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On the Meaning of Enclosure Shielding Effectiveness

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***Abstract*—This paper presents some thoughts on the meaning of shielding effectiveness (SE) for a real enclosure. It is demonstrated that the conventional measurement of SE is a value specific to the particular measurement and is not necessarily representative of the enclosure in any practical situation, including a different measurement. The SE of an enclosure depends both on the enclosure contents, including the measurement antenna and the effective transmission cross-section of the energy coupling mechanisms such as apertures, penetrations, seams and diffusion through walls.**

Keywords—electromagnetic shielding, power balance, enclosure shielding

I. INTRODUCTION

The aim of this paper is to present the meaning of shielding effectiveness (SE) in a different way, which we hope may stimulate some discussion, help researchers and practicing designers understand the meaning of measured, and simulated SE. We begin with a conventional definition of SE in Section II and consider some of the limitations of it. We then review the Power Balance (PWB) view of shielding in Section III in order to determine a fundamental relationship that better describes the shielding capabilities of an enclosure than SE and is easily applied in the reverberant case. In Section IV we consider how the ideas developed in Section III can be applied to enclosures that are not operating in the reverberant regime.

II. SHIELDING EFFECTIVENESS

A. Definition of Shielding Effectiveness

The IEEE 299 standard [1] defines shielding effectiveness as: "The ratio of the signal received (from a transmitter) without the shield, to the signal received inside the shield; the insertion loss when the shield is placed between the transmitting antenna and the receiving antenna." Later in the standard this is expressed in decibels as:

$$SE = 20\log_{10}\frac{|V_0|}{|V_S|}\ \text{dB} \qquad (1)$$

where $|V_0|$ is the magnitude of the voltage measured by a receiver from the measurement antenna with no enclosure present and $|V_S|$ is the magnitude of the voltage from the same antenna when placed inside the enclosure. The measured voltages are assumed to be proportional to the electric field, giving electric field shielding, or the magnetic field, giving magnetic field shielding. This is illustrated in Fig. 1 for the electric field case and in physical terms the electric field SE is:

$$SE = 20\log_{10}\frac{|E_0|}{|E_S|}\ \text{dB} \qquad (2)$$

and similarly for the magnetic field. A given enclosure will have different electric and magnetic SE at low frequencies so separate consideration of electric and magnetic fields is appropriate. At higher frequencies, when the enclosure is electrically large, the magnetic and electric field SE tend to be the same and usually the SE is measured in terms of electric field or power density.

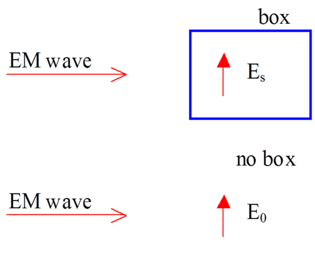

Fig. 1. A definition of electric field shielding effectiveness

The IEEE 299 [1] and IEC-61000-4-21 [2] standards also define SE in terms of the received power as:

$$SE = 10\log_{10}\frac{P_0}{P_S}\ \text{dB} \qquad (3)$$

where P_0 is the power measured by a receiver from the measurement antenna with no enclosure present and P_S is the power from the same antenna when placed inside the enclosure. In the case of electrically large enclosures, the received power can be considered to represent the electromagnetic power density so we might consider SE as:

$$SE = 10\log_{10}\frac{S_0}{S_S}\ \text{dB} \qquad (4)$$

where S_0 is the power density with no enclosure present, or the

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power density incident on the enclosure, and S_S is the power density inside the enclosure. The power density is, of course dependent on the square of the total magnetic or electric fields and is often written, e.g. in the electric field case. as:

$$S = \frac{E_t^2}{\eta_0} \tag{5}$$

Where E_t is the total electric field (root sum square of thre orthogal field components), and η_0 is the characteristic impedance of free-space.

