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ELECTROMAGNETIC COUPLING ANALYSIS OF TRANSIENT SIGNAL THROUGH SLOTS OR APERTURES PERFORATED IN A SHIELDING METALLIC ENCLOSURE USING FDTD METHODOLOGY

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Abstract—The paper presents electromagnetic coupling of an electrical fast transient plane wave penetrating through slots or apertures perforated in one side of a shielding metallic enclosure. Numerous slots and apertures of different configurations and dimensions have been developed, which include a single slot of different length, a single aperture of different width, multiple-angular apertures of different geometry, multiple-cell aperture of different cell numbers, multiple thin slots, an aperture-cell array making up the whole side of the enclosure, and a miscellany case simulating a PC main frame. FDTD numerical method is applied to the EMI/EMC model, while time-domain outputs are converted to frequency-domain responses for further analyses using a FFT program. Practical conclusions and recommendations are drawn to aid shielding enclosure design and electromagnetic interference protection.

1 Introduction

2 Theory and Analysis

3 Formulation of the Problem Studied

1. INTRODUCTION

Compliance to electromagnetic compatibility (EMC) directives or standards is increasingly a challenge for electronic designers due to the great amount of electromagnetic phenomena to which electronic equipment should be immune. The electronic equipment, particularly high-speed digital system, is susceptible to reversible or permanent damages induced by electromagnetic interference (EMI), such as electrostatic discharge (ESD) and electrical fast transient pulse or burst (EFT).

A shielding metallic enclosure is typically used to attenuate different types of emissions produced by electronic equipment [1]. These emissions include radiated electric field, magnetic field, plane wave, power line and signal line conducted emissions, electrostatic discharges (ESD), and electrical fast transient pulses, etc. The shielding enclosure is also used to reduce the susceptibility of the equipment to external EMI. It is practically found that the shielding efficiency of the shielded enclosure is mainly determined by energy penetration through apertures or slots in the enclosure rather than through the enclosure walls, although an exception to this can be found at audio frequencies [2]. The apertures or slots are widely used as very efficient antennas. However, they are undesirable sources of EMI problems owing to this characteristic, for both radiated emission and radiated susceptibility. The apertures or slots, such as those due to windows and displays, or those for cooling purposes and cable connections, will degrade the shielding effectiveness of shielded enclosures. The electromagnetic coupling between internal components and EMI outside the shielding enclosure is resulted. Moreover, the intrinsic resonant behaviour of the enclosure may give rise to very intense internal fields at resonant frequencies, many of which can be excited by broadband external noise signals.

It is desirable to quantify the electromagnetic coupling from external sources through apertures or slots of a shielding enclosure. It is also essential to determine how well electronic equipment will function when subject to unwanted electromagnetic radiation and how well it is shielded against unintentional EMI, since EMI from apertures or slots in a shielded enclosure is of great concern in meeting some EMC directives' radiated susceptibility limits, such as EN 61000-4-4 (electrical fast transient or burst). Moreover, an understanding of electromagnetic coupling mechanism to and from the enclosure is essential in minimising EMI and susceptibility risk in a new design, at both system level and device level.

2. THEORY AND ANALYSIS

The electromagnetic coupling between internal components and external EMI of a shielding enclosure can be approached in either time-domain or frequency-domain. Much attention has been given to attempts to solve time-domain integral equations directly except for limited progress in the case of wires and a few body shapes. Good summaries of such accomplishments can be found in [2, 3]. In the case of time-harmonic (or frequency-domain) fields, considerable attention has been devoted to investigations of penetration through slots in a conducting surface [4–6].

There is a variety of modelling techniques associated with EMC, such as Method of Moments (MoM), Finite Element Method (FEM), and Finite-difference Time-domain method (FDTD) [7–11]. Different modelling techniques are suited to different problems. In this study, the FDTD technique is preferable, since it is an effective volume-based method. Both time-domain data and corresponding frequency-domain outputs can be determined by performing a fast Fourier transform (FFT) of the time-domain results at some specific testing points.

Theoretically, a plane wave excitation represents the simplest electromagnetic source and therefore is particularly suitable to test numerical techniques. In this work, the Gaussian plane wave, a typical transient impulse plane wave with a wide frequency spectrum, is applied to simplify the difficulty of the studied problem without losing its practical applications.

