A Circuital Approach to Evaluating the Electromagnetic Field on Rectangular Apertures Backed by Rectangular Cavities

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***Abstract*—In this paper, the problem of evaluating the electromagnetic field on rectangular apertures backed by rectangular cavities is investigated. The electromagnetic-field distribution is derived by using a circuital model of an aperture and suitable forcing terms introduced into the equations related to the aperture model. The effects of a rectangular cavity on the aperture-field distribution are assessed by considering the rectangular cavity as a load impedance. The impedance value is obtained by modeling the rectangular cavity as a length of rectangular waveguide back-ended by a short. The distribution of the electromagnetic field on the aperture is used as an exciting source to evaluate, through a modal expansion, the electromagnetic field inside the cavity. Numerical simulations are in a good agreement with both other theoretical models and experimental data.**

***Index Terms*—Electromagnetic modeling, EMC, radiated immunity, shielding effectiveness.**

I. Introduction

In the last few years, there has been a growing interest within the electronic industry regarding problems related to the applications of shielding devices.

Some works have faced the problem of emission from an aperture caused by an internal field source. In this problem, the aperture is treated as an aperture antenna that radiates in the external region. First, the field due to the internal source is computed on the aperture. Such a field is then used as the source in the aperture antenna problem [1], and the radiated field is obtained by imposing suitable boundary conditions between the internal and external regions.

Another typical problem is the evaluation of the penetration of an electromagnetic field through apertures on the surface of a metallic cabinet. When one considers an external electromagnetic field that impinges on the metallic cabinet, the problem becomes a scattering one. In these kind of problems, the difficulty is in finding the correct distributions of the electromagnetic field on the apertures and to match the electromagnetic field with that inside the metallic cabinet. The numerical evaluation of the electromagnetic field inside the metallic cabinet may be obtained to a high degree of accuracy by using various computational methods such as the method of moments (MoM), finite-difference time domain (FDTD) [2], [3], finite-element method (FEM) [4], Fourier transform, and mode matching [5]. However, the computational efforts required by such methods does not always justify their use, especially when the designer is searching for a quick (even though approximate) solution.

In some works, the electromagnetic wave is modeled by using a voltage source with an internal impedance equal to the vacuum impedance [6]. This approach is very simple and gives good results, but the electromagnetic wave cannot be well determined; in particular, this model does not permit one to specify the incidence angle and polarization of the electromagnetic wave.

In other works, the field distribution on apertures is often evaluated by means of an infinitely perfect conducting plane sheet, and the solution based on Maxwell equations is obtained by imposing correct boundary conditions on the apertures. For example, in [7], an elegant theoretical formulation is presented that considers the effects of diffraction of the electromagnetic wave by holes that are small as compared with the wavelength.

The main purpose of this paper is to present a method based on a circuital approach that is able to predict the field distributions on rectangular apertures backed by rectangular cavities. To this end, an aperture is modeled as a length of rectangular stripline ended by a short, and the metallic box backing the aperture is modeled as a load impedance that is calculated by regarding the box as a length of rectangular waveguide ended on one side by a short, and by considering only the fundamental propagation mode TE_{10}. In particular, the voltage distribution on the aperture (without cavity) is determined by using a well-known approach [8], [9] that was originally developed to evaluate the effects of an electromagnetic field on a transmission line. The Thevenin equivalent of this structure is evaluated and connected to the load given by the backing cavity. In order to evaluate the electromagnetic field on the aperture, the final value of the field is calculated by considering the divider between the impedance of the aperture and the impedance of the metallic cabinet. After these steps, we find an approximate, but accurate enough valuation of the field distribution on the aperture, and we exploit it as a source for the computation of the field inside the cabinet.

