Critical study of calibration techniques for a reverberation chamber

(Article begins on next page)

17 June 2024

CRITICAL STUDY OF CALIBRATION TECHNIQUES FOR A REVERBERATION CHAMBER

L.Musso*,**, J.Bossé*, V.Berat*, F.G.Canavero**
*Technocentre Renault, Guyancourt, France; **Politecnico di Torino, Torino, Italy
(Principal contact: luca.musso@polito.it)

Abstract: This paper describes the calibration study carried out on a reverberation chamber installed within an industrial context. Due to the lack of a definitive international standard for a reverberation chamber qualification, several methods based on experience and four standards have been considered. Criteria that quantify the lower frequency limit for a good operating chamber are presented, as well as experimental results. Calibration results for different standards are then compared, their limitation are highlighted, and possible explanations for discrepancies are suggested.

1. Introduction

In an industrial context, the introduction of the reverberation chamber (or mode-stirred chamber) as a site for Electromagnetic Compatibility tests, in both radiated emission and susceptibility is desirable for several reasons. Low realization costs, possibility of uncertainty statistical control and best measure reproducibility are among the advantages that can be obtained by the use of a reverberation chamber.

Since various years, several works dealing with the development of an international calibration standard for a reverberation chamber are under development. Several procedures and criteria can be adopted, based on the principle of evaluating fields spatial statistical uniformity. Most of standards proposed until now provide direct field uniformity evaluation by volume boundary measurement, that is very similar to anechoic chamber calibration methods. On the other hand, a reverberation chamber is governed by statistical laws that describe electromagnetic environment. The developed theory allows to characterize the statistical properties of electric and magnetic fields anywhere inside a delimited volume of an ideal chamber by the knowledge of a single point field [1]. The theory development for a real chamber could be useful for the evaluation of field uniformity near the walls and for low frequencies. This would be helpful to develop chamber design rules as well as to optimize standards criteria.

A reverberation chamber setting up inside an industrial context is considered here, and the qualification measurement results are presented. The chamber under consideration is installed at Technocentre Renault located in Guyancourt, France, and is the result of the transformation of a Faraday cage by the introduction of a mechanical stirrer. The size of the chamber allows to contain an entire automotive vehicle and such dimensions imply a first resonance at about 30 MHz. The stirrer has been conceived in order to maximize dimensions and avoid all symmetries. The maximum stirrer dimension is about 2/5 of the chamber maximum dimension.

Section 2 will propose several possible criteria to explore useful domain for the chamber, with a special regard to chamber lower frequency. The results will allow critical considerations about the utilization of criteria coming from different approaches. Section 3 will introduce four different standards (three of which are drafts) for reverberation chamber calibration. The standards will be applied to Renault chamber calibration. Finally, the concluding remarks will contain a comparison of standards calibration results and some considerations with respect to the principles exposed in Section 2.

2. Calibration principles for a reverberation chamber

A reverberation chamber is a metallic enclosure provided with a mechanical stirrer, which changes electromagnetic field boundary conditions during time. The stirrer rotates in order to achieve statistical uniformity for the fields during a complete turn. Statistical uniformity implies spatial homogeneity, isotropy and random polarization.

The validity domain for statistical uniformity of a real chamber is given by a frequency band (called *useful frequency band*) and a limited volume far from the walls (called *useful volume*).

By the modal approach explained by Wu and Chang in [6], lower frequency limitation is due to the fact that, at such low frequencies, the stirrer is not able to stir cavity modes and thus to give random properties to fields. This lower frequency is greater than the first resonance frequency of an empty chamber, which is the function of physical and geometrical parameters of the chamber.

Statistical uniformity of fields implies statistical equivalence of field rectangular components. This equivalence cannot be respected near chamber walls, where fields must respect boundary conditions (zero tangential electric field and zero normal magnetic field on the walls). Hence, the consideration arises, that spatial uniformity will be respected only from a minimum distance from the walls and from any metallic object.

Several simple empirical criteria exist, which estimate reverberation chambers performances as a function of frequency. This section will present some of the most common criteria by means of physical explication and measurement results.

By the modal approach proposed in [6], statistical uniformity in a reverberation chamber can be obtained when two conditions are verified: the first one is to operate in overmoded conditions and the second one is that the stirrer is able to perform a good stirring of excited modes.

