Modeling complex systems for EMC applications by considering uncertainties

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Abstract

The objective of this work is to present a new approach to the random modeling of complex systems in ElectoMagnetic Compatibility (EMC). This contribution aims to compute high orders statistics and study the impact of parameter uncertainties on various EMC topics including transmission lines, radiation and immunity problems. The agreement between results from the Stochastic Collocation (SC) method and Monte-Carlo (MC) simulations guarantee the SC accuracy and robustness. The combination of SC with computations from analytical and tridimensional numerical models (Finite Difference in Time Domain) underlines its advantages (efficiency, non-intrusive integration).

1. Introduction

Nowadays, numerous efficient and accurate computational methods are used to simulate complex systems in order to solve ElectroMagnetic Compatibility (EMC) problem. Most of these tools are deterministic ones giving a unique result for exact (with an infinite precision) input data. Unfortunately, the uncertainties are intrinsic in EMC problems: the parameters of the electromagnetic sources are not perfectly known, various uncertainties are observed in electric and geometric parameters of materials in the case of large production, and industrial devices can present slightly variations, due to environmental factors (thermal, mechanical). Therefore, material features can be considered as stochastic and it becomes necessary to take into account these various uncertainties for an efficient and realistic modeling methodology. Nevertheless, the acquired experience and the performances of the developed deterministic numerical tools led us to envisage not intrusive methods to handle EMC issues.

2. The Stochastic Collocation Method

In this paper, we use an original non intrusive Stochastic Collocation (SC) method [1] based on Lagrange's polynomials which presents the simplicity of Monte-Carlo (MC) simulation, but with higher convergence rates. This procedure is computationally very efficient, since it is performed with a limited number of well-chosen points related to the distribution of the random variables.

Let us consider a function I with a random value L defined as $L=L^0(1+aX)$. X is a Random Variable (RV) following, without any loss of generality, a uniform law on [-1, 1], L^0 is the central value, and a the magnitude in percent of the uncertainty (for example a=4%). The first step of the SC method consists in projecting the function $x \rightarrow I(L^0;x)$ on a Lagrange's basis $L_i(x)$ and then, using the main property of the Lagrange's polynomials: $L_i(x_j)=\delta_{ij}$ where δ_{ij} denotes the Kronecker delta, the SC method gives the I mean and variance as

$$< I(L^0;X) >= \sum_{i=0}^{n} \omega_i I_i(L^0), \qquad \mathrm{var}(I(L^0;X)) = \sum_{i=0}^{n} \omega_i I_i^2(L^0) - < I(L^0;X) >^2 \tag{1}$$

And the skewness / kurtosis following

$$Skew(I(L^0;X)) = \frac{\sum_{i=0}^{n} \omega_i \left(I_i(L^0) - < I(L^0;X) >\right)^3}{\left(\mathrm{var}(I(L^0;X))\right)^{3/2}}, \qquad Kurt(I(L^0;X)) = \frac{\sum_{i=0}^{n} \omega_i \left(I_i(L^0) - < I(L^0;X) >\right)^4}{\left(\mathrm{var}(I(L^0;X))\right)^2} - 3 \tag{2}$$

Where ω_i are the weights associated to the $n+1$ collocation points x_i and we have $I_i(L^0)=I(L^0;x_i)$. Similar formulae can be derived for two or more random variables.

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3. EMC Examples

We illustrate the interest of the stochastic collocation method through three typical EMC cases: field to transmission line coupling, shielding characterization and radiation problem.

3.1 Field to Transmission Line Coupling

For a simple transmission line of diameter d^0=1mm, at frequency $f^{\,0}$=15MHz, length $L^0=4.2m$, placed at a height h^0=20mm above an infinite ground plane, and illuminated by a uniform linearly polarized plane wave (Fig.1), an analytical formulation can be obtained for the current $I(L)$ at the load $Z_L=1k\Omega$ [2].

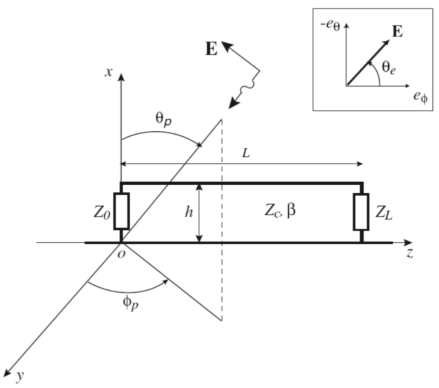

Fig.1: Line illuminated by a plane wave.

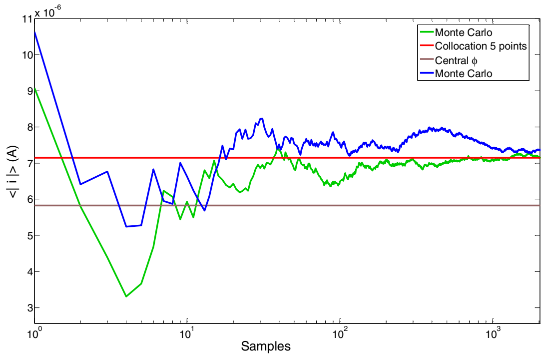

Fig.2: Comparison including two MC drafts and SC for a 10% uncertainty on ϕ_p angle.

In this problem, all the previous variables as well as the direction of propagation of the incident wave, characterized by $\phi_p{}^0=\pi/2.1$ and $\theta_p=\pi/10$, the direction of the electric field, characterized by $\theta_e=0$, can be considered as RV. Regarding only the angle ϕ_p as a RV (a=10%), the Fig.2 indicates that the SC method with only 5 points (i.e. 5 simulations) provides the same results as 2000 MC simulations. One can also notice that considering only the central value is not a valuable approximation in this case.

