Power spectroscopy with electrical reverberation chambers for EMC

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Abstract. Critical frequencies at which electromagnetic fields couple into an electronic device can be identified by comparing the power dissipation of a loaded electromagnetic reverberation chamber to that of an unloaded one. However, working conditions that ensure the required statistical electromagnetic field distribution may also imply a bad signal-to-noise ratio for the measured dissipated power. The purpose of this work is to discuss a measurement procedure and methods for data processing that, nevertheless, allow for gaining significant information from a power spectral analysis in a reverberation chamber. This comprises methods that are based on a fit of suited parametric models for the power absorption of uni- or multi-modal resonators. Their validity has been proven by simple DUTs with previously known characteristics.

I. Introduction

Classical electromagnetic compatibility (EMC) tests tend to be time consuming due to the large number of field parameters to be screened, e.g., frequency, field direction, or polarization of the interfering field. If critical coupling frequencies of a device under test (DUT) are previously known, subsequent EMC testing can significantly be reduced. However, in typical situations the possible coupling frequencies of complex electronic devices are not a priori known, even to the manufacturer.

This work deals with a method for the identification of critical coupling frequencies of an unknown device by nondestructive measurement in an electromagnetic reverberation chamber (ERC): The power absorption of the DUT as a function of frequency is determined from comparing the power loss of the loaded chamber to the power loss of an empty one. The method has first been proposed in [1]. Basically, the idea of microwave spectroscopy [2] is transferred to detect possible resonances of electronic devices. Applications of microwave spectroscopy include the analysis of interstellar gases from radio telescope data [3], cancer detection and diagnosis [4], and nondestructive testing for the food industry [5].

The capability to identify local absorption maxima relies on a field exposure that covers statistically equally all possible field directions and polarization planes. An ERC is optimally suited for providing such samples of electromagnetic (EM) fields: In its normal operation, variation of the resonator's geometry or of the field excitation leads to mean values for the EM field that are equally distributed with respect to any field parameter, e.g. [6], [7], [8]. Hence, a possible coupling of the field in the DUT at a certain frequency should occur during the test.

DUTs are usually small compared to the size of the ERC, and, hence, the power loss of the loaded chamber hardly differs from that of the empty one. Hence, taking the difference of these figures may yield a critical signal-to-noise ratio. The identification of coupling frequencies is additionally complicated due to the fact that a complex device may possess an unknown number of resonant modes, whose frequencies may lie close to each other. Hence, a statistical recovery procedure of resonances by fitting a relevant parametric model to the measured data is applied instead of a direct search for absorption maxima.

II. Power spectra measured in an ERC

To measure power spectra, an ERC is fed by a radio frequency (RF) generator via an antenna. The chamber should match the requirements of the standard [9] in terms of size, calibration, stirrer efficiency, and DUT position to enable proper measurements. Ideally, one ensures that the magnitude of all components of the electric field vector possess a Rayleigh distribution [8]. To determine the power absorbed by a DUT, first, the power P_{in} generated by the RF generator and the power P_{out} at the base of the receiving antenna inside the empty ERC are simultaneously measured for any geometry. We use a classical mode stirrer here. Then, the average power values over one turn of the stirrer are calculated. Via

$$P_{\mathrm{loss,empty}} = P_{\mathrm{in,empty}} - P_{\mathrm{out,empty}} \tag{1}$$

the losses in the empty chamber can be determined, which are, depending on frequency, mainly due to power dissipation in the metallic walls of the ERC and antenna losses [6]. In case of a proper arrangement, aperture- and dielectric losses in antenna stands and mounts of the DUTs can be neglected. In a second step, the ERC is loaded with the DUT, P_{in} and P_{out} are again measured, and

$$P_{\mathrm{loss,loaded}} = P_{\mathrm{in,loaded}} - P_{\mathrm{out,loaded}} \tag{2}$$

is determined. By calculating the difference of the losses in the loaded and unloaded chamber, the power

$$P_{\mathrm{DUT}} = P_{\mathrm{loss,loaded}} - P_{\mathrm{loss,empty}} \tag{3}$$