The quantity MD_{BWQ} (Q bandwidth mode density) gives the number of modes excited simultaneously in a cavity with a quality factor Q, for a given frequency f. For a rectangular cavity this number is given by [7]:

$$MD_{BW_Q} = \frac{8\boldsymbol{p} \cdot Vol \cdot f^3}{c^3 Q} \qquad (1)$$

where Vol is the volume of the chamber, f is the frequency of excitation and c is the speed of light.

The curve of Fig.1 shows MD_{BWQ} for the Renault reverberation chamber between 80 MHz and 2 GHz.
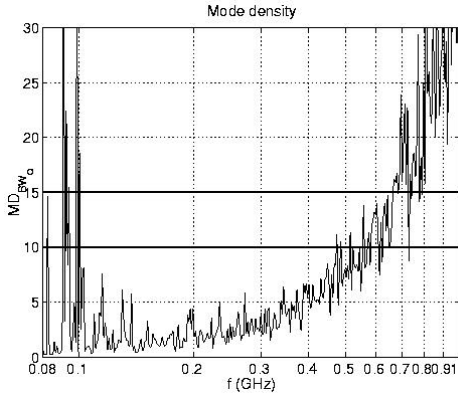
**Fig. 1:** Mode density of Renault's chamber

If we consider a number of 15 modes (as proposed in [7]) as lower limit for overmoded condition, the chamber is overmoded only above 700 MHz.

However, overmoded condition is not sufficient for giving field uniformity. The size, the geometry and the position of the stirrer are fundamental for a correct stirring [6].

For a fixed frequency, an effective stirring can be measured by a parameter called *stirring ratio SR* ([5] and [7]), defined as the ratio between the maximum and the minimum power received by an antenna placed in a fixed point during a complete stirrer turn, i.e.,

$$SR = \frac{P_{rec\,MAX}}{P_{rec\,min}} \qquad (2)$$

The measured stirring ratio is shown in Fig.2.
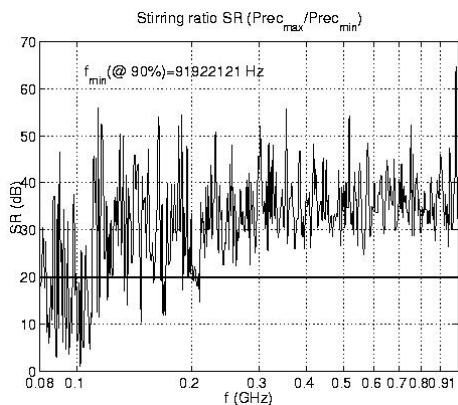
Fig. 2: Stirring ratio of Renault's chamber

The lower limit normally accepted for the stirring ratio is 20 dB ([5] and [7]). Hence, we can assert that the chamber is effective above about 200 MHz. The stirring ratio takes into account both the overmoded condition and the stirrer effectiveness. At the frequency of 200 MHz the number of modes excited is weak (Fig.1), so it seems that a great number of modes is not a necessary condition for a good stirred field.

The third considered criterion concerns the statistical nature of fields and power received by an antenna inside a reverberation chamber. It has been shown that inside a chamber, where fields are homogeneous, isotropic and randomly polarized, the power received by any matched antenna is Chi-squared distributed with two degrees of freedom [1]. Conversely, if power samples of a real chamber follow such a distribution, then statistical uniformity properties are verified.

Such a test has been tested in Renault reverberation chamber for the power received by a log-periodic antenna. To compare the theoretical and experimental distributions two statistical criteria were adopted. The cumulative distribution densities for standardized and mean normalized data have been used. For these data, standard deviation test and Kolmogorov-Smirnov test have been applied.

Standardized and mean normalized data coming from a Chi-square distribution have standard deviation value equal to 1 [7]. Results different from this value indicate a bad agreement with theory and consequently weak uniformity for the fields. The experimental standard deviation is shown in Fig.3, in conjunction with the usual acceptance limits 0.9 - 1.1 [7].
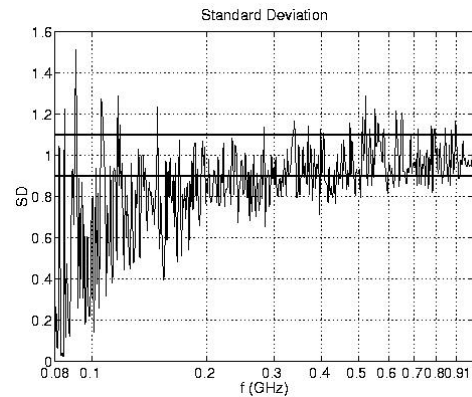
Fig. 3 Results of the standard deviation test applied to Renault's chamber measurements

As expected, only for high frequencies, the standard deviation value approaches the ideal limit of 1. Nevertheless, arbitrary limits are not strictly respected for high frequencies.

