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Wideband Shielding Effectiveness Simulations of an Enclosure with an Aperture

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Abstract

Numerical simulations are performed for calculating the electric and magnetic shielding effectiveness of a rectangular enclosure with a rectangular aperture. A wide frequency band from 100 Hz up to 1 GHz is investigated by using the method of moments. Two wave transmission mechanisms were identified: through the aperture at high frequencies, and through the enclosure body at low frequencies for the magnetic field.

1 Introduction

As technology advances, the electronic circuits of many devices become more sensitive to electromagnetic interference, and demands for their immunity are increasing. For example, electronic boxes in electric and hybrid vehicles should coexist in a dense environment, but are constantly exposed to electromagnetic pulses, hazards which can cause severe damages and should be prevented by a proper compatibility design. Conducting materials are commonly used for shielding, but it cannot be totally opaque due to the presence of cables, connectors and ventilation holes. These should be considered when determining the efficiency of the shielding for proper functionality of our device.

Shielding effectiveness, which is defined as the ratio of field strengths in the presence and absence of an enclosure, is the measure to evaluate the electronic device immunity to electromagnetic interferences. This ratio is defined for the electric as well as the magnetic fields, where the electric shielding effectiveness (S_E) and the magnetic shielding effectiveness (S_M) are equal for a perfectly conducting enclosure but differ for a finite conducting enclosure. Generally, when an enclosure with an aperture is illuminated by a plane wave, we can assume that the dominant leakage mechanism of energy is through the aperture, at sufficiently high frequencies of tens and hundreds of MHz.

A basis analytical solution for shielding effectiveness was published by Bethe based on the theory of diffraction through small holes [1]. Subsequently, works related to the penetration of an electromagnetic pulse through apertures in conducting surfaces were developed [2]. Additionally, the theory of electromagnetic radiation from metallic enclosures with apertures excited by an internal source was presented [3], which treated the enclosure with an aperture as a cavity with a small aperture in a wall, and as a waveguide section short-circuited at one end and open at the other.

Recently, several numerical techniques were adopted to confront the challenge of shielding effectiveness calculation for arbitrary contours of envelopes and bodies. Although these simulations can be time consuming and demand special computational resources, the main advantage of this approach is its ability to model complex structures, where a more basic mathematical description and solution are not applicable. The most common numerical methods to cope with shielding effectiveness predictions are the method of moments (MoM) [4], the finite difference time domain (FDTD) [5] and the transmission line method (TLM) [6].

Robinson developed an analytical formulation of the shielding effectiveness for an enclosure with an aperture in order to reduce the computational resource [7]. Its solution is based on TLM, where the enclosure and the aperture are treated as a rectangular waveguide and as a coplanar strip transmission line, respectively. This enables the authors to present the S_E and S_M versus the frequency at a few points in front of the aperture inside the enclosure. Further works which use a combination of numerical methods determined the shielding effectiveness of enclosure with off-center apertures and numerous apertures [8]; off-axis observation points for an enclosure with an off-axis aperture [9]; incident angle and polarization angle of the electromagnetic wave [10]; and the effect of aperture shape [11], and references therein.

Since the shielding effectiveness at low frequencies is rarely investigated, in this contribution we employ the MoM by FEKO [12] and focus on analysis at a wide frequency band from 100 Hz up to 1 GHz. Our goal is to evaluate the amount of RF interference and to investigate whether we can fulfill the electromagnetic compatibility standards requirements, such as MIL-STD-461-G (RE101 and RE102). For a rectangular enclosure with a rectangular aperture, we have validated the simulation results with analytical formulations.

2 Numerical Simulation

In order to predict the shielding effectiveness of a rectangular enclosure with an aperture, we used FEKO software, the core of which is based on the MoM, to provide a full wave solution of Maxwell's integral equations in the frequency domain. We used the surface equivalence principle (SEP) which introduces equivalent electric and magnetic currents on the surface of a closed dielectric body, which is discretized using triangles. Fig. 1 presents the model of the simulated enclosure with a size of 300 X 120 X 300 mm, made by aluminum of 1.5 mm width, and an aperture with a size of 100 X 5 mm. The adaptive simulation meshing contains approximately 10,000 triangles with an average edge length of 10 mm. The model was illuminated by a plane wave normal to the longer size of the aperture, where the electric field vector is as shown by the red arrow in the left of Fig. 1.