dissipated in the DUT at a given frequency is determined. Repeating this measurement for a range of frequencies, the spectral power coupling into a DUT from an external EM field can be determined. The peaks of the resulting function $P_{\mathrm{DUT}}(f)$ are the critical frequencies. To avoid that a critical frequency might be missed, a sufficiently good field distribution is required. However, experiments have shown, that the method even works if the EM field's phase is not equally distributed. Further, it is required that the system consisting of the ERC, antennas, stands, cables, and the DUT is in a steady state at each measurement. The field distribution inside the ERC must not be influenced by the DUT, and nonlinear effects of the DUT may only excite frequencies within the bandwidth of the power meter connected to the receiving antenna.

III. Validation of the method by generic DUTs

To analyze the potential of the approach described above, the method is validated with the help of generic DUTs with known resonant frequencies. For this purpose, various monopoles with known properties connected to a terminating load were designed (see Fig. 1). These generic DUTs possess a unique single resonant frequency between 1.25 and and 2 GHz. The monopole DUTs (made

Table 1. List of generic DUTs [10]

No. of DUT	f_0 GHz	length mm	R_r in Ω	L nH	C pF
1	1.25	52	11.0	0.3	54.0
2	1.50	42	9.5	0.6	18.7
3	1.75	31	6.0	1.0	8.3
4	2.00	24	5.0	1.0	6.3

from copper plate with 1 mm thickness) are sketched in Fig. 2, where top views are shown in images a) and b) (the version with the additional diode is not further considered in this work). A side view of a target is provided in c), and d) gives details of the termination of the monopoles. The resonant frequencies of the DUTs, as displayed in Table 1. , have been determined by two independent methods: A numerical simulation of the DUTs with the commercial software CONCEPT II [11] and a measurement of the change of the transmission coefficient between a sending and receiving horn antenna, when the DUT is placed between them. Further, the inductance L, capacitance C, and the wave impedance R_r are given in Table 1. .

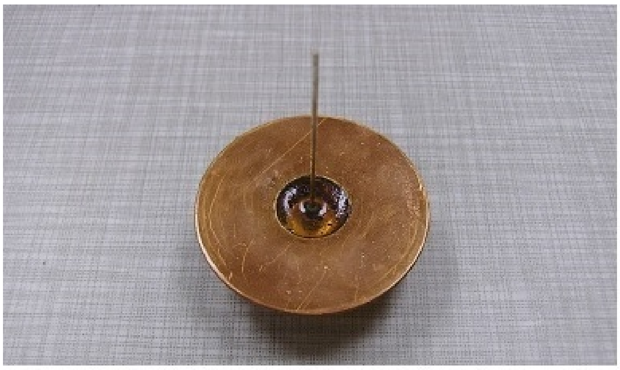

Fig. 1. Typical generic DUT [10].

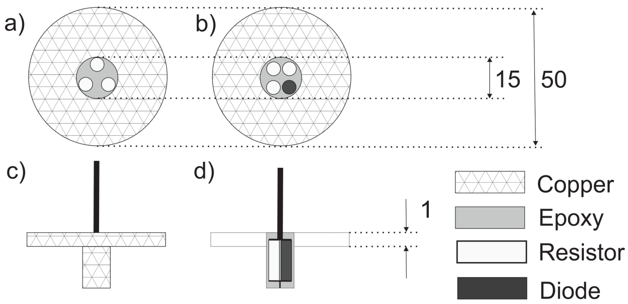

Fig. 2. Construction of generic DUTs [10].

IV. Measurement setup

A small aluminum ERC is used with dimensions of $1000\,\mathrm{mm} \times 800\,\mathrm{mm} \times 650\,\mathrm{mm}$, yielding an estimated frequency of about 800 MHz for the sixtieth eigenmode. However, a Rayleigh distribution for the magnitude of all field components was only observed above 1.6 GHz. Nevertheless, the method turned out to work properly for frequencies above 1.25 GHz. The upper boundary of usable frequencies is limited by the snail shaped antennas at approximately 2.5 GHz. Several tests were performed to guarantee proper operation including calibration in accordance with IEC 61000-4-21[9]. A vector network analyzer (VNA) is used to create and measure the RF signal. The whole set up, including the step motor, works automatically controlled by a computer using MATLAB via GPIB bus.

