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A Novel Emission Test Method for Multiple Monopole Source Stirred Reverberation Chambers

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Abstract — **This paper presents a novel method for predicting the electromagnetic field radiated by an equipment under test (EUT) in free space. The method is based on the knowledge of the electric field values close to the metallic walls of a reverberation chamber (RC) where the device is placed. From these field samples, a set of equivalent sources is retrieved. The equivalent sources likewise produce in free space the same field radiated by the EUT.**

Keywords-component: emission test; reverberation chamber; source stirring;

I. INTRODUCTION

THE use of reverberation chambers (RCs) to measure the power radiated by an equipment under test (EUT) has been explored since 1976 [1]. According to the stochastic behavior of this measurement environment [2], the intrinsic directivity of the radiating element is mostly hidden [3]. RCs are however used for the measurement of the radiated emissions of an EUT according to standard [4] [5], by estimating its maximum directivity D from physical dimensions [6], [7] [8].

On the basis of the original idea applied to TEM and GTEM cells, where a small EUT was represented by equivalent dipole moments [9], the present paper proposes a new method to predict the free space radiated field of an EUT starting from the field that it generates inside a closed and completely metallic structure. More precisely, the closed enclosure is an RC where a particular source stirring technique is applied, the multiple monopole source stirring (MMSS) technique. It essentially consists in using a set of monopoles mounted on chamber metallic walls to change modal excitation and so achieving a well stirred electromagnetic field [10] [11]. This kind of RCs provide a suitable environment to carry out immunity tests as in traditional mechanically stirred RCs [12] [13]. The signal acquired by this set of monopoles might be used to compute the total radiated power by the EUT, after applying an ensemble averaging and a proper calibration, as done in traditional mechanical stirred RCs. In the present paper, this averaging process is not done and the electric field values, sampled by the monopoles on the metallic surface, are adopted to formulate a set of electric and magnetic equivalent sources able to approximate the EUT true electromagnetic field Such equivalent sources are then used to predict the EUT field radiated in free space. In that way, the method returns the maximum electric field produced by the EUT and also its radiation pattern, without any a-priori assumption on its maximum directivity.

It should be noted that the method is not another application of the spherical sampling techniques applied in anechoic environment to sample the field around a device, for NF to FF transformations. In the present case, the sampling is not spherical and the device is inside a resonant enclosure typically used as an RC in place of an anechoic chamber for EMC testing. The particular RC based on the MMSS technique allows straightforward application of the proposed technique, because the necessary sampling is carried out without moving antennas and/or EUT. The method is based on the assumption that the EUT radiates the same power in the RC and in the free space, but this assumption is fundamental also for the traditional method based on the determination of the total radiated power in RC, under whatever stirring technique.

Finally, it is important to specify that the term “equivalent source” is not used in the sense described by the equivalence theorem, rather, throughout the paper, the term is simply used with the meaning of “good approximation” of the EUT. The paper aims to demonstrate the theoretical feasibility of the method, so an EUT whose radiated field can be theoretically predicted is considered.

II. MODEL

The scenario consists in a Multiple Monopole Source Stirred (MMSS) RC [10], with an EUT placed into the working volume, and N_m monopoles on the RC walls.

The aim of this section is to investigate the theoretical possibility to estimate, with acceptable accuracy, the radiated emissions of the EUT in free space, from the knowledge of the electric field radiated by the EUT in a number N_m of sampling points on the RC walls. In this letter the number N_m is chosen according to the Nyquist criterion, making sure that the spacing between adjacent samples is less than half wavelength at the working frequency.

In particular, the proposed method requires the definition of equivalent sources that can represent the EUT emissions both in the RC and in free space.

The model is based on the assumption that the emission of the EUT does not appreciably change passing from the RC

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environment to free space. This assumption is acceptable if we consider the EUT inside a well operating RC.

It is worth specifying that the method was designed as an application of the MMSS-RC, because the chamber is equipped with many antennas on the chamber walls, and therefore the electric field can be easily sampled and their interaction can be modeled in terms of their mutual impedance, as described in [10].

The main goal is to characterize the EUT (the reference situation) in terms of a set of equivalent electric and magnetic elementary sources (the equivalent situation), whose electromagnetic behavior inside the MMSS RC can be analytically predicted.