The second criterion (Kolmogorov-Smirnov test, KS), is based on the evaluation of the maximum difference D between cumulative theoretical and experimental distributions. The limit that states the conformity depends on the number of experimental samples and the desired confidence level. Here the limit of 0.0557 for 480 samples proposed by [7] is adopted. In Fig.4, the D values and the limit above are shown.
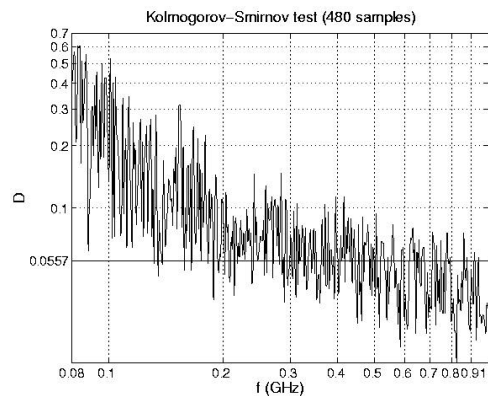
Fig. 4: Results of the Kolmogorov-Smirnov test applied to Renault's chamber measurements

As in the case of the standard deviation test, KS test shows best results at higher frequencies (as expected), but the

adopted limit is respected only for some frequencies.

3. Chamber Calibration

A direct method for uniformity evaluation is adopted by three of the considered standards ([2], [3] and [4]). The method consists in evaluating the maximum magnitude of each electric field rectangular component for a given number of positions within the chamber. This ensemble of data must fall inside a given uncertainty interval.

A fourth standard [5] proposes a different comparison between ideal and real behaviours of a reverberation chamber. The four standards will be applied and discussed in the following paragraphs. Particular attention will be placed on the differences between formulation of standards and consequent non-coherence in the results.

3.1 Calibration according to IEC 61000-4-3 [2]

This calibration method is based on field uniformity evaluation for the maximal values of the three electric field components at the 8 points shown in Fig.5.
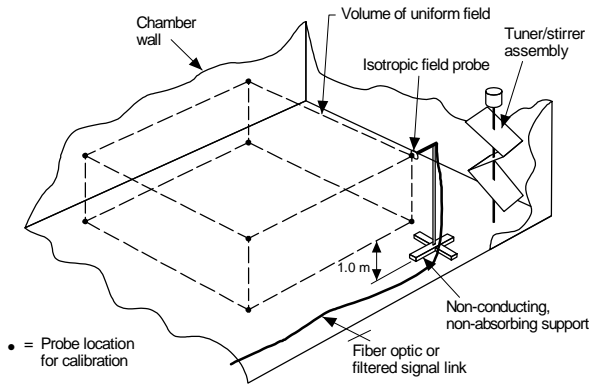

Fig. 5 Measurement configuration for calibration (figure taken from [3])

The field is considered uniform if the ensemble of maximum values falls inside the -0 dB +6 dB interval around the mean value for the 75% of the entire volume (i.e., at least 18 among the 24 points of measurement). A tolerance reaching 10 dB is allowed for a maximum of three frequencies or for 3% of measurement frequencies. The measurement result showing for each frequency the worst uniformity case for the 75% of volume points appears in Fig.6 with the 6 dB and 10 dB limits.
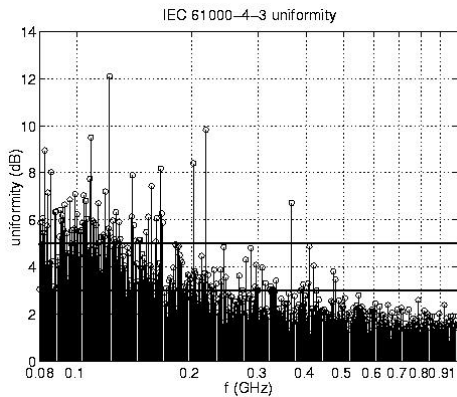

Fig. 6 Results of field uniformity analysis, according to IEC 61000-4-3

The 6 dB limit is respected above 477 MHz. The same limit, by removing the 3% of frequencies, is respected above 277 MHz. Therefore, the lower frequency allowed by [2] for the Renault chamber is $f_{0\,IEC-3} = 277$ MHz.