In order to test the model, the field inside the metallic cabinet is computed through a modal expansion [10]. Each term of the modal expansion is determined by using the field computed on the apertures as the exciting source. It is worth notice

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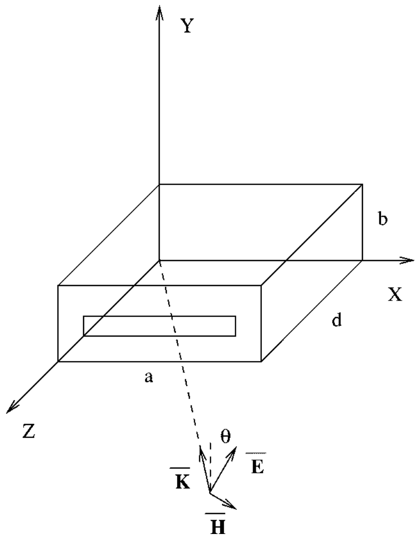

Fig. 1. Geometry of the problem.

that, whereas the field distribution along the rectangular aperture is computed considering only the fundamental propagation mode TE_{10} (and this approximation gives good accuracy in most cases of practical interest), the matching between the field distribution on the rectangular aperture and the field inside the enclosure is evaluated by using a modal expansion and also considering higher modes.

The proposed model provides a high degree of accuracy with a low computational burden, as compared with more complex numerical methods; moreover, the model is more variable than other circuital models [6], as the incident field can be well defined in terms of the propagation vector and polarization angle. With respect to a previous model by the authors [11], the present approach provides a better accuracy in the computation of the field inside the enclosure. Furthermore, the field source on the aperture is better matched with the modes of the rectangular cavity.

II. Mathematical Formulation

The first goal is to derive the circuital model of a rectangular aperture illuminated by an external uniform plane wave. The plane wave is characterized by an arbitrary propagation vector $\mathbf{k}$ and an arbitrary polarization angle θ (see Fig. 1). In order to obtain the model, the Thevenin theorem is used and the aperture is considered separate from a metallic cabinet.

The rectangular aperture is characterized by the dimensions l, w, and t, which are, respectively, the width, height, and thickness of the metallic sheet (see Fig. 2).

In order to apply the Thevenin theorem, the impedance of the rectangular aperture must be calculated. This task is accomplished by following the method presented in [6], where the characteristic impedance of a rectangular aperture is derived as the impedance of two lines ended with shorts and having the characteristic impedance of a coplanar-strip transmission line

$$Z_{\mathrm{ap}} = \frac{1}{2} jZ_{\mathrm{cs}} \tan \frac{k_0 l}{2} \tag{1}$$

where $k_0 = 2\pi/\lambda$ and Z_{cs} is the characteristic impedance of the strip [12].

The approximation used to model an aperture as a transmission line also permits one to find the equivalent voltage source, which models the coupling between the electromagnetic wave and aperture. The approach to evaluating the coupling between the electromagnetic field and the transmission line involves introducing suitable forcing terms into the transmission-line equations [8], [9].

According to this method, the usual equations for a transmission line are modified by introducing two forcing functions as follows:

$$\frac{\mathrm{d}V(x)}{\mathrm{d}x} = -j\omega LI(x) + V_f(x) \tag{2}$$

$$\frac{\mathrm{d}I(x)}{\mathrm{d}x} = -j\omega CV(x) + I_f(x) \tag{3}$$

where L and C are the inductance and capacitance (per unit length) of the line, respectively, and $V_f(x)$ and $I_f(x)$ are the two forcing functions.

According to the notation used in Fig. 2, the forcing functions can be written as follows [8]:

$$V_f = j\omega \int_{y_1}^{y_2} \mathbf{B^i} \cdot \hat{a}_z \,\mathrm{d}y \tag{4}$$

$$I_f = j\omega C \int_{y_1}^{y_2} \mathbf{E^i} \cdot \hat{a}_y \,\mathrm{d}y \tag{5}$$

where $\mathbf{B^i}$ is the magnetic induction vector incident on the aperture, $\hat{a}_z$ is the z-axis versor, $\hat{a}_y$ is the y-axis versor, and $\mathbf{E^i}$ is the electric-field vector incident on the aperture. The above relations are found by using quasi-TEM approximations.

By combining the relations (2) and (3) and introducing the forcing functions (4) and (5), the following differential equation is obtained:

$$\frac{\mathrm{d}^2V(x)}{\mathrm{d}^2x} + \omega^2 LCV(x) = -j\omega LI_f(x) + \frac{\mathrm{d}V_f}{\mathrm{d}x}. \tag{6}$$

The vertical slabs are assumed to be the two conductors that act as load for the transmission line and give the correct boundary conditions (7) necessary to solve the linear differential equation (6) as follows:

$$\begin{cases} V(x_1) = 0 \\ V(x_2) = 0 \end{cases} \tag{7}$$

where $x_1$and x_2 are the positions of the shorts at the end of the line.

