On the Equivalent Use of TEM Waveguides for EMC Measurements and Calibrations

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Abstract

This paper gives explanations on the use of transverse electromagnetic (TEM) waveguides in emission and immunity testing as well as in antenna calibration radiation pattern measurements. The methods described in this paper are based on an equivalent antenna model for the TEM waveguides. It is shown, that this equivalence can be used to adopt large parts of the uncertainty budgets of CISPR 16-4-2 or IEC 61000-4-3. Furthermore it is shown, how the validation of the TEM waveguide can be combined with the uncertainty analysis and corrections for immunity measurements as well as emission measurements. An example is given, on how the TEM waveguide can be used for the determination of the radiation patterns of antennas.

1. Introduction

Traditionally the open area test site (OATS) is the test method for radiated emission [1] and immunity [2]. However, alternative test methods (ATM) as fully anechoic rooms (FAR), transverse electromagnetic (TEM) waveguides and reverberation chambers (RC) have been developed to allow better, faster or cheaper testing. For immunity testing these alternative test methods are well defined, while there are still some difficulties for emission measurements. For example, some of the ATM capture electric field strength directly and allow an easy comparison with OATS limits, while the RC records the radiated power of the equipment under test (EUT). To compare the results with the OATS limits the maximum directivity of the EUT needs to be known. The basic correlation algorithm for TEM waveguides as described in the IEC 61000-4-20 [3] also requires the knowledge of the EUT's directivity. In general, this maximum directivity has to be estimated from the electrical size of the EUT and the frequency [4]. Unfortunately, such an estimate results in a hardly quantifiable measurement uncertainty. That disadvantage can be overcome, if an equivalent antenna model for the TEM waveguide is used. It was shown, that such a model allows good comparison with the results obtained from an ETM [5, 7].

In section 2 the equivalent antenna model for TEM waveguides is described in terms of directivity and antenna factor. These values are compared with traditional broadband antennas. In the third section the validation of the TEM waveguide is described. Section 4 exemplifies the EUT positions required for emission and immunity measurements. In Section 5 it is shown, that TEM waveguides equipped with turn tables can be used for the determination of radiation patterns of antennas. The uncertainty contributions of TEM waveguides are explained and commented in section 6.

2. Equivalent Antenna Model

A summary of the electromagnetic fields in TEM waveguides and those induced by an EUT can be found in [6]. In this work Wilson shows, how the electric and magnetic dipole moments can be calculated from a set of TEM waveguide measurements. However, in the frequency range above 1 GHz this dipole assumption is a strong simplification for many EUTs. Therefore it was proposed, to represent the TEM waveguide by an equivalent antenna model [7]. As a first approximation the directivity D_{TEM} of the waveguide can be calculated from the electrical properties and physical dimensions according to equation (1), where $L_{\max}$ is the maximum length of the waveguide, $h_{\max}$ the maximum septum height, Z_t the waveguides impedance and Γ_0 the free space wave impedance [7]. Based on the theory of reciprocity, the assumption of a electrically small dipole antenna in the measurement distance z_0 between

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dipole antenna and waveguide port leads to equation (2) for the antenna factor of a TEM waveguide, where f is the signal frequency and c_0 the speed of light in vacuum [7].

$$D_{\mathrm{TEM}} \approx \frac{Z_{\mathrm{T}} 4\pi}{\Gamma_0} \cdot \frac{L_{\max}^2}{h_{\max}^2} \qquad (1)$$

$$AF_{\mathrm{TEM}} \approx \frac{f}{c_0} \cdot \frac{\Gamma_0}{Z_{\mathrm{T}}} \cdot \frac{h_{\max}}{L_{\max}} \qquad (2)$$

Evaluating equations (1) and (2) for a gigahertz transverse electromagnetic (GTEM) cell with a maximum septum height $h_{\max} = 1250$ mm and a maximum length $L_{\max} = 5490$ mm results in a directivity $D_{\mathrm{TEM}} = 30$ dB. This number depicts why TEM waveguides allow testing with high field strengths without the need for high power amplifiers. The resulting antenna factor is proportional to the signal frequency. For the frequency range from 30 MHz to 6 GHz the antenna factor of the GTEM cell is -15 dB/m to 30 dB/m. A typical broadband bilog antenna that covers the same frequency range is slightly less sensitive with antenna factors from 10 dB/m to 42 dB/m.