3. FORMULATION OF THE PROBLEM STUDIED

Analysis of EMI penetration via improperly seated apertures or slots into a shielding enclosure is an important study in designing high sensitivity instruments, TV monitors, computer hardware systems, other high-speed digital systems, and military applications systems such as aircraft, missiles, and satellites. There are no specific definitions for apertures and slots, which are sometimes treated as equivalent. For simplicity and comparison, apertures and slots are distinguished based on their discrete ratios of length to width. The lengths of slots are regarded much longer than their widths, while the lengths of apertures are comparable with their widths.

There are different sources related to apertures and slots in different applications. Most of them can take the forms of the following, windows, air vent, heat dissipation, light transmission, input/output (I/O) cable penetration, CD-ROMs, disc-drivers (soft disc and zip disc), speakers, plate-covered ports, reserved connector ports and other possibilities.

The problem studied here consists of an empty shielding metallic enclosure and slots or apertures in a front side of the enclosure. The enclosure dimensions are $30\,\mathrm{cm} \times 41\,\mathrm{cm} \times 21\,\mathrm{cm}$. The enclosure is illuminated by a Gaussian transient plane wave impinging vertically on the slots or apertures in the front side of $41\,cm \times 21\,cm$. The Gaussian plane wave has electric field polarisation along the negative vertical-axis with its amplitude varying in time as a step function. The electric field distributions are calculated at the centre point inside the enclosure. Both the enclosure walls (conductivity: $\sigma = +\infty$) and the air dielectric ($\sigma = 0$) inside and outside the enclosure are considered ideal materials, which will not lose the general precision of the study. For simplicity, the enclosure dimensions in all the studied cases are kept to be the same.

The FDTD model uses a regular square mesh of $\Delta 1 = 1\,\mathrm{cm}$. The work space is $45 \times 55 \times 35$ nodes (absorbing boundary condition), allowing for sufficient "free space" around the enclosure, which is discretised into $30 \times 41 \times 21$ cubic cells with cell size of $\Delta 1 = 1\,\mathrm{cm}$. In another words, the enclosure volume is divided into 25,830 cubic cells with 21 layers. The thickness of each enclosure wall is assumed to be 1 cm. The relative dielectric constant and conductivity of the enclosure are regarded as ideal, i.e., $\varepsilon_r = 1$ and $\sigma = +\infty$. The external absorbing boundaries are placed at a distance between $6\Delta l$ and $8\Delta l$ from the discrete enclosure wall. The testing point of interest is located at the geometrical centre point inside the enclosure. At 10 cells per wavelength, a reasonable frequency spectrum bandwidth of 3 GHz with

32 time steps is resulted. Since the electric field amplitude will decay significantly at higher frequency, the frequency bandwidth of interest can be reduced from 3 GHz to 1.5 GHz, where the amplitude is reduced around 6 dB at 1.5 GHz with respect to the zero frequency value [12]. A commercial code XFDTD [12] based on the FDTD method and a simple FFT program have been applied to simulate, convert and process the outputs of the studied problem efficiently.

4. RESULTS AND ANALYSES

Various configurations of slots and apertures have been investigated, covering most practical possibilities associated with perforation in a metallic enclosure. These configurations will assist in disclosing some particular aspects of concern for enclosure designs, which generally include 1) EMI coupling mechanism (slot or aperture resonance or metallic enclosure resonance modes); 2) relationship between EMI and slot or aperture length; 3) multiple slots or apertures interactions.

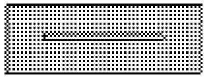
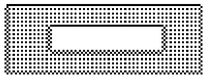
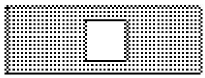
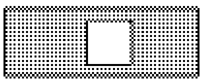
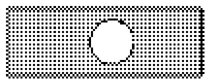
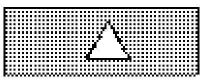
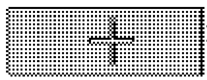
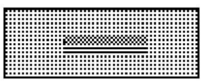
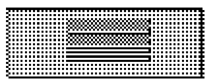
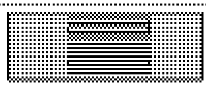
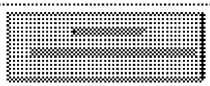
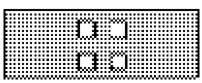
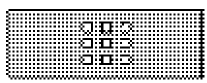
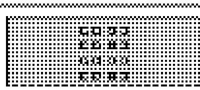
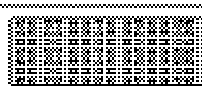
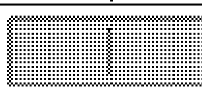
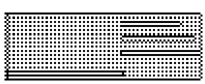
For comparison purpose, all the studied configurations are categorised into eight classes: single slot, single aperture, square aperture, multi-angular aperture, multiple slots, multi-cell aperture (including aperture-cell arrays composing the whole front side), vertical slot, and miscellany-case, which are tabulated in Table 1. The enclosure dimensions remain the same in all cases as well as the excitation source of the normalised Gaussian transient plane wave.