The following relation gives the solution to (6) that represents the voltage $V(x)$ along the line:

$$V(x) = Ae^{-j\omega\sqrt{LC}\,x} + Be^{+j\omega\sqrt{LC}\,x} + Ke^{-jk_x x} \tag{8}$$

where K, A, and B are complex constants. We refer the reader to [11] for a detailed solution.

Now the circuital model of the aperture is complete, (1) gives the equivalent impedance of the aperture and (8) gives the equivalent voltage source representing the plane wave; therefore, the Thevenin theorem can be correctly applied.

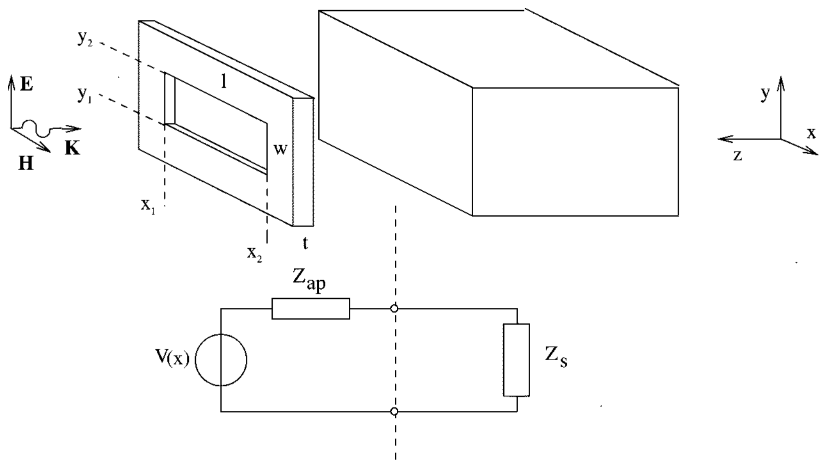

Fig. 2. Circuital model and geometries of the enclosure, aperture, and plane wave.

The last step is to derive the value of the electric field $E_y(x)$ from $V(x)$. This goal could be attained by using the following relation [13]:

$$E_y(x) = V(x)\sqrt{\frac{2}{ab}} \tag{9}$$

which is valid for an infinite rectangular waveguide whose cross-sectional dimensions are a and b, respectively.

In the present case, however, a discontinuity exists between the aperture and enclosure (that is our rectangular waveguide). To account for such a discontinuity let us introduce the following transformation ratio [11]:

$$R = \sqrt{\frac{ab}{wl}} \tag{10}$$

where w and l are the dimensions of the aperture.

By using R, the relation between $E_y(x)$ and $V(x)$ becomes

$$E_y(x) = V(x)\sqrt{\frac{2}{ab}} \cdot R = V(x)\sqrt{\frac{2}{wl}}. \tag{11}$$

The value of the electric field found by (8) and (11) is the y component of the electric field; thus, the model obtained gives a good approximation only if the horizontal dimension l is much larger than the vertical dimension w. Anyway, an extension for square apertures may be simply achieved by applying the same method in order to find the x component of the electric field $E_x(y)$. This task can be accomplished by considering the vertical slab as a coplanar-strip transmission line and the horizontal slab as a short, analogously to the computation of the y component of the electric field $E_y(x)$.

The circuital model of an enclosure without any aperture is now necessary in order to complete the model. The enclosure is taken as a rectangular waveguide in which only the fundamental mode TE_{10} is excited. Within this approximation, the enclosure is modeled as a length of transmission line ended by a short and having the same characteristic impedance Z_g and the same propagation constant k_g as the TE_{10} mode of a rectangular waveguide, i.e.,

$$Z_g = \frac{Z_0}{\sqrt{1-\left(\frac{\lambda}{2a}\right)^2}} \tag{12}$$

$$k_g = k_0\sqrt{1-\left(\frac{1}{2a}\right)}. \tag{13}$$

The enclosure may be seen as an impedance Z_s given by the following relation:

$$Z_s = jZ_g\tan(k_g d). \tag{14}$$

Fig. 2 shows the equivalent circuit that models the enclosure, aperture, and plane wave.

