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# Chaotic reverberation chambers for electromagnetic compatibility

Olivier Legrand, Ulrich Kuhl, Fabrice Mortessagne,  
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**Abstract** Electromagnetic reverberation chambers are now commonly used in the domain of ElectroMagnetic Compatibility (EMC) where electronic devices or wirelessly connected objects are, for instance, submitted to immunity tests. By modifying the standard geometry of current reverberation chambers – which are metallic Faraday cavities – to make them chaotic, we have shown that the statistical requirements of a well-operating reverberation chamber are better satisfied in the more complex geometry due to its spatial and spectral statistical behaviors being very close to those predicted by random matrix theory. More specifically, we have shown that in the range of frequency corresponding to the first few hundred modes, the suppression of non-generic modes could be achieved by drastically reducing the amount of parallel walls. Among other results we could demonstrate that, in a chaotic cavity, the low frequency limit of a well operating reverberation chamber can be significantly reduced under the usual values met in conventional mode-stirred reverberation chambers.

## 1 Introduction

Mode-stirred reverberation chambers (MSRC) play an important role in Electromagnetic Compatibility (EMC). They have been designed initially to cope with the measurements of the electromagnetic (EM) emission of ra-

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diofrequency sources. By extending the concerned frequencies from hundreds of MHz to tens of GHz, the reduction of the wavelength came with a decrease of the antenna size, so that the production of intense fields obtained through the confinement in the reverberant environment had to be favored. By producing oversized cavities compared to the wavelength, generation of fields of random amplitudes is currently achieved by mode-stirring [1] with the help of complex-shaped metallic mechanical rotating stirrers. With their help it is possible to obtain statistically valuable results for the EM radiation emitted from or impinging upon an object under test. In particular, thanks to the presence of a mechanical stirrer, devices under test are expected to be submitted to an isotropic, statistically uniform and depolarized electromagnetic field. Those properties are believed to be satisfied under the condition that the frequency is above the so-called *lowest useable frequency* (LUF). There are many definitions of the LUF [2,3] but they all suffer from an important drawback since they don't explicitly take the overlap of resonances, induced by the losses, into account [4]. Indeed, the LUF being the frequency above which the condition of a statistical uniformity of the field is achieved, the use of a stirrer is supposed to ensure the validity of the so-called *continuous plane wave-spectrum* hypothesis. This statistical hypothesis about the EM field inside reverberation chambers is commonly used by the EMC community and was originally proposed by D. A. Hill [5,6], who assumed that the field is statistically equivalent to a random superposition of traveling plane waves. This hypothesis is generally well verified if the excitation frequency is much larger than the LUF, a result that has long been acknowledged in room acoustics literature [7,8] due to large modal overlap. However, in a frequency regime close to the LUF, the EM field might be neither uniform nor isotropic and this is in spite of any stirring. In this regime, conventional reverberation chambers, which are not chaotic cavities, display a highly non-universal behavior, which may depend on their geometries, the types of antennas used or the object under test.

Moreover, in order to get reliable statements about the fluctuations of the EM field, it is necessary to use statistically independent experimental realizations. Therefore, the statistical ensemble usually achieved by a mode-stirrer has to be mixing enough to make the intensity patterns of the MSRC statistically independent from each other.

All the previously mentioned statistical requirements of a well-stirred MSRC above the LUF closely correspond to the natural behavior of a chaotic cavity [9–11]. For more than five years now, our group has been investigating the spectral and spatial statistical properties of three-dimensional (3D) chaotic cavities, in collaboration with Elodie Richalot and colleagues from ESYCOM at UPEMLV, and has proposed to use chaotic reverberation chambers (CRC) as a new paradigm for applications in EMC [12–14].

Beyond EMC concerns, MSRCs also allow one to simulate complex propagation environments related to multiple reflections, a particularly interesting feature for applications towards modern telecommunication techniques. In particular, CRCs have been recently shown to provide well-adapted benchmarks to test the quality of communication between antennas when the influence of reverberation cannot be neglected [15].

In the following section, we will briefly review the main statistical features of the electromagnetic response of a CRC that can be deduced from a Random Matrix model introduced in [14, 16]

## 2 Statistics of the response in a chaotic reverberation chamber

When Hill's hypothesis is not valid, below or in the vicinity of the LUF, the real and imaginary parts of each component of the EM field are not identically distributed [17]. For a given configuration of an ideally chaotic cavity, they are still independently Gaussian distributed, but with different variances. The ensuing distribution of the modulus of each component  $|E_a|$  is then no longer a Rayleigh distribution but depends on a single parameter  $\varrho$ , called the *phase rigidity*, defined by:

$$\varrho = \frac{\int_V \mathbf{E} \cdot \mathbf{E} d\mathbf{r}}{\int_V \|\mathbf{E}\|^2 d\mathbf{r}}. \quad (1)$$

Note that for  $|\varrho| \rightarrow 1$  the system tends to be lossless, a situation corresponding to non-overlapping resonances at low frequency well under the LUF, whereas  $|\varrho| \rightarrow 0$  corresponds to a completely open system, which recovers the limit of validity of Hill's assumptions for frequencies much larger than the LUF. More specifically, due to the *ergodicity* of the modes that contribute to the response, for a given excitation frequency and a given configuration, the probability distribution  $P(\mathcal{E}_a; \varrho)$  of the normalized field amplitude of the Cartesian component  $\mathcal{E}_a = |E_a| / \langle |E_a|^2 \rangle_r^{1/2}$  depends solely on the modulus of  $\varrho$ . Since the *phase rigidity* is itself a distributed quantity, the distribution of the normalized field amplitude for an ensemble of responses resulting from stirring thus reads

$$P_a(\mathcal{E}_a) = \int_0^1 P_\varrho(\varrho) P(\mathcal{E}_a; \varrho) d\varrho \quad (2)$$

where  $P_\varrho$  is the distribution of the *phase rigidity* of the responses. Our investigations, based on numerical simulations of the Random Matrix model described in [14, 17], have shown that  $P_\varrho$  depends solely on the mean modal