A. The Algorithm

The equivalent sources are calculated forcing the electric field values sampled by the monopoles on the walls to be the same for the reference and the equivalent situation. The value of the current flowing in each of the equivalent elementary sources is calculated according the following algorithm:

1. Considering N_m the number of monopoles on the RC walls and therefore of the field samples, and N_s the number of the equivalent sources chosen to represent the EUT, the quantity d_i, defined as

   $$d_i = \frac{\sum_{n=1}^{N_m} |E_n - Z_{ni} I_i|}{\sum_{n=1}^{N_m} |E_n|} \qquad i = 1, .., N_s \tag{1}$$

   is calculated for each i-th equivalent source. In (1) E_n is the *n-th* field sample on the wall, and $Z_{ni} I_i$ is the field generated by the *i-th* equivalent source in the n-th sample point. The coefficient Z_{ni} is analytically known and represents the coupling term between the elementary source and the chamber. The vector notation for the fields is omitted because, obviously, only the electric field component normal to the wall is taken into account. Therefore, d_i represents the distance between the reference field and that generated by the i-th equivalent source.

   The value of the current that minimizes d_i can be analytically found and its value is

   $$I_i = \frac{\sum_{n=1}^{N_m} (E_n Z_{ni}^*)}{\sum_{n=1}^{N_m} |Z_{ni}|} \ . \tag{2}$$

2. The application of (1) generates a set of N_s values for d_i. The minimum value is chosen according to $d_{i*}=\min(d_i)$ and the corresponding i*-th equivalent source I_{i*} is fixed, because its field represents the best fitting of the EUT field.
3. Residual electric field values E_n^{new} are re-calculated in each sample point according to

   $$E_n^{new} = E_n^{old} - Z_{ni*} I_{i*} \qquad n=1, \dots, N_m \ . \tag{3}$$

4. The procedure restarts from point 1. with the updated electric field values, and it iterates until the quantity

   $$err = \frac{\sum_{n=1}^{N_m} |E_n^{new}|}{\sum_{n=1}^{N_m} |E_n|} \tag{4}$$

   assumes a value lower than a desired threshold.

At the end of the iterations, the algorithm provides a set of N_s currents values of elementary sources that generate on the RC walls the best approximation of the reference EUT field, and we assume that they also radiate in free space the same field of the EUT in free space, as shown in the next sections.

B The Impedance Coefficients

The coefficient Z_{ni} appearing in (1) can be easily evaluated according the following procedure.

If we consider a short electric dipole placed into a rectangular metallic cavity, the expression of the electric field can be easily derived from [10], assuming a constant current distribution along the dipole.

As an example, for a dipole of length l_d oriented along the z axis, placed in (x_d, y_d, z_d) and fed by a current I_z , the electric field orthogonal to the RC's wall located in the plane x=0 is, according to the classical field modal expansion [14]:

$$\begin{aligned} E_x(y,z) = -\frac{16 I_z}{j\omega\varepsilon} \sum_{m,n,p} \Bigg[& \frac{1}{abd} \sin(k_y y) \sin(k_z z) \cdot \\ & \cdot \sin(k_z l_d) \sin(k_x x_d) \sin(k_y y_d) \sin(k_z z_d) \cdot \\ & \cdot \left(\frac{k_x}{k_{nmp}^2} + \frac{k_x k^2}{\delta_p k_{nmp}^2 \left(k_{nmp}^2 - k_{TM}^2 \right)} \right) \Bigg] \ , \end{aligned} \tag{5}$$

where $k_x = \frac{m\pi}{a}, k_y = \frac{n\pi}{b},\ k_z = \frac{p\pi}{d}\ , k_{mnp}^2 = k_x^2 + k_y^2 + k_z^2$,
$\delta_i = \begin{cases} 2, & i = 0 \\ 1, & i \neq 0 \end{cases},\ \ k_{TE,TM}^2 = k^2 \left(1 - (j-1) \frac{\omega_{mnp}}{\omega\, Q_{mnp}^{TE,TM}} \right)$,
k is the wavenumber, ω_{mnp} is the angular resonant frequency for the *(m,n,p)-th* mode and $Q_{mnp}^{TE,TM}$ is the quality factor of the RC related to the *(m,n,p)-th* TE or TM mode.

