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An Experimental Study of the Variability of the Shielding Effectiveness of Circuit Board Shields

Andrew C Marvin
Department of Electronic Engineering
University of York
York, UK
andy.marvin@york.ac.uk

John F Dawson
Department of Electronic Engineering
University of York
York, UK
john.dawson@york.ac.uk

Haiyan Xie
Northwest Institute of Nuclear Technology
Xi'an, China
xiehaiyan@nint.ac.cn

Linda Dawson
Department of Electronic Engineering
University of York
York, UK
l.dawson@york.ac.uk

Arunkumar Venkateshaiah
Department of Electronic Engineering
University of York
York, UK
arunkumarvenkateshaiah@york.ac.uk

Abstract—**The paper examines the variability of the Shielding Effectiveness of board level shields measured in a reverberation chamber at frequencies from 200 MHz to 20 GHz. Results show that at any particular frequency the Shielding Effectiveness exhibits a typical variability of $\pm$20 dB about the mean value.**

Keywords—shielding effectiveness, board level shields, reverberation chambers.

I. Introduction

Small circuit board level shielded enclosures are used in many electronic devices to shield their contents from neighbouring components or sub-systems on the same circuit board or nearby. A printed circuit board with a shield installed is likely to be inside the larger equipment enclosure: it is a shielded enclosure inside a larger shielded enclosure. In the microwave frequency range the larger shielded enclosure is likely to be resonant or even reverberant: the board level shield itself is likely to be resonant. Thus the electromagnetic environment in which the circuit board level shield and the nearby interference sources or victims it is designed to protect exists is unknown and variable. In this paper we show that the shielding performance of the board level shield depends on its immediate external environment and we quantify this variability.

Various techniques for examining the performance of board level shields have been described previously, for example in [1],[2],[3]. A number of techniques for the definition of and the measurement of the shielding effectiveness (SE) of these shields is under examination in the IEEE collaborative project *P2716 Guide for the Characterization of the Effectiveness of Printed Circuit Board Level Shielding* [4]. The project description has the following statements.

The methods that are currently described in IEEE 299 and IEEE 299.1 for stand-alone shielded enclosures are not applicable to board level shielding because of some particularities with board level shielding:

- a board level shield is not a stand-alone enclosure as it only provides 5 of the 6 walls to make a complete Faraday cage, with potentially no or poor electrical connectivity to the circuit board ground plane, should the circuit board have a full ground plane.

- the user of a board level shield is responsible for the connection to and the realization of the 6th wall. As such, he/she needs methods to characterize this.

- the source is always very close to the board level shield, so it is near-field shielding.

These statements show how board level shields differ from conventional six sided shielded enclosures and illustrate the need for a new approach to their assessment. As part of the programme the York team proposed two shielding metrics for board level shields, Stirred SE and Unstirred SE. These are described in Section III below. In addition to these metrics, in this paper the data gathered for the University of York's contribution to P2716 is used to investigate the statistics of the variability of the SE. A third metric, Point SE, is used for this as described in Section IV below.

In order to reproduce the range of possible variation in the electromagnetic environment that the board level shield may be subject to we have measured the SE of the board level shield in a reverberation chamber. We postulate that the electromagnetic environment variability in the reverberation chamber mimics the range of variability found in real equipment enclosures.

II. Shielding Effectiveness Measurement Jig

A measurement jig has been designed to enable the measurement of circuit board level shields. Images of the jig is shown in Fig. 1. Three 50 Ω characteristic impedance parallel plate transmission lines of length 25 mm are situated above a groundplane. The board level shield is attached to the groundplane covering the transmission line marked 'Shield' in the lower image of Fig.1. The remaining two parallel plate lines marked 'Orthogonal' and 'Parallel' in the lower image of Fig.1 are displaced 50 mm from the centre of the 'Shield' transmission line. The SE of the board level shield is measured by comparing the coupling between the Shield and the 'Parallel' transmission line or the 'Orthogonal' transmission line with and without the board level shield installed. This arrangement of transmission lines mimics the practical installation of a board level shield where source or victim circuits are located in the vicinity of the board level shield. The current jig design is a prototype for proof of concept measurements. It has not yet been formally adopted as an output of the P2716 project.

