Numerical Investigation of the Induced Voltage on a Cable Placed at Random Locations Inside a Metallic Enclosure*

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***Abstract*—In this paper, we investigate the induced voltage on a cable when placed at random locations inside a metallic enclosure. The analysis consists of a cable of defined length and fixed terminals, but different layouts, placed in a metallic enclosure containing an aperture. The induced voltages for the different layouts are computed for a plane wave incident on the aperture. A second analysis is performed with no cable (i.e., an empty enclosure) and the results are compared to those for the cable present. The results are compared to the resonance frequencies of the closed cavity and the aperture.**

Keywords- *finite-difference time-domain (FDTD) method; induced voltage; metallic enclosures; random fields, statistical analysis; susceptibility problems*

I. INTRODUCTION

Susceptibility problems arising in cables located inside a metallic box are of particular importance. Manufactured electric and electronic equipment usually contain cables with defined lengths and fixed terminals, but whose shapes vary randomly inside an enclosure or cavity from one product to another. As we will show, voltages induced in those cables depend strongly on the particular cable layout. If the equipment is enclosed in a metallic enclosure, which is typically the case in order to avoid interference, the induced voltages depend also on the resonance frequencies of the enclosure or cavity. Moreover, because any metallic enclosure needs to have apertures for interacting with its environment, the induced voltages may also depend on the resonance frequencies of the apertures.

In this paper, we consider a rectangular metallic enclosure with a rectangular aperture. A cable of defined length and fixed terminals is placed at different positions inside the enclosure. The voltage induced in the cable is computed for a plane wave incident on the aperture. Initially, the analysis is performed in the time domain, via a finite-difference time-domain (FDTD) scheme, and the final results are given in the frequency domain after performing a fast Fourier transform (FFT).

A statistical study is carried out for the condition where both ends of the cable are fixed, using various cable layouts. We computed the mean value and the standard deviation for the induced voltage, using different cable layouts.

Afterwards, the same problem is solved without the cable; i.e., for the empty cavity. The voltages along the paths previously occupied by the cable are then computed without the influence of any metallic cable. Both the mean values and the standard deviations are compared for the two different situations. Finally, we analyzed the possible influences of the cavity resonances, as well as those of the aperture.

II. DEFINITION OF THE PROBLEM

Fig. 1 shows the problem considered in this study. A z-polarized plane wave is incident on a metallic box with a rectangular aperture. The box is a cube of edge $L = 150$ mm and the aperture is a rectangle of dimensions 75 x 30 mm. The incident plane wave is a normalized Gaussian pulse, whose time and frequency domain expressions are, respectively

$$E_z(t) = \mathbf{exp}\left[-k\left(\frac{t-\alpha}{\alpha}\right)^2\right] \quad (1)$$

$$E_z(f) = \alpha\sqrt{\frac{\pi}{k}}\,\mathbf{exp}\left[-(\pi\alpha f)^2/k\right], \quad (2)$$

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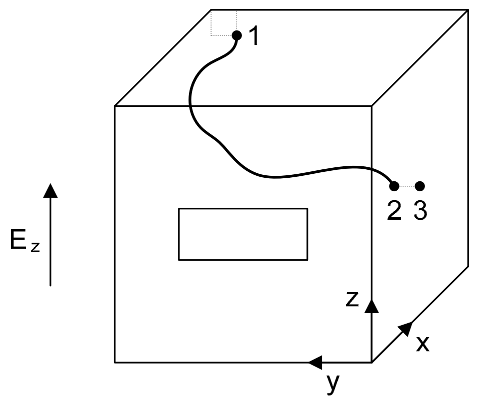

Figure 1. Geometry of the problem.

where k = 10 and α = 0.35 ns. This corresponds to a -3 dB bandwidth of 1.7 GHz. If we extend the analysis up to 4 GHz, the field amplitude will be reduced to –16.8 dB at this frequency.

For numerical analysis purposes, this geometry is quite representative of commercial equipment and was considered previously in [1].

III. NUMERICAL MODELING

The problem is analyzed using the FDTD method. Generation of an incident plane wave is performed by means of a Huygens surface. A perfectly matched layer (PML) is used to achieve the absorbing boundary condition. Details of these two implementations are given in [1].

In order to obtain a acceptable accuracy, 10 samples per wavelength have been used. This means that the cell size is Δs = 7.5 mm for a maximum usable frequency of 4 GHz. Thus, the number of cells for modeling the box is 20 x 20 x 20. The Courant stability condition gives a time increment $\Delta t \leq$ 14.43 ps, and the chosen value was Δt = 14.4 ps.