The analytical expressions of the modal quality factors are the following

$$Q_{mnp}^{TE} = \frac{k_{mnp}^3 \eta_0\, abd\, k_c^2}{4R_S \left(bd\, k_y^2 k_z^2 + \frac{k_c^4}{\delta_m} + ad\, k_x^2 k_z^2 + \frac{k_c^4}{\delta_n} + ab\, k_c^2 k_z^2 \right)} \ , \tag{6}$$

$$Q_{mnp}^{TM} = \frac{k_{mnp} \eta_0\, abd\, k_c^2}{4R_S \left(bd\, k_z^2 + ad\, k_y^2 + ab\, k_z^2 \right)}, \tag{7}$$

where $R_S = \frac{1}{\sigma_{eff}\delta}$, $k_c^2 = k_x^2 + k_y^2$ and $\delta = \frac{1}{\sqrt{\sigma_{eff}\omega\mu/2}}$,

being η_0 the wave impedance in free space.

In particular, the model takes into account all RC losses in terms of an effective conductivity (σ_{eff}) of the RC's walls, obtained by matching the theoretical and experimental quality factor of the chamber, as described in [10].

Equation (5) can be written in compact form as

$$E_x = Z_{x,z} I_z \ , \tag{8}$$

where the term $Z_{x,z}$ of dimension [Ωm^{-1}], is an example of the impedance coefficients appearing in equation (1).

Similar expressions can be derived for the electric field on all the RC faces, and generated by other electric and magnetic equivalent sources oriented in whatever direction of the chamber Cartesian coordinate system.

III. CASE STUDY

This section reports the results of the proposed method applied to one significant case study concerning the unintentional emissions of an EUT. All results presented in this section are obtained when the sources representing the EUT and their equivalent sources, obtained using the algorithm proposed in Section II, radiate in free space at a distance of 10 m. In an emission test the most important parameter to characterize is the maximum field intensity, therefore the electric field values radiated by the EUT and by the equivalent sources in free space are compared. However, the comparison is also extended to the whole radiation pattern, because this represents a significant parameter to test the "equivalence" of the two sets of sources.

In all simulations the frequency of 1 GHz is considered. The RC dimensions are: a = 0.8 m, b = 0.9 m, and d = 1.0 m, the same of the RC in our labs [11].

The samples are chosen according to a regular grid of 56 points on each wall (8 samples along the longest side of the rectangular face, and 7 samples along the other side). In this way, their distance is lower than half wavelength.

In most practical cases, unintentional emissions are due to apertures, therefore in the present case study we consider a rectangular aperture centered in (x_{ap}, y_{ap}, z_{ap}), orthogonal to the x axis, and with dimensions 2w = 16 cm along y and 2s = 1 cm along z. In the present case, we simply adopted a current in space to get an analytical solution for the radiated field in both chamber and free space. A z-polarized TE_{10} distribution for the aperture electric field, with maximum value E_{ap} = 1 V/m, is assumed.

As an example, the expression of electric field on the RC wall in x=0 is shown

$$
\begin{aligned}
E_x(y,z) \\
= \frac{16\pi E_{ap}}{abdw} \sum\nolimits_{m,n,p} \Bigg[& \frac{\cos(k_z z_{ap}) \sin(k_y y_{ap}) \cos(k_x x_{ap})}{k_y^2 - \left(\frac{\pi}{2w}\right)^2} \\
& \cdot \frac{\sin(k_z s) \cos(k_y w) \sin(k_y y) \sin(k_z z)}{k_c^2} \\
& \cdot \left(\frac{k_y^2}{\delta_m \delta_n (k_{nmp}^2 - k_{TE}^2)} + \frac{k_x^2}{\delta_p (k_{nmp}^2 - k_{TM}^2)} \right) \Bigg] . \qquad (9)
\end{aligned}
$$

Similar expressions can be obtained for the fields on the other walls. We can observe that in this case only resonant TE and TM modes are excited.

Under the assumption that we have no a priori information, we placed the equivalent sources on the surface of the parallelepiped that includes the EUT (dimensions 200 mm × 150 mm × 100 mm): in the centre of each face, in the centre of each side, and in each vertex for a total of 26 source points.

In order to ensure the most general approach, in each source point both electric and magnetic equivalent sources in the three space directions have been placed.

Considering the dimension of the EUT, this choice also satisfies the Nyquist criterion for the distance between adjacent sources at the adopted frequency.

Fig. 1 shows the reconstruction of the electric field samples in terms of equivalent sources. For a better readability of the picture, only the first 30 samples are reported.

