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Measuring the shielding properties of flexible or rigid enclosures for portable electronics

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Summary

Heaviside, in volume one of Electromagnetic Theory, considered shielding of conducting materials in the form of attenuation. This treatment is still significant in the understanding of shielding effectiveness. He also considered propagation of electromagnetic waves in free-space. What Heaviside (1850 – 1925) could never have imagined is that 125 years later, there would be devices we know as mobile 'phones (or cell 'phones, handies, etc.) with capabilities beyond the dreams of the great science fiction writers of the day such as H. G. Wells (1866 – 1949) or Jules Verne (1828 – 1905). More than this, that there would be a need for law enforcement agencies, amongst others, to use electromagnetically shielded enclosures to protect electronic equipment from communicating with the 'outside world'. Nevertheless, Heaviside's work is still fundamental to the developments discussed here. This paper provides a review of Heaviside's view of shielding and propagation provided in Volume 1 of Electromagnetic Theory and develops that to the design of new experiments to test the shielding of these portable enclosures in a mode-stirred reverberation chamber, a test environment that relies entirely on reflections from conducting surfaces for its operation.

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1. Introduction

1.1. Contribution from Oliver Heaviside's "Electromagnetic Theory"

Electromagnetic Theory, volume one, was originally published in 1893. The commentary here is based on [1]. The preface of this edition gives an insight into his approach to communicating and quotes the "Heaviside Centenary Volume" [2] by saying "*As the reader can see by opening the present volume almost at random, Heaviside seldom writes more than a page or two without introducing a pleasant touch of informality or humour*". It also quotes "Oliver Heaviside" by E.T. Whittaker where it describes, what would be identified today, as a disadvantaged childhood. This led to the desire to leave home. Professor Charles Wheatstone of Kings College London was his uncle by marriage and, through that connection, Heaviside became a telegraph operator in Newcastle. This employment also saw his agile and probing mind turn to problems in telegraphy where he would publish several paper in *inter alia* the Philosophical Magazine. He left this job when only 24, his last formal employment. From then, his life was dedicated to the study of electromagnetics and related phenomena.

His approach to intellectual investigation resulted in his summarising and condensing Maxwell's equations into the four equations that we recognise and describe today as "Maxwell's Equations". (Perhaps they should be referred to commonly as the Heaviside-Maxwell equations.)

His work on transmission lines is still widely used and, with the general increase in electrical length of circuits and resulting prevalence in signal integrity, perhaps more so than previously. However, he did not endear himself to the establishment by doing things like pointing out the conditions for distortionless transmission against the commonly held understanding of the day. This non-conformist approach to research extended to mathematics with the development of Operational Calculus which, again, was poorly received at the time by the establishment. Now, much of his work is regarded as, at least, ground-breaking and his three volumes on Electromagnetic Theory as seminal.

This paper considers the measurement of shielding of portable enclosures for electronics. This is a problem that encompasses electromagnetic propagation, shielding and reflections in a reverberation chamber. Heaviside described the foundations of these in [1] in the following sections:

§180 Describes the relationship between the electric and magnetic fields in a plane wave

§181 Presents wave fronts

§184 Talks about the behaviour of a perfect conductor in a wave as an obstruction but noting it does not absorb

§189 Introduces internal obstructions and conduction on the surface

§190 Discusses reflections

§191 Continues the discussion of conductors

§193 Describes thin plates

§195 Discusses attenuation

§206 Presents thoughts on the guiding of waves

While Heaviside produced mathematical analyses of clarity and vision, his use of mathematics was as a support to his more discursive approach to communication.

The discussions in this paper are clearly grounded in both the scientific foundations and style of communication laid down by Oliver Heaviside.

1.2. Shielding for portable electronics

Portable electronics, such as mobile telephones, laptops and tablets all have myriad connectivity options with receiving and/or transmitting functions available for WiFi, cellular telephone connectivity, GPS, Bluetooth, near field communications (NFC), etc. There are situations where these devices need to have their connectivity limited in a way that turning on “airplane mode” is simply not appropriate. Some examples of this are to avoid distractions while driving, to ensure there can be no surreptitious transmission of conversations during sensitive meetings, or to allow law enforcement agencies to render the equipment isolated without turning it off (which means it is impossible for the call log or messages to be deleted remotely, potentially removing evidence of nefarious activities).

With the growing sophistication in electronic crime, especially involving the use of computer systems, it has become important to have the opportunity to secure such items of electronics with protective shielding. Such portable items of electronics may contain personal information and data which if not protected could be maliciously hacked (such as NFC hacking). A shielded enclosure will utilize a conductive material or a mesh to attenuate the propagation of electronic fields into the enclosure. Sufficient shielding (attenuation) of the enclosure is important to make it difficult to connect to the devices (wirelessly) and alter, delete data or add corrupt digital materials/data onto the devices [3], or to allow the devices to act remotely to perform such functions such as timer based dialling of a detonator on an improvised explosive device.

