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Original
Radiated Immunity Testing of a Device with an External Wire: Repeatibility of Reverberation Chamber Results and Correlation with Anechoic Chamber Results / Musso, L.; Canavero, Flavio; Demoulin, B.; Berat, V.. - STAMPA. - 2:(2003), pp. 828-833. (Intervento presentato al convegno 2003 IEEE International Symposium on EMC tenutosi a Boston (MA) nel August 18-22) [10.1109/ISEMC.2003.1236715].

Publisher:
Piscataway, N.J. : IEEE

Published
DOI:10.1109/ISEMC.2003.1236715

Radiated Immunity Testing of a Device with an External Wire: Repeatability of Reverberation Chamber Results and Correlation with Anechoic Chamber Results

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Abstract

We present the experimental radiated immunity results of an electronic device with an external wire obtained in reverberation and anechoic chambers. Repeatability and reproducibility of reverberation chamber measurements are investigated by repeating the test in three reverberation chambers with different characteristics. We show how the current state of the art allows a statistical control of RC measurement repeatability within an industrial installation, and that a statistical correlation with AC results frequency by frequency is possible in particular cases relevant to automotive applications.

Keywords

Reverberation Chamber – Anechoic Chamber – Mode Tuning – Radiated Immunity – Automotive EMC.

INTRODUCTION

The use of electronics in automotive industry has increased at a phenomenal rate in the last decades, leading to more than 70 electronically driven functions on most recent cars. As a consequence, automotive industries are faced to the problem of conceiving robust electronic systems, with respect to internal and external perturbations, with low electromagnetic (EM) emissions. To such EMC constraints, typical automotive constraints must be added, such as the use of low-cost and low-weight cables and devices. For this last reason, most of automotive devices and related wire bundles are unscreened.

This work deals with methodologies for testing the radiated immunity of automotive electrical and electronic devices. Experience shows that the most frequent radiated immunity problems of cars in the frequency range of 100 MHz – 1 GHz are related to the EM energy coupled to wire bundles. In order to anticipate problems at a system level (whole car), benchtests are performed at a subsystem level, on single subsystems and devices. During benchtests, devices are connected to wire bundles of normalised lengths. Furthermore, to simulate the presence of the car body, benchtests are performed with the device standing above a conducting plane. Measurements are usually carried out in (semi-) anechoic chamber (AC), where devices are exposed to the EM perturbation for one incidence direction (frontal), each one with two field polarizations (horizontal and vertical). Such testing methodology proves to be unsatisfactory from the point of view of quality and cost-effectiveness. From a quality point of view, the major difficulties consist in the dependence of the measurement repeatability from the measurement configuration, and in the correlation between subsystem- and system-level testing. From a cost-effectiveness point of view, AC methodology is expensive mainly due to EM absorbers and to power amplifiers. Furthermore, the current methodology has a limited robustness, since a few incidence directions and field polarisations are tested. Such practical and economic difficulties, have inspired the investigation of alternative methods, among which the use of the reverberation chamber (RC) (or mode-tuned/mode-stirred chamber) is promising because of its practical and economic advantages.

In the last decade, many efforts have been made to introduce RC testing methodology within the industrial context, leading to the formulation of an IEC standard [4]. This work contributes to the diffusion of the RC methodology by showing the feasibility of the statistical control of measurement uncertainty and of the statistical correlation with immunity results obtained in AC, wihin an automotive industrial context.

Repeatability of RC radiated immunity results and correlation with AC results have been separately investigated in previous works (see e.g. [3] and [2]). Both subjects are experimentally investigated in this work, focusing the attention on radiated immunity testing of a simple electronic device representative for automotive devices. The paper is organised as follows. The next Section gives a description of the device chosen to perform radiated immunity tests. Radiated immunity measurements conducted in three different RCs will be then described and and the results obtained will be exposed focusing the attention on reproducibility of measurements. Finally, measurement results obtained in AC will be exposed, and the correlation with RC results will be analysed in the last Section.