B. Spatial variation of Shielding Effectiveness

As electromagnetic fields are vector fields, it should not be surprising that the SE measured may depend on both the orientation of the illuminating field and that of the receiving antenna. It is usually assumed that the transmitting and receiving antennas are co-polarised [1], but depending on the coupling mechanism and enclosure geometry, including any contents, the actual fields inside the enclosure may not follow the polarisation of the illumination. Also as the receive antenna has some directivity, the direction in which it points is also likely to affect the value measured. The modal structure in the chamber will also mean that the magnitude of the fields measured, and hence SE, will depend also on the location of the antenna [3]. As the number of modes excited in an enclosure increase the statistics of the fields, and hence SE measured at different places will change until the enclosure has sufficient modes excited to be considered reverberant [4].

In reverberant enclosures, the SE measured is usually assumed independent of the antenna position and orientation, as when averaged over a number of configurations the field is assumed to be both spatially uniform and to have equal power density in any polarisation or direction [5].

C. Effect of Contents on Shielding Effectiveness

Most standards specify the measurement of an enclosure empty, except for the measurement antenna. However, any contents placed in the enclosure, including the measurement antenna, will affect the internal fields by virtue of both a change in boundary conditions and by absorption of energy [6]-[8]. This presents two fundamental problems:

1) the measured SE for any enclosure must depend on the type of antenna used, as well as its position, in addition to the properties of the enclosure under test;
2) the actual SE achieved by the enclosure when in use will depend on the contents present and vary with position.

In the following sections we hope to address the above problems.

III. A Power Balance View of Shielding

A. The Power Balance Method

The power balance method for analysing the shielding effectiveness of electrically large enclosures under reverberant conditions [9]-[10] provides a simple technique for the analysis of the SE of enclosures with apertures and contents, and reveals a fundamental relationship that determines the SE of an enclosure.

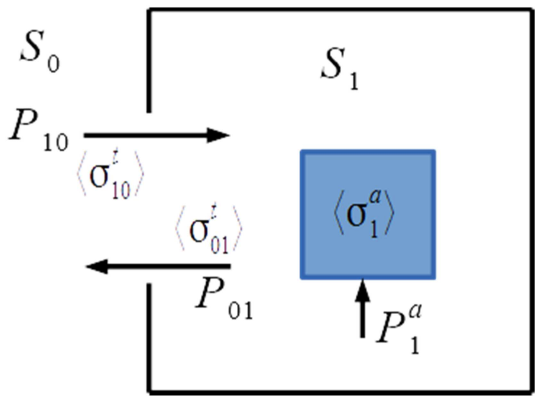

Fig. 2. Power flow in an enclosure with an aperture and energy absorptive contents

Fig. 2 shows the flow of power in an enclosure with an aperture and energy absorptive contents. S_0 is the power density of the reverberant electromagnetic field outside the enclosure (e.g. inside a reverberation chamber), and S_1 is the power density inside the enclosure, so the SE of the enclosure in terms of a power ratio, could be defined as:

$$SE = \frac{S_0}{S_1} \tag{6}$$

The power balance in the steady state requires:

$$\langle P_{10}\rangle = \langle P_{01}\rangle + \langle P_1^a\rangle \tag{7}$$

where $\langle P_{10}\rangle$ is the average power flow into the enclosure due to the external power density, $\langle P_{01}\rangle$ is the average power flow out of the enclosure due to the internal power density, and $\langle P_1^a\rangle$ is the average power absorbed in the enclosure contents due to the internal power density. For simplicity, we have taken $\langle P_1^a\rangle$ to include any energy absorbed in antenna(s) in the enclosure, its contents and any losses in the walls. All of the power flows will be proportional to the driving power density. The power flow through the aperture is:

$$\langle P_{10}\rangle = \langle \sigma_{10}^t\rangle S_0 \tag{8}$$

$$\langle P_{01}\rangle = \langle \sigma_{01}^t\rangle S_1 \tag{9}$$

where $\langle \sigma_{10}^t\rangle$ is the average transmission cross-section (TCS) of the aperture for energy traveling into the enclosure and $\langle \sigma_{01}^t\rangle$ is the average TCS of the aperture for energy traveling out of the enclosure. In the case of reverberant energy both inside and outside the enclosure, they are equal and depend only on the geometry of the aperture [9]-[10]. The energy absorbed into the contents is:

$$\langle P_1^a\rangle = \langle \sigma_1^a\rangle S_1 \tag{10}$$

where $\langle \sigma_1^a\rangle$ is the average absorption cross-section (ACS) of the contents. The ACS of the contents may be the sum of the individual ACSs of the walls, any antennas, and any other contents. The absorption and transmission cross-sections may be frequency dependent and are the only source of frequency dependence in the PWB formulation.

Since in the reverberant case, the power density is assumed to be uniform in space and isotropic, in that equal energy travels in every direction with every polarisation, the position of the aperture and contents does not matter. Substituting (8)-(10) into (7) we get:

$$\langle\sigma_{10}^t\rangle S_0 = \langle\sigma_{01}^t\rangle S_1 + \langle\sigma_1^a\rangle S_1 \quad (11)$$

which can be solved to give:

$$SE = \frac{S_0}{S_1} = \frac{\langle\sigma_{01}^t\rangle+\langle\sigma_1^a\rangle}{\langle\sigma_{10}^t\rangle} = \frac{\langle\sigma^t\rangle+\langle\sigma_1^a\rangle}{\langle\sigma^t\rangle} \quad (12)$$

if the transmission cross-section is the same in both directions.

It can be seen therefore that any SE measured in a reverberant environment will depend on the transmission cross-section of any apertures (or any other means of field penetration), and the absorption cross-section of the contents which is the sum of the effects of the enclosure, any receiving antenna, and any other contents:

$$\langle\sigma_1^a\rangle = \langle\sigma_{1enc}^a\rangle + \langle\sigma_{1ant}^a\rangle + \langle\sigma_{1cont}^a\rangle \quad (13)$$

where $\langle\sigma_{1enc}^a\rangle$ is the intrinsic absorption cross-section of the inside of the enclosure (wall losses etc.), $\langle\sigma_{1ant}^a\rangle$ is the absorption cross-section of the antenna, and $\langle\sigma_{1cont}^a\rangle$ is the absorption cross-section of any other contents.

B. *Intrinsic Properties of the Enclosure*

It is clear from (12) and (13) that the intrinsic properties of an enclosure that determine its SE are the TCS of the coupling paths into the enclosure and the ACS of the inside of the enclosure. The ACS of any contents must also be known to predict the SE from the intrinsic enclosure properties.

When we measure the SE of an enclosure, we have only a single measurement which depends on several unknowns. We may be able to measure or otherwise predict the ACS of the contents [11], and the antenna [10], but a single SE measurement does not reveal the TCS of the enclosure apertures or the internal ACS of the enclosure. However, for metal enclosures with absorptive contents such as printed circuit boards, the internal absorption due to the enclosure itself may be negligible and if we measure the SE with contents whose ACS is known and much larger than that of the enclosure we can then deduce the TCS of any apertures:

$$SE = 1 + \frac{\langle\sigma_1^a\rangle}{\langle\sigma^t\rangle} \rightarrow \langle\sigma^t\rangle = \frac{\langle\sigma_1^a\rangle}{SE-1} = \frac{\langle\sigma_1^a\rangle}{S_0/S_1-1} \quad (14)$$

The TCS can then be used to predict the SE with other contents of known ACS [12] as long as it much larger than the enclosure intrinsic ACS. We have proposed the use of a representative-contents [13] for use in SE measurement for this reason. If the SE is measured twice with contents of different and known ACS the enclosure internal ACS may also be deduced.