4.1. A Single Slot

A rectangular slot is cut in the front side of the enclosure, as shown in Fig. 1 of Table 1. Four typical slots with a fixed width of 1 cm have been investigated, whose lengths are 10 cm, 15 cm, 30 cm and 39 cm, respectively. Time histories of electric fields in the centre of the shielding enclosure, for the four cases of different lengths, are depicted in Fig. 9, accompanied by their respective frequency-domain outputs by the aid of a FFT program.

The resonant behaviour of the slot is highlighted by oscillations. It is noted that, after 2 ns from the plane wave application (at about 1.1 ns time point), the cancellation of the electric field can be observed, which is due to the wave reflected by the shielded wall opposite to the slot. The time taken by the wave to travel forward and backward along a path of $a = 30$ cm is almost 2 ns. After 4 ns this effect is enforced by a sign change of the slope in the plane waveform, which produces a high positive peak of the electric field value. For longer time, this obvious wave interference is masked by oscillations of the plane wave

Table 1. Configurations of slots or apertures cut in a front side of a shielding metallic enclosure (inclusive of Figs. 1–8).

CASES	CONFIGURATIONS (SIDE-VIEW)	
A Single Slot	 Fig. 1	
A Single Aperture	 Fig. 2	
A Square Aperture	 Fig. 3	
A Multi-angular Aperture	 Fig. 4.1	 Fig. 4.2
	 Fig. 4.3	 Fig. 4.4
Multiple Slots	 Fig. 5.1	 Fig. 5.2
	 Fig. 5.3	 Fig. 5.4
Multi-cell Aperture	 Fig. 6.1	 Fig. 6.2
	 Fig. 6.3	 Fig. 6.4
A Vertical Slot	 Fig. 7	
Miscellany Case	 Fig. 8	

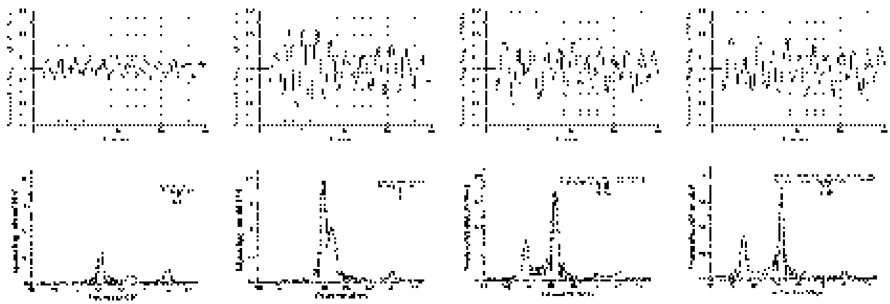


Figure 9. Time histories and frequency-domain responses in the case of a single slot.

current and by multiple reflections coming from all other metallic walls. The phenomenon is applicable to all the cases of different length slots, except that the electric field level of 15 cm slot is a little higher than those of smaller and longer slots, which is mainly due to the higher composite result of incident and loss energy for the 15 cm slot. Such a phenomenon might also be common to all the cases studied with simple slots and apertures, since the testing point and dimensions of the enclosure are the same, which makes the same propagation time from the incident point to the testing point after the reflection of the plane wave. But it will not be available if slots and apertures cut in the enclosure side become more complicated.

The frequency-domain responses provide more comfortable visualisation for the resonance and oscillations. The coupled electric fields at the centre testing point of the enclosure are reported as a function of frequency. Three major resonance peaks are observed in the frequency range up to 1.5 GHz, two of which correspond to the first two resonant frequencies of the enclosure [1], while the third one is associated with the resonance of the slot. The first resonance of the enclosure is

$$\mathrm{TE}_{110} = c/2\sqrt{1/0.3)^2 + (1/0.41)^2} = 619\,\mathrm{MHz}$$

and the higher resonance of the enclosure may be

$$\mathrm{TE}_{201} = c/2\sqrt{2/0.3)^2 + (1/0.21)^2} = 1,229\,\mathrm{MHz}\,.$$

The slot resonance is typically half-wavelength resonance. However, the full-wave resonance of the slot is not excited, because it results in a magnetic current that is an odd-function of the vertical axis, which is not excited since the normally incident excitation contains

