Measurements and Power Balance Calculations of the Shielding Effectiveness of Partitioned Equipment Enclosures

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Abstract— **This paper presents calculated and measured Shielding Effectiveness data for shielded enclosures operated in the frequency range where the enclosure is reverberant. The calculated data are obtained from component measurements and are calculated using the Power Balance technique. The Shielding Effectiveness of the different cavities of an enclosure partitioned by stacked circuit cards is obtained.**

Keywords—Shielding effectiveness measurement. Power Balance. Reverberant enclosures.

I. Introduction

Conventional evaluations of Shielding Effectiveness (SE) of equipment enclosures assume an empty enclosure with no account taken of the enclosure contents, for example [1]. Recent work [2] has highlighted an alternative view of the shielding mechanisms contributing to an enclosures SE by consideration of the transmission cross-section of the various apertures in the enclosure structure and the absorption cross-sections of the enclosure contents comprising the internal enclosure walls, artifacts such as printed circuit boards (PCBs) and any installed probe antennas. The use of these ideas was illustrated in [3] where the effects of PCB absorption on SE is shown. The design of surrogate PCBs, i.e. representative contents or recos is discussed in [4]. The Power Balance technique (PWB) enables the prediction of average power density in a system of coupled reverberant cavities [5]. An equipment enclosure with PCBs stacked inside can be considered to be a set of coupled cavities separated by the PCBs. In the frequency range where the cavities can be considered to be reverberant the PWB technique can be used to evaluate the SE values of the different parts of the enclosure. In this paper we demonstrate that the PWB technique gives equivalent results to measurements when used to estimate the varying SE in the different cavities of an equipment enclosure partitioned by PCBs. The advantage of this technique is that it enables the SE of a partitioned enclosure to be estimated prior to the assembly of the enclosure and its contents. The partitioning of the enclosure by stacked PCBs results in different SE values in each of the cavities. The differences arise as the energy penetrates through the aperture(s) in the enclosure walls and propagates past the PCBs, each of which absorbs a fraction of the energy present. The technique eliminates the need for multiple measurements of SE for each cavity.

II. Shielding Effectiveness and Power Balance

A. *Simple Enclosure with Absorbing Contents*

Consider an enclosure with a single absorbing structure inside and a single aperture through which electromagnetic energy can penetrate as illustrated in Fig.1. The absorbing contents may be a circuit card or other electronic system. For enclosure SE assessment the contents may be representative contents (from now on referred to as a “reco”) with absorbing properties tailored to match the properties of typical circuit cards [4]. In the frequency range where the enclosure is reverberant, the SE can be measured by placing the enclosure in a measurement reverberation chamber using the methodology described in [1] and shown in Fig. 1. The average power density in the measurement reverberation chamber is S_0 and the average power density in the enclosure placed inside the reverberation chamber is S_1. The Arrowed quantities are the power flows between the exterior and the interior of the enclosure and into the enclosure contents. It has been shown in [3] that the SE of the enclosure in the frequency range for which it is reverberant can be expressed in terms of absorption and transmission cross-sections as follows.

$$SE = \frac{S_0}{S_1} = \frac{\sigma^a_{1:wall}+\sigma^a_{1:\mathrm{ant}}+\sigma^a_{1:\mathrm{reco}}+\sigma^t_{10}}{\sigma^t_{10}} \qquad (1)$$

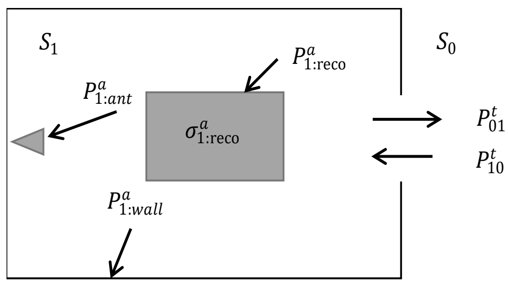

Fig. 1. Power Flow around the Simple Enclosure and its Contents

In (1) the terms σ^a refer to the absorption cross-sections of the internal walls of the enclosure, the reco and the internal probe antenna if present. The σ^t_{10} term is the transmission cross section of the transmission aperture in the enclosure wall.