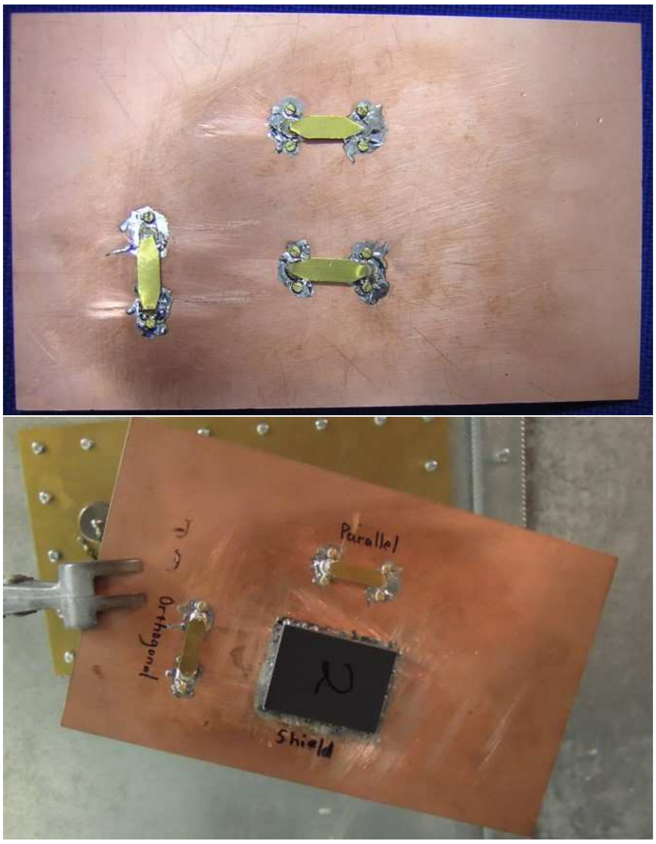

Fig. 1 Measurement Jig; Upper, empty jig. Lower; Jig with shield installed.


Fig. 2 Measurement Jig in the Reverberation Chamber.

An image of the jig inside the reverberation chamber is shown in Fig. 2. The transmission lines are connected to the reverberation chamber connector panel through semi-rigid cables. The other ends of the transmission lines are terminated in 50Ω loads. The reverberation chamber has a rotating mechanical stirrer. Its linear dimensions are length 4.7 m, width 3 m, and height 2.4 m.

III. Shielding Effectiveness Definitions

The coupling between the transmission lines is measured with a vector network analyser. In these preliminary measurements it was found that all ports were sufficiently well matched to enable corrections for input mismatch to be ignored. Thus the SE can be defined in terms of the ratio of the coupled power into the shield transmission line with and without the shield present by taking the ratio of the S_{21} parameter describing the coupling between the shield transmission line and the parallel and orthogonal transmission lines. In the initial P2716 measurement programme report the York team proposed two definitions of SE. These are Unstirred SE and Stirred SE as defined below.

A. Unstirred SE

Unstirred SE is the ratio of the unstirred coupling between the shield transmission line and the parallel or orthogonal transmission lines. The unstirred coupling is derived from the phasor average of the S_{21} parameter averaged over the stirrer rotation.

$$SE_{\mathrm{us}} = 10\log_{10}\left(\left|\frac{\langle S_{21\mathrm{u}}\rangle}{\langle S_{21\mathrm{s}}\rangle}\right|\right)^2 \qquad (1)$$

Here $\langle S_{21u}\rangle$ is the average of the unshielded S_{21} over the stirrer rotation and $\langle S_{21s}\rangle$ is the average of the shielded S_{21} over the stirrer rotation. The Unstirred SE represents the direct coupling between the source and the shield interior transmission line and excludes reverberant coupling.

B. Stirred SE

Stirred SE is the ratio of the stirred coupling between the source and the shield interior. This is derived by subtracting the phasor averages from the coupling to leave only the reverberant coupling.

$$SE_{\mathrm{st}} = 10\log_{10}\left(\frac{\langle |S_{21\mathrm{u}}-\langle S_{21\mathrm{u}}\rangle|^2\rangle}{\langle |S_{21\mathrm{s}}-\langle S_{21\mathrm{s}}\rangle|^2\rangle}\right) \qquad (2)$$

The Stirred SE represents the coupling between the source and the shield interior transmission line excluding the direct coupling.