3. Validation of the Uniform Area

According to the IEC 61000-4-20 the testing volume of the waveguide has to be validated. This is done by the evaluation of two figures of merit: The field homogeneity and the quality of the TEM waveguide. To do so, the electric field strength has to be measured in a regular grid in a given number of measurement points. The number of measurement points depends on the size of this so called uniform area since the space between two points must not excel 500 mm. In each measurement point the primary field component E_{prim}, e.g. the main component that is used for immunity testing and the secondary field components E_{sec} are recorded for a constant forward power P_{fwd}. The secondary field components represent the longitudinal field components and the components transverse to both the direction of propagation and the primary field component. It was shown, that the electromagnetic field in the uniform area can be assumed to be sufficient homogeneous and the TEM mode adequate, when the σ_{E} and $Q_{75\%}$ in equations (3) and (4) are within the limits listed in table 1 [7].

$$\sigma_{\mathrm{E}} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(E_{\mathrm{prim,i}} - \overline{E}_{\mathrm{p}}\right)^2} \qquad \overline{E}_{\mathrm{p}} = \frac{1}{N}\sum_{i=1}^{N} E_{\mathrm{prim,i}} \qquad (3)$$

$$Q_{75\%} \approx \sqrt{\frac{\ln(4)}{N}\sum_{i=1}^{N}\left(\frac{E_{\mathrm{sec,i}}}{E_{\mathrm{prim,i}}}\right)^2} \qquad (4)$$

Table 1: Criteria for the field distribution

Criterion	For at least 95% of test frequencies	For a maximum of 5 % of test frequencies
Homogeneity	$\sigma_{\mathrm{E}} \le 2{,}61$ dB	2,61 dB < $\sigma_{\mathrm{E}} \le 4{,}34$ dB
TEM-mode	$Q_{75\%} \le 0{,}5$	$0{,}5 < Q_{75\%} \le 0{,}794$

The calibration data from the validation of the uniform area can also be recycled in order to obtain a number for the uncertainty contribution associated with the field distribution. A short example is given in section 6 of this paper. If the criteria in table 1 are fulfilled for the uniform area, the TEM waveguide can be used for the emission and immunity testing. In order to obtain test results that are equivalent to measurements performed with traditional EMC antennas, some considerations on the position of the uniform area are given in the next section.

4. EUT Positions and Measurement Distance

According to IEC 61000-4-20 the uniform area for the validation of the TEM waveguide should be evaluated at the beginning $z_{\min}$ and at the end $z_{\max}$ of the test volume in Fig. 1. For waveguides with an inherent shape like the GTEM cell depicted in Fig. 1, the standard states that it is sufficient to validate the uniform area at the end $z_{\max}$ of the test volume only. This procedure is well established and quiet correct – though the position of EUT and uniform area must be kept in mind, when the required forward power for immunity testing or the equivalent measurement distance for emission testing are calculated. With the established test method the fieldstrength for immunity testing is calculated for the front of the EUT at the position z_{EUT} in Fig. 1.

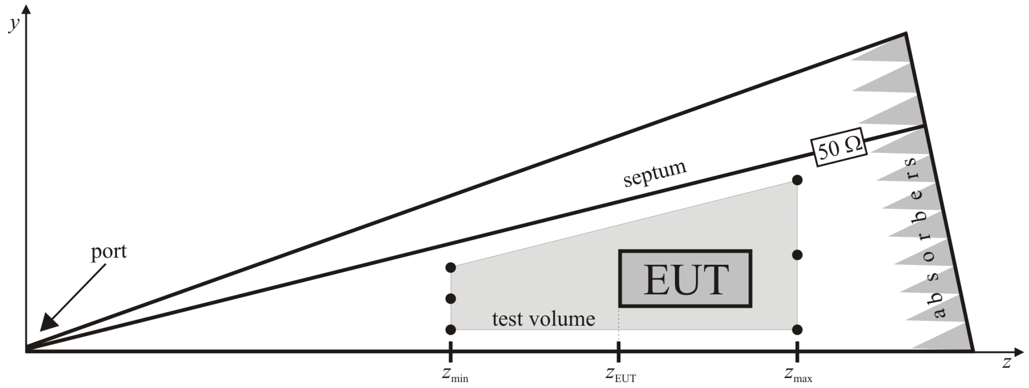

Figure 1: Side view of a GTEM cell with the test volume and the calibration points at z_{min} and z_{max}

At this position, the fieldstrength in the empty waveguide is higher than the fieldstrength in the uniform area at z_{max}. Therefore immunity testing with the field strength E_{test} has to be performed with the forward power P_{test} that is calculated from the validation data according to equation (5) and the correction term consisting of z_{max} and z_{EUT}. For emission testing z_{EUT} has to be taken into account as nominal measurement distance from the equivalent antenna model. If, for example, the electric free space field strength in a distance d = 3 m is to be measured, equation (6) contains the correction term for the distance z_{EUT} between the port of the waveguide and the front of the EUT. For large EUTs z_{EUT} in equation (6) has to be understood as the distance between the port of the waveguide and the contour of the smallest cylinder or sphere that can possibly enclose the EUT in all dimensions. If these corrections are applied, the field strength data of the validation of the uniform area can be used analogues to measurements according to IEC 61000-4-3 and the result of the emission measurement corresponds to the definitions in CISPR 16-2-3.