Input and output power are computed from the scattering parameters of the two port system represented by the antenna transmission line inside the ERC. With the reflection coefficient S_{11} at the base of the emitting antenna and the transmission coefficient $S_{21} = S_{12}$ of the transmission line, one obtains both in the loaded and unloaded case

$$P_{\mathrm{loss}} = \left(1 - |S_{11}|^2 - |S_{21}|^2\right) P_0 \tag{4}$$

with the output power P_0 of the VNA.

For the empty ERC, the mean value of $P_{\mathrm{loss,empty}}$ after averaging over 200 full turns of the stirrer with 50 stirrer positions in each full turn is displayed in Fig. 3. Both presented curves have been measured within a distance of several weeks, showing that the results may stay stable as long as environmental influences are controlled. The

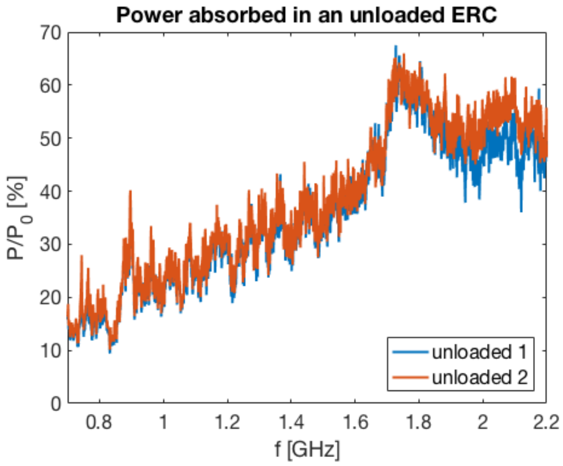

Fig. 3. Power absorbed by empty ERC, unprocessed.

input power was set to $1\,\mathrm{mW}$. The absorbed power of the four observed generic targets as a function of frequency is plotted in Fig. 4 (thin dashed lines). While the resonant frequency is clearly visible, the plot shows that $P(f)$ is affected by strong noise with a signal-to-noise ratio of approximately $0\,\mathrm{dB}$.

V. Data processing

Fitting a suitable parametric model, whether physically motivated or purely statistically, has turned out to be a favorable way to overcome the bad signal-to-noise ratio: In a different context, this type of data analysis was proposed and validated in [12].

The generic DUTs are equivalent to series RLC-circuits. Hence, the effective power $P(f)$ absorbed under periodic excitation is represented by a Lorentz curve

$$P(f) = \frac{A}{1 + \frac{\pi^2}{\delta^2}\left(f - f_0^2/f\right)^2}\,. \tag{5}$$

Here, A represents the amplitude, f_0 the resonance frequency of a non damped oscillation, and δ the loss factor or attenuation coefficient. These quantities can be related to electric properties as follows:

$$A = \frac{U^2}{R_\mathrm{d}}\,, \quad f_0 = \frac{1}{2\pi\sqrt{LC}}\,, \quad \delta = \frac{R_\mathrm{d}}{2L}\,. \tag{6}$$

Here, U denotes the triggering voltage and R_d the ohmic resistance. The model is fitted to the measured data by a nonlinear least squares approach with the CF-Tool of MATLAB. Since – under suitable conditions – the iterative method converges to a local minimum, it should be initiated several times with different starting values.