IV. Point Shielding Effectiveness

In this paper we suggest a third definition of SE based on further consideration of the measurement system and the shield installation. The installation of a board level shield on a circuit board inside an equipment enclosure means that the exterior electromagnetic environment of the shield is unknown. The SE obtained in a particular board installation will depend on the exterior environment. The SE definitions in III above do not give any insight into the actual SE for a particular combination of shield and installation. The stirring of reverberation chamber is used to mimic the range of external installation environments that a particular shield may be installed in. This range can be examined by evaluating the SE for each stirrer position.

The Point SE is defined as the population of n SE values derived by taking the S_{21} ratios for each of n stirrer positions. Thus the S_{21} between the source and the shield transmission line is measured for a set of stirrer positions without the shield in position and with the shield in position. For each stirrer position the S_{21} ratio is taken to measure the SE at that stirrer position corresponding to a particular external electromagnetic environment for the shield. In the measurement set-up care is taken to keep the jig and its semi-rigid cabling in the same position in the reverberation chamber.

The Point SE is:

$$SE_n = 10\log_{10}\left|\frac{S_{21\mathrm{u}(n)}}{S_{21\mathrm{s}(n)}}\right|^2 \qquad (3)$$

where SE_n is the SE value at stirrer position n and $S_{21\mathrm{u(n)}}$ and $S_{21\mathrm{s(n)}}$ are the S_{21} parameters measured at stirrer position n with the shield removed and installed respectively. The mean value of this population is $SE_{\text{point (mean)}}$.

$$SE_{\text{point(mean)}} = 10\log_{10}\left\langle\left|\frac{S_{21u}(n)}{S_{21s}(n)}\right|^2\right\rangle \qquad (4)$$

The mean value of the dB values is:

$$SE_{point(mean\ dB)} = \left\langle 10\ log_{10}\left|\frac{S_{21u}(n)}{S_{21s}(n)}\right|^2\right\rangle \qquad (5)$$

The use of these SE definitions allows the range of SE values possible for a given shield in otherwise unknown installations to be assessed.

V. SHIELDING EFFECTIVENESS MEASUREMENTS

The measurements of SE have been taken over a frequency range of 200 MHz to 20 GHz with a frequency increment of 50 MHz. The lower frequency is the lowest useable frequency (LUF) of the University of York (UoY) reverberation chamber as measured using the field uniformity criterion in the IEC standard [5]. In order to optimise the trade-off between measurement dynamic range and measurement time the maximum output power setting of 20 dBm on the network analyser was used along with a measurement bandwidth of 10 kHz. One hundred stirrer positions were used with the stirrer set to the same start point for each set of measurements.

The dynamic range of the measurement set-up was evaluated by disconnecting and terminating the shield transmission line at the jig whilst maintaining the cable position in the reverberation chamber. Fig. 3 shows the dynamic ranges achieved. The SE data presented below are all within the measurement dynamic range.

Examples of typical S_{21} data are shown in Fig.4. The upper images show the set of complex S_{21} values for the one hundred stirrer positions. The spots are the phasor averages. The radii of the continuous circles are the rms values of the S_{21} data used for the Unstirred SE estimates. The radii of the dashed circles are the rms values of the centred stirred S_{21} data (S_{21} - <S_{21}>) used for the Stirred SE estimates. The lower images show the probability density histograms of the real and imaginary parts of the S_{21} data overlaid with the normal distributions with the same mean and standard deviation. These are scaled to give a unit area under the curve.