DEVICE UNDER TEST DESCRIPTION

With the aim of disposing, for our investigations, of a simple device both representative of automotive devices and susceptible over a wide frequency range, we realized a simple test board with an external 50 cm long bare wire connected to a critical input of the circuit. The test board (DUT in the following), shown in Figure 1, is made of commercial integrated circuits and components, and its core is constituted by a timer and a voltage comparator (National Semiconductor LM555 and LP311 respectively). The external wire is connected to the negative input of the voltage comparator, whose output is connected to the timer trigger. This basic assembly allows to identify a threshold field level which, coupling to the external wire, is able to "disturb" the normal timer operation. The output of the timer is checked via optical fiber, allowing to detect possible DUT failures. The DUT is supplied with a 9V battery.

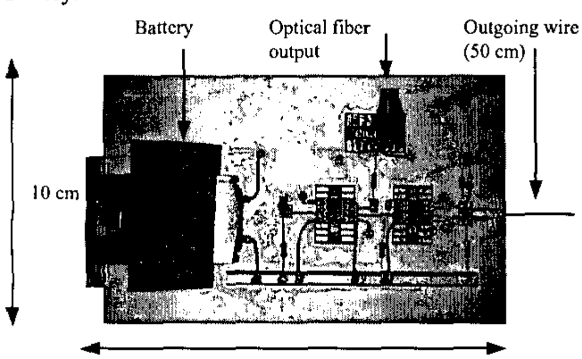

Figure 1. The device uncer test

The DUT, even if simple, for our purposes can be considered representative of an unscreened automotive device connected to an unscreened external wire.

REVERBERATION CHAMBER TESTS

The DUT described in the previous Section has been tested for radiated immunity with a continuous wave (CW) EM field in three different RCs: the Technocentre Renault chamber (RC1), the TELICE laboratory chamber (RC2) and the UTAC laboratory chamber (RC3). The three chambers have different sizes (RC1 has a volume of 221m^3, RC2 of 14m^3, RC3 of 48m^3) and characteristics as well as different instrumentations. We first analyze the measurement repeatability in RC1 for different test positions of the DUT inside the working volume of the chamber. During the test, the DUT was located over a dielectric block without a nearby ground plane: this was done in order to avoid discrepancies that might appear in different chambers merely due to different ground planes. Measurements were made according to [4], with a mode-tuning technique (with a stirrer rotation in n=50 steps per turn), over the whole frequency range. According to this procedure, the result of the immunity test is expressed as the maximum of the r-th rectangular component of the electric field $\lceil E_{r\text{-RC}} \rceil_n$ to which the DUT is exposed over the n stirrer positions. Field levels inside the testing volume of the chamber are pre-determined by a calibration procedure, carried out with an isotropic electric field probe in the 8 corners of the volume. The threshold fields values $E_{Test\text{-RC}}$ corresponding to DUT failures, over the frequency range of 200 MHz to 1 GHz, are reported in Figure 2, for 4 measurement positions (test-1 to test-4).

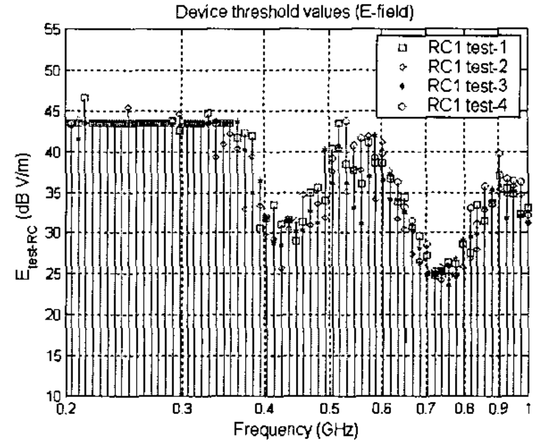

Figure 2. Repeatability of the DUT immunity results in RC1

We then considered the measurement reproducibility in different chambers, testing the device in RC2 and RC3. Results for the 3 facilities, over the frequency range of 500 MHz to 1 GHz, are shown in Figure 3. Results are proposed starting from 500 MHz since this is approximately the lowest usable frequency of the smallest chamber (RC2).