These enclosures can be in the form of flexible pouches, with or without inspection windows, or solid rigid boxes. Figure 1 shows some examples of commercial products designed to achieve these goals. The construction of the enclosures is not standardized and so various approaches and materials are used by different vendors and for different applications. The authors have seen clearly spurious claims for the shielding of similar devices based on measurements of materials alone, and not accounting for any seams, folds or fasteners. These factors indicate the importance of producing a test method that is reliable, repeatable and robust.

The quality of this shielding is vital in being able to achieve necessary isolation. A typical measure for shielding effectiveness (SE) is as given in equation 1

$$SE = -20\, log_{10}\left(\frac{E_S}{E_{NS}}\right) \tag{1}$$

Where E_S is the electric field strength with the shield in place and E_{NS} is the electric field strength with no shield in place, but all other elements in the configuration remain the same. The minus sign is there to allow a positive level of shielding to be reported.

An obvious question is how much shielding is needed for a given application? This, of course, depends on factors such as the separation between the electronics and the transmitter. By way of example, consider electromagnetic propagation according to the classic empirical Hata-Okamura model [3]. Equation (2) gives the model:

$$P_L\,(dB) = 26.16\log f_r - 13.82\,log h_{bs} + \;(44.9 - 6.55\log h_{bs})R - H + 69.55 \qquad (2)$$

Where f_r is the frequency of operation, h_{bs} is the height of the transmitter, R is the distance between the transmitter and receiver and H is a factor based on the height of the receiver and frequency, and is dependent on the classification of the environment. Figure 2 shows how the level of shielding relates to the distance from the transmitter for different 'bar levels' of a mobile telephone. It can be seen that the effective usable distance reduces substantially as the shielding increases.

Clearly, knowledge of the value of the shielding performance of the enclosures is of utmost importance, particularly where the performance of those enclosures is critical. This is a particularly timely question given the rise in shielding products coming onto the market and the need for *inter alia* law enforcement agencies being able to specify the performance they need or to be able to compare the cost effectiveness for various competitor products. This is a piece of work that has been picked up by the IEEE EMC Society in their standards project P2710 [4] which looks to define an approach to measuring this shielding effectiveness that can be used by manufacturers, vendors, and purchasers to ensure consistency of measurements and their comparison. This paper is a foundational contribution to that study and shows how a mode-stirred reverberation chamber in conjunction with a broadband source can provide a robust measurement of the shielding.

The rest of this paper looks at mode stirred reverberation chamber measurements. It defines the proposed test method and looks at some typical results. The conclusion is drawn that the approach is both suitable and robust.

2. Reverberation Chamber Tests

The mode stirred reverberation chamber is a large, over-moded, resonant cavity with moving elements internally that modify the boundary conditions which give rise to modal patterns that vary as the moving elements change position. Typically, an internal paddle or similar stirrer is used, centred on an axis, with sufficient steps through a complete revolution to ensure good stirring and statistical independence of fields from one step to the next. This change in modal pattern over a full revolution of the stirrer gives rise to any test object in the chamber, excited by an antenna (also in the chamber), receiving a statistically uniform field illumination. Any radiator in the chamber is, as a consequence, statistically isotropic. This has the consequence that, through one revolution of the stirrer, a maximum field coupling should occur between the source and receiver, irrespective of the polarity or orientation of either. That has the benefit of allowing tests to be undertaken in the chamber with the position of both the transmitter and receiver having little influence on the results obtained providing that the test object is placed within a 'working volume' [5].

The reverberation chamber is a resonant cavity with a notional modal structure as given in equation (3). Notional is used because the presence of the internal stirrer will cause some variation from this.

$$f_{m,n,p} = \frac{c_0}{2}\sqrt{\left(\frac{m}{l}\right)^2 + \left(\frac{n}{w}\right)^2 + \left(\frac{p}{h}\right)^2} \tag{3}$$

Where c_o is the speed of light; m,n,p are mode number integers and l, w, h are the length, width and height of the cavity.

According to [7] the minimum number of cumulative modes that should be present for the tests to be valid is 60. A useful rule of thumb is also three times the fundamental frequency. These are generally relatively closely aligned. So, for example, the reverberation chamber at De Montfort University is illustrated in plan in Figure 3. The cumulative 60 modes occurs at 174 MHz. The fundamental frequency is 58.6 MHz, meaning the “three times” frequency is 178 MHz. Typically, for convenience, 200 MHz is used as the lowest frequency of record.