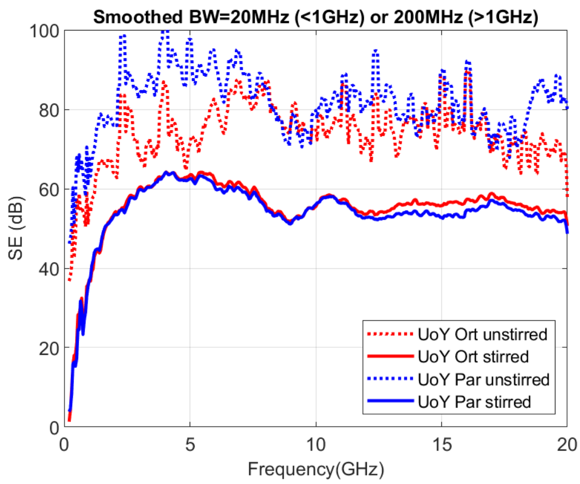

Fig. 3 Dynamic range of SE measurements for parallel and orthogonal stirred and unstirred SE

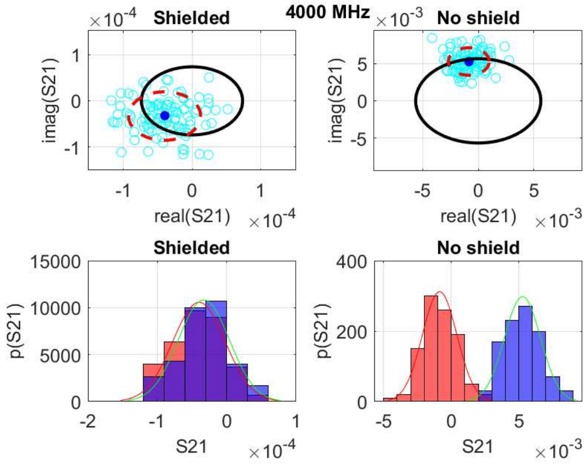

Fig. 4 Typical S_{21} data for SE measurements

The stirred and unstirred SE data for a typical board level shield are shown in Fig. 5. The data in this example are for parallel transmission line coupling to the shield transmission line. The stirred SE data follow the lower stirred dynamic below 1 GHz. The SE values are typical for the range of shields measured.