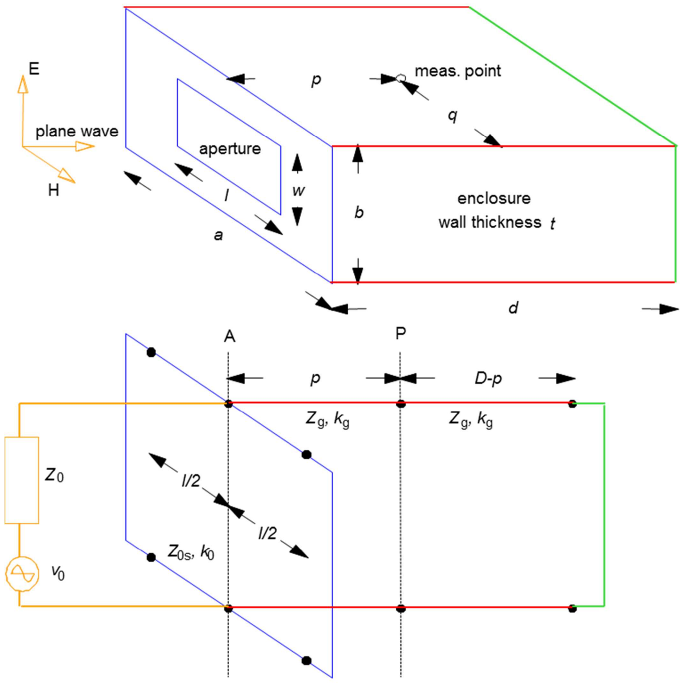

Fig. 3. Single mode model of an enclosue with an aperture [14]

IV. Power Balance in the Non-Reveberant Case

The power balance method is simple to use for the reverberant case as the power density is assumed to be uniform in the enclosure so there is no need to consider the geometry of the enclosure, of any coupling paths, or of the contents. However, the fundamental power balance concept must apply to any shielding scenario. The difference, in the non-reverberant case, is that the detailed field configuration must be taken into account in order to determine the TCS of any aperture and the ACS of any contents. Here we use the simple single mode model of an enclosure with an aperture, as proposed by Robinson et al [14] as an example. The enclosure is represented by a rectangular waveguide with a short circuit at the back. Only the TE_{10} mode is considered here, which limits the upper frequency of validity of the model to around the cut-off frequency of the second mode. Losses within the enclosure are represented by a distributed loss in the waveguide controlled by the factor, ζ, as described in [14]. The aperture is represented as a short circuited co-planar waveguide and a normal incident illuminating plane wave is represented by a 2 V source with a series resistance equal to the characteristic impedance of free space resulting in an assumed 1 V/m forward wave impinging on the aperture. The vertical electric field at a point p,q is then:

$$E_z(p,q) = v\left(p,\frac{a}{2}\right)\sin\frac{\pi q}{a} \quad (15)$$

where $v\left(p,\frac{a}{2}\right)$ is the voltage on the transmission line corresponding to the centreline of the waveguide and the sinusoidal variation of the E-field across the line is assumed from knowledge of the waveguide mode. The Magnetic field can also be determined from the mode structure.

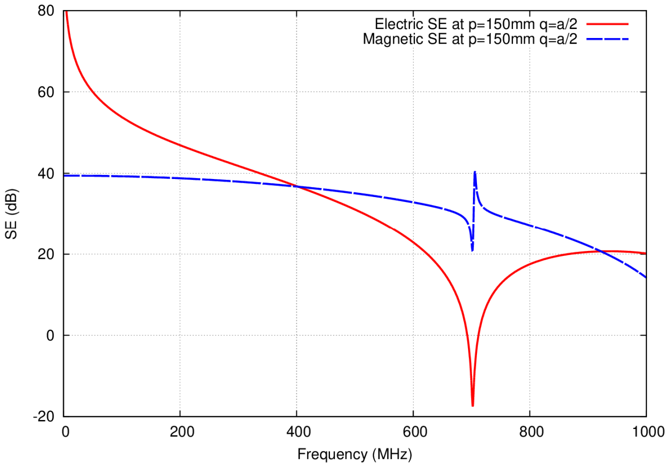

Fig. 4. Electric and magnetic field shielding effectiveness predicted by waveguide model for an enclosure where a=300 mm, b=120 mm, d=300 mm, l=100 mm, w=5 mm, t=1.5 mm, ζ=1/300.