B. *Enclosure partitioned by a Single Circuit Board.*

In the case of an enclosure with a single printed circuit board (PCB) the spaces either side of the circuit board can be considered to be two cavities. Fig. 2 shows the power flow into and out of the enclosure and between the two cavities of the partitioned enclosure. The power flow between the cavities can be either around the edges of the circuit board or through the circuit card as shown by the arrowed quantities. The average power densities in the exterior space, the reverberation chamber, and the two cavities from which the SE is evaluated are S_0, S_1 and S_2.

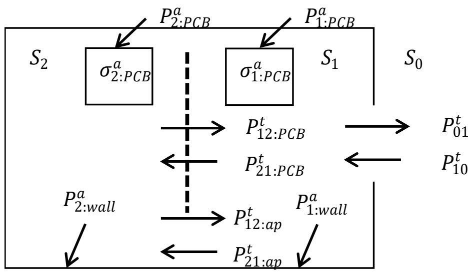

Fig.2. Enclosure Partitioned by a Single Printed Circuit Board.

The printed circuit board is assumed to be populated on both sides and the absorption cross-section of the board is divided between the two sides as $\sigma^a_{1:PCB}$ and $\sigma^a_{2:PCB}$. These are shown in Fig.2 as separate absorbing blocks to simplify the diagram. In reality they are attached to each side of the central partitioning PCB. Measurements performed on typical PCBs indicate that energy transmission through the boards is negligible [6], thus $P^t_{12:PCB}$ and $P^t_{21:PCB}$ can be ignored in the PWB calculation. Energy is exchanged between the two cavities as indicated by the arrowed power flows $P^t_{12:ap}$ *t* and $P^t_{21:ap}$ passing through the aperture between the two cavities with equal transmission cross-sections $\sigma^t_{12:ap}$ and $\sigma^t_{21:ap}$. See (2) below.

Application of the PWB formalism results in the following formula for the SE in cavities 1 and 2 expressed in matrix form.

$$\begin{bmatrix}\frac{S_0}{S_1}\\ \frac{S_0}{S_2}\end{bmatrix} = \begin{bmatrix}(\sigma^a_{1:wall}+\sigma^a_{1:PCB}+\sigma^t_{21:ap}+\sigma^t_{10}) & -(\sigma^t_{12:ap})\\ -(\sigma^t_{21:ap}) & -(\sigma^a_{2:wall}+\sigma^a_{2:PCB}+\sigma^t_{21:ap})\end{bmatrix}^{-1}\begin{bmatrix}\sigma^t_{10}\\ 0\end{bmatrix} \quad (2)$$

In (2) the SE in cavity 1 is S_0/S_1 and the SE of cavity 2 is S_0/S_2. The absorption cross-sections and transmission cross-sections in (2) are those associated with the similarly sub-scripted arrowed power flows shown in Fig.2.

C. *Enclosure Partitioned by Two Circuit Boards*

The formalism shown in Section II.*B* above can be extended to the case of an enclosure partitioned by two PCBs forming an enclosure with three cavities with associated power densities S_0 (exterior), S_1, S_2, S_3 with S_1 containing the aperture.

The associated SEs in (3) are S_0/S_1, S_0/S_2 and S_0/S_3. The super-scripts and sub-scripts in the absorption and transmission cross-sections in (3) follow the nomenclature used in (2)

III. MEASUREMENTS OF SE IN THE REVERBEREATION CHAMBER

All the SE measurements reported in this paper were undertaken in a mechanically stirred reverberation chamber according to the method described in [1]. The chamber has dimensions of 4.7m x 3.0m x 2.37m. The printed circuit board absorption cross-section measurements were made in a mechanically stirred reverberation chamber with dimensions 0.9m x 0.8m x 0.7m as described in [4]. The internal field in the enclosure was measured using an internal probe monopole antenna positioned on the enclosure lid in the centre of each cavity. Measurements were made from 1GHz to 20GHz.

