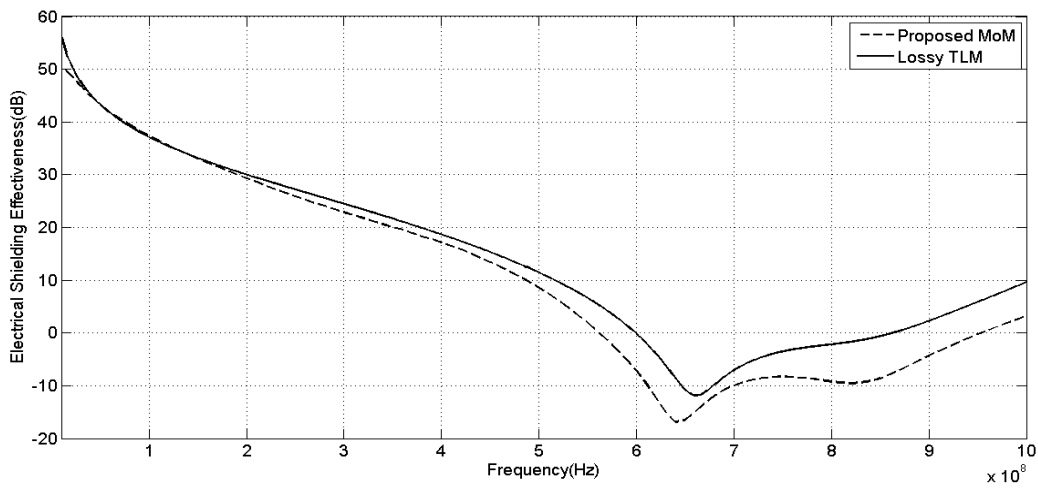

Fig.9.SE comparison for the enclosure of Fig. 3 with conductivity of 10^5 S/m for lossy TLM technique
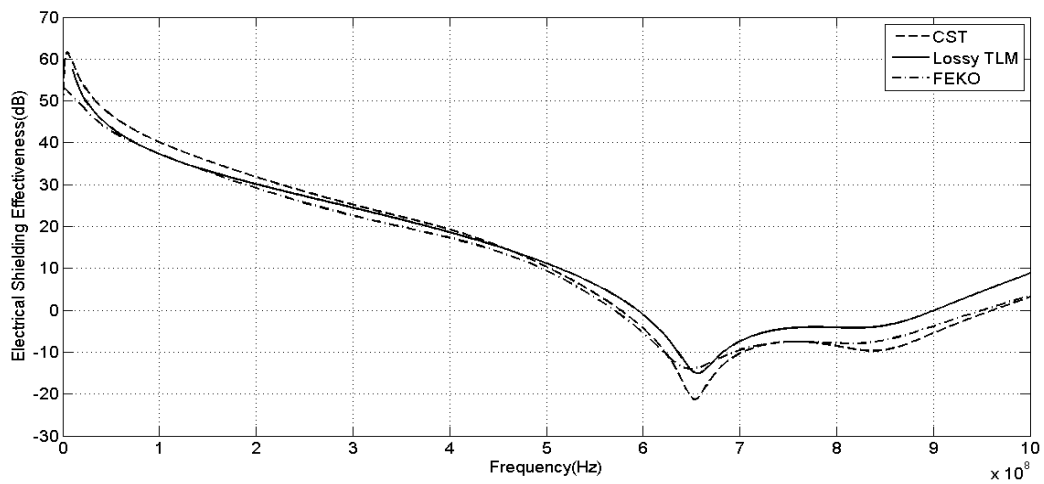