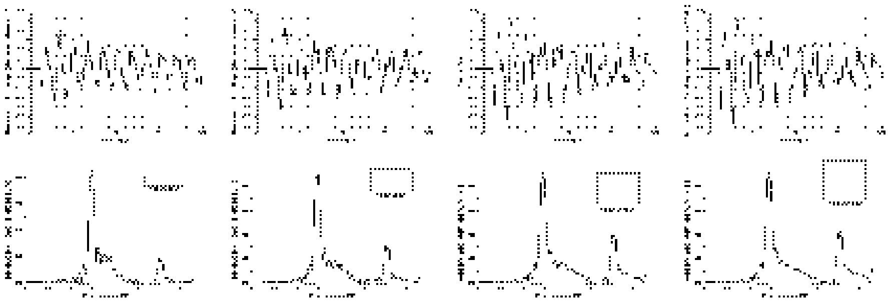


Figure 10. Time histories of frequency-domain responses in the case of a single aperture.

no corresponding odd-function component. Thus, full-wave resonance is not possible for normally incident excitation. When the slot length becomes longer, the half-wave resonance of the slot reduces accordingly, which is clearly evident in the frequency-domain analysis shown in Fig. 9. While the first two resonant frequencies of the enclosure remain almost unchanged except their electric field amplitudes.

4.2. A Single Aperture

Four different apertures are simulated using the FDTD method as depicted in Fig. 2 of Table 1, whose widths are 3 cm, 7 cm, 11 cm, 13 cm, and 15 cm, respectively, while the length for each aperture is kept the same as 15 cm. The time-domain behaviour and corresponding frequency-domain analyses of the electric fields presented in Fig. 10 are sampled at the centre point in the enclosure.

As the aperture area is increased, the coupled electric field level through the aperture increases slightly. This may be due to the fact that the magnitude is mainly determined by its length, since the polarisation of the incident source is vertical to the aperture length. The resonance behaviour (oscillation) in the time-domain still exists in each case.

It is obvious that there are two resonance peaks in each frequency-domain figure, which may be associated with two resonant frequencies of the shielding enclosure, TE_{110} and TE_{201} excited by the incident Gaussian source. Between both resonance, there are several resonance of lower level, which might correspond to "computational noise". In the case of the smallest aperture of $15\,\text{cm} \times 3\,\text{cm}$, the aperture resonance behaves like three close resonance in sequence. This may be excited by three equivalent parallel and thin slots of $15\,\text{cm} \times 1\,\text{cm}$. Their electric field magnitudes are relatively lower compared to that of a single

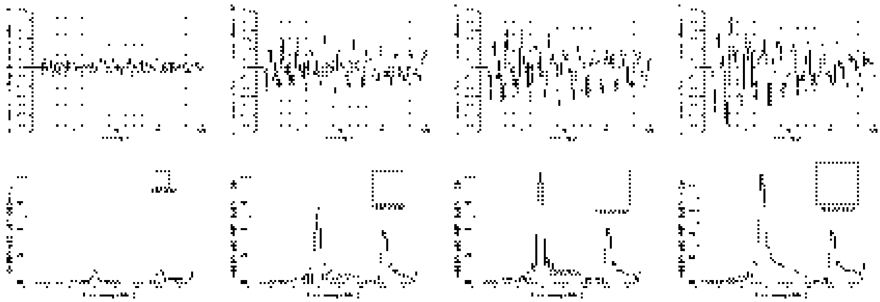


Figure 11. Time histories and frequency-domain responses in the case of a square aperture.

slot of 15 cm × 1 cm, since a larger aperture will introduce a greater loss. As the aperture width is increased, the aperture resonance decay evidently, while both enclosure resonance remain unchanged except that the magnitude of the higher order resonance increases slightly.

4.3. A Square Aperture

It is desirable to quantify electromagnetic coupling through an aperture into the shielding enclosure, as the coupled electric fields may trigger the integrated circuits or other sensitivity systems inside the shielded structures such as aircraft, missiles, and satellites. The coupled signal may exceed given threshold values of integrated circuits thus producing non-linear behaviours, malfunctions and irreversible damages. The knowledge of the excitation in an electrical system can be understood well if the amplitude of induced electromagnetic fields is obtained through studies. This is achieved by comparing coupled electric fields inside the enclosure via a square aperture cut in the front side of the enclosure, as shown in Fig. 3 of Table 1.