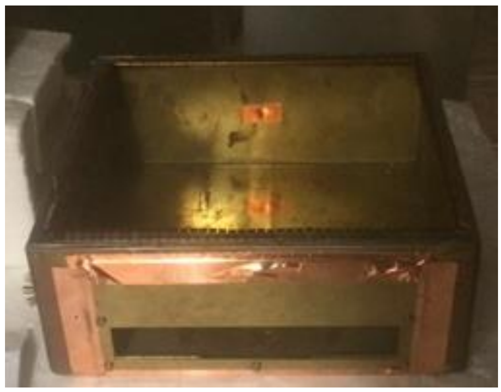

Fig.3. Photo of the Enclosure used in the Measurements with its Lid Removed.

The enclosure used in the measurements reported here is a brass enclosure, shown in Fig. 3 with its lid removed. It has dimensions 300mm x 300mmx 120mm. The aperture shown in one face is 200mm x 30mm. The reco(s) used in the experiments as surrogates for PCBs comprised aluminium sheets with four carbon loaded polyurethane foam blocks attached on each side (two sided reco). The size of these blocks was tuned to match the absorption cross-section of the

$$\begin{bmatrix}\frac{S_0}{S_1}\\ \frac{S_0}{S_2}\\ \frac{S_3}{S_0}\end{bmatrix} = \begin{bmatrix}(\sigma^a_{1:wall}+\sigma^a_{1:PCB}+\sigma^t_{31:ap}+\sigma^t_{10}) & 0 & -(\sigma^t_{13:ap})\\ 0 & (\sigma^a_{2:wall}+\sigma^a_{2:PCB}++\sigma^t_{32:ap}) & -(\sigma^t_{23:ap})\\ -(\sigma^t_{31:ap}) & -(\sigma^t_{32:ap}) & (\sigma^a_{3:wall}+\sigma^a_{3:\mathrm{reco}}+\sigma^t_{23:ap}+\sigma^t_{13:ap})\end{bmatrix}^{-1}\begin{bmatrix}\sigma^t_{10}\\ 0\\ 0\end{bmatrix} \quad (3)$$

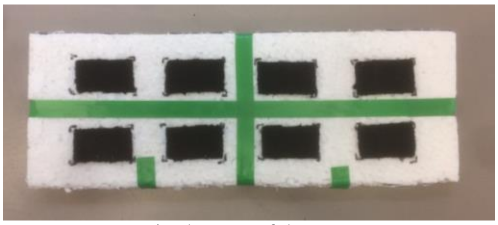

Fig. 4 Image of the reco.

reco to that of a typical similarly sized PCB as described in [4]. Fig. 4 shows the reco used. The expanded polystyrene surround holds the absorbing blocks in place. The aluminium plate ensures no transmission through the reco and replicates the PCB ground-plane.

The wall absorption cross sections were derived from Q-factor measurements of the empty enclosures. The transmission cross-sections were all one quarter of the physical areas of the apertures concerned under the assumption that all apertures were electrically large. Antenna absorption cross sections were derived from the isotropic antenna aperture modified by the average power mis-match factor. These data are presented in Section IV below.

IV. MEASUREMENT AND PWB CALCULATION RESULTS

A. Measured SE of the Simple Enclosure with Absorbing Contents. Not partitioned.

In this section the SE of the enclosure is presented with the reco positioned in the enclosure placed as shown in Fig.5. The reco is centrally placed, supported on expanded polystyrene. The aperture can be seen at the bottom of the image. With the reco in this orientation, the enclosure is not partitioned. In Fig. 6 the measured absorption and transmission cross-sections contributing to the SE and used in the PWB calculations are shown.