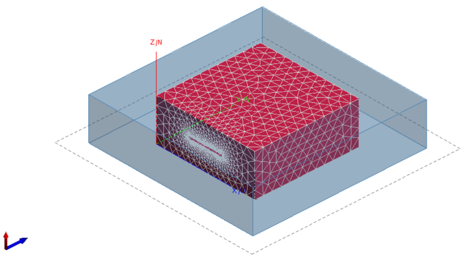

Figure 1. FEKO model for an enclosure with an aperture.

In order to validate our simulation predictions we have compared the results with the analytical formulations given by Robinson in [7]. In this contribution, which follows previous publications [3], the enclosure is treated as a waveguide and a single mode of propagation is assumed (TE_{01} mode). The solution for the electric and magnetic shielding is valid above and below the cutoff frequency, and for electrically large and small apertures.

3 Results

Robinson [7] validated the analytical formulations with measurements, by using stripline and log-periodic antennas at a frequency band of 10 MHz - 1 GHz, and found a fairly good agreement. Furthermore, their model assumed that the conductivity of the walls of the enclosure is so high that the only significant path of energy is through the aperture, which is reasonable above 10 MHz. Since we are interested in a wider spectrum, we have divided our analysis into two frequency bands: high (10 MHz - 1 GHz) which is covered by the Robinson model, and low (100 Hz - 10 MHz) which is not. Following [7] we have calculated the S_E and S_M versus the frequency at a few points inside the enclosure, where parameter p (in meters) denotes the distance from the aperture.

3.1 High Frequency Band

Fig. 2 presents S_E (in dB) as a function of frequency for different values of p (in meters), where the continuous and dashed curves relate to the Robinson model (R) and FEKO predictions (F), respectively. As can be seen in Fig. 2 good agreement is achieved with discrepancies up to 10 dB, with an exception near the resonance frequency for p=0.03. Generally, S_E decreases with frequency and increases with distance from the aperture. Furthermore, the enclosure resonant frequency (which is defined by its physical dimensions) sits approximately at 700 MHz with a negative value of S_E, i.e. electric field enhancement.

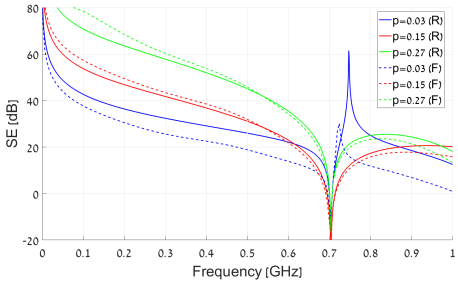

Figure 2. Electric shielding effectiveness at high frequencies.

Fig. 3 presents S_M (in dB) as a function of frequency for different values of p (in meters), for the same parameters described in Fig. 2. As for the electric shielding effectiveness, the simulation predictions for the magnetic shielding effectiveness are consistent with mathematical model as well. Interestingly, the resonance frequency close to the aperture at p=0.03 differs, an issue which will be investigated in the future.

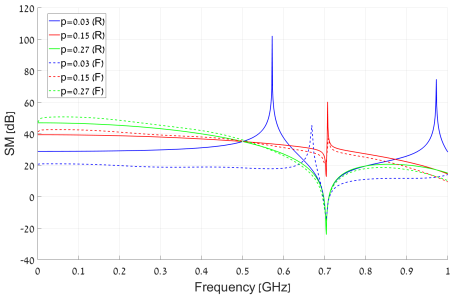

Figure 3. Magnetic shielding effectiveness at high frequencies.

3.2 Low Frequency Band

To the best of our knowledge, there is no validated shielding effectiveness model below 100 KHz, whereas we are interested in considering frequencies down to 100 Hz. As mentioned previously, Robinson validated their model for frequencies above 10 MHz, assuming that the radiation can penetrate into the enclosure only via the aperture, and not through the enclosure envelope. However, at low frequencies the latter is the main penetration mechanism. Fig. 4 presents the S_E behavior at lower frequencies on a logarithmic x-axis scale, from 300 Hz up to 30 MHz. As can be seen, the Robinson model (R) predicts that S_E increases monotonically as frequency decreases. Nonetheless, FEKO simulation (F) envisions a breaking point at a certain frequency which depends on the value of p, and below this frequency the S_E is almost stable (or at least does not continue to increase at the same pace as before). This behavior originated from the reason that FEKO simulation considers the mechanism of transmission through enclosure body (as well as penetration from the aperture), which is neglected by Robinson model.