The value of the electric field on the aperture is obtained by defining the voltage divider between Z_s and Z_{ap} as

$$E_y^{\mathrm{ap}}(x) = E_y(x)\,\frac{Z_s}{Z_s+Z_{\mathrm{ap}}}. \tag{15}$$

The value of E_y^{ap} takes into account the effects due to the presence of the aperture and enclosure.

The value obtained by (15) is used to evaluate the electromagnetic field inside the enclosure through a modal expansion expressed by the following relation [10]:

$$\mathbf{E} = \sum_m \left[-\frac{\int_s \left(\hat{a}_z \times \mathbf{E}^{\mathrm{ap}}\right)\cdot\nabla\times\mathbf{e}_m\,\mathrm{d}s}{\left(k_m^2-k_0^2\right)\int_v |\mathbf{e}_m|^2\,\mathrm{d}v}\right]\mathbf{e}_m \tag{16}$$

where $\mathbf{E}^{\mathrm{ap}}$ is the field distribution along the rectangular aperture, which represents the exciting source, $\hat{a}_z$ is the normal vector of the cross section of the aperture, k_m is the wavenumber corresponding to the mth mode, v is the volume of the enclosure, s is the surface of the aperture, and $\mathbf{e}_m$ are the divergenceless electric eigenvectors of a rectangular cavity [10]. From (16), it can be deduced that each mode is weighted considering the exciting source $\mathbf{E}^{\mathrm{ap}}$, working frequency, and dimensions of the enclosure. We noticed that, in most cases of practical interest, only a few modes are needed to achieve a satisfactory evaluation of the field inside the metallic cabinet.

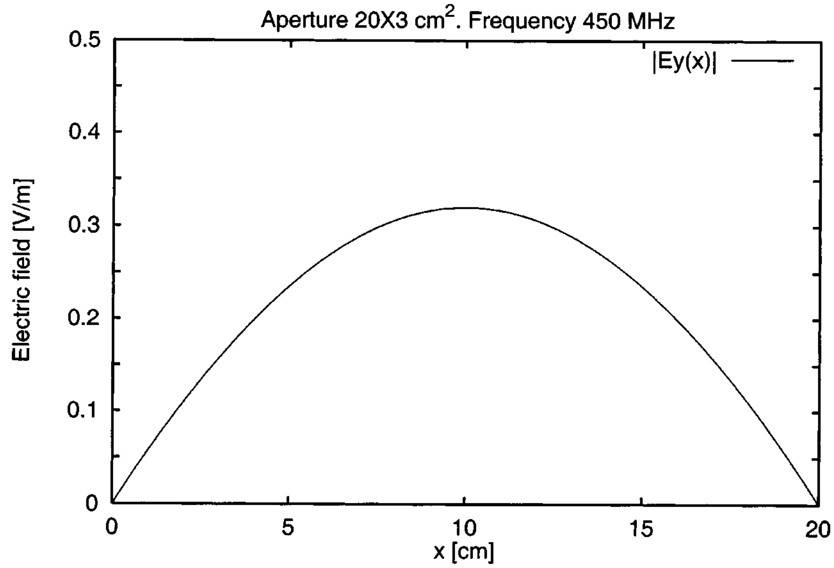

Fig. 3. Simulated electric field along the length of a rectangular aperture of 200 mm $\times$ 30 mm. Enclosure dimensions: 300 mm $\times$ 120 mm $\times$ 300 mm. Frequency: 450 MHz.