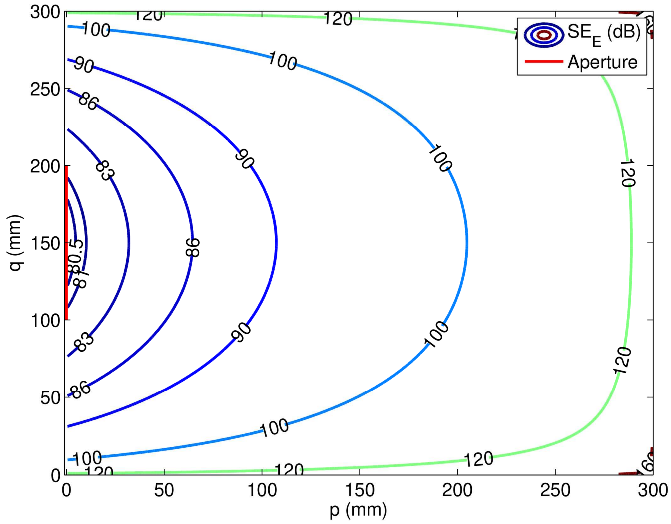

Fig. 5. Electric field shielding predicted by waveguide model at 1 MHz

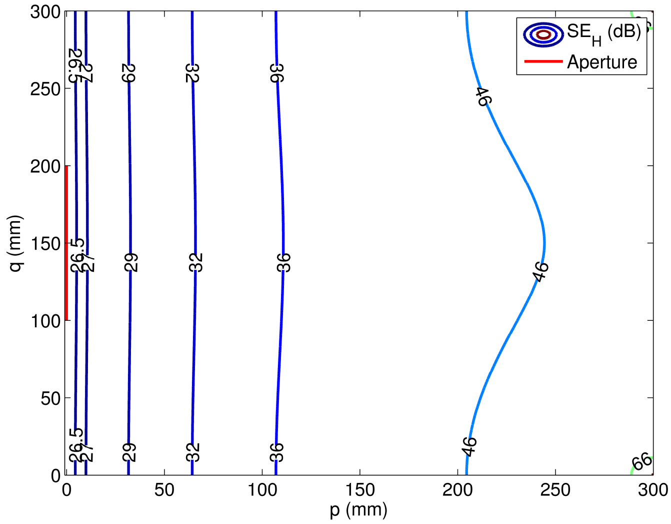

Fig. 6. Magnetic field shielding predicted by waveguide model at 1 MHz

A. Field structure in the enclosure

Before we look at power balance we will consider the field structure and variation of SE in the example enclosure. Fig. 4 shows the electric and magnetic SE at the centre of an enclosure, predicted by the model, as a function of frequency. Fig. 5 to Fig. 10 show the predicted variation in the shielding effectiveness with position at a number of frequencies. At 1 MHz (Fig. 5 and Fig. 6) the mode is evanescent in the enclosure and both fields fall rapidly with distance from the aperture.