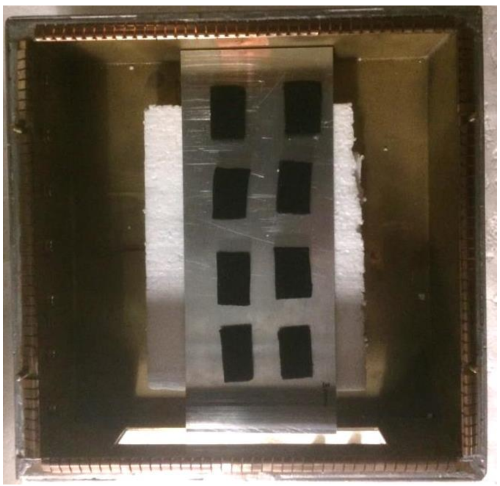

Fig.5. Reco placement in the Enclosure. Not partitioned. Aperture on the lower face.

In Fig.7 the measured SE of the enclosure is shown in comparison with the PWB calculated SE from (1) based on the cross-section data in Fig.6. There is good agreement

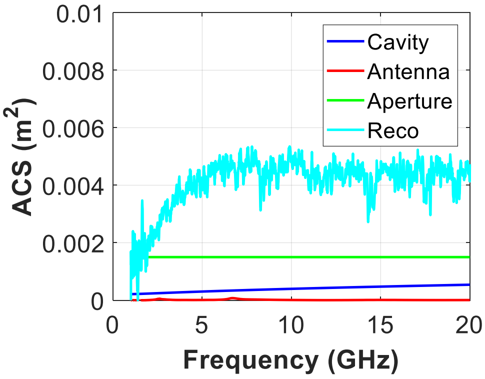

Fig.6. Absorption and Transmission Cross-sections contributing to the SE.

above 5GHz. Below this frequency the reverberant structure field in the enclosure is not well established.

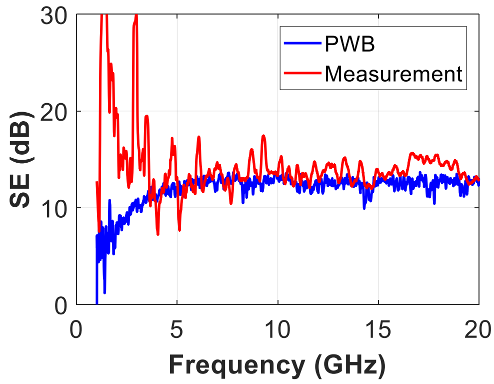

Fig.7. Measured and PWB Calculated SE of the Enclosure without partitioning.

B. Measured and PWB Calculated SE of the Enclosure Partitioned by a Single PCB

Fig.8. Enclosure centrally partitioned by a single reco.

Here the enclosure is partitioned by a single, two sided reco placed centrally as shown in Fig 8. The reco is placed centrally in the enclosure, partitioning it into two equal sized cavities. There is a gap of 8mm around the periphery of the reco forming the aperture coupling the two cavities with transmission cross-sections (assumed equal) $\sigma^t_{12:ap}$ and $\sigma^t_{21:ap}$. Note that the total size of this aperture is 8mm x 176mm, the gap width and the peripheral length of the reco, ensuring that the gap is electrically large in the frequency range of interest. Measured and PWB calculated SE data are shown in Fig. 9. Good agreement between the measured SE and the PWB calculated SE is obtained for frequencies above 5GHz. Note that the measured and PWB calculated SE of cavity 2 is substantially higher than that of cavity 1.

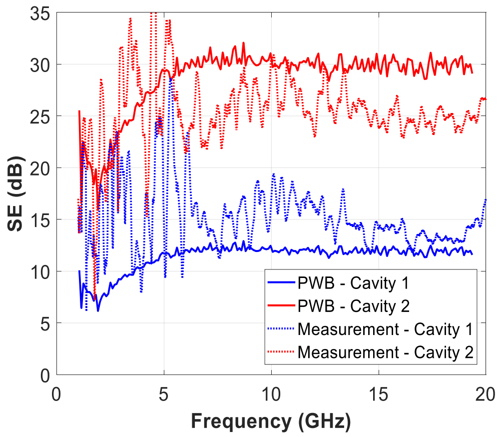

Fig.9. Measured and Calculated SE for the Enclosure with one Partition.