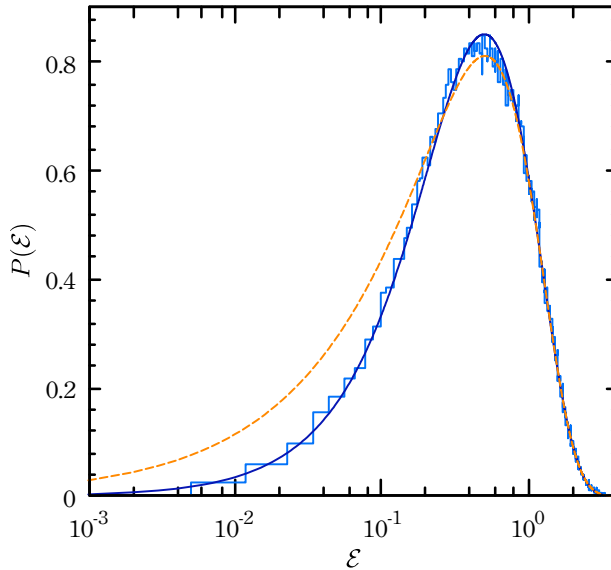
overlap  $d$ . This overlap  $d$  is defined as the ratio of the average modal bandwidth to the average difference between neighboring modal frequencies. We assume that within the investigated frequency range, the latter quantities vary only slightly. Similar results have also been obtained for the phase of the response in a CRC [18].

These theoretical results as well as spectral statistical features like the so-called *level repulsion* between frequencies of the modes, the distribution of the widths of the resonances [19], or the distribution of the width shifts obtained through parametrical variation of the CRC [20] have been tested experimentally and confronted with measurements that are meaningful for the statistical requirements (for instance the *uniformity criterion*) [16], which should be met in well-operating MSRCs according to the IEC standard [3].



**Fig. 1** 180-degree photograph of the chaotic RC at ESYCOM. The commercial RC consists in a rectangular metallic cavity of dimensions  $W = 2.95$  m,  $L = 2.75$  m and  $H = 2.35$  m and was modified by placing 3 hemispheres with radii of 40 cm (one at the ceiling and two on adjacent walls). The mechanical stirrer in the far corner can be seen.

One of the RCs we investigated is shown in Fig. 1 and is located in our partners' lab at ESYCOM. It has a volume  $V \simeq 19$  m<sup>3</sup> and was made chaotic by the addition of three or six metallic half-spheres with a radius of 40 cm located on different walls [13, 16]. The commercial RC we have modified consists of a rectangular metallic cavity of dimensions  $W = 2.95$  m,  $L = 2.75$  m and  $H = 2.35$  m equipped by a mode-stirrer in rotation around the vertical axis and located in a corner. To illustrate the validity of our theoretical approach in an actual CRC, Fig. 2 shows a comparison of the histogram of the normalized field amplitude deduced from experimental data measured in the CRC of Fig. 1, with the prediction (2), where the value  $d = 0.89$  was used. A best fit with a Weibull distribution used in [21] is also shown, demonstrating that the latter cannot account for the experimental data neither in the bulk nor for the small amplitude part of the histogram.

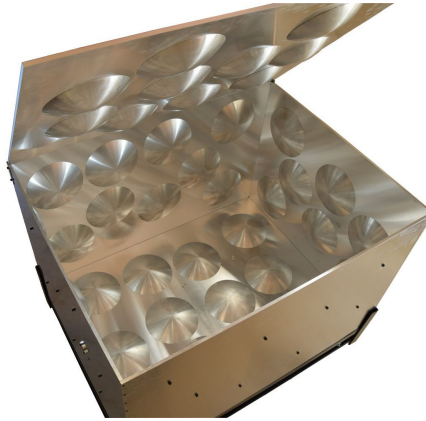


**Fig. 2** Histogram of the normalized field component amplitude from experimental data, compared with the prediction (2) (continuous line) and the corresponding probability distribution of  $P_\varrho(\varrho)$  where the value  $d = 0.89$  was used. Weibull best fit (dashed curve).

Another CRC was specifically designed by our group in INPHYNI for testing communication between monopole antennas in a complex reverberating environment (see Fig. 3) in the framework of experimental investigations concerning the statistics of reflection and transmission in the moderate and strong modal overlap regimes of fully chaotic reverberation chambers [22].

### 3 Conclusion

Here, we have briefly reviewed our theoretical and experimental investigations concerning chaotic electromagnetic cavities leading to the proposal of chaotic reverberation chambers as a new paradigm for applications in EMC, in collaboration with Elodie Richalot from ESYCOM. The results from our group have confirmed the key role of the ergodic character of the response of a chaotic RC to improve the statistical behavior of an RC for frequencies below or in the neighborhood of the LUF. In particular, the statistical criterion proposed in [3] to evaluate the uniformity of the spatial field distri-



**Fig. 3** Photograph of the chaotic RC at INPHYNI with length  $L=100$  cm, width  $W=77$  cm and height  $H=62$  cm. At the walls 54 spherical caps of radius  $r_c=10$  cm and cap height  $h_c=3$  cm are used. The total internal volume is  $V=0.451$  m<sup>3</sup>.

bution, when used near the LUF or at lower frequencies, is only valid if the RC is chaotic since the universality of the statistics of the response cannot be ensured in the case of a conventional non-chaotic RC.

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