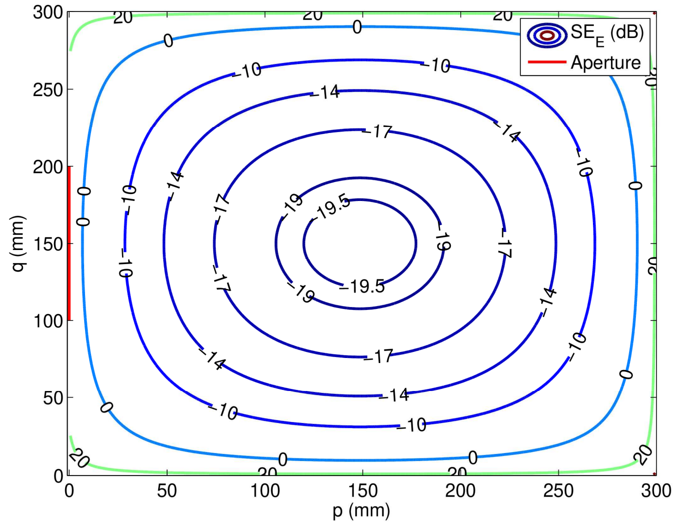

Fig. 7. Electric field shielding predicted by waveguide model at 702 MHz

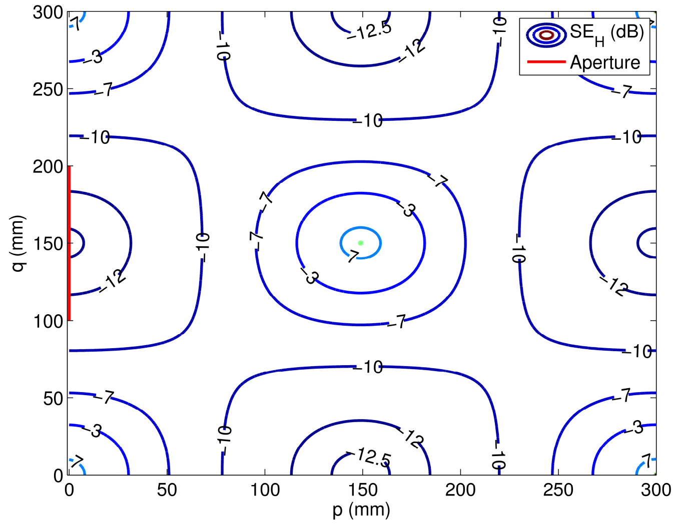

Fig. 8. Magnetic field shielding predicted by waveguide model at 702 MHz

Fig. 7 and Fig. 8 show the SE at 702 MHz which is the first cavity resonance. It can be seen from Fig. 4 that the electric field SE in the centre reaches around -20 dB. Although the power balance equations must apply, the fields and power density can be higher inside the cavity than outside at some points as considerable energy can be stored in a resonance.

Fig. 9 and Fig. 10 show the SE at 800 MHz where the electric field standing wave in the enclosure can be seen to have a minimum (maximum shielding) at 50 mm from the front face.