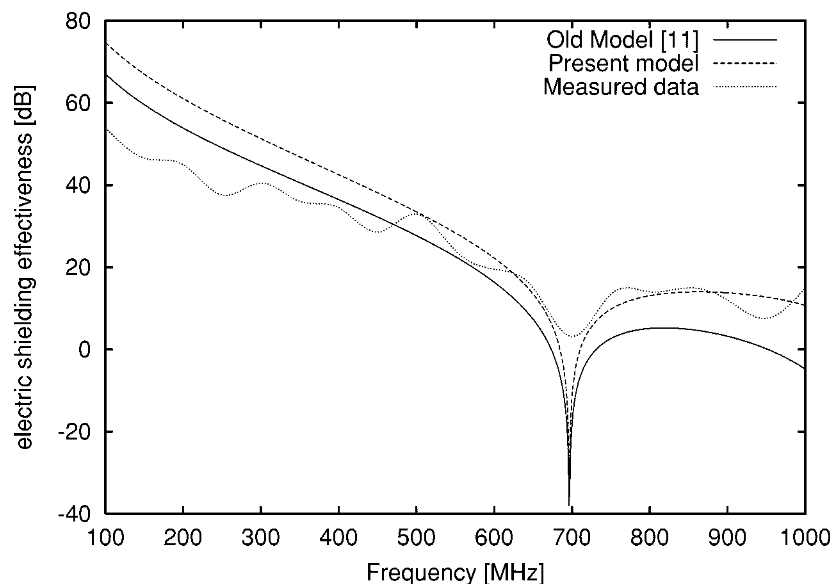

Fig. 4. Plot of the shielding effectiveness at the center of an enclosure for a frequency range from 0.1 to 1 GHz. Continuous line: model yielded in [11]. Dashed line: present model. Dotted line: measured data. Enclosure dimensions: 300 mm $\times$ 120 mm $\times$ 300 mm. Aperture dimensions: 100 mm $\times$ 5 mm.

III. Numerical Results

In this section, in order to evaluate the efficiency of the developed method, the shielding effectiveness of some enclosures and apertures are calculated by using (14) and compared with experimental data and with other numerical data obtained by another method [6]. The electric shielding effectiveness is defined as

$$SE = -20\log\left|\frac{E_p}{E'_p}\right| \tag{17}$$

where E_p is the amplitude of the electric field inside the box at a specified point p and E'_p is the amplitude of the electric field at the same point with the enclosure removed.

Furthermore, in order to give an example of a field distribution on the aperture, Fig. 3 shows the module of the electric field evaluated along the length (x-axis) of a rectangular aperture of 200 mm $\times$ 30 mm, when the aperture is backed by a rectangular cabinet of 300 mm $\times$ 120 mm $\times$ 300 mm. The electromagnetic source is a plane wave characterized by a frequency of 450 MHz and a polarization along the y-axis.

Fig. 4 shows the electric shielding effectiveness versus frequency for an enclosure of 300 mm $\times$ 120 mm $\times$ 300 mm with an aperture of 100 mm $\times$ 5 mm. The frequency was changed from 0.1 to 1 GHz. The measurement point was at the center of the enclosure. The numerical data were compared with the experimental ones, and with the data obtained by using the model proposed in [11]. The comparison between the data obtained by the present model and measured data are in a good agree-