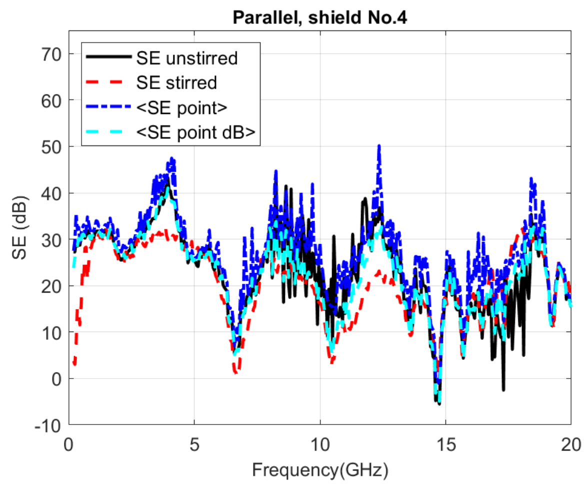

Fig. 5 Typical SE data for a board level shield

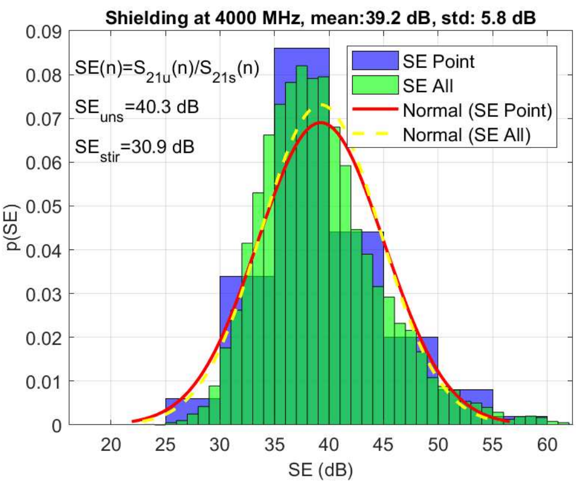

Fig. 6 PDF of Point SE data at 4GHz

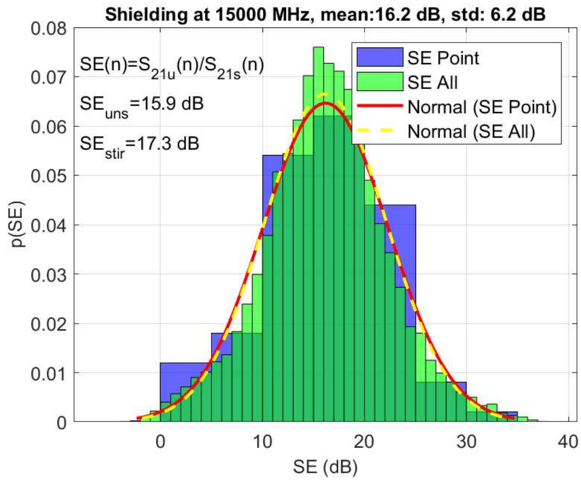

Fig. 7 PDF of Point SE data at 15 GHz

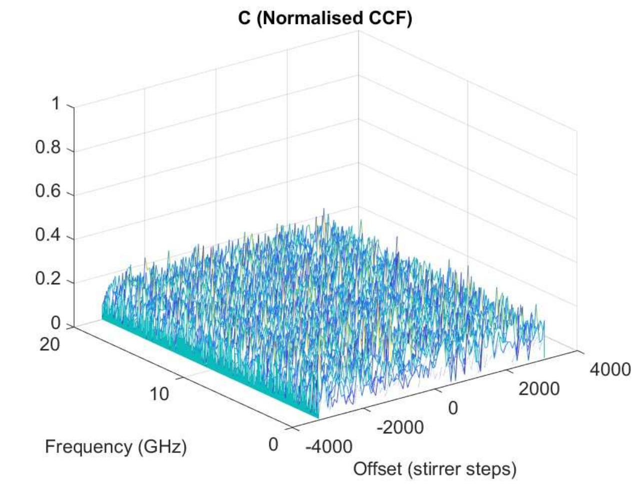

Fig. 8 Cross-correlation between shielded and unshielded S_{21} as a function of stirrer offset (6400 steps per revolution) at each frequency

The data show that the SE of the typical board level shield is variable and that there are excursions into negative SE values (when expressed in dB) at a number of frequencies in the higher frequency range above 10 GHz. The use of the Point SE data enables a more informative examination of the range of SE values.

Figure 6 and Fig. 7 show the probability density functions (PDF) of the Point SE measurements at frequencies of 4 GHz and 15 GHz along with the normal distributions having the same mean and standard deviation plotted out to three standard deviations (99.7 % of population).

It can be seen from these figures that the Point SE varies significantly with stirrer position over a range of approximately 40 dB. The figures also show the distribution obtained when each unshielded stirrer position is ratioed with each shielded stirrer position (SE All). SE All gives virtually the same normal distribution as the Point SE.

Figure 8 shows the cross-correlation between shielded and unshielded S_{21} as a function of stirrer offset in steps (6400 steps per revolution, $\pm$3200 on the Offset axis) at each frequency, and demonstrates that there is no significant correlation between the fields measured in the shielded and unshielded cases. This along with the similarity between the "All points" and the Point SE of the PDFs in Figs 6 and 7 suggests that there is no need to take the ratios of unstirred