3.2 Calibration according to IEC 61000-4-21 [3]

Similarly to previous standard, [3] requires electric field uniformity evaluation for the 8 positions shown in Fig.5.

Standard deviation values are used instead of simple difference from reference level. The significant difference with respect to the previous standard is that the whole set of experimental data must be considered, that is all frequency and spatial points used for measurements. Standard deviation results as well as the limits for a desired lower frequency of 100 MHz are shown in Fig.7.
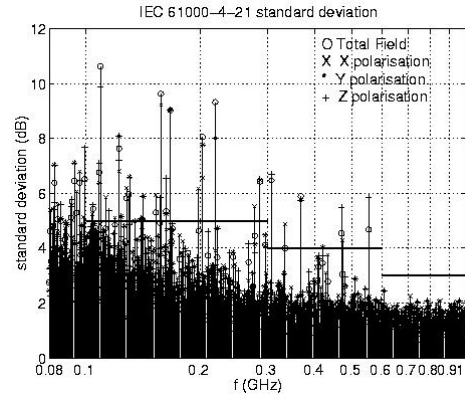

Fig. 7 Results of field uniformity analysis, according to IEC 61000-4-21

Referring to Fig.7, the appropriate frequency for passing the uniformity test is $f_{0\,IEC-21} = 550$ MHz.

3.3 Calibration according to RTCA DO-160D [4]

Calibration criteria according to [4] are identical to those of the previous standard [3] except in some details that have no influence, in this case, on the final result. The standard deviation result and the imposed limit are shown in Fig.8.
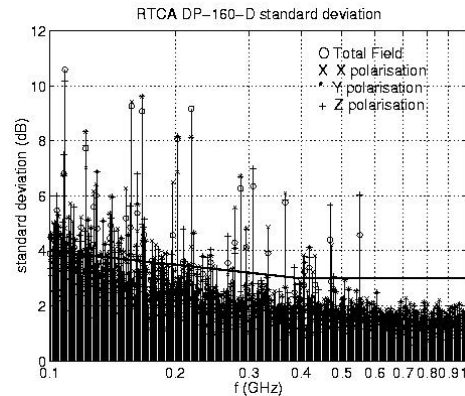

Fig. 8 Results of field uniformity analysis, according to RTCA DO-160D

As shown in Fig.8, the chamber lower frequency is $f_{0\,RTCA} = 550$ MHz.

3.4 Calibration according to SAE J1113/27 [5]

A set of several criteria, which are different from other standards, are used for chamber calibration according to [5]. The different criteria will not be described here, where we just report the calibration result for lower usable frequency.

The rule giving the lower frequency is based on a lower limit for the *stirring ratio* presented in Section 2. The minimum imposed limit for *stirring ratio* is 20 dB (for the 90% of frequencies). Referring to Fig.2, this limit is respected above 92 MHz, thus giving $f_{0SAE} = 92$MHz.

4.   Discussion of results

Calibration results reported in Section 3 will be discussed first. These results show a great variability for the lower usable frequency of the chamber ranging from 92 MHz to 550 MHz. A marked difference could be expected between the SAE standard and the others, since the former is based on a different rationale. However it is more surprising that the other standards (IEC 61000-4-21 and RTCA DO-160D on one hand, and IEC 61000-4-3 on the other hand, showing lower frequencies of 550 MHz and 270 MHz, respectively) present a so wide range of values, since such standards are based on about the same uniformity criteria.

The difference is amenable to the procedure devised to calculate uniformity. For IEC 61000-4-3 it is possible to remove a certain percentage of worst measurement points, that is somehow a statistical principle; the lower frequency found is 277 MHz. The other two standards require the whole set of measured data; this leads to increase the lower frequency.

As it can be seen in figures 7 and 8, the uniformity limits are exceeded only for a small number of isolated frequencies, and the fact of removing 25% of measurement positions and 3% of frequencies correspond to have a difference of about 200 MHz on the lower frequency of the chamber.

Such a consideration points out two possible problems. First of all, it must be considered that the number of frequency points could influence the results. In fact, we used a number N of logarithmic equally spaced frequency points much higher than the minimum number required by the standards. Now, a lower number of total frequencies leads to a lower probability to find isolated points that stand out of the limits.

