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Universal behaviour of a wave chaos based electromagnetic reverberation chamber

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HIGHLIGHTS

- We present a numerical investigation of 3D electromagnetic chaotic cavities.
- Chaotic reverberation chambers (RCs) display universal statistics at low frequency.
- Chaotic RCs with losses fulfil the statistical requirements of a well-operating RC.

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ABSTRACT

In this article, we present a numerical investigation of three-dimensional electromagnetic Sinai-like cavities. We computed around 600 eigenmodes for two different geometries: a parallelepipedic cavity with one half-sphere on one wall and a parallelepipedic cavity with one half-sphere and two spherical caps on three adjacent walls. We show that the statistical requirements of a well operating reverberation chamber are better satisfied in the more complex geometry without a mechanical mode-stirrer/tuner. This is due to the fact that our proposed cavities exhibit spatial and spectral statistical behaviours very close to those predicted by random matrix theory. More specifically, we show that in the range of frequency corresponding to the first few hundred modes, the suppression of non-generic modes (regarding their spatial statistics) can be achieved by reducing drastically the amount of parallel walls. Finally, we compare the influence of losses on the statistical complex response of the field inside a parallelepipedic and a chaotic cavity. We demonstrate that, in a chaotic cavity without any stirring process, the low frequency limit of a well operating reverberation chamber can be significantly reduced below the usual values obtained in mode-stirred reverberation chambers.

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1. Introduction

Electromagnetic reverberation chambers (RCs) are nowadays commonly used for electromagnetic compatibility (EMC) applications [1]. Thanks to the presence of a mechanical stirrer of irregular geometry (generally a rotating metallic object), electronic devices under test are subjected to an isotropic, statistically uniform and depolarised electromagnetic field. Those properties are satisfied as long as the frequency is above the so-called *lowest useable frequency* (LUF). Very often, this LUF is referred to as the *lowest overmoded frequency* [2,3]. The overmoded condition suffers from the lack of a proper definition and is often associated with the concept of a modal density threshold irrespective of the amount of losses [4]. Consequently, several definitions of the LUF can be found in the literature, that are not necessarily equivalent: the LUF can either be between

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three and six times the cutoff frequency f_c of the fundamental mode, or defined as the frequency around which 100 modes are counted above f_c *and* at which the modal density is greater than 1.5 modes/MHz [2,1]. It is quite obvious that the latter definition strongly depends on both the size of the chamber and on the importance of modal overlap related to losses [5] (either at walls or due to antennas). Moreover, as the LUF is understood as 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 description of the electromagnetic field as a random superposition of plane waves, which is named the *continuous plane wave-spectrum* hypothesis [6,4]. However, it has been acknowledged that even for $f > \text{LUF}$, the field may not be statistically uniformly distributed in the RC as a consequence of bad stirring [7,8]. Thus, the behaviour of mode-stirred RCs proves to be highly non-universal, depending on the position and design of the stirrer [2,9]. To improve the properties of an EM RC, the question of lowering the frequency range of well-operating RCs is primordial. However, Bruns et al. [2] have numerically established that all stirrers are equally ineffective below the conventional LUF whatever their shape, orientation, or electrical size.

The above mentioned statistical requirements of a well-stirred RC above the LUF closely correspond to the natural behaviour of a chaotic cavity [10–12]. In this paper, we propose to investigate spectral and spatial statistical properties of three-dimensional (3D) chaotic cavities as a new paradigm for a reverberation chamber. Indeed, in a chaotic cavity, generic modes (also called *ergodic* modes [10–12]) display Gaussian statistics of the fields. This statistical behaviour can be met at relatively low frequency, thereby suggesting that statistically isotropic fields and random polarisations can be obtained even in an unstirred cavity. Quantum or wave chaos has been a very active field of research for decades, concerned with the spectral and spatial asymptotic properties of wave systems whose ray counterpart is chaotic [13–15]. Predictions of random matrix theory (RMT) have been extensively verified, both numerically and experimentally in two-dimensional (2D) or pseudo-2D electromagnetic cavities [16,17,15,18,19] as well as in the 3D case [20–24]. Previous works have already called for the similitude between the expected statistical properties of a well-stirred RC and the intrinsic behaviour of individual *ergodic* modes of a chaotic cavity, to propose strategies for improved operation of an EM RC [7,25,26]. We believe that, along with these studies, the results presented here have practical implications for an effective reduction of the lowest useable frequency (LUF) in chaotic RCs.

In the present paper, we demonstrate that the description of the electromagnetic field as a continuous plane wave-spectrum [6,4] can only be justified at high frequencies where modal overlap is large, which is not necessarily the case near the LUF according to the commonly accepted definitions of the latter recalled above. Thus, the main reason why a conventional mode-stirred RC can operate satisfactorily near the LUF is that the presence of the stirrer makes it more like a pseudo-integrable system, equivalent to a barrier 2D-billiard [27], where many eigenmodes are similar to *ergodic* modes of a chaotic cavity [28,29,23]. Nevertheless, even at high frequencies, pseudo-integrable cavities have a non-negligible number of superscar modes [29], with non-Gaussian field distributions. These unwanted features are clearly due to the non-universal spatial or spectral behaviour of pseudo-integrable cavities. It is therefore the universality of chaotic cavities which will serve as the unifying thread of our investigations, keeping in mind that the operation of actual RCs is not restricted to high frequencies and that the modifications of geometry we propose should remain effective at a reduced cost.

In the following section, we introduce key concepts concerning spectral properties of chaotic wave systems, to provide diagnosis tools for RCs. More specifically, universal properties of spectral fluctuations are analysed through the nearest neighbour spacing distribution (NNSD) and the so-called number variance derived from the two-level correlation function. We then investigate these quantities in 3D Sinai-like cavities to exemplify the influence of non-generic modes in departures from non-universal spectral behaviours in 3D chaotic cavities. We also illustrate how universal spectral properties are intimately connected to spatial properties of fields, namely the Gaussian distribution of amplitudes of field components for generic *ergodic* modes.

In the final section, we study the effect of losses on the complex response of 3D RCs. Using the dyadic Green's function (DGF), in a perturbative approach, we study the spatial statistical distribution of fields near the LUF. By accounting for a small or moderate modal overlap we compare a classical rectangular RC without stirrer to a chaotic RC, demonstrating how the latter can fulfil the required statistical features of a well-stirred RC, concerning the spatial distribution of the field, without the use of a stirring process.

2. Spectral and spatial statistics

2.1. Universal spectral statistics of chaotic cavities

Since the Bohigas–Giannoni–Schmit conjecture [13] concerning the universality of level fluctuations in chaotic quantum spectra, it is customary to analyse spectral fluctuations of chaotic cavities with the help of statistical tools introduced by RMT. These tools will be used to check the *chaoticity* of the RCs we study.

Starting from the modal density:

$$\rho(f) = \sum_i \delta(f - f_i) \tag{1}$$

f_i denoting the eigenfrequencies of the cavity, one defines the counting function:

$$N(f) = \int_0^f \rho(\nu)d\nu \tag{2}$$

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