Table 2. shows the identified values with the resonant frequency of the DUT in column two, the values of the fitted parameters in columns three to five, and in column

Table 2. Results of fitting a Lorentzian

DUT No.	f_0 GHz	$f_{0,\mathrm{id.}}$ GHz	A μW	δ GHz	R^2 %	error %
1	1.25	1.199	169	1.04	53.92	4.1
2	1.50	1.436	556	2.41	42.66	4.3
3	1.75	1.814	210	1.93	27.53	3.7
4	2.00	2.059	68	1.05	39.13	3.0

six, the R^2-value quantifying the amount of data variation that could be explained by the fitted model. The figures in the last column indicate the deviation of the identified from the nominal frequency. The identified Lorentzians have been plotted for all DUTs in Fig. 4. The results

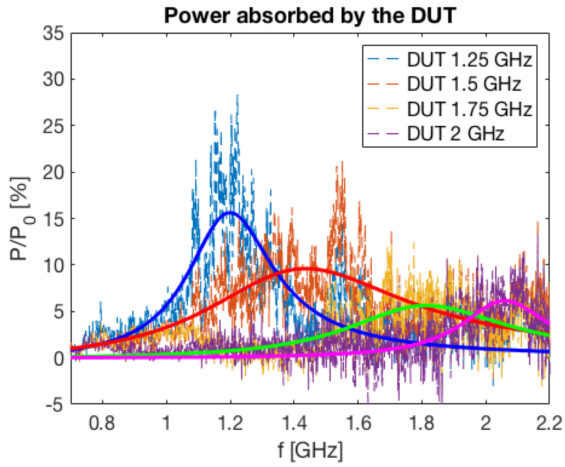

Fig. 4. Power absorbed by targets with different resonance frequencies and resulting Lorentz curves.

in Table 2. indicate that resonant frequencies can be identified with this method in high precision. Further, from the computed attenuation coefficient δ, the damping behavior of signals coupled into the DUT can also be concluded. If the inductance L is known, the ohmic resistance R_d can be computed via (6), and together with the wave impedance R_r the antenna efficiency η can be determined as well as other quantities such as its effective area A_eff, and the gain G_0 due to

$$\frac{R_\mathrm{r}}{R_\mathrm{d} + R_\mathrm{r}} = \eta = \frac{G_0}{D} = \frac{1}{D}\frac{4\pi}{\lambda^2}A_\mathrm{eff}\,. \tag{7}$$

Here λ denotes the wavelength, i.e. $f\lambda = c$, with the speed of light c. As an example, the directivities D of the four DUTs have been determined from a calculation of the DUTs' wave impedance R_r and simulated values for A_eff. The obtained values are $D_1 = 1.6968$, $D_2 = 2.1775$, $D_3 = 2.6647$, $D_4 = 3.1932$ in the order of increasing resonance frequency. These values cover approximately the range between monopole and dipole antennas, which is reasonable, since the copper ground plane significantly deviates from an infinite ground plane.

In practical tests of an unknown DUT any number of resonance frequencies my occur. To capture all resonant modes of the DUT, a more general parametric model has to be introduced. Such models can either be based on an advanced physical modeling or be of purely statistical nature. Currently, different classes of multimodal models are tested. Fig. 5 shows an example of a target consisting of two coupled oscillators with individual resonance frequencies at nominal 1.25 and 2 GHz. Here, the model

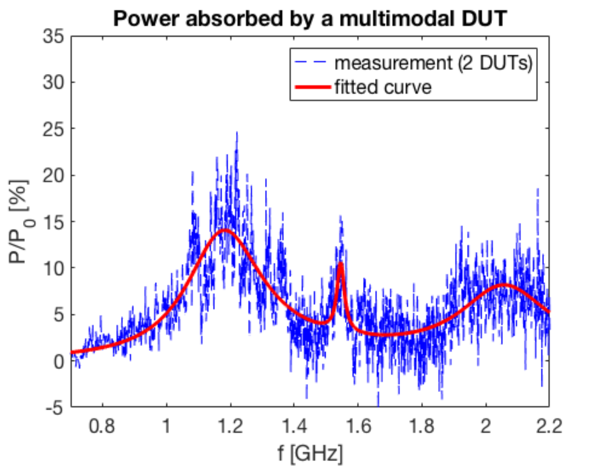

Fig. 5. Power absorbed by two coupled targets and fitted model curve.

$$P_{\text{loss}}(f) = P_0 \left(c_0 + \sum_{k=1}^{3} \frac{A_k}{1 + \frac{\pi^2}{\delta_k^2}\left(f - f_k^2/f\right)^2} \right) \quad (8)$$

with the 10 parameters c_0, A_k, f_k, δ_k has been chosen. Surprisingly, it has turned out, that already with the mono-modal model of a single Lorentzian, multiple resonance frequencies can be identified by choosing a bunch of different initial values, since the Newton iteration will converge to different local maximum depending on the chosen starting value. On the other hand, statistical models offer a better fit to the model data, e.g., due to an auto-adaptive dynamical control of the degree of data-smoothing and the general shape of the fitting function by efficient algorithms.