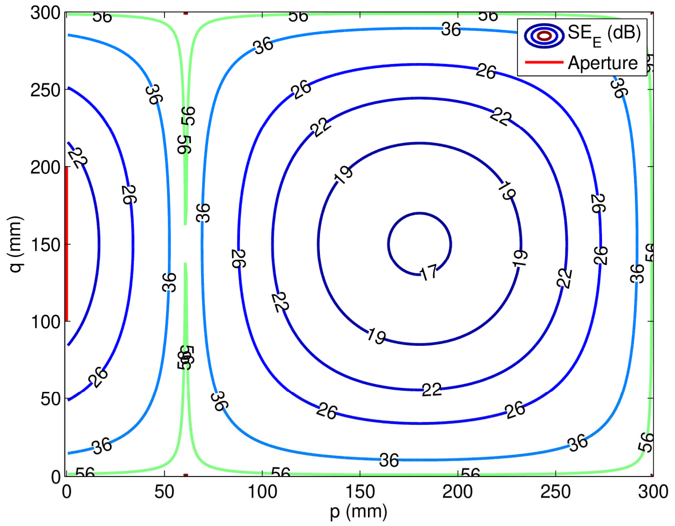

Fig. 9. Electric field shielding predicted by waveguide model at 800 MHz

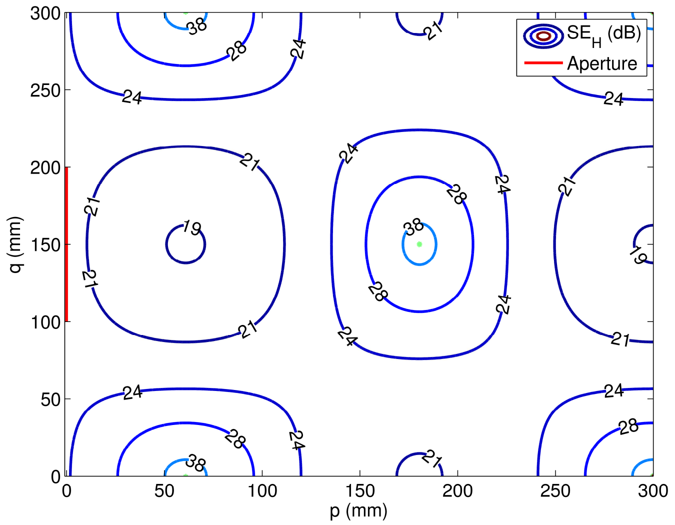

Fig. 10. Magnetic field shielding predicted by waveguide model at 800 MHz

B. Application of Power Balance

The power absorbed by the enclosure, due to any losses in the waveguide, due to the parameter ζ in this model [14], is:

$$P_1^a = \frac{ab}{2} V_{aps} \left(\frac{V_{aps}}{Z_{ins}}\right)^* \qquad (16)$$

where the star superscript indicates complex conjugate, Z_0 is the characteristic impedance of the source equal that of free space, and Z_{ins} is the impedance looking into the enclosure when the end of the waveguide is short-circuited:

$$Z_{ins} = \frac{Z_{ap} Z_3(0)}{Z_{ap} + Z_3(0)} \qquad (17)$$

and V_{aps} is the voltage at the aperture:

$$V_{aps} = \frac{V_0 Z_{ins}}{Z_0 + Z_{ins}} \qquad (18)$$

as given in [14], Z_{ap} is the impedance of the aperture and $Z_3(0)$ is the impedance looking into the shorted guide at the aperture (i.e. at $p = 0$):

$$Z_3(p) = jZ_g \tan k_g(d-p) \qquad (19)$$

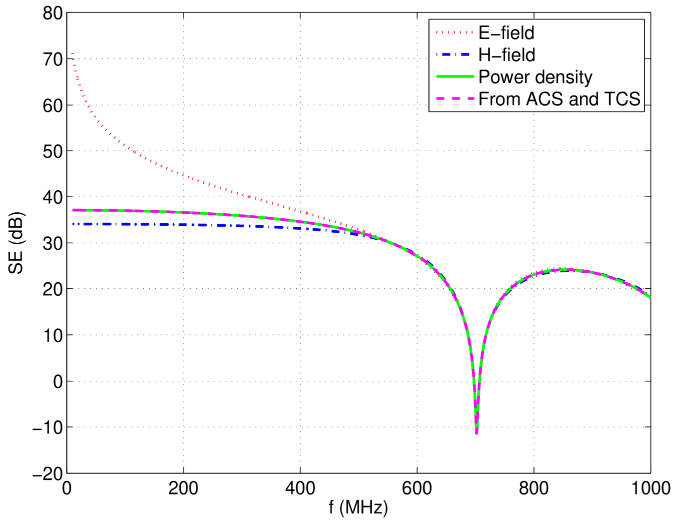

Fig. 11. SE based on average energy in E-, H-field, the combination of both (Power density), and from the TCS and ACS calculations.

So the ACS of the enclosure contents is:

$$\sigma^a = \frac{P_1^a}{S_1} \qquad (20)$$

where S_1 is the average power density in the enclosure which can be computed from the mode structure within the enclosure in the same way as Fig. 5 to Fig. 10.

We can also compute the enclosure SE from the incident and internal power densities as in (6). The result of determining the SE from the average power density from the E-field only, the H-field only and the average of both, is shown in Fig. 11. It can be seen that at low frequencies the magnetic field dominates the behaviour as it carries most of the energy, whereas at higher frequencies equal energy is stored in both fields and the curves are identical.

