1. Karolina MAŁECKA, 2. Jan SROKA, 3. Robert OLCZYK

Politechnika Warszawska, Wydział Elektryczny
ORCID: 1. 0000-0003-4431-1671; 2. 0000-0003-3210-3904; 3. 0000-0002-3292-7463

doi:10.15199/48.2025.03.51

Pushing the limits: exploring the dynamic range in shielding effectiveness measurements

***Abstract**. This paper examines how window shape and size affect a dynamic range of shielding effectiveness measurements in GTEM cell. By analysing the limitations imposed by window geometry, we provide valuable insights for researchers and engineers seeking to enhance the accuracy and reliability of their shielding effectiveness measurements. We also examine the dynamic range below theoretical cutoff frequency.*

***Streszczenie.** W artykule zbadano, w jaki sposób kształt i rozmiar okna wpływają na dynamikę układu pomiarowego w pomiarach skuteczności ekranowania w komorze GTEM. Analizując ograniczenia nałożone przez geometrię okna, dostarczamy cennych informacji dla badaczy i inżynierów, którzy chcą zwiększyć dokładność i niezawodność swoich pomiarów skuteczności ekranowania. Artykuł zajmuje się również zakresem dynamiki poniżej teoretycznej częstotliwości odcięcia. (**Przekraczanie granic: badanie dynamiki układu pomiarowego w pomiarach skuteczności ekranowania**).*

Słowa kluczowe: kompatybilność elektromagnetyczna, skuteczność ekranowania, dynamika układu pomiarowego do pomiarów skuteczności ekranowania, komora GTEM
Keywords: electromagnetic compatibility, shielding effectiveness, dynamic range of test setup for shielding effectiveness measurements, GTEM cell

Introduction

Shielding effectiveness (SE) measurements are essential for evaluating the ability of materials and structures to attenuate electromagnetic interference. However, the accuracy and reliability of these measurements are heavily influenced by the dynamic range (DR) of the test setup. This paper delves into a detailed analysis of the impact of the shape and size of the window in the mounting case on the DR in SE measurements in Gigahertz Transverse Electro Magnetic (GTEM) cell with a particular focus on issues involving cutoff frequency (CF).

In this paper core concept of dynamic range is explored. Additionally, it examines briefly how various factors, with an emphasis on the components of the test setup, can limit the DR achievable. Moreover, three topics are analysed in detail:

- theory behind the CF,
- correlation between CF and size and shape of the window in the mounting case, which translate to size and shape of the measured sample,
- CF impact on DR of test setup for SE measurements.

Additionally, the paper deals with a practical application of the discussed theory. Test setups are introduced and calculations for the beforementioned test setups are provided. The authors also present the results of DR measurements for 80 MHz – 1 GHz frequency range and confront them with theoretical issues related to CF.

Dynamic Range

DR in SE measurements refers to the ability of a test setup to accurately measure both high and low levels of electromagnetic signals. It is typically defined in Db scale as the difference between the maximum and minimum measurable signal levels. In this case maximum can be defined as measurement without shielding material (maximum open situation) and minimum as measurement of ambient noise. We do not use measurement of field for fully closed case (maximum closed situation), which in theory should be our minimum measurable signal level, because it is impossible to successfully measure below the noise level, which is higher than signal level measurement for closed case. The DR value in dB can be obtained using:

(1) $$DR^E = 20\,log(|E_{WS}|/|E_A|)$$

(2) $$DR^H = 20\log(|H_{WS}|/|H_A|)$$

where: DR^E – DR in dB measured for E, DR^H – DR in Db measured for H, $|E_A|$ – absolute value of ambient noise in V/m, $|H_A|$ – absolute value of ambient noise in A/m, $|E_{WS}|$ – absolute value of field without shielding in V/m, $|H_{WS}|$ – absolute value of field without shielding in A/m.

Shielding Effectiveness

Shielding effectiveness is a quantitative measure of a material's or structure's ability to attenuate electromagnetic radiation. It is often expressed in decibels, with higher dB values indicating greater shielding performance. The shielding effectiveness value in dB can be obtained using [1]:

(3) $$SE^E = 20\log(|E_{WS}|/|E_s|)$$

(4) $$SE^H = 20\log(|H_{WS}|/|H_S|)$$

where:
SE^E – SE in dB measured for E, SE^H – SE in Db measured for H, $|E_S|$ – absolute value of field with shielding in V/m, $|H_S|$ – absolute value of field with shielding in A/m.