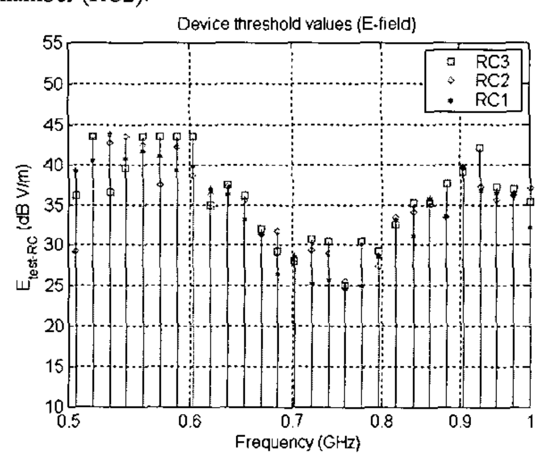

Figure 3. Reproducibility of the DUT immunity results in three different chambers

We analyse now the results reported in Figure 2 and Figure 3. For an ideal RC with an ideal instrumentation, given the fields spatial uniformity and isotropy, the ideal RC fields statistics is the only contribution to the overall measurement uncertainty, making the RC test independent of the specific facility. This is one of the advantages that one can expect in using RCs for EMC testing. However, care must be taken to define "good operating conditions" such that this hypothesis be verified. Good operating conditions can be defined by means of statistical tests carried out on fields and power measurements inside the working volume of the chamber, assessing the agreement of measured fields with ideal RC fields (a) and the number of uncorrelated stirrer positions available at each frequency (b) (see [8] and [9]). The result of such tests consists in the number of stirrer positions which can be used at each frequency respecting (a) and (b). In such conditions, a statistical control of measurement repeatability and reproducibility can be achieved. The residual (unexplained) uncertainty can also be estimated as the residual overall non-uniformity and non-isotropy of fields inside the working volume of the chamber for good operating conditions. The residual uncertainty for RC1 has been estimated on the order of 1 dB [9].

Thus, if we use a proper RC methodology, since $E_{Test\text{-}RC}$ is expressed in terms of maximum values of one electric field rectangular component, measurement repeatability and reproducibility can be related to the maximum values uncertainty for electric field rectangular components. RC maximum values uncertainty can be computed by using extreme order statistics [10]. With 50 independent stirrer positions we expect a 95% confidence interval on maximum values of 4.6 dB. Experimental results show that 73% of susceptibility frequency points in Figure 2 and 76 % of points in Figure 3 fall within a 5 dB range. These results show that, for properly defined testing conditions, RC testing is independent from the specific facility (even for very different chamber sizes) and used instrumentation. Measurement reproducibility in different facilities is thus of the same order of measurement repeatability in the same chamber, which can be statistically controlled.

ANECHOIC CHAMBER TEST AND CORRELATION WITH REVERBERATION CHAMBER TEST

We tested also the DUT inside the UTAC semi-AC, where absorbing panels were placed on the floor to obtain a fully-anechoic effect. The DUT was placed over a wooden table, and the emitting antenna was placed at a distance of 1m from the DUT. A one-point electric field calibration was performed prior to the test. We tested the DUT for 10 inspection angles laying over one principal plane (the plane containing the test board) and 2 polarizations (horizontal and vertical) for each incidence direction. For each test frequency, we retained the worst immunity case over the 20 measurements, corresponding to the lowest field level $E_{Test\text{-}AC}$ producing a DUT failure. AC immunity results are shown in Figure 4, together with RC results of Figure 3, over the frequency range 600 MHz – 1 GHz. The lowest usable frequency is imposed here by the ability of AC available power amplifiers to generate adequate field strengths.