The power flow out of the enclosure can be computed from the reverse travelling wave inside the waveguide at the aperture:

$$P_{01} = \Re\left(\frac{ab}{2} V_r(0) \cdot \left(\frac{k_g}{\omega\mu} V_r(0)\right)^*\right)(1 - |\rho_{01}|^2) \qquad (21)$$

where , the aperture reflection coefficient from inside the guide, ρ_{01}, is computed from the known impedances. The reverse traveling wave is computed from the source voltage by considering the transmission coefficient of the aperture and summing the infinite series of reflected waves:

$$V_r(0) = \frac{V_0}{2}\frac{\tau_{10}\rho_s \exp(-2jk_g d)}{(1-\rho_{01}\rho_s \exp(-2jk_g d))} \quad (22)$$

The power flow into the enclosure can be computed from the power balance (7). The transmission cross-sections can then be computed from the known power flow and power densities as using (8) and (9).

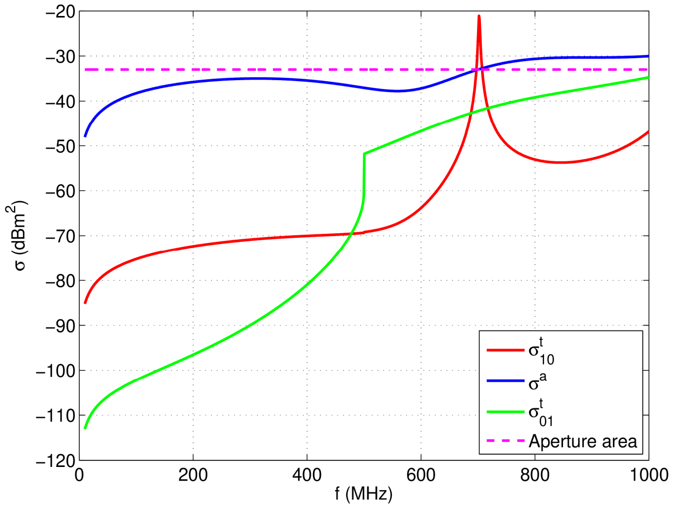

Fig. 12. Computed transmission and absorption cross-sections for the aperture and waveguide losses, the actual area of the aperture is also shown.

Fig. 12 shows the computed values of absorption and transmission cross section using the waveguide model. The actual aperture area is shown and it can be seen that the transmission cross-section, σ_{10}^t, is larger than the physical aperture area around the 700 MHz resonance of the enclosure. Fig. 11 also shows the SE computed from the transmission and absorption cross-sections, it is directly superimposed on the SE computed from the energy densities.

V. Conclusions

We hope to stimulate some thought and discussion about the meaning of shielding effectiveness and its measurement. In particular, we conclude that SE is not an intrinsic property of an enclosure. The SE of an enclosure depends on both the transmission cross-section of any apertures or penetrations and the absorption cross-section of its contents as given in (12). The contents in this sense includes, any losses in the enclosure walls, any energy absorbed by a measurement antenna, and energy absorbed by any contents.

In the case of electrically large enclosures, which can be considered reverberant, there are simple closed form solutions for the transmission cross-section of simple apertures. The absorption cross section of the walls, and contents can often only be determined by measurement. The position of apertures and contents has little effect on the SE as the power density is approximately uniform throughout the volume of the enclosure.

In the case of enclosures that cannot be considered reverberant, the variation of the fields throughout the volume of the enclosure, which depends on the modes excited, means that the energy absorbed by any contents, and the coupling through any apertures will depend on their geometry and position. With the exception of that proposed in [14] and the many subsequent improvements, which treat a limited number of simple geometries, there are no simple analytic solutions.

So whilst a measurement or calculation of SE may be of use to compare the performance of enclosures, if we cannot determine the transmission and absorption cross-sections of the enclosure and its contents we cannot easily predict the behaviour of the enclosure with different contents.

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