Factors Affecting Limits for Measurements of High and Low Levels of Electromagnetic Signals

For high DR values we want our upper limit as high possible and our lower limit as low as possible. That is why it is important to analyse factors that affect them, such as:

- sensitivity of the receiver: the receiver's ability to detect low-level signals directly impacts the lower limit of measurement,
- noise floor of the test environment: ambient electromagnetic noise can interfere with the measurement, limiting the lower limit of measurements,
- dynamic range of the signal generator: the generator's ability to produce a wide range of signal levels affects the upper limit of measurements,
- sensitivity of the measurement probe: affects the lower limit of measurements.

Impact of Limits for Measurements of High and Low Levels of Electromagnetic Signals on the Measurement of High and Low Shielding Effectiveness

For high SE values, the upper measurement range may be lower than the actual SE value, thus measurements may not present the full SE capability of the test material. On the other hand, for materials with very low SE values, the lower measurement range may be higher than SE value of the material, and thus reliable measurements will be impossible.

Aperture Antennas

Window in a mounting case can be considered as an unintentional aperture antenna [1]. Because of that we must consider its cutoff frequency, according to theory below this frequency, our measuring probe inside the mounting box will not receive the emitted radiation or will receive it to a limited degree even without shielding material.

A certain group of antennas is characterized by a certain clearly distinguished area, called the aperture, through which the electromagnetic wave passes. For the purposes of this article, we will look at the radiation produced by rectangular and circular apertures.

For a rectangular aperture, the directivity for an aperture with uniform radiation can be obtained with [2]:

(5) $$D^{\square} = \frac{4\pi}{\lambda^2} L_x L_y$$

where: $D^{\square}$ – directivity for a rectangular aperture, λ – wavelength in m, L_X – X Dimension of aperture in m, L_Y – Y Dimension of aperture in m.

For a circular aperture, the directivity for an aperture with uniform radiation can be obtained with [2]:

(6) $$D^{\bullet} = \frac{4\pi}{\lambda^2} (\pi a)^2$$

where: $D^{\bullet}$ – directivity for a circular aperture, a – radius of circular aperture in m.

Due to the simplifications used for the above calculations, they are assumed to be correct for wavelengths much shorter than the dimensions of the apertures as original purpose of these calculations were for visible light (wavelength from around 380 nm to about 750 nm, frequency from 400 THz to 700 THz). For low frequencies, where the wavelength is close to or longer than the aperture dimensions, testing and analysis is needed, such analysis is provided later in this paper.

Cutoff Frequency

CF is in our case maximal frequency, up to which the window is not capable to radiate and therefore below CF wave cannot fully pass into the mounting case. For the specified aperture dimensions, we can use (5) and (6) to estimate the wavelength and then the CF for a rectangular and circular aperture, respectively, as shown below [1]:

(7) $$\lambda^{\square} < 2\sqrt{\pi L_x L_y}$$

(8) $$\lambda^{\bullet} \sim < 11{,}14r$$

(9) $$f_{CF}^{\square} > \sim \frac{84{,}63}{\sqrt{L_x L_y}}$$

(10) $$f_{CF}^{\bullet} > \sim \frac{26{,}93}{r}$$

where: $\lambda^{\square}$ – wavelength corresponding to CF for a rectangular aperture in m, $\lambda^{\bullet}$ – wavelength corresponding to CF for a circular aperture in m, $f^{\square}_{CF}$ – CF for a rectangular aperture in MHz, $f^{\bullet}_{CF}$ – CF for a circular aperture in MHz.

Cutoff Frequency Impact on Dynamic Range of Test Setup for Shielding Effectiveness Measurements

Low CF means achieving optimal DR values for the test setup even at low frequencies, thus increasing the frequency range for which meaningful SE measurements can be made, which is also particularly important due to the high cost of equipment used for high-frequency measurements. Checking DR behaviour below CF is also important for determining the actual frequency range for obtaining meaningful measurements.

Test Setups

Measurements were carried out using two test sets. Both used multi-functional device NSG 4070 (AMETEK CTS), probe LSProbe 2.0 (LUMILOOP), dual directional coupler C5982 (WERLATONE), power amplifier 80RF1000-300 (MILMEGA) as well as WIN6000 software. The difference between them is the GTEM cell used - the first measurement system used GTEM 500 (ASTAT), the second one used GTEM 5317 (ETS-LINDGREN). The names of these GTEM cells will be used in further descriptions and legends to distinguish both test setups for simplicity.