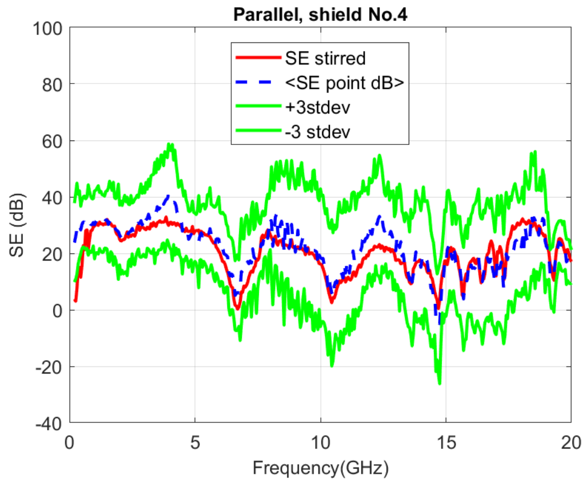

Fig. 9 dB Average Point SE with three standard deviation bounds

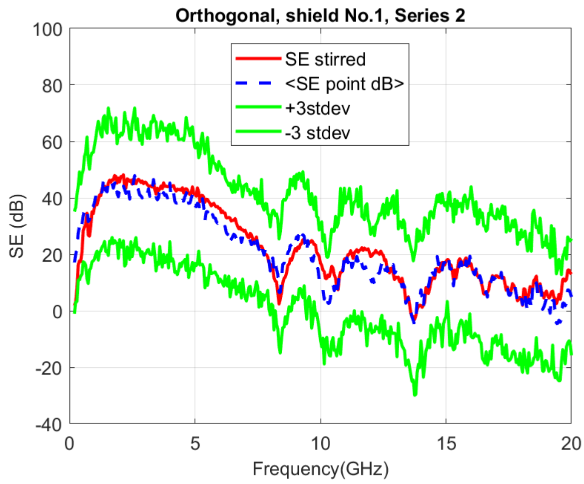

Fig. 10 dB Average Point SE with three standard deviation bounds

and stirred coupling values at identical stirrer positions in order to obtain the SE PDF.

Figure 9 and Fig. 10 show plots of Point SE for two typical board level shields along with the three standard deviation bounds. The 3σ range of Point SE values is consistently around 30 to 40 dB over the entire frequency range. Note that the Point SE mean data closely follow the Stirred SE data.

The data shown in Fig 3 show that the dynamic range of the measurement system employed in this investigation is adequate to measure the range of SE values exhibited by typical board level shields. The exception is for the Stirred SE measurements at frequencies below 1 GHz where the dynamic range reduces. The measured Stirred SE value plots follow the dynamic range plots at these lower frequencies. This low dynamic range is believed to be associated with the low frequency behaviour of the reverberation chamber. The stated LUF is based on field uniformity which may not be an appropriate parameter in this case.

The measured SE data presented here for all three SE metrics are typical of the data obtained for the range of seven board level shields examined in the P2716 programme. The shield giving the data in Fig 5 and Fig 8 is 32 mm square and 5 mm high. The shield giving the data for Fig 9 is 20 mm by 38 mm and 8 mm high. The shield, orthogonal and parallel transmission lines are all 25 mm long. Any significant resonances associated with these structures would be expected to be at harmonics of 6 GHz. This is not apparent in the data. Both these shields have the lowest order unperturbed cavity resonance frequency (TE110) at approximately 6.5 GHz. Evidence of resonant behaviour from this frequency upwards is present in the SE data with the resonant artefacts appearing at non-harmonically related frequencies.

The modest SE values observed are to be expected at microwave frequencies. The board level shields typically have an open frame that is soldered to the circuit board along with a clip on shell. Others have an array of small ventilation holes. Each shield has discrete solder attachment points to the groundplane so that there is a set of small apertures around the shield edge where it meets the groundplane. The reduction in SE with increasing frequency is a feature of all the shields measured and is consistent with energy penetration through electrically small apertures.

The negative SE values shown in the data for stirred and unstirred SE and the negative SE values shown in the three standard deviation data for the point SE measurements are to be expected when the shields are exposed to a reverberant exterior environment and the shields themselves are exhibiting internal resonances.

The point SE data exhibits a log-normal probability density distribution as shown in the examples in Fig 6 and Fig 7, i.e. the SE data expressed in dB follow a normal probability density distribution. This is to be expected as the shielding process is multiplicative with external propagation, shield energy penetration and internal shield propagation processes all being present.

VI. Conclusions

In this paper we have demonstrated that the SE exhibited by a board level shield is dependent on the external environment of the shield. Coupling to the internal transmission line in the shield from similar transmission lines adjacent to the shield on the same circuit board has been used to mimic the way in which a board level shield may be used. The variable external environment has been mimicked by using a mechanically stirred reverberation chamber. Each stirrer position represents a candidate external environment. The statistics of the population of external environments show that the 3σ variability of the SE is up to $\pm$20 dB about the mean value. The result is valid over the entire frequency range examined from 200 MHz to 20 GHz. The statistics follow a log-normal probability density distribution.

We also conclude that it is not necessary to use the same stirrer positions for the Point SE calculation as we found the same distribution over the population of SE obtained by pairing each unshielded S_{21} with each shielded S_{21}.

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