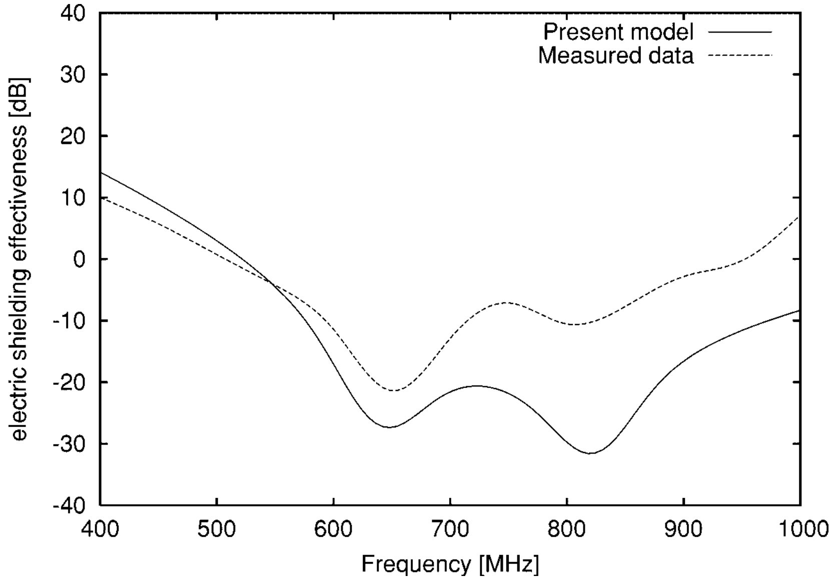

Fig. 5. Plot of the shielding effectiveness at the center of the same, enclosure as in Fig. 4, but for a frequency range from 0.4 to 1 GHz. Continuous line: present model. Dashed line: measured data. Enclosure dimensions: 300 mm $\times$ 120 mm $\times$ 300 mm. Aperture dimensions: 200 mm $\times$ 30 mm.

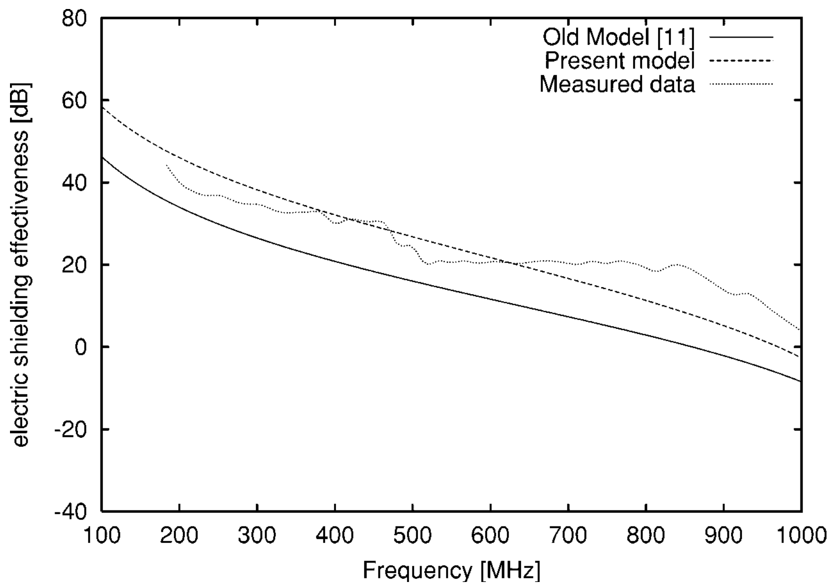

Fig. 6. Plot of the shielding effectiveness at the center of an enclosure for a frequency range from 0.2 to 1 GHz. Continuous line: model yielded in [11]. Dashed line: present model. Dotted line: measured data. Enclosure dimensions: 222 mm $\times$ 55 mm $\times$ 146 mm. Aperture dimensions: 100 mm $\times$ 5 mm.

ment, particularly in the frequency range from 500 MHz up to 1 GHz. The comparison between the data obtained with the model presented in [11] and the measured data shows a satisfactory agreement only for a frequency range from 100 up to 500 MHz instead of for frequencies above 500 MHz, where the electric shielding effectiveness is underestimated.

As expected, the shielding effectiveness decreased in the neighborhood of 700 MHz, as the dimensions of the aperture were very small and the structure tended to behave like a perfect rectangular resonator (which would have a resonance frequency of 707 MHz). Fig. 5 shows the electric shielding effectiveness versus frequency for the same enclosure as in the previous example, but with an aperture of 200 mm $\times$ 30 mm. The measurement point was at the center of the enclosure. The frequency ranged from 400 MHz to 1 GHz. Again, the numerical results were compared with the measured ones. In this case also, the results obtained by the proposed model were in good agreement with the measured data.

Fig. 6 shows the electric shielding effectiveness versus frequency for an enclosure of 222 mm $\times$ 55 mm $\times$ 146 mm with an aperture of 100 mm $\times$ 5 mm.

The frequency was varied from 0.2 to 1 GHz. Also in this example, the numerical data were compared with the experimental ones. The agreement between the numerical data and experimental ones was very good for the whole frequency range considered. The data obtained with the present model are also compared with the data obtained by means of the model proposed in [11]. From Fig. 6, it can be noted that the model proposed in [11] gives worse results with respect to the data obtained by means of the present model for the whole frequency range considered.