Calculations for Test Setups

For calculations presented below (7), (8), (9) and (10) were used. For each of the cases CF, half of CF (1/2 CF), quarter of CF (1/4 CF), three quarters of CF (3/4 CF), one and a half of CF (3/2 CF) and double of CF (2 CF) were calculated. Not all calculated values were found within the measurement range, so these values were omitted from further considerations.

Two square apertures of side d = 0,104 m, d = 0,075 m and one circular aperture of radius r = 0,03 m were studied for GTEM 500. Two square apertures of side d = 0,21 m, d = 0,163 m and one circular aperture of radius r = 0,094 m were studied for GTEM 5317. The second of the square apertures had similar surface area as the circular one.

Table 1. Calculations for Test Setups

Shape and size [m] of the window	*Wavelength for CF [m]*	*CF [MHz]*	*½ CF [MHz]*	*¼ CF [MHz]*	*¾ CF [MHz]*	*1.5 CF [MHz]*	*2 CF [MHz]*	*GTEM*
Square $d = 0{,}104$	0,3669	818	408	204	613	1226	1635	500
Square $d = 0{,}075$	0,2658	1128	564	282	846	1692	2256	500
Circle $r = 0{,}03$	0,3342	897	448	224	672	1345	1794	500
Square $d = 0{,}21$	0,7442	403	201	100	302	604	806	5317
Square $d = 0{,}163$	0,5777	519	259	129	389	778	1038	5317
Circle $r = 0{,}094$	1,04716	286	143	71	214	429	572	5317

Results

Frequency range for all of measurements was from 80 MHz to 1 GHz. There were performed with open loop and 40 dBm forward power level was generated using integrated NSG 4070 amplifier and directional coupler, and 50 dBm forward power level was generated using NSG 4070 with dual directional coupler C5982 and power amplifier 80RF1000-300. For circular aperture of radius r = 0,03 m only 40 dBm forward power level was generated because of equipment malfunction.

Analysis

For measurements for rectangular apertures, in some cases an upward trend can be observed starting from 1/4 CF, while for all cases 1/2 CF is a distinctive frequency, followed by a sharp increase in DR. In almost all cases, the difference in DR between 3/4 CF and CF is about 10 dB or less. Above CF, a further increase in DR is observed, but in a more limited and less rapid manner.

For measurements for circular apertures below 3/4 CF, clear trends in monotonicity or distinctive frequencies are difficult to observe, while, as in the case of rectangular apertures, the DR difference between 3/4 CF and CF is about 10 dB. Above CF, there is a further apparent increase in DR level, in a significantly greater range and more rapid manner than for rectangular, even suggesting the use of 2 CF instead of CF as lower threshold for frequency. This may be due to the fact that the wavelength of rectangular apertures is 3,54 times their dimensions, while for circular apertures it is already 11,14, which makes the approximation less accurate for circular apertures.

An interesting observation that requires further research is the significant similarity of the results obtained for circular and rectangular apertures with similar surface area. The shape of the characteristics, distinctive frequencies and achieved DR levels are almost identical for both cases.