Fig. 11 shows the time histories and the corresponding frequency-domain outputs of the electric field distributions at the centre point of the enclosure. Four different apertures are studied and are chosen to be 5 cm × 5 cm, 10 cm × 12 cm, 12 cm × 12 cm, 15 cm × 15 cm, respectively. It is noted that, compared to the maximum of the incident Gaussian electric field, the coupled electric field due to the aperture is small. As the aperture area is reduced, the coupled electric field drops in amplitude. This trend shows that the shielding effectiveness of the enclosure greatly is improved by reducing the aperture area, as the electric field penetration through the enclosure is preferably prohibited because of the smaller aperture size. From the frequency-domain point

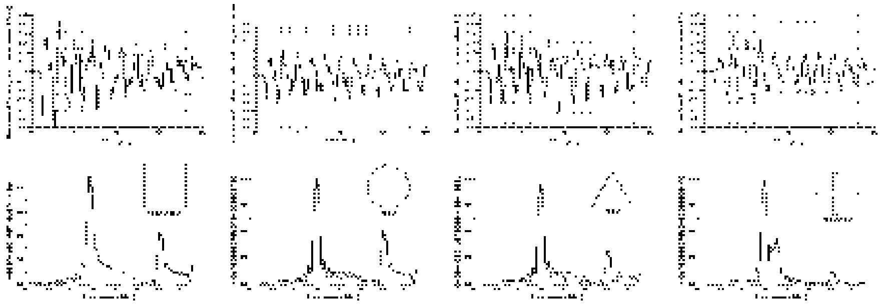


Figure 12. Time histories and frequency-domain outputs in the case of a multi-angular aperture.

of view, there are two major resonance peaks. The first one is related to the first mode, TE_{110}, of the rectangular enclosure, and the second resonance corresponds to TE_{201}. The resonance amplitude increases with the aperture area, which agrees with the analysis of time-domain data. It is noted that the aperture resonance degenerates significantly compared to those for thin slots. This suggests that the slot radiator phenomenon is mainly valid for thinner slots.

4.4. A Multi-angular Aperture

Four configurations have been simulated, i.e., square-aperture, circle-aperture, equilateral triangle-aperture, and cross-aperture, as plotted in Figs. 4.1–4.4 of Table 1. Fig. 12 presents the simulated results of the electric fields induced at the centre point inside the enclosure, in both time-domain and frequency-domain. The largest dimension of the four geometry is the same as 15 cm, while the width of the cross-aperture is 1 cm, i.e., the mesh cell unit.

The electric field magnitude decreases as the geometry is shifted from square to cross-aperture, i.e., the decreased area of the aperture. This is similar to the case of a square aperture, where the electric field magnitude decreases as the area of the aperture decreases. In the frequency-domain analysis, two resonant peaks exhibit obviously, which are related to two eigen-resonant modes of the shielding enclosure, TE_{110} and TE_{201}. The amplitudes of both resonant peaks decrease as the aperture area decreases, agreeing with that in the time-domain analysis. Interestingly, in the case of the cross-aperture, there exists another apparent resonant peak nearby the first resonance of the enclosure. This may be excited by the transverse element, i.e., a thin slot, of the cross-aperture, since the half-wavelength frequency

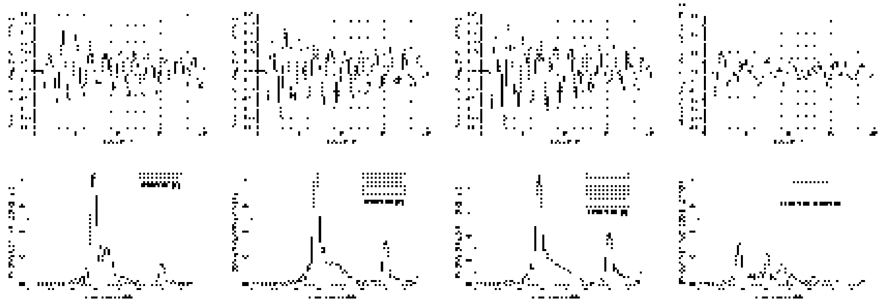


Figure 13. Time histories and frequency-domain responses in the case of multiple slots.

of the slot is close to this resonant frequency. It is noted that this slot resonance is accompanied by another smaller resonance with lower amplitude, which may be associated with another eigen-mode of the enclosure that is in the proximity of the first mode of TE_{110}.