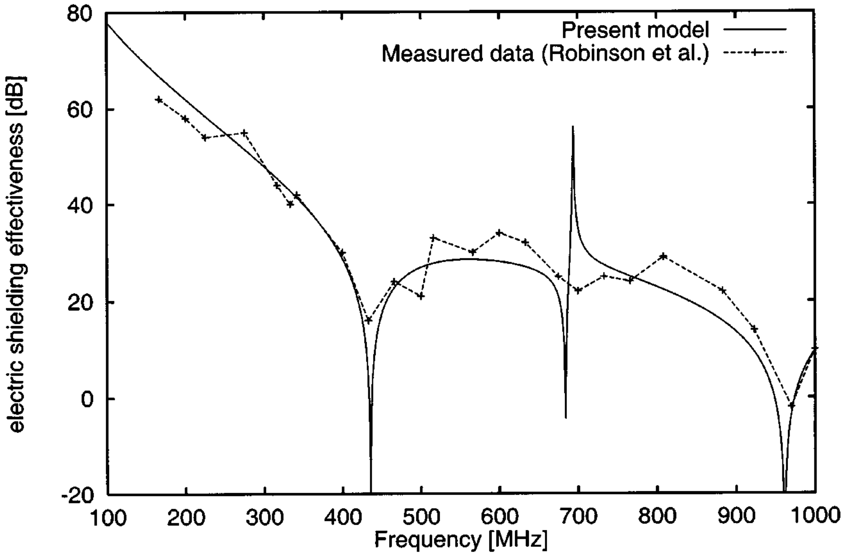

Fig. 7. Plot of the shielding effectiveness at the center of an enclosure for a frequency range from 0.1 to 1 GHz. Continuous line: present model. Dashed line: measurement data [6]. Enclosure dimensions: 483 mm × 120 mm × 483 mm. Aperture dimensions: 100 mm × 5 mm.

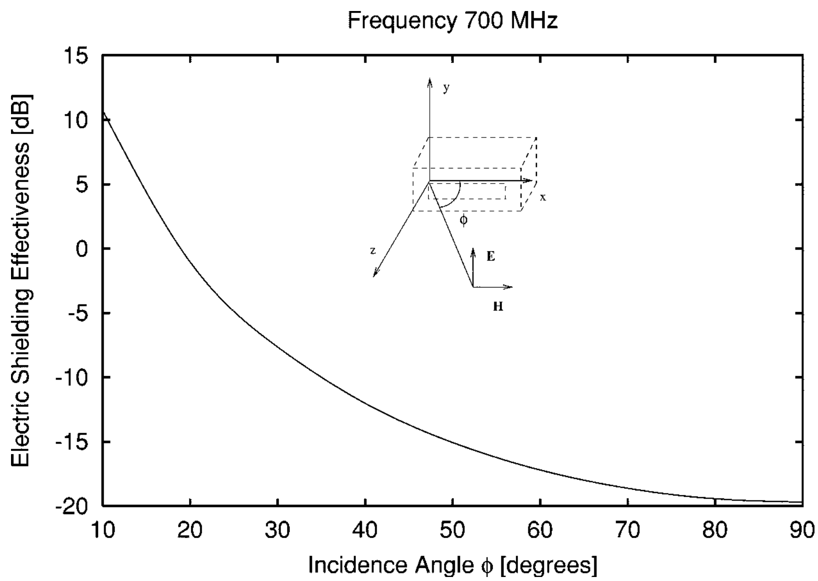

Fig. 8. Plot of the shielding effectiveness at the center of an enclosure for different incidence angles ϕ. Frequency: 700 MHz. Enclosure dimensions: 300 mm × 120 mm × 300 mm. Aperture dimensions: 100 mm × 5 mm.

In the following example, the electric shielding effectiveness versus frequency for an enclosure of 483 mm × 120 mm × 483 mm with an aperture of 100 mm × 5 mm was evaluated. The frequency ranged from 0.1 to 1 GHz. The numerical data obtained by the proposed model were compared with the measurement results provided in [6]. Fig. 7 shows the comparison between the experimental data and the result provided by the present model. It can be seen that the overall agreement is very good.