Inside the enclosure, there is a metallic cable whose length is always 35Δs = 262.5 mm, but its layout (or path) varies. One of its ends is fixed at point 1, whose coordinates are (20, 18, 18)Δs, referred to the metallic enclosure. The other end is fixed at point 2, having coordinates (10, 2, 11)Δs. The induced voltage along the cable is computed as the integral of the electric field between the points 2 and 3, the last one having coordinates (10, 0, 11)Δs. In this integral, a straight line is considered from point 2 to 3. In the analysis, 12 different cable layouts are considered, maintaining both ends at the same positions and varying the cable layout (or path). The results obtained in the time domain are then transformed to the frequency domain, using the FFT.

IV. RESULTS

Fig. 2 shows the mean value of the voltage $\overline{V}$ between points 2 and 3 for the 12 cable layouts considered and Fig. 3 shows the corresponding standard deviation σ. In both cases, the frequency range is from 0 to 4 GHz. As we observe, σ is of the same order of magnitude as $\overline{V}$, or even greater. This means that the cable layout has a strong influence on susceptibility problems. The same cable, with a defined length and with its ends fixed at the same points, may have a very different induced voltage depending on its layout.

Additionally, from these figures, we see that the trends of both graphs are more or less similar. Thus, at frequencies below 0.7 GHz, the interference and deviations have a very low amplitude. On the other hand, a very “noisy” region appears at frequencies between 1.2 and 1.9 GHz. In the rest of the band, medium level interference and deviations are observed.

In order to better understand these results and to try to relate them with the cavity and aperture resonances, a second analysis has been carried out. The cable has been removed and the empty cavity has been analyzed. In this case, the voltages considered are the integrals of the electric field between points 1 and 2 along the same 12 paths where the cable was located in the first analysis.

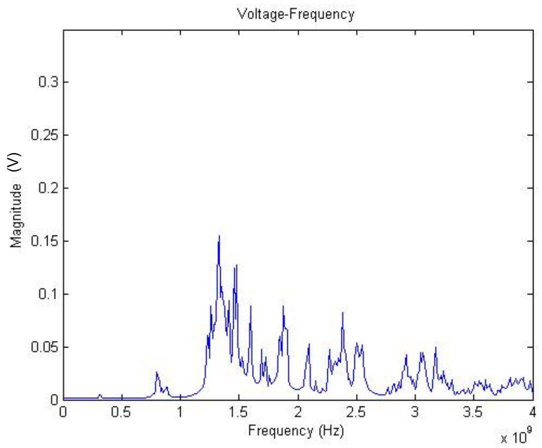

Figure 2. Main value of the voltage induced on the cable for 12 different layouts.

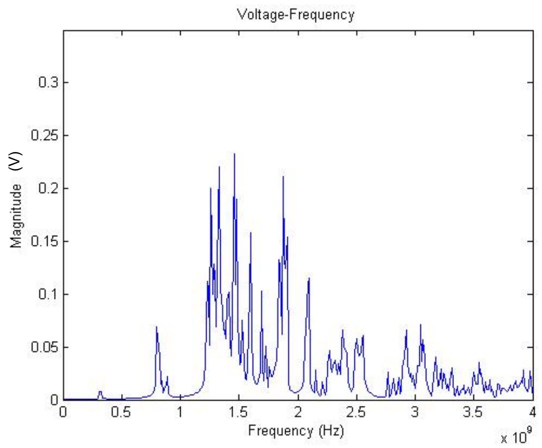

Figure 3. Standard deviation of the voltage induced in the cable for 12 different layouts.

Note that in this second analysis, the integral of the electric field between points 2 and 3, following a straight line, is negligible compared with the integral between points 1 and 2. Taking Maxwell's equations into consideration, we have

$$\oint_L \vec{E} \cdot d\vec{L} = -j\omega\mu_0 \iint_S \vec{H} \cdot d\vec{S} \quad . \tag{3}$$

This states that what we are obtaining is just the magnetic flux across the loops defined by the integration paths and the walls of the metallic box.

The same interpretation is valid for the first analysis, where the voltages induced in the cable also correspond to the magnetic flux across the same loops. Thus, if the magnetic fields were similar in both analyses, the results would also be similar. However, the currents induced in the cable in the first analysis modify the magnetic field and, thus, the magnetic flux across the loops considered.

From a numerical point of view, another difference between the first and second analyses must be made clear. The former needs to be solved each time the cable shape is changed, while the latter is solved just once, irrespective of the number of paths considered for integration. An additional advantage of the second analysis is that the path length can be changed without additional computational cost. Even the positions of points 1 and 2 can be changed with no additional cost. In summary, solving for the electric field in the empty cavity once allows for a wide variety of results, including the shape of the integration path, its length and its ends.