4.5. Multiple Slots

In some specific applications, several slots of either the same length or different length may exist in one side of an enclosure, as depicted in Figs. 5.1–5.4 of Table 1. The first three configurations have the same slot length of 15cm and the last one has different lengths of 12 cm and 30 cm. The width of each slot is 1 cm. The spacing gap of the same length cases is chosen to be 1cm, while that with different slot lengths is 5cm so as to make their induced resonant frequencies distinct enough for visualisation. Fig. 13 shows the time histories and their respective frequency-domain responses. As the slot number increases in the same length slot cases, the electric field amplitude increases slightly, while the oscillation phenomenon in each case almost remains unchanged except the pulse width of oscillation, which suggests that there are some common resonance and other distinct resonance.

From the viewpoint of the time-harmonics (frequency-domain) analysis, two major resonance peaks are observed. Both resonance peaks are related to two resonant frequencies of the metallic enclosure, TE_{110} and TE_{201}. In the case of two slots of the same length, two additional resonance of smaller amplitude nearby the first enclosure resonance are also observed. They are associated with both thin slots. As both slots are very close to each other and exhibit the similar half-wavelength frequency characteristics, the expected outcome may be two separate resonance that are very close to each other. The amplitudes of both slot resonance are relatively lower compared to that of a single slot of the same length, because the electromagnetic energy leakage or loss of two slots from the inside of the enclosure is higher than that of a single slot. As the slot number increases, the slot resonance decays significantly. This suggests that the combination of several parallel slots of the same length close to each other, may be similar to an aperture with similar total width and length. The wide aperture does not exhibit the half-wavelength characteristics, as the current distribution around the aperture does not simulate that of a dipole antenna any longer. It is also noted that the electric field amplitude of the higher resonance of the enclosure increases significantly with the increase of the slot number, while the first resonance amplitude of the enclosure remains almost unchanged. This means more energy is illustrated into the enclosure to excite the higher resonance, as the "aperture width" increases. This phenomenon is also related to the polarisation direction of the incident source.

In the case of two slots with different length as shown in the last vertical figure-pair of Fig. 13, there are three major resonance peaks within the frequency spectra of interest. The first and the third ones are related to the longer (30 cm × 1 cm) and the shorter slots (12 cm × 1 cm), respectively, while the middle one corresponds to the first resonance mode of the shielding enclosure. All the resonance amplitudes are relatively lower compared to their discrete amplitude with a single slot. The higher mode resonance of the enclosure decays significantly in this case.

4.6. Multi-cell Aperture

It is of necessity, take air ventilation for example, to cut apertures or slots in an enclosure side. The apertures or slots will definitely reduce the shielding effectiveness of the enclosure, where a trade-off shall be made to guarantee its function. From the standpoint of the shielding application, it is desirable to determine which kind of configuration is suitable for ventilation without markedly scarifying the shielding effectiveness of the enclosure.

Figs. 6.1–6.3 in Table 1 show three typical configurations of different multi-cell apertures perforated in the centre of the front wall of the metallic enclosure with the overall external aperture dimensions of 15 cm × 15 cm. Fig. 6.1 presents four identical aperture-cells of 5 cm×5 cm, and the cell-gap between two adjacent cells is 5 cm. Fig. 6.2 has nine identical aperture-cells of 3 cm × 3 cm, with the cell-gap being 3cm. Fig. 6.3 shows sixteen aperture-cells of 2 cm × 2 cm, and the vertical cell-gap is 2 cm, while the horizontal cell gap is 3 cm. While Fig. 6.4 depicts the front side perforated with an aperture-cell array

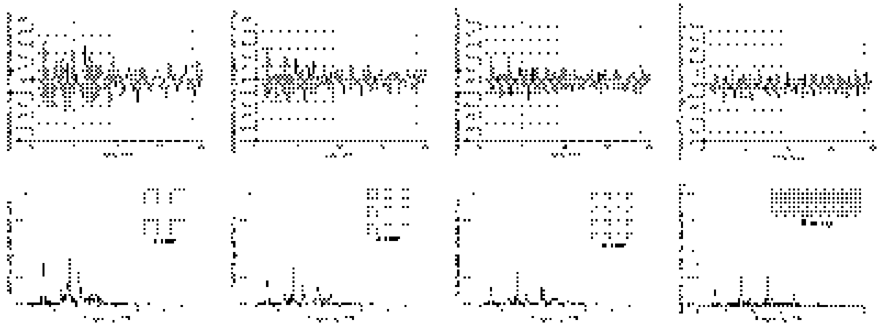


Figure 14. Time histories and frequency-domain responses in the case of multi-cell aperture.

that covers the whole side of the enclosure. This is one of the extreme cases for multiple-cell aperture and is applicable for the air ventilation. The aperture-element-cell size of the array is 1 cm × 1 cm and the edge-to-edge spacing or gap of the aperture-cell is 2 cm. The total number of the aperture-element-cells is ninety-eight in this configuration.