VI. Conclusions and outlook

Electromagnetic reverberation chambers can be used for high accuracy, nondestructive identification of critical coupling frequencies and other electrical properties of unknown electronic devices. The critical signal-to-noise ratio has been tackled by parametric models that are fitted to the measurement results. Good viability of this approach has been demonstrated for mono-modal and even multi-modal DUTs. The method behaves robust, and even works at non optimum field distributions in the ERC. A quantitative analysis of the influence of all details of the measurement process is currently carried out to finally obtain an easy to use setup for a fast and accurate determination of the coupling characteristics of an unknown device. An analysis of the ERC's coherence bandwidth should lead to further inside into the applicability of the method[1]. Moreover, the method is currently applied to several engineering systems, e.g. to analyze critical frequencies of RFID systems (cf. [13]).

REFERENCES

[1] L. O. Fichte, S. Potthast and K. U. Wendt, *"Modenverwirbelungskammer zur Prüfung elektronischer Schaltungen"*, German Patent DE102012024373 A1, 2014.

[2] W. Gordy, *"Microwave Molecular Spectra in Technique of Organic Chemistry",* vol. IX, edited by A. Weissberger, Interscience, 1970.

[3] K. P. R. Nair, J. Demaison, G. Wlodarczak and I. Merke, *"Millimeterwave rotational spectrum and internal rotation in o-chlorotoluene"*, Journal of Molecular Spectroscopy vol. 237, no. 2, 2006.

[4] M. Lazebnik, Changfang Zhu, G. M. Palmer, J. Harter, S. Sewall, N. Ramanujam, S. C. Hagness, *"Electromagnetic Spectroscopy of Normal Breast Tissue Specimens Obtained From Reduction Surgeries: Comparison of Optical and Microwave Properties"*, IEEE Trans. on Biomed. Eng., vol. 55, no. 10, 2008.

[5] J. H. Goh, O. Korostynska, A. Mason, A. I. Al-Shamma'a, *"Investigating water holding capacity (WHC) of meat using microwave spectroscopy"*, Sixth Int. Conf. on Sensing Techn. (ICST), 2012.

[6] P. Besnier and B. Demoulin, *"Electromagnetic Reverberation Chambers",* ISTE Ltd., London, 2011.

[7] H. G. Krauthäuser, *"Grundlagen und Anwendungen von Modenverwirbelungskammern",* Habilitationsschrift, Magdeburg, 2007.

[8] G. Orjubin, E. Richalot, O. Picon and O. Legrand, *"Chaoticity of a Reverberation Chamber Assessed From the Analysis of Modal Distributions Obtained by FEM,"* IEEE Trans. on EMC, vol. 49, no. 4, 2007.

[9] IEC 61000-4-21, *"Reverberation Chamber Test Methods"*, 2011.

[10] K. U. Wendt, *"Definition und Aufbau eines Messstandes zur berührungslosen Bestimmung der HF-Eigenschaften unbekannter Schaltungen",* Master thesis, Univ. of Appl. Sciences Köln (RFH), 2009.

[11] H. Singer and H.-D. Bruns, *"Concept II - Theory",* Hamburg, 2008.

[12] P. J. Petersan and P. J. Anlage, *"Measurement of resonant frequency and quality factor of microwave resonators: Comparison of methods"*, Journal of Applied Physics, vol. 84, no. 6, 1998.

[13] T. Hurtig, L. Adelöw, M. Akyuz, M. Elfsberg, A. Larsson and S. E. Nyholm, *"Destructive high-power microwave testing of simple electronic circuit in reverberation chamber",* IEEE Int. Symp. EMC, 2015.

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