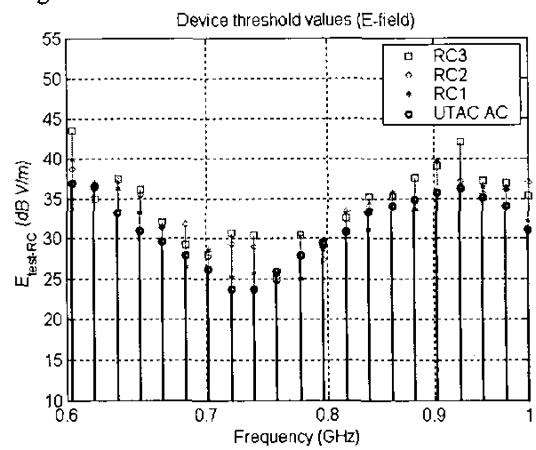

Figure 4. Comparison of DUT immunity results in one anechoic chamber (UTAC AC) and three reberberation chambers

We analyse in the following the correlation between AC and RC results reported in Figure 4. Firstly we recall the general correlation approach, which we applied to our specific case.

The differences between AC and RC tests are evident. In RC, the devices are exposed to an omni-directional un-polarized stochastic EM perturbation, while in AC the devices are exposed to a directional perturbation and the failure field level corresponds to a deterministic field predetermined by a calibration procedure. However, it is possible to investigate for a statistical correlation between the two methodologies, when testing several inspection angles and polarizations in AC. This subject has been investigated in several past works from the point of view of the correlation of the power coupled into a linear electrical object (see e.g. [6] and [1]). In this work we make the hypothesis of linearity for the considered DUT and apply the same approach, which is reformulated in the following for correlating fields threshold values in the two facilities.

Some simplifying hypothesis are necessary. First, we assume to use an ideal RC, as discussed in the previous Section. Secondly, we suppose that inside the AC the DUT is exposed to an ideal plane wave EM environment. The latter hypothesis is verified only in far-field regions, in absence of scattering phenomena in the chamber. We identify in this case with $|E_{AC}|$ the plane wave amplitude, that is the linearly polarised electric field strength to which the DUT is exposed for each inspection angle and polarization. We consider then for simplicity a "complete" fully-AC test, that is with a large number of incidence directions and field polarizations. The outcome of such test is the field strength $E_{Test\text{-}AC}$ corresponding to the threshold level for the DUT, for the worst-case inspection angle and field polarization (as already discussed above).

We consider then a linear DUT, and we characterise failures with regard to the electrical power level P_{rec} received at two identified DUT electric terminals. A DUT failure is present if the received power P_{rec}, due to external EM fields, is $P_{rec} \geq P_{fail}$. In the case where the AC test incidence directions and polarization angles can be assumed as uniformly distributed in space (over the solid angle and over the plane angle, respectively), the following equation can be derived [6]:

$$\frac{\langle P_{rec-\mathrm{AC}} \rangle}{\langle P_{rec-\mathrm{RC}} \rangle} = \frac{|E_{\mathrm{AC}}|^2}{3 \cdot \langle |E_{r\text{-}\mathrm{RC}}|^2 \rangle} \tag{1}$$

where:

- $\langle P_{rec-\mathrm{AC}} \rangle$ is the mean received power by the DUT in AC with respect to inspection angle and field polarization;
- $\langle P_{rec-\mathrm{RC}} \rangle$ is the mean received power in RC with respect to the stirrer rotation;
- $|E_{\mathrm{AC}}|^2$ is the square amplitude of the AC plane waves, as defined above;
- $\langle |E_{r\text{-}\mathrm{RC}}|^2 \rangle$ is the mean value of the square amplitude of one electric field rectangular component in RC.

The maximum received power in AC $\lceil P_{rec-\mathrm{AC}} \rceil$, with respect to the inspection angle and the field polarization, and the maximum received power in RC $\lceil P_{rec-\mathrm{RC}} \rceil_n$, with respect to n stirrer positions, can be expressed as a function of the relative mean values according to:

$$\lceil P_{rec-\mathrm{AC}} \rceil = 2 \cdot D_{DUT}(f) \cdot \langle P_{rec-\mathrm{AC}} \rangle \tag{2}$$

$$\lceil P_{rec-\mathrm{RC}} \rceil_n = \Uparrow_n (P_{rec-\mathrm{RC}}) \cdot \langle P_{rec-\mathrm{RC}} \rangle \tag{3}$$

where:

- $D_{DUT}(f)$ is the frequency dependent maximum directivity of the DUT, as defined in antenna theory (see also [8]);
- $\Uparrow_n (P_{rec-\mathrm{RC}})$ is the maximum-to-average function of the received power in RC, which is a function of the number n of stirrer positions n and is independent of the specific DUT. The complete formulation of this function can be found in [7], and point estimations can be found in [6].