As shown in the time histories of electric field strengths of the centre point in Fig. 14, the oscillation amplitude of the electric field decreases with the increase of the cell number, and hence, with the decrease of the cell size. This suggests that the incident energy of EMI into the enclosure will be decreased if the dimension of the aperture-element-cell get reduced, which oppositely increases the preferable shielding effectiveness of the shielding enclosure. This tendency is equivalently existent from the standpoint of frequency-domain responses. For viewing possible higher resonant frequencies associated with the enclosure and multi-cell apertures, a wider frequency range from 0 to 6 GHz is cited in this case, although the frequency range of interest is mainly focused on from 0 to 1.5 GHz. There are several resonant peaks in the frequency-domain responses, which are related to some lower-order resonant modes of the enclosure. As the size of the aperture-element-cell decreases, the peak amplitude of the resonance degenerates significantly, while the resonant frequency remains unchanged, which suggests there is no resonance excited by the apertures. In summary, it is preferable to introduce an equivalent large aperture composed of lots of fine-sub-cell elements, such as a honeycomb configuration instead of a single large aperture, for the air ventilation or the like, in which way the shielding effectiveness of the enclosure will not be scarified excessively.

In the case of an aperture-cell array that covers the whole side of the enclosure, there are several resonant peaks within the frequency

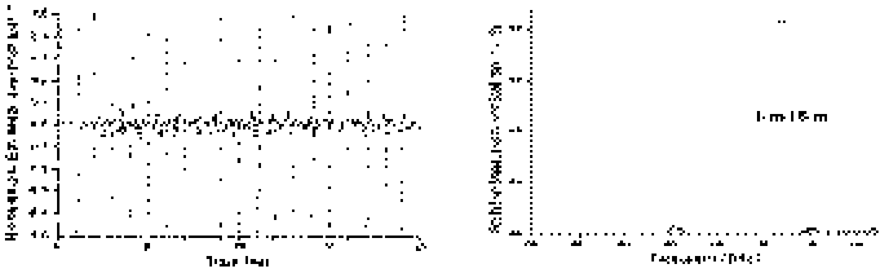


Figure 15. Time history of frequency-domain response in the case of a vertical thin slot.

spectra of interest, which are related to some resonant modes of the enclosure. Based on the calculated values of the resonant modes using eigen-mode equation of the cavity theory, these resonant peaks, from left to right in the frequency range of interest, may be considered as TE_{110}, TE_{201}, TE_{112}, TE_{330}, TE_{440} and other higher modes of the enclosure. The amplitudes are very lower compared to the larger multi-cell apertures mentioned above, since less external EMI will penetrate into the enclosure through smaller cells.

4.7. A Vertical Slot

Fig. 7 in Table 1 presents a typical configuration of the front side perforated with a vertical slot. This case will be similar to that of an incident plane wave with a horizontal polarisation penetrating normally to the front side perforated with a horizontal slot. Three vertical slots of different lengths, i.e., 10 cm, 12 cm and 15 cm, have been investigated. The width of all the slots is 1cm. Only the result of the 15cm-long slot is plotted in Fig. 15, since all the three cases have the similar characteristics.

Some details of the time-domain response are worthy of comment. Firstly, the vertically directed magnetic current in the testing point is negative during the early stage of the excitation, since the incident source direction is of negative vertical-axis. This is reasonable based on an equivalent magnetic current equation $\vec{M} = \vec{E} \times \vec{n}$, $\vec{E}$, being the electric field on the testing point and $\vec{n}$ being the unit vector normal to the slot. Secondly, the magnitude of the electric field is very small compared to that of a horizontal slot of the same length illuminated by a plane wave with vertical polarisation. This may be due to the very low magnetic current induced in the vertical slot, which results in much less electromagnetic energy penetration into the inside of the

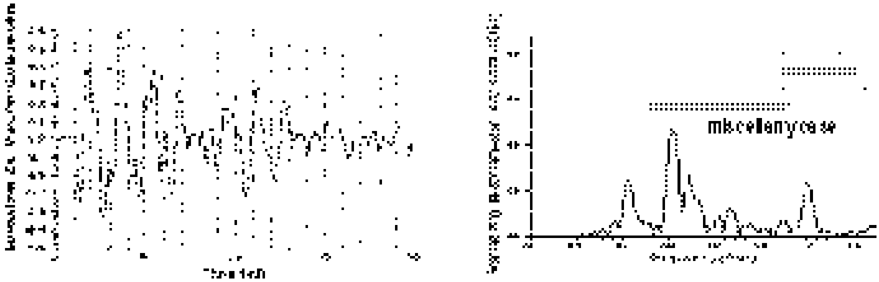


Figure 16. Time history and frequency-domain response in the miscellany-case.