The effect of the stirrer can be seen in the sequence of simulations shown in Figure 4, which is a simulation of the field strength of a horizontal cross section of the reverberation chamber as a function of stirrer position. Here, for the purpose of generating the illustration, 20 steps were used to complete a full revolution (as opposed to the 200 normally used for formal testing). The stirrer is two 1 m^2 vanes either side of the axis – they can be seen as parallel thin blue lines in the top right corner of each pane. The red dot in the bottom right of each pane is the source. A temperature colour scale has been used with Blue being low field strength and Red high field strength

2.1. Test configuration

There are a number of specific requirements required for undertaking the shielding tests. The first is that any enclosed transmitter or receiver should allow the enclosure to be operated as designed. Any enclosed transmitter or receiver should be broadband, allowing early generations of cellular telephony to be tested alongside newer generations and emerging WiFi applications. Given that the shields are reciprocal, a well stirred chamber renders a source (and receiver) as statistically isotropic and the fields are statistically uniform, it was decided that placing a transmitter in the enclosure would be the most sensible of approaches. In this case, the best approach for a broadband source would be a comb generator. A comb generator is a frequency source based on the generation of harmonics of a fundamental. The discrete frequencies produced, when viewed in the frequency domain, resemble a comb. Figure 5 shows the characteristic performance of the comb generator, when tested in the reverberation chamber (for an indicative 20 positions of the stirrer) of the comb generator used at De Montfort University. This was a simple battery powered comb generator kit bought for a few pounds off the internet coupled with a WiFi antenna. This approach allowed a “compare and contrast” approach to be used against the professional level comb generator used by Eurofins York (formerly York EMC Services). This diagram also shows that there is an approximately 60 dB of dynamic range at ~1 GHz reducing to about 30 dB of dynamic range at ~3 GHz.

Following on from the definition in equation (1), the approach used to determine the shielding of any enclosure is to perform coupling measurements in the reverberation chamber with and without the enclosure shielding the comb generator.

One question that needed to be addressed is whether the presence of the shield would have any material effect on the location of the resonances due to loading of the transmitter. Any such effect would make a comparison between the two measurements difficult to undertake. A simple experiment to consider loading was undertaken where a foil sheet was placed close to the comb generator. This showed that there was no change in the location of the resonances, only their amplitudes, as expected.

An illustration of the component elements of the tests in the De Montfort University reverberation chamber is given in Figure 6, which shows the stirrer, an enclosure and the measurement antenna.

The comparator measurements were undertaken by Eurofins York (formerly York EMC Services), using a similar approach of having a broadband comb generator in a large reverberation chamber (similar in size to the De Montfort University Chamber). In this case, the comb generator was a professional-level noise source, the design of the paddle and number of steps were different (nearly full height, narrower and half the number of steps), the receive antenna was a wall mounted blade antenna rather than a bi-log antenna. Figure 7 shows the schematic and Figure 8 shows an internal view of the chamber.

3. Results

The above experiments were undertaken to obtain the shielding measurements of a number of container designs.

The effect of any possible loading on the circuit was investigated to ensure that the peaks were consistent in frequency between reference tests and tests with the signal generator placed in the containers. Figure 9 shows representative results of one of those tests, located around one frequency point. It can be seen that the coupling value has changed but the location of the peaks is reasonably consistent. Note that this was with the low cost comb generator at the De Montfort University facility, so some inherent drifting between experiments might be expected.

A further investigation about the effect on the placement of the signal generator within a large enclosure was undertaken. This was to identify the contribution that placement might make on the results. The comb generator was placed at various positions inside the container (in this case a bag designed to hold something like a large laptop) undertaken at the EY facility. The “top” was close to the opening, which was folded over and fastened with hook-and-loop fasteners. Figure 10 shows the effect of placement, near to or away from various seams and fasteners, in the spirit of IEEE Standards 299 and 299.1 [9] [10]. It can be seen that there is some variation between the various tests but, given the variability over the frequency range, it is difficult to argue that this is significant. One factor to note is that there is a greater reduction in shielding effectiveness at the higher frequencies when the signal generator is placed near the folded opening of the bag.

Tests were undertaken of the shielding effectiveness in the two different facilities. The DMU results are shown in Figure 11. Note the upper frequency of 3 GHz. It can be seen that the shielding effectiveness is approximately 50dB up to 1.75 GHz, reducing to 20 – 30 dB at 3 GHz. The comparative results from the EY facility are shown in Figure 12. A very similar structure is seen, with values close to 50 dB being seen in the lower frequencies reducing to 20 – 30 dB at the middle to higher frequencies

A further interesting investigation is the identification of the minimum shielding effectiveness of different sized enclosures. Figure 13 shows three different sized constructions, a holdall size, a laptop size and a tablet size. All three use the same materials and construction approach. It is interesting to note that the lowest shielding effectiveness occurs at the same frequencies and is of a very similar level, indicating that the limitation may very well be the material itself (although this is the subject of additional investigations).

4. Conclusion

This paper has investigated the shielding of containers used to provide radio-security for electronic devices with inherent connectivity. The purpose being to develop a measurement technique that is reliable between facilities in order to allow designers, manufacturers and specifiers to have confidence in the reported shielding of these products.

The foundations of much of the research involved in this paper can trace its origins to [1].

The results show that a reverberation chamber based test method, using a comb generator as a broadband noise source produces consistent results and is a strong candidate technique for [5].

An area for further study is the effect of the enclosure on the antenna used for the measurements. It is likely that there will be some performance change in the antenna with it either inside or outside the enclosure and should that be different for different types of antennas used for the measurement and in the devices the enclosure is designed for, the accuracy of the results would be enhanced by better understanding this.

Authors' contributions

All authors made approximately equal contribution to the work described in this paper.

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