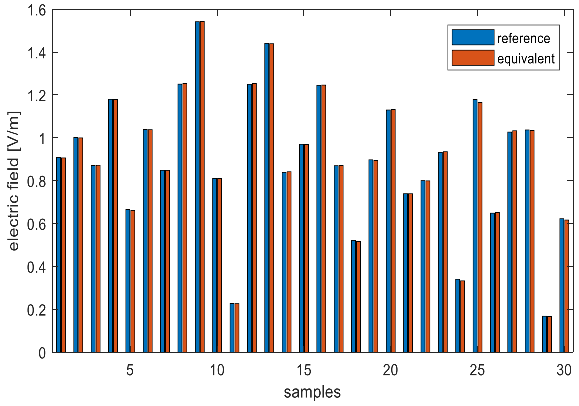

Fig.1. Reference and reconstructed electric field for the first 30 field samples

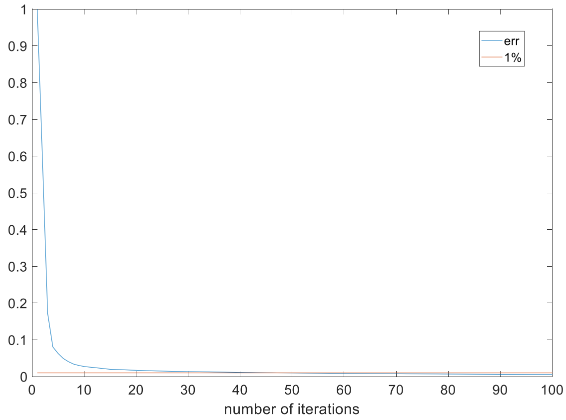

Fig.2. Convergence of the algorithm as a function of the iterations.

The convergence of the parameter "*err*" defined in (4) is shown in Fig.2 as a function of the number of iterations; the proposed threshold of 1% is reached by the algorithm in 40 iterations. The CPU time required by the algorithm is very short (some seconds on a standard workstation) because the impedances Z_{ni} in (1) are computed only at the first iteration. We can observe that the accuracy of the field reconstruction is good, and one can conclude that the elementary sources are equivalent to the reference sources inside the RC.

Finally, the reference and the equivalent sources are considered in free space and Fig. 3 shows the electric field at a distance of 10 m radiated by them. Both E plane and H plane are reported. We can observe a good agreement as far as the maximum value of the radiated field is concerned (red curve). The radiation pattern is also satisfactorily reconstructed, considering that no a priori assumption was supposed about the nature of the EUT.

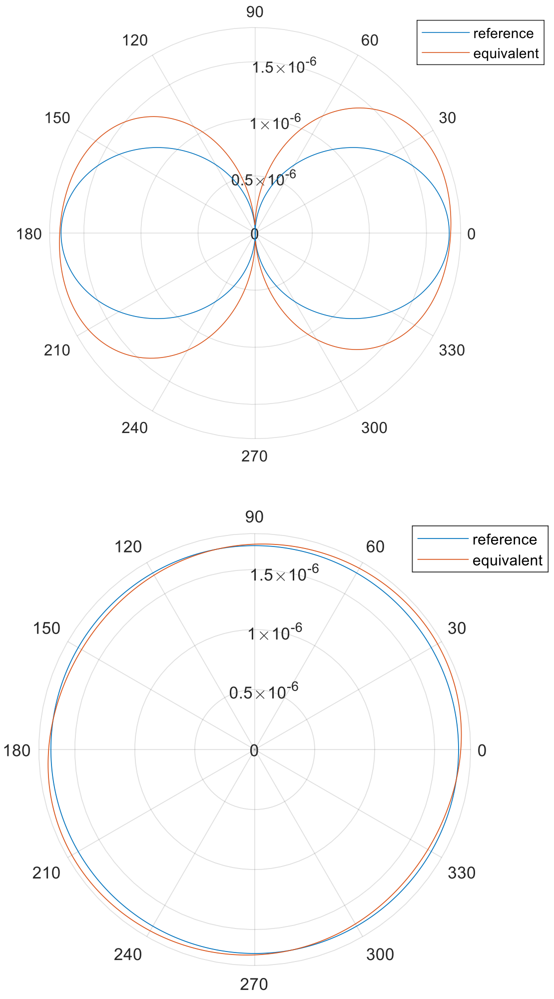

Fig.3. Electric field radiated [V/m] in free space at the distance of 10 m, by a slot (w = 8 cm, s = 5 mm) on a metallic chassis, being E_{ap} = 1 V/m. The H-plane (up) and the E-plane (down) radiation patterns are reported.