enclosure. It is more obvious in the frequency-domain analysis, where the amplitudes of the enclosure resonance peaks are significantly small compared to those in a horizontal slot case. The excited resonant frequencies of the enclosure are regarded as TE_{110}, TE_{201}, and TE_{112}, etc., while no slot resonance is observed.

4.8. Miscellany Case

In a practical situation, a PC (personal computer) main frame for example, there may be several different slots perforated in its shielding enclosure, as shown in Fig. 8 of Table 1. Four typical slots with the width of 1cm simulate some possible leakage or openings resulted from a soft disc (10 cm), a CD-ROM (14 cm), a zip disc (16 cm) and an air vent (26 cm) in sequence from top to bottom in the enclosure of the PC main frame. The vertical gap is 4 cm, 5 cm and 4 cm, respectively, while the soft disc is located 3 cm below the top line and the air vent above the bottom line of the enclosure.

Fig. 16 presents the time-history of the coupled electric fields tested at the centre point of the enclosure and its corresponding frequency-domain response. Since there is more than one single slot in this scenario and all the slots have different lengths, the oscillation in the time-domain is not simply regular any more, which suggests that several different resonance will be existent. This is verified by its frequency-domain output. There are mainly six resonance peaks within the frequency spectra of interest from 0 to 1.5 GHz. The second peak and the last one are related to two lower-order resonant frequencies of the metallic enclosure, TE_{110} and TE_{201}. The other four peaks are associated with those slot resonance excited by the air vent, the zip disc , the CD-ROM and the soft disc, which are characterised by their discrete lengths. The longer the slot, the lower its resonant frequency.

It is noted that the resonant frequencies of all the slots are not exactly equivalent to their respective half-wavelength frequencies, since the slot-slot interaction and the slot-enclosure interaction as well as the slot edges will affect their resonance slightly.

5. CONCLUSIONS AND RECOMMENDATIONS

The electromagnetic coupling of a Gaussian transient plane wave penetrating through eight different classes of slots and apertures perforated in a front side of a shielding metallic enclosure has been presented and discussed in detail. Based on the exhaustive investigations in this wok, a list of conclusions and recommendations are drawn as follows to aid shielding enclosure design and EMI protection in critical applications.

a. Electromagnetic shielding by the aid of some kind of shielding metallic enclosure is frequently used to reduce emissions from or improve immunity of electronic equipment. However, any slot, aperture and their combination perforated in the enclosure, will compromise its shielding effectiveness.
b. The shielding enclosure itself will possess a set of characteristic resonance behaviour excited by external interference signals passing through the enclosure. The presence of slots and apertures cut in the enclosure will complicate resonant characteristics of the enclosure for high-speed digital or analogue electronic equipment. Unwanted electromagnetic radiation penetrated into the enclosure and enclosure characteristic resonance will interfere with the proper operation of the electronic equipment.
c. The resonance of a thin slot is typically half-wavelength resonance. The longer the slot, the lower the resonant frequency. In the case of shielding higher frequencies, the slot length shall be critically chosen to avoid its characteristic resonance.
d. As the slot width increases, the electric field amplitude of its resonance will decrease. The wider the slot (i.e., aperture), the more its resonance decays. However, an aperture will allow for more electromagnetic energy penetration compared to a slot of the same length. An aperture of smaller size will introduce less electromagnetic energy incidence than that of larger size.
e. Apertures of different geometry will exhibit similar resonant behaviour inside a shielding enclosure, if they have similar aperture areas. A cross-slot made of two thin slots will provide the similar characteristic resonance to that of a thin slot of the same length.

f. If several parallel slots are applied, it is advisable to make all the slots have the same length to reduce extra slot resonance. The thinnest slot will dominate the resonant behaviour, while the wider slots of the similar length increase electromagnetic energy penetration.

g. For air ventilation or heat dissipation applications, it is advisable to introduce an equivalent aperture that is composed of an array of fine aperture-element-cells, such as a honeycomb configuration. The smaller the aperture-element-cell is, the less EMI will penetrate through the perforated aperture in the enclosure.

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