Fig. 4 shows the voltage $\overline{V_0}$ between points 1 and 2 when the box is empty and Fig. 5 shows the corresponding standard deviation, σ_0. Comparing Fig. 4 with Fig. 2, we can state that, although the results are different, they are of the same order of magnitude. We also found a high-level interference region in the second analysis.

Let us examine in depth these last results. First, σ_0 is of the same order of magnitude as $\overline{V_0}$. Second, as the frequency ranges from 0 to 4 GHz, some resonance peaks can be observed. We expect that these peaks are related to the resonances of the corresponding closed cavity as well as to the aperture resonances [2].

In a closed cubic cavity (without an aperture) of 150 mm sides, the resonance frequencies are given by

$$f_r = 10^9 \sqrt{m^2 + n^2 + p^2} \ , \tag{4}$$

where m, n and p are integer numbers in which only one of them can be zero. So the first resonance frequency is precisely 1.4 GHz (with two of the indices m, n and p equal 1 and the other one equal to 0), which corresponds to the first resonant peak in Fig. 4.

The next resonant frequency is 1.7 GHz (for the indices $m = 1$, $n = 1$, $p = 1$), which is hardly seen in the figure. This is due to the fact that the incident electric field is linearly polarized along z. So, if we seek for a z-polarized electric field inside the cavity, this second resonance has null electric field at the plane $z = L/2$, just where the excitation through the aperture takes place.

The third resonance frequency is 2.2 GHz (for the indices $m = 1$, $n = 2$, $p = 0$ or $m = 2$, $n = 1$, $p = 0$), which again can be observed in the figure, although slightly displaced, which is likely due to the increasing effect of the aperture. For higher frequencies, the effect of the aperture is no longer negligible, so no more resonances have been analyzed.

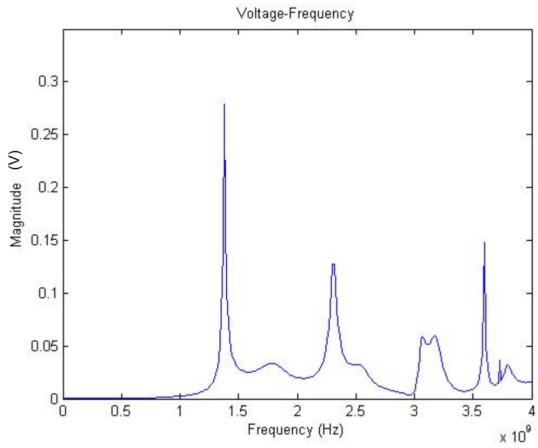

Figure 4. Main value of the voltage computed in the empty box for 12 different integration paths.

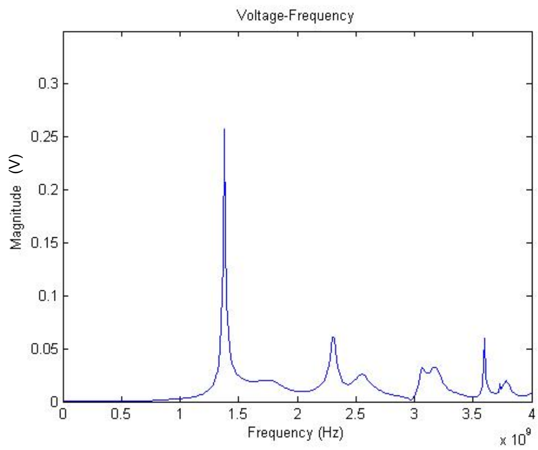

Figure 5. Standard deviation of the voltage computed in the empty box for 12 different integration paths.

Finally, for the aperture, whose largest dimension is 75 mm, the resonances occur at 2 and 4 GHz in the frequency range considered here. As seen in Figs. 4 and 5, there is no peak at 2 GHz. The reason seems to be that there is no cavity resonance at this frequency. So, in this case the energy coupling is governed mainly by the cavity resonance frequencies and not by those for the aperture.

V. CONCLUSIONS

We have conducted a statistical study of susceptibility problems arising in cables inside metallic boxes by analyzing the induced voltages in the cables. A cubic box with a rectangular aperture was considered. The induced voltages on a cable inside the enclosure, with defined length and fixed terminals, but different layouts (or paths), were computed for a plane wave incident on the aperture.

The results were compared with those obtained with the box enclosure; that is, without the cable. This second analysis has enormous numerical advantages compared to the first one. Although both results are not equal, the same order of magnitude has been found for the computed voltages, and the most critical frequency band from the EMC point of view has been detected. Due to the practical importance of this problem, further analyses considering lossy materials inside the box are now ongoing.

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