Correlating RC and AC immunity results implies to equate the maximum power received by the DUT in the two facilities. This can be done by equating to 1 the ratio of (2) and (3). If we do so, and we take into account (1) and the following relation, valid for an ideal RC (see [6]):

$$\frac{\langle |E_{r\text{-}\mathrm{RC}}|^2 \rangle}{|\lceil E_{r\text{-}\mathrm{RC}} \rceil_n|^2} = \frac{4}{\pi} \frac{1}{[\Uparrow_n (|E_{r\text{-}\mathrm{RC}}|)]^2} \tag{4}$$

we finally obtain the following relation:

$$\frac{E_{Test\text{-}\mathrm{AC}}}{E_{Test\text{-}\mathrm{RC}}} = \sqrt{\frac{12}{\pi}} \cdot \frac{1}{\sqrt{2 \cdot D_{DUT}(f)}} \cdot \frac{\sqrt{\Uparrow_n (P_{rec})}}{\Uparrow_n (|E_{r\text{-}\mathrm{RC}}|)} \tag{5}$$

which relates the field threshold level $E_{Test\text{-}\mathrm{AC}}$ in AC and the field threshold level $E_{Test\text{-}\mathrm{RC}}$ in RC for a given device. It is useful to remember that (5) holds for the previously defined testing conditions in the two facilities. In particular, $E_{Test\text{-}\mathrm{AC}}$ corresponds to the electric field amplitude of the incident plane wave of a fully AC complete test, and $E_{Test\text{-}\mathrm{RC}}$ corresponds to the maximum of one electric field rectangular component over n stirrer positions, according to the measurement procedure in [4].

In the right-hand side of (5), the second factor expresses the dependence from the DUT characteristics, as a function of the DUT directivity. The first and the third factors express the dependence from the choice of the "equivalent test conditions" and the number of stirrer positions used in RC. Different choices of "equivalent test conditions" are discussed in [6]. It must be underlined also that (5) is valid for a "complete" AC test, that is when a large number of incidence directions and polarization are inspected in order to find the real maximum received power. In most cases, for practical applications, only a few inspection angles are tested, for one or two orthogonal field polarization. This means that there is a potential risk of missing the real worst case angle. Thus, for experimental results, the equality in (5) should be replaced by "larger than".

The major difficulty in the practical use of (5), is tied to the dependence from the maximum directivity $D_{DUT}(f)$ of the tested device. For a general device, the directivity is not known a-priori. Thus, in most cases, estimated values have to be inserted in (5). Methods for estimating the directivity of intentional and non-intentional emitters are discussed in [5]. However, the validity of such methods is not general. For instance in [2], it is shown how, for a shielded enclosure with apertures, given the great variability of the DUT directivity versus frequency, it is difficult to obtain a frequency by frequency correlation between AC and RC results based on directivity estimation.

However, for our particular case, the problem of estimating the DUT directivity can be simplified, given the nature of the device. For instance, we could approximate the DUT directivity by the external wire directivity. By this approximation, we suppose that the sole responsible of the DUT susceptibility is the EM energy picked-up by the wire. This hypothesis was experimentally verified by testing the DUT with and without the external wire. The directivity of the external wire was estimated in an analytical way as the directivity of a perfectly conducting 50 cm long wire, loaded with an open circuit at one end. In the 600 MHz – 1 GHz range, the estimated directivity is a slowly-varying function of frequency ranging from 1.8 to 2.4.