IV. CONCLUSIONS

The letter presents the theoretical feasibility study concerning the possibility of estimating the radiated emissions of an EUT in free space from the knowledge of field samples measured inside an RC. In particular, the electric field normal to the metallic walls is used. This choice is quite natural in the case of MMSS-RC because the walls are equipped with antennas for the stirring action. The proposed method consists in replacing the EUT with a set of equivalent sources able to reproduce the same field inside the RC. We have shown that the equivalent sources are also able to radiate with a good approximation the same field of the EUT in free space, that is the environment where international standards define the emission limits: the extension to a standardized OATS is straightforward.

The results obtained for a practical situation show that the agreement is quite satisfactory.

The method is general because it does not require any information about the real EUT, considered as a black box.

These preliminary results are very encouraging considering that only the normal component of the electric field on the walls has been used.

Future work will aim at the reduction of number of electric samples to improve the implementation practicality, also including the analysis of the accuracy due to uncertainty of the field sample acquisition.

The practicality of the method might be further improved by using a spectrum analyzer, so we are studying an extension of the method when only field sample amplitudes are available.

REFERENCES

[1] P. Corona, G. Latmiral, E. Paolini and L. Piccioli, “Use of a Reverberating Enclosure for Measurements of Radiated Power in the Microwave Range”, in IEEE Transactions on Electromagnetic Compatibility, vol. EMC-18, no. 2, pp. 54-59, May 1976.

[2] R. Serra et al., “Reverberation chambers a la carte: An overview of the different mode-stirring techniques”, in IEEE Electromagnetic Compatibility Magazine, vol. 6, no. 1, pp. 63-78, First Quarter 2017.

[3] D. A. Hill, "Plane wave integral representation for fields in reverberation chambers," in IEEE Transactions on Electromagnetic Compatibility, vol. 40, no. 3, pp. 209-217, Aug. 1998.

[4] Reverberation Chamber Test Methods, International Electrotechnical Commission (IEC), Std. 61 000-4-21, 2011.

[5] C. L. Holloway, P. F.Wilson, G. Koepke, and M. Candidi, “Total radiated power limits for emission measurements in a reverberation chamber,” in *Proc. 2003 IEEE Int. Symp. Electromagn. Compat.*, vol. 2, pp. 838–843.

[6] M. Candidi, C.L. Holloway, P. Wilson, and D. Camell, “Comparison of radiated emission measurements for 500 MHz to 2GHz in various EMC Facilities,” in Proc. EMC Europe 2002: Internal. Symposium. on Electromagnetic Compatibility, September 9-13, Sorrento, Italy, 2002, pp. 823-828.

[7] G. Koepke, D. Hill, J. Ladbury, “Directivity of the test device in EMC measurements” in Proc. 2000 IEEE International Symposium on EMC, Washington, D.C., pp. 535 -539, August, 2000.

[8] P. F. Wilson, D. A. Hill, and C. L. Holloway, “On determining the maximum emissions from electrically large sources,” *IEEE Trans. Electromagn. Compat.*, vol. 44, no. 1, pp. 79–86, Feb. 2002.

[9] P. Wilson, “On correlating TEM cell and OATS emission measurements”, in IEEE Transactions on Electromagnetic Compatibility, vol. 37, no. 1, pp. 1-16, February 1995.

[10] A. De Leo, V. M. Primiani, P. Russo and G. Cerri, “Low-Frequency Theoretical Analysis of a Source-Stirred Reverberation Chamber”, in IEEE Transactions on Electromagnetic Compatibility, vol. 59, no. 2, pp. 315-324, April 2017

[11] A. D. Leo, G. Cerri, P. Russo and V. M. Primiani, “Experimental Validation of an Analytical Model for the Design of Source-Stirred Chambers”, in IEEE Transactions on Electromagnetic Compatibility, vol. 60, no. 2, pp. 540-543, April 2018.

[12] A. De Leo, G. Cerri, P. Russo and V. M. Primiani, "Statistical Analysis of the Induced Voltage on a DUT in a Reverberation Chamber where Mechanical and Source Stirring Actions are Implemented," International Symposium on Electromagnetic Compatibility, Barcelona, 2019, pp. 241-246.

[13] De Leo, V. M. Primiani, P. Russo and G. Cerri, “Analytical prediction of common mode noise in a source stirred reverberation chamber”, 2015 IEEE International Symposium on Electromagnetic Compatibility (EMC), Dresden, 2015, pp. 1207-1212.

[14] J. Van Bladel, Electromagnetic Fields (A SUMMA Book). Washington, DC: Hemisphere, 1985.