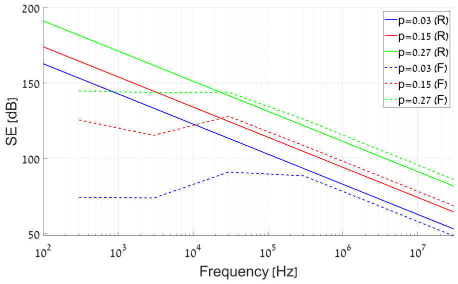

Figure 4. Electric shielding effectiveness at low frequencies.

Fig. 5 presents the S_M behavior in a similar way as in Fig. 4. As can been, the Robinson model (R) predicts that S_M is constant over the lower frequency band (100 Hz - 10 MHz). However, FEKO simulation (F) once again envisions a breakpoint at a certain frequency which depends on the value of p, and below this frequency S_M decreases as the frequency decreases. Field [13], following [14], discussed the behavior of S_E and S_M at low frequencies (but above 100 KHz), and found a similar trend as shown in Fig. 4 and Fig. 5, respectively. Their findings project that the value of S_M is zero around DC and rises with frequency, first because of field cancellation by eddy currents, and then also because of the skin effect. Similar results were demonstrated by using the finite element method (FEM) with COSMOS/M software [15], and also by using magnetic moment approximations combined with TLM approach by CST software [16], although at a somewhat different frequency band, enclosure and aperture dimensions and materials. We should note that the value of the breakpoint frequency is a function of the enclosure characteristics, i.e its permittivity, permeability, conductivity and thickness. Robinson mentioned that the frequency at which the "finite conductivity" S_M becomes comparable to the "aperture" S_M is at 10 - 100 KHz [7], similar to our finding, whereas Frikha who explored a somewhat different setup (enclosure and aperture dimensions and materials), found the breakpoint at around 1 KHz [16].

4 Discussion and Summary

In this contribution we have modeled the electric and magnetic shielding effectiveness of an enclosure with an aperture, illuminated by an external plane wave, in a wide frequency band by using the method of moments. A rectangular geometry was chosen since it is commonly encountered in cabinets and enclosures. We have investigated the behavior of S_E and S_M as a function of frequency, inside the enclosure, and for different distances from the aperture. The simulation predictions were validated with other published results at a frequency band of 10 MHz - 1 GHz, showing fairly good agreement. Furthermore, in this frequency band below the resonance, S_E decreases with frequency and increases with distance from the aperture. In the lower frequency band of 100 Hz - 10 MHz, S_E increases as frequency decreases up to the breakpoint frequency and then it remains constant, whereas S_M is constant as frequency decreases up to the breakpoint frequency and then it decreases as frequency decreases. For the lower frequency band, both S_E and S_M increase as p increases. Additionally, we have identified two main radiation penetration mechanisms: approximately above 100 KHz the dominant apparatus is by penetration through the aperture whereas below 100 KHz it is by transmission through the enclosure body. The mode transition frequency is determined by the enclosure material, i.e. its electromagnetic parameters and thickness, and the aperture dimensions.

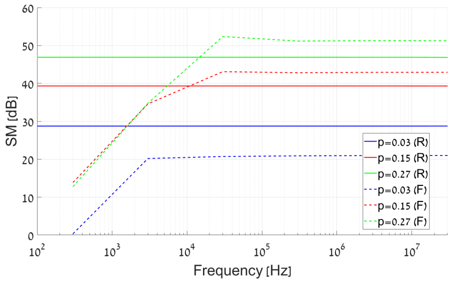

Figure 5. Magnetic shielding effectiveness at low frequencies.

As for future work, we intend to validate the simulation predictions with measurements, which will allow us to investigate the influence of the enclosure size and material, aperture size and wave polarization on the enclosure shielding effectiveness in order to avoid electromagnetic interferences. Furthermore, we intend to study the parameters sensitivity of the mode transition frequency it depends on.

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