

Efficient Reconstruction of the Sensitivity Map Characterizing the Equivalence of Working Volumes in Reverberation Chambers

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The equivalence of working volumes in reverberation chambers (RCs) is investigated by the regime of state-of-the-art sensitivity analysis (SA) techniques by inspecting the effect of changing configuration parameters to the field uniformity (FU) in a frequency-dependent study. The Sobol' indices as sensitivity analysis measures are evaluated at each stirrer step and frequency. For efficient calculation, different state-of-the-art surrogate modeling techniques are utilized to substitute the full-wave simulation model depending on the characteristics of the working volumes. The computational expenses of the problem are further reduced by using a decreased number of stirrer steps and frequencies, which are achieved by means of adaptive sampling techniques through kriging interpolation. Furthermore, the size of the experimental design set, i.e., the number of different configurations is controlled by performing convergence studies. The proposed method is able to reconstruct the 2D sensitivity map (SM) of the configuration parameters as functions of the stirrer steps and the frequency with a fewer number of samples.

Index Terms—Reverberation chambers, Data-driven modeling, Sensitivity, Numerical simulation

I. INTRODUCTION

THE ELECTROMAGNETIC field distribution and its statistical properties in a reverberation chamber (RC) are exploited in several application area of measurement techniques, so as in the field of electromagnetic compatibility (EMC). There exist many so-called stirring techniques for slightly displacing the eigenfrequencies occurred in such cavity resonators to achieve the desired statistical field properties [1]. However, the majority of automotive standards, e.g., [2] favor the traditional mechanical stirring. The possibility of testing parallelization is a powerful feature of RCs, exploiting the theoretically position-independent field properties. During such a process, multiple devices under test (DUTs) can be tested at once. However, the lowest operation frequency required by the automotive standards [2] is comparable with the LUF of an RC of typical sizes. Moreover, there is no unequivocal agreement for the exact value of the LUF, as no abrupt change is present between overmoded and undermoded condition [1]. That is why it makes sense to investigate the equivalence of simultaneously present working volumes inspected with respect to the local statistical field properties. In this work, as in, e. g., [3] a full-wave computational model is substituted by a black-box model to efficiently calculate the chosen sensitivity analysis measures. The input parameters of the abstraction are the configuration parameters corresponding to the working volume and the stirrer, while the output parameter is the composite quality factor (Q-factor) calculated as in [4]. Performing such sensitivity analysis is resource-demanding, requiring to evaluate hundreds of simulations even in case of minimum number of stirrer steps defined by the standards [2]. Carrying out a frequency-dependent study requires a computationally efficient solution to reconstruct qualitatively the

same SM from a lower number of simulations. For this sake, an adaptive algorithm was proposed in [3] based on kriging interpolation by utilizing a 2D input parameter space defined by the stirrer steps and the frequency points. The investigations were performed around the lowest usable frequency (LUF), and validated against the pointwise evaluation of the stirrer steps and frequencies with equidistant sampling. In this paper, this approach is extended to the most important frequency range in radiated immunity testing, where the standard FU evaluation procedure requires a prescribed decrease in the standard deviation of the field components from 6 dB to 3 dB in the bandwidth from 100 MHz to 400 MHz.

II. METHODOLOGY

A. Global SA, Metamodeling

The Sobol indices are defined to represent the contribution of each variable (single, overall) formed in the input parameter vector to the output vector, which define quite descriptive quantities scaled to the [0,1] interval. In order to obtain these indices in a more computationally efficient way, it is favourable to replace the full-wave simulation model by a functional approximation $\mathcal{M}(\mathbf{X}) \approx \mathcal{M}^{\text{Meta}}$. The function $\mathcal{M}$ represents an operator which maps the input variables formed in vector $\mathbf{X}$ to the output quantity, and $\mathcal{M}^{\text{Meta}}$ is its approximation by utilizing a surrogate modeling technique. The kriging metamodel [5] considers the model output as a realization of a Gaussian process, which is formulated by the subsequent equation

$$\mathcal{M}^K(\mathbf{X}) = \beta^T \mathbf{f}(\mathbf{X}) + \sigma^2 Z(\mathbf{X}, W) \quad (1)$$

where the first term is the trend, i.e., the mean value of the Gaussian process, formed as the linear combination of known $\mathbf{f}(\mathbf{X})$ basis functions, e.g., polynomials, while the second term

is a multiplication of the variance of the Gaussian process σ^2 and a zero-mean, unit-variance stationary Gaussian process $Z(\mathbf{X}, W)$. The underlying probability space is represented by W . The latter one is defined in terms of a correlation function, i.e., a correlation family. In our case, the Matérn-3/2 covariance function with separable correlation function exhibited the best performance in handling the fluctuations. A more detailed description about the utilized surrogate modeling techniques can be read in, e.g., [5].