By inserting the above estimated directivity, and the number of stirrer positions n=50, used for RC measurements, into (5), we obtain an expected ratio between AC and RC results which is a slowly varying function of frequency ranging from -0.7 dB to –2.0 dB.

These results are consistent with the results of Figure 4, pointing out the validity of the approach for correlating immunity results obtained in AC and RC. Moreover, results in Figure 4 suggest that when dealing with non directive devices (over the considered frequency range) an almost direct correlation between AC and RC immunity results is possible, with AC results being a few dB more severe than RC results. Finally, since a non-directive object has a smoothed radiation pattern, for a given number of inspection angles there is a large probability of inspecting the worst case coupling direction. In other words, a few incidence directions have to be inspected in order to find the worst susceptibility case for non-directive devices. This is the case of our DUT, for which, given also the rotational symmetry, with only 10 inspection angles, we obtain a good correlation with RC results. Missing the worst incidence or polarization case in AC would have resulted in higher field threshold values in Figure 4.

Such considerations support the feasibility of correlating AC and RC immunity results for non directive devices.

CONCLUSIONS

One of the potential advantages in using RCs for radiated immunity testing lays in the possibility of a statistical control of uncertainty, which makes the test results independent from the measurement configuration and from the specific test-facility and instrumentation used. In this work, we assessed this possibility for the repeatability and reproducibility of radiated immunity measurements of an electronic device. This was done by repeated immunity benchtests for a specially-conceived electronic device for several configurations within the same chamber and in different chambers with different instrumentations. Experimental results show that both the measurement repeatability (within the same facility for different configurations) and the measurement reproducibility (in different facilities) agree pretty well with the confidence intervals of an ideal RC. The only hypothesis we used, is the one of working with RC in good operating conditions. For a proper characterization of the measurement uncertainty, we recommend to use rigorous chamber evaluation statistical tests as discussed in [8]and [9].

Correlation of RC and AC radiated immunity results was also addressed in this work. The two testing approaches have difference nature, and while the AC test is strongly dependent on the radiation pattern of the DUT, the omni-directional RC testing is transparent to the radiation pattern. As a matter of fact, a correlation between single direction tests in AC and RC test is not possible. On the other hand, a correlation is possible when considering a "complete" fully AC test, which considers multiple inspection angles and field polarizations. A statistical correlation between the two methods has been proposed, which has a practical interest under particular conditions. In particular, we showed the applicability of this method when dealing with non-directional devices, as for instance automotive devices with external wires. In this case, a direct correlation between worst case susceptibility with regard to inspection angle in AC and worst case susceptibility over stirrer rotation in RC, is possible, provided a correct definition of the equivalent test conditions.

Several aspects and other possible advantages of RC immunity testing must still be investigated and consolidated. Some of them are suggested by automotive applications. With the aim of establishing automotive specifications for RC radiated immunity benchtests, the analysis performed in this work should be extended to all the categories of automotive devices. This will impose to deal also with devices with complex radiation patterns and/or strongly directive, and thus to face the problem of a difficult correlation with AC tests. Furthermore, nowadays benchtests are carried out in AC with standardised incident field strengths, which are independent on the particular device directivity. Nevertheless, given the different nature of RC testing, a constant test level in AC will correspond to different test levels in RC for devices with different directivities, as underlined by (5). This implies the reflection about a new approach for establishing EMC specifications. Finally, the directivity of the tested device may influence the low frequency limit of RC test. In fact, if we consider a plane wave model for RC, we know that by decreasing the excitation frequency, the number of independent plane waves in the chamber decreases as well. This means that a lower number of equivalent incidence directions is tested in RC, resulting in a possible over-estimation of the device threshold susceptibility level.

ACKNOWLEDGMENTS

This work is supported in part by the French research agency ANRT (National Association of Technical Research) and in part by Renault car industry. The authors wish to thank Dr. Lamine Kone for the measurement campaigns at the TELICE (Laboratory of Telecommunications, Interferences and Electromagnetic Compatibility) and Dr. Serge Ficheux and his staff for measurement campaigns at the UTAC (Technical Union of Car, motorcycle and Cycle) EMC laboratory.

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