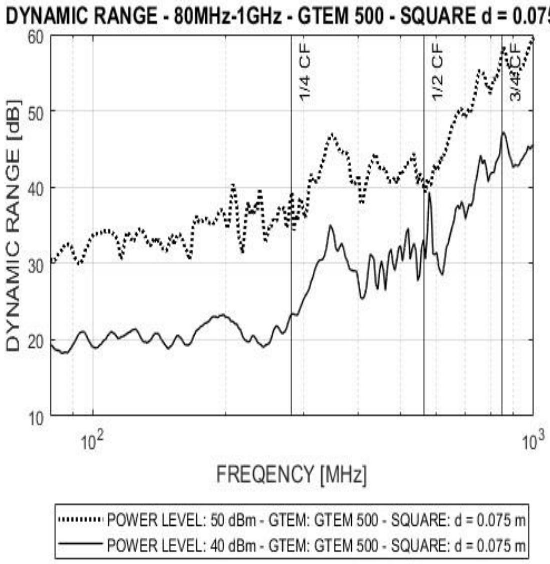

Fig. 1. Dynamic range for square aperture d = 0,075 m

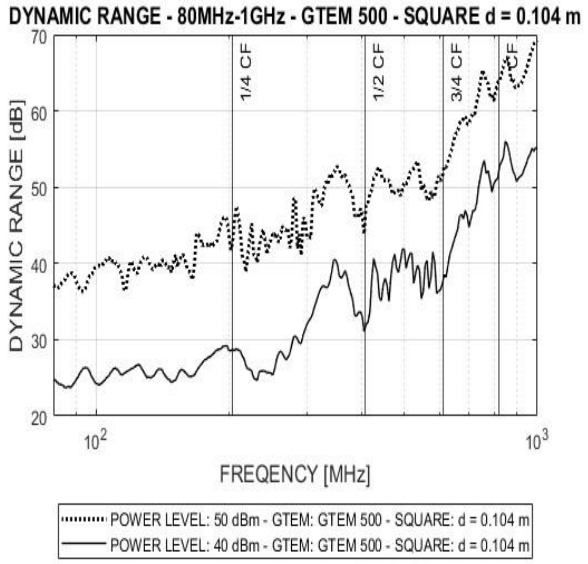

Fig. 2. Dynamic range for square aperture d = 0,104 m

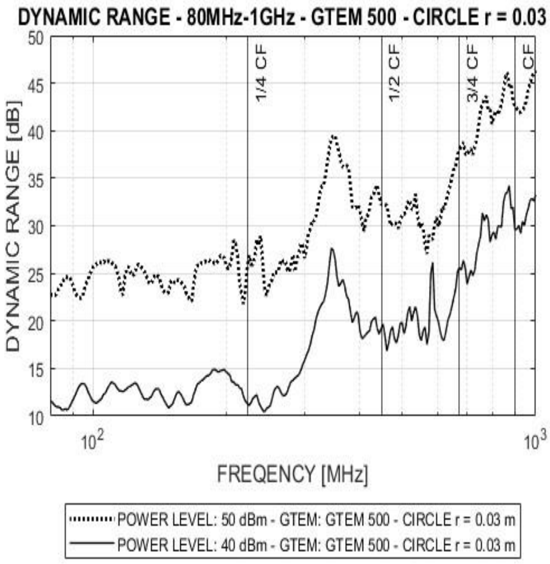

Fig. 3. Dynamic range for circular aperture r = 0,03 m

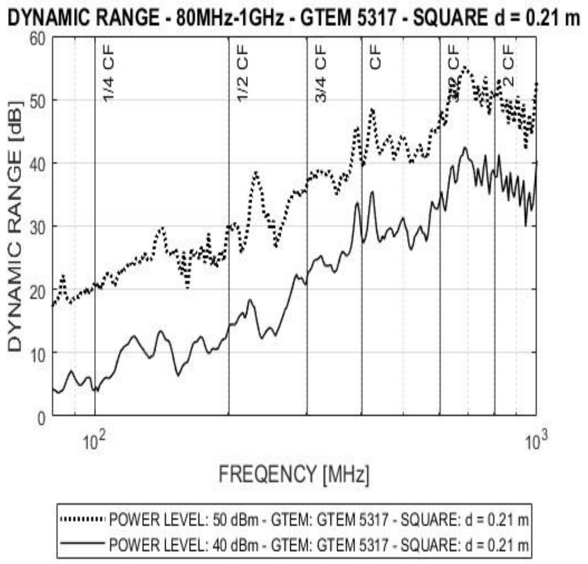

Fig. 4. Dynamic range for square aperture d = 0,21 m

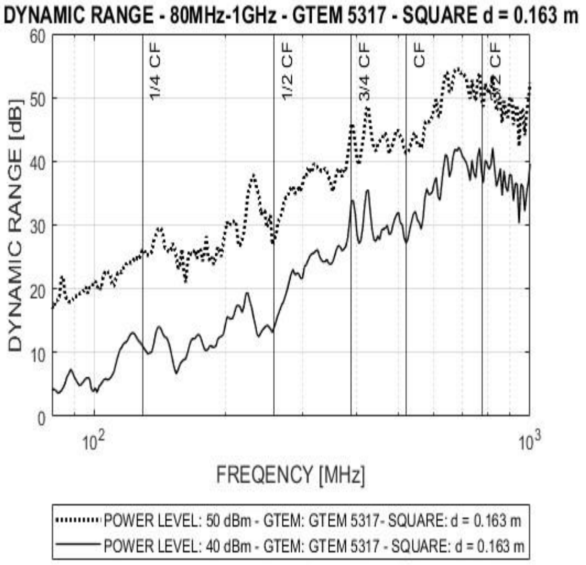

Fig. 5. Dynamic range for square aperture d = 0,163 m

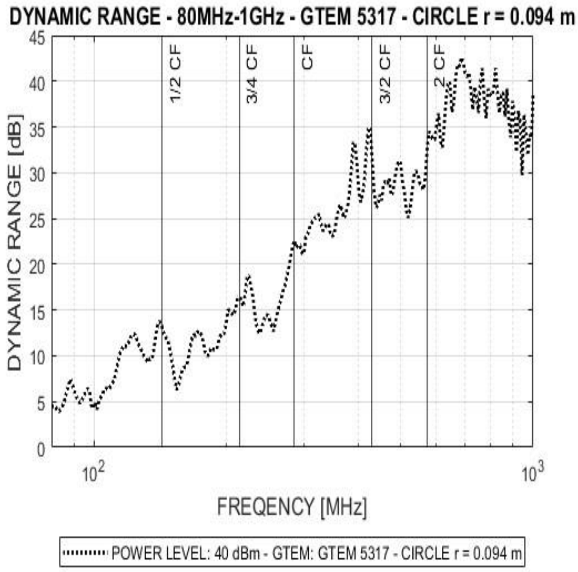

Fig. 6. Dynamic range for circular aperture r = 0,094 m

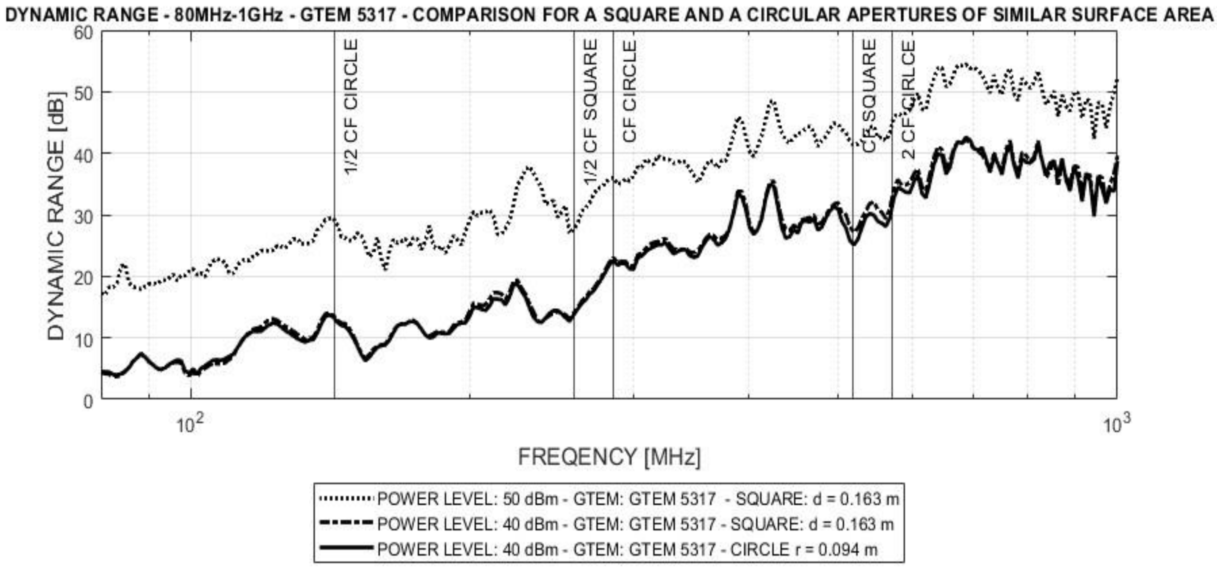

Fig. 7. Comparison of DR for apertures of similar area

Summary

Through an analysis of the limitations of the DR in SE measurements in GTEM cell correlation to the shape and size of the window in the mounting case this paper equips researchers and engineers with a deeper understanding of this crucial aspect of SE measurements. Through the presented results, it also shows that depending on the selected shape of the window in the mounting box it is possible to obtain quite satisfactory DR values even below theoretical CF, but for round windows for obtaining much higher DR levels it is recommended to double the CF, where for a rectangular window high DR values can be obtained just above the CF.

REFERENCES

[1] Sroka J., Compendium on ElectroMagnetic Compatibility, WUT Publishing House, 2021
[2] Szóstka J., Fale i anteny, WKŁ, 2001
[3] Sroka J., Niepewność pomiarowa w badaniach EMC. Pomiary emisyjności radioelektrycznej, WUT Publishing House, 2009
[4] Małecka K., Olczyk R., Sroka J. and Urbaniak G., Critical aspects of the uncertainty budget in the shielding effectiveness measurements. 2023 International Symposium on Electromagnetic Compatibility – EMC Europe, Krakow, Poland, 2023, pp. 1-6, doi:10.1109/EMCEurope57790.2023.10274191.
[5] IEEE Standard 2715-2023 "IEEE Guide for the Characterization of the Shielding Effectiveness of Planar Materials", doi: 10.1109/IEEESTD.2023.10115252