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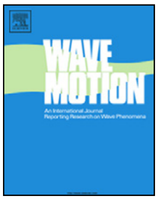

Mode-stirred reverberation chambers: A paradigm for spatio-temporal complexity in dynamic electromagnetic environments

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HIGHLIGHTS

- Overview of use of dynamic multi-mode cavity resonators in EMC.
- Bessel function sampling distributions apply when number of excited modes is small.
- Single-mode stirring is feasible at frequencies below the 'lowest usable frequency'.
- Nonstationary field distributions improve the estimation of the maximum-to-mean ratio.
- Static and dynamic degrees of freedom are intercompared.

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ABSTRACT

We investigate probability distributions in dynamic multi-mode electromagnetic cavities, commonly referred to as mode-stirred reverberation chambers. We show that Bessel K and Bessel I distributions play a prominent role when a large but finite number of excited modes, loss of energy (through aperture leakage or dissipation), or nonstationary transient fields are involved. With the aim at reducing the number of simultaneously excited cavity modes as much as possible while maintaining a well-characterizable quasi-random field, measurement results indicate that single-mode stirring is feasible at certain frequencies well below the usual 'lowest usable frequency' of the cavity. Distributions for nonstationary fields are shown to allow for improved estimation of the maximum-to-mean ratio of the received power during stepwise rotation of the mode stirrer.

1. Introduction

Although the propagation and scattering of time-harmonic electromagnetic (EM) waves is one of the longest and most intensively studied topics in classical physics, its research continues to reveal new insights and unusual results, particularly regarding ultra-wideband (UWB) modulated signals in dynamic and/or multi-path ('complex') EM environments (EMEs). Depending on the topology and detailed geometrical characteristics of EMEs and their size relative to the carrier wavelength(s), the environment may be envisaged as a complex medium and can be modeled as a rough surface, composite

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Abbreviations: BC, boundary condition; CDF, cumulative distribution function; CE, compound exponential; DoF, degree of freedom; EM, electromagnetic; EMC, electromagnetic compatibility; EME, electromagnetic environment; PDF, probability density function; MSRC, mode-stirred reverberation chamber; TPDF, transition probability density function; UWB, ultra-wideband.

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material, structured surface, open or closed billiard cavity, quantum dot, etc. From a system's point of view, the EME represents a time-variant and possibly nonlinear filter between excitation and measured fields.

Static and dynamic EM enclosures with dimensions that are exceedingly large[1] compared to the wavelength have been studied extensively under different names or implementations: overmoded cavities, untuned resonators, integrating spheres, reverberation rooms, multi-mode channels, fading environments, echo boxes, 'breathing' closed or open billiards, mode-stirred chambers, ergodic cavities, complex resonators, diffusing-wave spectroscopes, microwave ovens, etc. While these often show differences at a technical level, their central common feature is the fact that the interior field structure is not a 'regular' simple spatially harmonic pattern, as found in a single-mode waveguide or resonant cavity with smooth and perfectly conducting boundaries, but one that shows high irregularity (including inhomogeneity) in space and time. Early measurements [3] already demonstrated the extreme sensitivity of the interior microwave field to small geometric perturbations of a room.

On the other hand, the area of electromagnetic compatibility (EMC) concerns itself with EM interference and coexistence between electr(on)ic systems in the space–time–frequency domain. This involves aspects of immunity to ambient EM fields (i.e., the ability of a system to avoid malfunctioning caused by an external field) and emission of EM energy (radiation) by intentional or unintentional natural and man-made EM sources. Shielding offers a practical solution to problems caused by intolerably large emissions (e.g., unacceptably high power levels or field strengths generated by radio sources) or low immunity (e.g., vulnerability of a relatively sensitive component or subsystem to ambient fields). EM cavities and waveguides provide such a shielded environment and, hence, they form the basis of reference sites for performing traceable and repeatable EMC and material measurements.

Dynamic multi-mode resonant cavities, known as mode-stirred reverberation chambers (MSRCs), allow for generating higher field strengths and measuring total emitted power, compared to other EMC test facilities such as, e.g., anechoic chambers. However, the interpretation of test results in MSRCs requires greater care than in plane-wave anechoic environments, because of the fundamental non-plane-wave nature of the field: due to large and irregular variation of the multi-modal field across the cavity volume, the phase planes perpendicular to the local wave vector are severely restricted in area. This area is typically much smaller than the aperture of any measurement instrument or test object.

Historically, MSRCs have been investigated in EMC since the mid-1970s [4], following earlier developments in microwave spectroscopy [5] that in turn were based on extensive studies of acoustic rooms with rotating vanes [2,6] and sound decay in general room acoustics [7]. There is also a large body of literature on the dynamics of fields in the presence of moving bodies, including dynamic cavities, that started around the mid-1960s [8]. Nowadays, MSRCs are increasingly used in the aerospace [9], automotive [10], and telecommunications [11] applications as a robust and cost-effective alternative EMC test method, compared to open-area test sites and (semi-)anechoic chambers. Several generic [1,12,13] and product-specific international standards exist that prescribe validation and test procedures for MSRCs. Fig. 1 shows an experimental set-up for testing of electronic systems in vehicles and a typical reverberation chamber for research that meets the chamber validation test specified in [1].

Despite this large uptake, more fundamental study is required for further improvement of field characterization, with a view to achieve greater economy in cavity shape and size (including costs of real-estate, construction and materials), faster stirring (reduced test time), greater stir efficiency, and increased accuracy of test methods. To this end, accurate statistical and stochastic characterization of MSRCs at relatively low frequencies is of key importance. If sufficiently large levels of perturbation of the field could be achieved closer to the lowest resonance frequency of a MSRC, based on few- or even single-mode excitation per stir state, then the cavity size could be kept close to a minimum. This possibility will be investigated in this paper. Other selected areas of ongoing research are the characterization of extreme field values (for immunity (maximum value) or fading (minimum value)), wide-band excitation (including short-pulsed radar signals), time-domain response, alternative stirring techniques, line-of-sight propagation effects, reliability, correlation, absorption, dynamics and transients in MSRCs, etc. All these aspects are important with a view to reducing test times, improving the accuracy of the estimated level of uncertainty, and widening the areas of applications.

Unlike complex cavities for scalar waves (acoustic, optical, quantum resonators), the vector nature of EM waves introduces three-dimensional (3D) partial polarization of the random field [14,15]. EM boundaries [16] and large aspect ratios of a cavity [14] introduce statistical anisotropy, i.e., a scenario in which the angular direction and magnitude of the local Poynting vector are not spherically uniformly distributed, when considered across the ensemble of all stir states of the cavity. On the other hand, the much larger velocity of propagation for EM compared to acoustic waves makes dynamic effects of propagation of transient fields less common.

2. Probability distributions of field and energy

Generally, probability density functions (PDFs) are tools for quantifying the distribution of probability for values of the local random field across their range. While marginal PDFs describe local space–time properties, these can be combined with an appropriately chosen family of copulas [17] to yield joint PDFs at two or more space–time locations that characterize space–time properties and, hence, the wave structure. With regard to immunity and shielding testing, distributions of the

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[1] Typically by a factor of ten or more [1], but specifically dependent on the nature of any wave diffusers used inside the cavity [2].