$$P_{test} = \left(\frac{z_{EUT}}{z_{max}}\right)^2 \cdot \frac{E_{test}^2}{\left(\overline{E}_p - 1{,}15 \cdot \sigma_E\right)^2} \cdot P_{fwd} \quad (5)$$

$$E_{3m} = \frac{z_{EUT}}{3m} \cdot U_{TEM} \cdot AF_{TEM} \quad (6)$$

With this antenna model and the corrections in equations (5) and (6) the measurement procedure of OATS or FAR can be adopted in most instances. One difference between waveguide testing and ETM remains in the fact, that the polarization of the waveguide cannot easily be changed. Therefore, instead of changing the polarization of the antenna with an ETM, the EUT has to be tilted in the waveguide. It was shown, that a set of 12 measurement positions that result from the claim to turn each side of a cuboid EUT at least once with each polarization in the direction of the port of the waveguide, yield adequate results for EUT with a maximum directivity up to 10 dB [5]. However, using a turntable on the floor of the waveguide more accurate results can be obtained for highly directive EUT. The 12 measurement positions can also be obtained with a turntable and only two manual tilts.

5. Antenna Calibration and Radiation Pattern Measurements

The use of a turn table is not restricted to emission or immunity testing. With such a turn table the waveguide can also be used for the determination of radiation patterns of antennas in the H-Plane. For measurements in the E-plane the turntable has to be equipped with a second axis [5]. An example is given in Fig. 2, where the radiation pattern of the double ridged horn antenna in the left subfigure is shown for different frequencies.

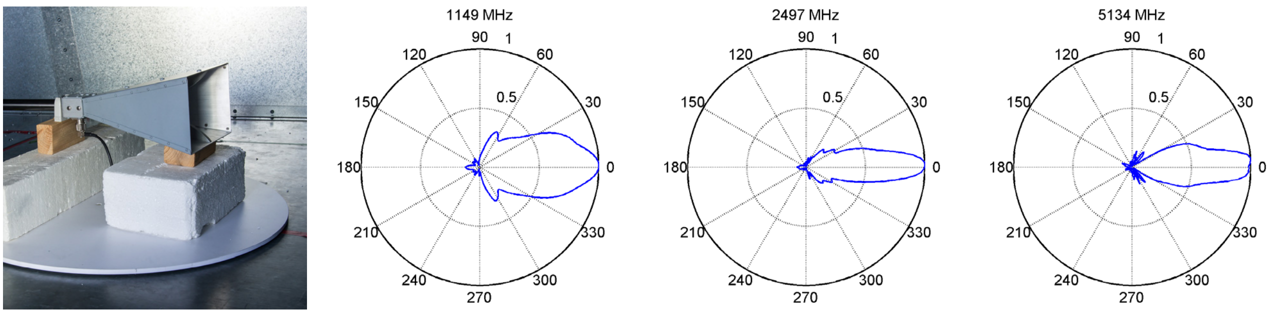

Figure 2: Turntable and horn antenna in GTEM 1250 with radiation patterns in H-plane

6. Measurement Uncertainties

With the definitions for the equivalent antenna model of the waveguide not only the measurement procedure can be adopted from the ETM. The uncertainty budgets described in IEC 61000-4-3 and CISPR 16-4-2 can be used for the general measurement instrumentation uncertainty. Instead of the antenna's contributions the waveguide is taken into account with his mismatch, the exactness of the measurement position z_{EUT} and the uncertainty contribution of the field distribution. The field distribution can be interpreted in terms of homogeneity and secondary field components. The standard deviation σ_E in equation (3) is a rough estimate for the standard uncertainty of the field distribution. However, this number is mainly influenced by the boundary of the uniform area, since only one of the nine typically used calibration point is in the center of the uniform area, where the field homogeneity is likely to be best. A better approximation can be obtained, if the primary field components are normalized to the forward power and the field factor e_{0y} of the waveguide [8, 3]. The analytical field factor e_{0y} can also be used to determine the field strength in the uniform area of an ideal TEM waveguide for a given input power and analyzed in order to identify the intrinsic uncertainty of a chosen uniform area and to optimize the precision of antenna or field probe calibration.

6. Conclusion

TEM waveguides allow fast, cheap and efficient immunity and emission testing. However, there were slight differences in immunity testing and some correlation difficulties in emission testing. In this paper an equivalent antenna model for TEM waveguides is described in terms of maximum directivity and antenna factor. It is shown, that a typical GTEM cell has a directivity in the range of 30 dB and antenna factors that are slightly better than those of traditional broadband bilog antennas. This comparison illustrates the efficiency and sensitivity of TEM waveguides as EMC test facility. Furthermore it is shown, which figures of merit for the validation of a TEM waveguide have to be evaluated und how the results of that validation can be used as calibration data as well as a data source to estimate the uncertainty contribution of the waveguide. Explanations on the different measurement positions and measurement distances in TEM waveguides are given to allow testing equivalent to IEC 61000-4-3 and CISPR 16-2-3. It is shown, that the use of turntables in TEM waveguides allow the determination radiation patterns in the H-plane of antennas. With the antenna model and the measurement techniques explained in this paper TEM waveguides can be used as equivalent, efficient and sensitive test methods for different types of measurement without the need of sophisticated correlation routines or the knowledge of an EUTs maximum directivity.

7. References

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