In all of the previous examples, the electromagnetic wave considered in order to test the model was a y-polarized ($\theta = 0$) uniform plane wave with a propagation vector $\mathbf{k}$ parallel to the z-axis ($\phi = 90$). The following two examples show the behavior of the model when the incident and/or the polarization angle change. Fig. 8 shows the electric shielding effectiveness for an enclosure of 300 mm × 120 mm × 300 mm. The measurement point was at the center of the enclosure.

The incident field was still a y-polarized ($\theta = 0$) uniform plane wave (with a frequency of 700 MHz), but the incidence angle ϕ was varied in a range from 10° up to 90°. It can be noted that, for $\phi = 90$, the propagation vector of the plane wave is z-directed, and the electric shielding effectiveness has a minimum. This is an expected result since, in this case, there is the better coupling condition between the incident wave and rectangular aperture, while, for values of the incidence angle upper or lower 90°, coupling decreases and the electric shielding effectiveness increases.

Fig. 9 shows the electric shielding effectiveness (for the same enclosure of the previous example; also in this example, the measurement point was at the center of the enclosure) when the incident field was a plane wave with the propagation vector along the z-axis ($\phi = 90$) and the polarization angle θ was varied from 0° up to 80°. For a polarization angle $\theta = 0$, the

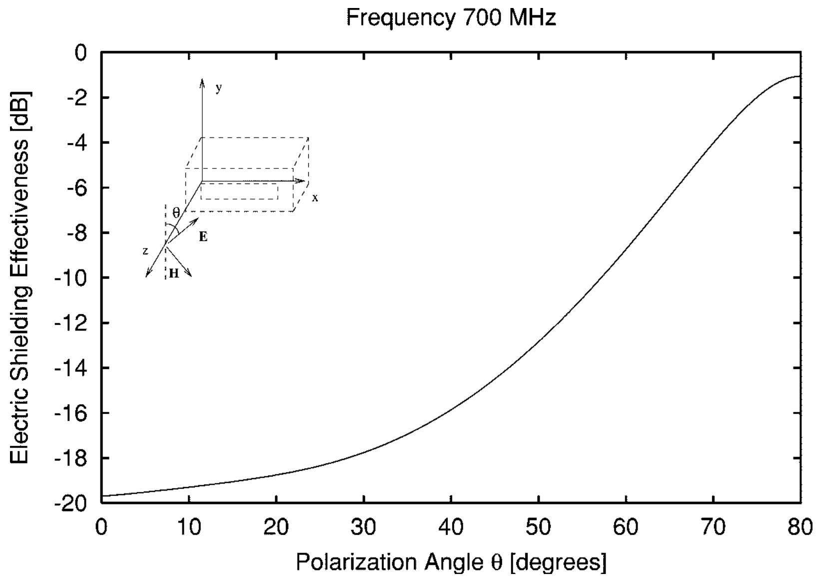

Fig. 9. Plot of the shielding effectiveness at the center of an enclosure for different polarization angles θ. Frequency: 700 MHz. Enclosure dimensions: 300 mm $\times$ 120 mm $\times$ 300 mm. Aperture dimensions: 100 mm $\times$ 5 mm.

plane wave is y-polarized and, since this is the better-coupling condition, the lowest electric shielding effectiveness value is reached. Instead, when the polarization angle θ is increased, the coupling between the incident field and the aperture gets worse and the electric shielding effectiveness increases.

IV. Conclusions

In this paper, the distribution of the electric field on various rectangular apertures backed by cavities has been theoretically investigated and used to calculate the electric shielding effectiveness. The results of the numerical simulations agree with the experimental data, as well as with the data obtained by other theoretical models. The proposed model is useful to estimate the electromagnetic field on rectangular apertures backed by rectangular enclosures to a high degree of accuracy, with a low computational burden, despite the approximations introduced. Furthermore, although in some cases the present model provide result that are no better than those given by other models [6], [11], it has some other useful features. In particular, it allows one to evaluate the field at every point inside the enclosure; moreover, with the present model, it is possible to account for the polarization angle and propagation vector of the incident field. We expect these advantages can be further exploited when considering apertures that are off-centered with respect to the middle of the front panel of the enclosure. This would be the topic for future work.

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