B. Adaptive Sampling

After the metamodels are built at each initial stirrer step positions at certain frequencies in a chosen bandwidth, the subsequent stirrer step - frequency pairs $\mathbf{q} = (k, f)$ are determined adaptively until specific criteria are reached. The sampling method is performed by means of the efficient global optimization (EGO) algorithm over a kriging metamodel, seeking for the maximum of the expected improvement (EI) function under the optimization criteria at each iteration step by exploiting the probability information, that the surrogate model provides. The aim of the optimization is to find the regions where the parameters *change importance*, i.e., when the respective Sobol' indices become higher than the other ones, which can be achieved by minimizing the absolute difference between the Sobol' indices of each input parameter pairs. This approach was introduced and used exclusively in [3]. In order to keep the number of new sampling points low, different restrictions are imposed, as in [3], which can prevent from unnecessary oversampling in regions, where the minimal difference is already determined. The expression for the EI function reads as follows

$$EI_i(\mathbf{q}) = u_i(\mathbf{q})\Phi\left(\frac{u_i(\mathbf{q})}{\hat{\sigma}_i(\mathbf{q})}\right) + \hat{\sigma}_i(\mathbf{q})\phi\left(\frac{u_i(\mathbf{q})}{\hat{\sigma}_i(\mathbf{q})}\right), \quad (2)$$

where $\Phi(\cdot)$ is the cumulative distribution function (CDF), $\phi(\cdot)$ is the probability density function (PDF) of a Gaussian normal distribution, $\hat{S}_{i,\text{diff}}(\mathbf{q})$ is the mean value, i.e. the kriging trend, $\hat{\sigma}_i(k)$ is the kriging variance, and

$$u_i(\mathbf{q}) = \min\{\hat{S}_{i,\text{diff}}(\mathbf{q})\} - \hat{S}_{i,\text{diff}}(\mathbf{q}), \quad i = 1 \dots \binom{N_X}{2}. \quad (3)$$

The EI functions are then normalized in the following way, in order to treat each difference equally, and the new stirrer step is determined by maximizing the EI function

$$EI(\mathbf{q}) = \frac{\sum_{i=1}^{\binom{N_X}{2}} EI_i}{\max EI_i(\mathbf{q})}, \quad \mathbf{q}_{\text{new}} = \arg \max_{\mathbf{q}} EI(\mathbf{q}). \quad (4)$$

C. Test Problem

The model of an RC with approximate sizes of $4 \text{ m} \times 5 \text{ m} \times 3 \text{ m}$ is built using the commercially available simulation software CST [6]. The E-field is monitored within the maximum number of achievable multiple working volumes placed horizontally next to each other as depicted in Fig. 1a, in accordance with the standards [2]. The input parameters corresponding to the stirrer are marked in red, while the working volume-related ones are highlighted in green. The aim is to investigate

the maximum achievable displacements taking into account the minimum distance between each metallic surface required by the standards [2], and the input parameter range is determined accordingly. As in [3], the so-called composite Q-factor was chosen as the output parameter. The following approximation can be used under well-stirred conditions [4]

$$\tilde{Q} \approx \frac{1}{2} \omega \varepsilon V \langle \tilde{E} \rangle^2, \quad (5)$$

where ω is the angular resonance frequency, ε is the permittivity of the air, V is the RC volume, $\langle \tilde{E} \rangle$ is calculated as a total average over all stirrer rotations and sampling positions, normalized with the square root of the average input power with respect to the stirrer rotation.

D. Results

The results obtained for workingvolume_1 are depicted in Fig. 1b. The investigated bandwidth is from 170 MHz to 180 MHz, around the estimated LUF. In [3], the results were compared with the sensitivity analysis carried out without the adaptive sampling by utilizing $N_{\text{stirrer}} \times N_{\text{freq}} \times N_{\text{conf}} = 12 \times 8 \times 100 = 9600$ samples, where the terms stand for the number of stirrer steps, frequency points and configurations, respectively. By carrying out convergence studies, it is possible to reduce N_{conf} approximately by half and the number of (k, f) pairs also could be decreased from 96 to 49, which can be further reduced as depicting the peak values is less important than identifying the regions of the *importance change*. This also means, that the sensitivity analysis can be performed involving a larger bandwidth by using number of samples in the same order. Further results and details will be introduced in the final paper.

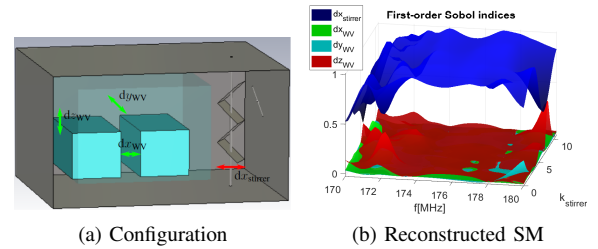


Fig. 1: The simulated RC and the obtained Sobol' indices[3]

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