Secondly, instrumentation characteristics must be taken into account. For calibration measurements, a network analyser and a passive electric probe have been used. The great instrumentation dynamic range and the reduced dimensions of the probe allow to detect the field peaks that characterize a resonant complex cavity. Probably, a lower instrumentation dynamic range and a probe of larger dimensions tend to smear out such peaks.

After the uniformity calibration results, some consideration can be carried out for lower frequency criteria exposed in Section 2. The *stirring ratio* criterion gives an idea of the effectiveness of mode stirring. Results show a good agreement between the *stirring ratio* criterion based on 20 dB limit (which is used in SAE standard [5]) and IEC 61000-4-3 (Fig.2 and Fig.6). On the other hand, there is no agreement with IEC 61000-4-1-21 and RTCA DO-160D. This means that the agreement strongly depends on the choice of the limits, and the introduction of a statistical criterion (IEC 61000-4-3) helps on increasing the correlation of results among different standards. Concerning the mode density criterion, results of Fig.1 indicate that Renault chamber is overmoded above 700 MHz, frequency much higher than any lower frequency imposed by the standards. Therefore we can conclude that overmoded conditions are not necessary to obtain statistical uniformity required by standards.

Finally, we consider standard deviation and Kolmogorov-Smirnov tests. Such statistical tests are applied to single point measurements during one stirrer turn, thus the comparison with field uniformity criteria, that are based on multiple points measurements, is not straightforward. By a direct comparison, the limits proposed for the statistical tests are too strict according to calibration standards. It seems however useful to adapt such statistical tests with respect to the required spatial uniformity level. Such a correspondence could be found by means of a deeper knowledge of ergodicity between stirrer rotation and space inside a reverberation chamber. In the same direction, the development of a statistical theory for the fields at the limits of the uniformity volume would be also useful.

5.   Conclusions

To take profit of reverberation chamber characteristics, statistical uniformity for electromagnetic fields must be ensured with a known confidence degree. Several criteria to quantify the lower frequency limit for a good operating chamber have been presented, as well as experimental results from Renault reverberation chamber. Two criteria concerning modal structure and stirring efficiency have been compared with statistical criteria. Some qualitative coherence has been found, but we have shown the difficulties to compare such different methods with the usually adopted criteria.

Secondly, reverberation chamber calibration has been considered by comparison of four different standards (of which, three are drafts). Calibration results show important differences in lower useful chamber frequency, which is a significant parameter for the chamber industrial utilization. A critical analysis of such differences points out an objective difficulty in reverberation chamber measurements. These considerations emphasize the importance of frequency stepping and instrumentation dynamic choices during calibration measurements.

Finally, comparisons among standards calibration criteria (as they are in this moment) and statistical criteria based on single position field measurement are reported. Results show that the agreement between the two methods is possible. However acceptance levels should be revised in order to establish a correlation, and theoretical basis on spatial statistics near chamber walls should be developed.

6.   References

[1] D.A. Hill, "Electromagnetic Theory of Reverberation Chambers" *National Institute of Standards and Technology (US) Technical Note 1506*, December 1998.

[2] "Alternative procedure – Reverberation chamber method", *IEC DRAFT 61000-4-3 A3 Ed. 1 : High frequency phenomena - Annexe J*, July 1999.

[3] "Reverberation Chamber Test Methods", *IEC DRAFT 61000-4-21 Electromagnetic Compatibility (EMC) Part 4 : Testing and measurements techniques - Section 21*, July 1999.

[4] "Radiated Susceptibility Test ; Alternate Procedure - Reverberation Chamber", *RTCA Inc. Environmental Conditions and Test Procedures for Airborne Equipment - DRAFT #5 for the change notice to : Section 20 Radio Frequency Susceptibility (Radiated and Conducted)*, April 26, 1999.

[5] "Electromagnetic compatibility measurements procedure for vehicle components - part 27 - Immunity to radiated Electromagnetic Fields - Reverberation method", *Surface Vehicle Electromagnetic Compatibility Standards Manual,* 1997 edition.

[6] D.I. Wu and D.C. Chang, "The effect of an Electrically Large Stirrer in a Mode-Stirred Chamber", *IEEE Trans. Electromagn. Compat.*, vol.31, No. 2, 1989, pp.164-169.

[7] M.Hatfield, "Reverberation chamber theory / experiment short course", *Naval Sea System Command (NSWC) Dahlgren Division*, 1998.