Fig. 10.SE comparison for the enclosure of Fig. 3 with conductivity of 1000S/m for lossy TLM technique
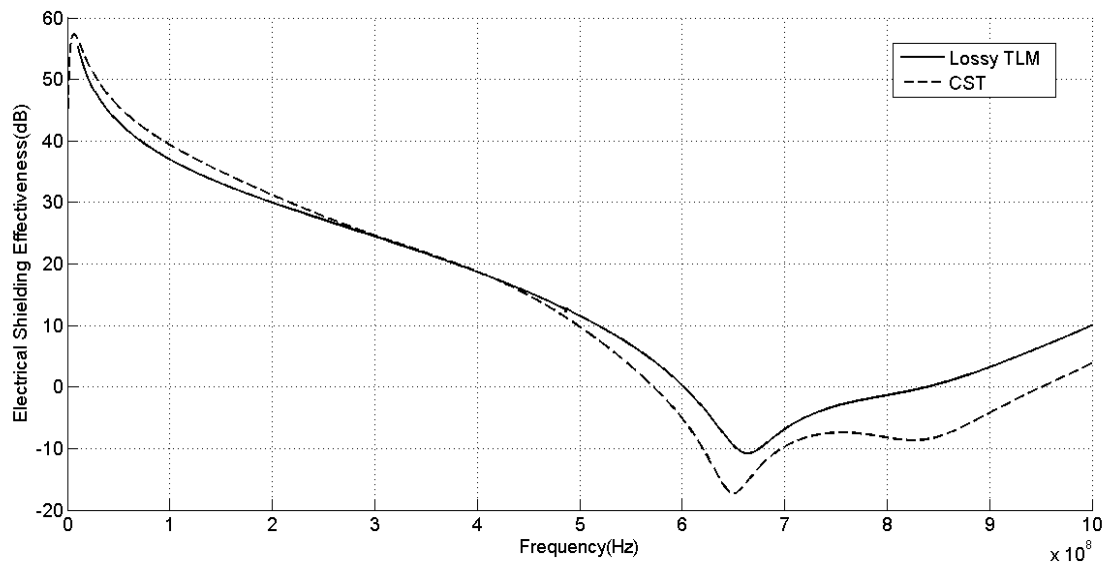
Fig.11.SE comparison for the enclosure of Fig. 3 with conductivity of 500S/m for lossy TLM technique
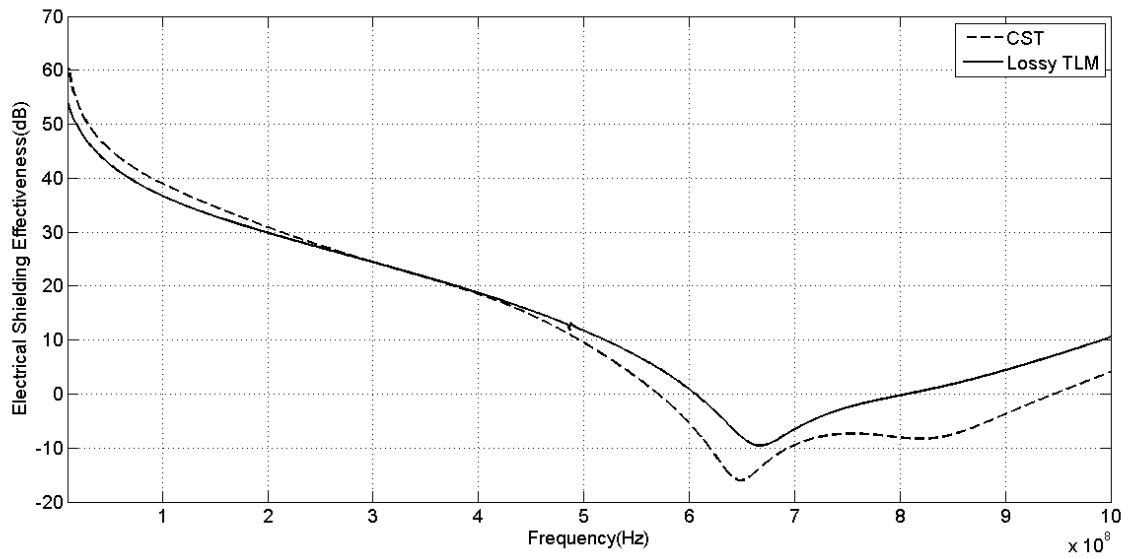

Fig.12.SE comparison for the enclosure of Fig. 3 with conductivity of 250S/m for lossy TLM technique

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