C. *Measured and PWB Calculated SE of the Enclosure Partitioned by Two PCBs*

In this sub-section the results of SE measurements and PWB calculations of SE are presented. The enclosure used above was partitioned into three equal cavities using two recos each with absorber on both sides replicating PCBs populated on both sides. The SE in each cavity was measured using the internal monopole probe as described above and the absorption and transmission cross-section data were used in the PWB calculation. The results are shown in Fig.10.

Again, Cavity 1 contains the aperture connecting the exterior and interior of the enclosure. For the data shown, the

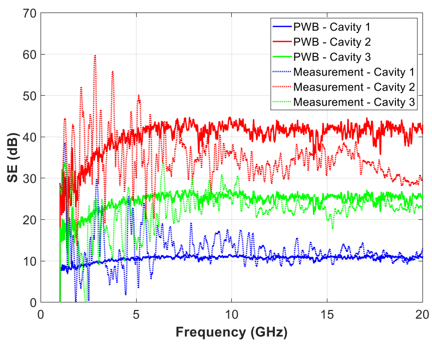

Fig.10. Measured and PWB calculated SE or the enclosure with two partitions.

peripheral gap between the reco and the enclosure walls for the reco partitioning cavity 1 and cavity 2 is 8mm as in IV *B* above. The peripheral gap between the reco and the enclosure walls for the reco partitioning cavity 2 and cavity 3 is 3mm. Note that Cavity 3 is the central cavity , cavity 2 being furthest from the aperture.

Here in Fig. 10 it can be seen that the agreement between the PWB calculation of SE and the measured SE is good. It can be seen that as the energy penetrates the successive cavities the SE increases as energy is absorbed into the recos.

V. CONCLUSIONS

In this paper we have extended our work on Shielding Effectiveness in the higher frequency range where the shielding enclosure exhibits reverberant properties to show the importance of the absorbing properties of the enclosure contents on the overall shielding performance. Concepts described in [2-4] have been used to calculate the SE in the separate cavities formed when PCBs are stacked in the enclosure. The calculated and measured SE values are in good agreement indicating that the calculations are a valid way to obtain SE data.

Of particular note here is the effect of multiple circuit cards stacked in parallel in the enclosure which divide the enclosure into multiple cavities. Each cavity has its own SE value which depends on the absorbing properties of all the PCBs and the positions of all the PCBs in the enclosure. The PWB calculations and the corresponding measurements were made with PCBs that almost filled the enclosure cross-section leaving a small gap between the PCB edge and the enclosure, 8mm or 3mm as discussed in Section III.*B* above. The peripheral length of this gap around the PCB is 176mm so the peripheral gap length is greater than a half-wavelength at the measurement frequencies above 1GHz and the gap can be considered to be electrically large. Clearly, if the width of the gap is increased substantially the assumption of multiple coupled cavities will no longer be valid. This limitation is yet to be explored.

The calculations are performed using the PWB technique described in [5]. The data required to perform the calculations are derived from the enclosure dimensions and measurements of the empty enclosure parameters to yield absorption cross-section data for the walls and enclosure aperture areas. The enclosure contents absorption cross-section data can be obtained by measurements of the PCBs outside the enclosure as described in [3]. The PCBs do not need to be in a powered state for these measurements as demonstrated in [7].

Recent work [8] has demonstrated the use of diffusion equation based techniques to calculate the power flux density and electromagnetic energy density within reverberant systems. In future work it is planned to use this technique to explore further the spatial variability of SE within each of the multiple cavities. This will also enable the limitations of the multiple cavity assumption referred to above to be explored.

It should be noted that the results presented here are measured at one point only in each cavity. The diffusion equation based calculations indicate that the energy density and hence the SE varies with position in each cavity. This effect may, in part, explain the small differences seen between the PWB calculated SE data and the measured SE data.

The PWB calculation of SE demonstrated here can be used before the enclosure is populated with its contents to establish the expected SE values. The effect of positioning the enclosure contents on the SE values obtained inside the multiple cavities can be calculated. Previous techniques have neither highlighted the differing SE values obtained in a populated enclosure partitioned by PCBs nor allowed the estimation of the SE values prior to building the populated enclosure. The technique thus has potential utility at the design stage.

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