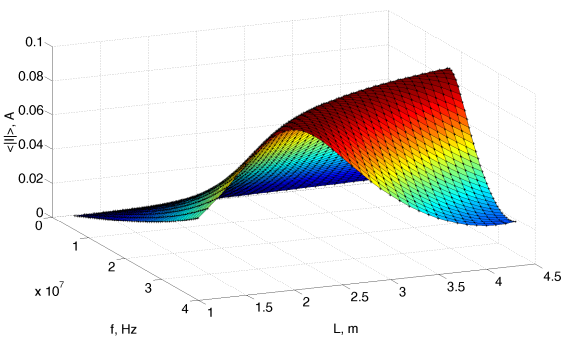

Fig.3: Mean of the current from the SC method (3pt and 5pt respectively in colored slice and black asterisks).

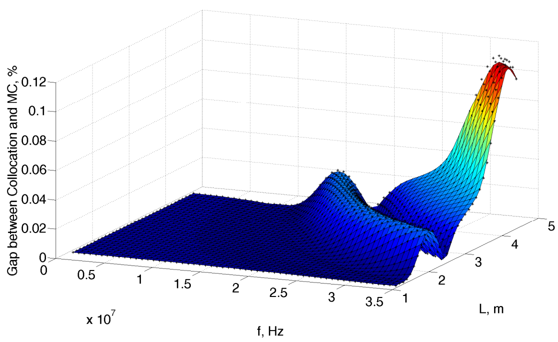

Fig.4: Convergence of the SC computations (3/5 points: colored slice/black asterisks) from MC reference.

The convergence of the SC method is shown on Fig.3 for two random variables: both the length L and the frequency f are RV (a=10%). Indeed, the absolute current means simulated by 3 or 5 SC points are in a good agreement. The Fig.4 indicate that the collocation method with 3 or 5 points (i.e. 3^2 or 5^2 simulations respectively colored slice and black asterisks) provides the same results as 10^5 MC simulations (reference), at a much lower computational cost. The accuracy of the SC approaches (3 and 5 points) is illustrated on Fig.4 since the relative error percentages from MC results are lower than 0.12%.

3.2 Shielding Effectiveness of Cabinets

The test problem consists in the statistical characterization of the classical EMC Shielding Effectiveness (SE) of a metallic box with an aperture (Fig.5) using an analytical formula from [3]. The box dimensions are a^0=0.26m, b^0=0.12m, d^0=0.4m. The aperture is in the z=0 plane with dimensions l^0=0.13m, w^0= 0.07m. The SE is evaluated in the middle of the box (p^0= 0.15m). Fig.6 illustrates the strong impact due to a simultaneous variation of 3% of the distance *p* from the slot and the box depth *d*. These two independent random variables are taking into account by the collocation method (Fig.7). The MC simulation needs in this case about 65000 samples to give similar results. Considering now four independent random variables (Fig. 4-b), the SC method requires 7 collocation points (7^4=2401 simulations) to converge but conserve a real advantage from MC for which the convergence is independent from the RV number.

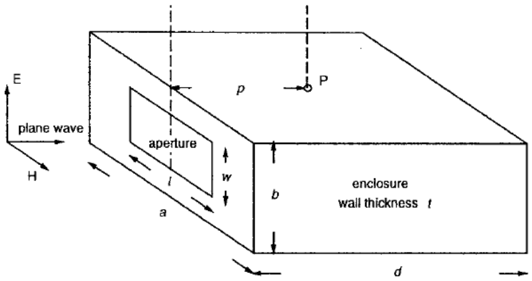

Fig.5: Metallic box with an aperture [3].

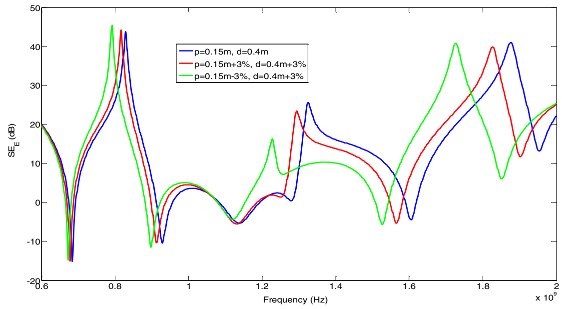

Fig.6: SE sensitivity for two parameters (*d* and *p*).

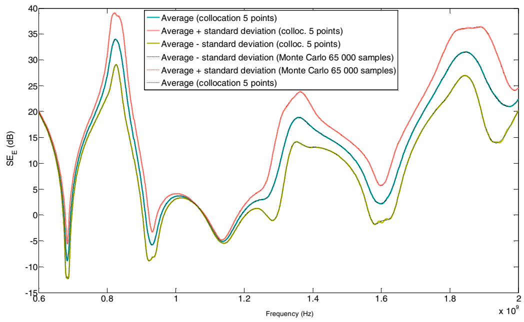

Fig.7: Two RV: *p* (3%), *d* (3%) .

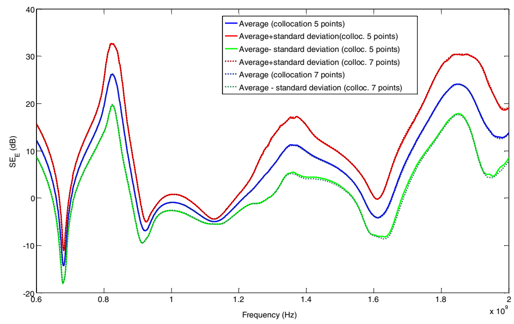

Fig.8: Four RV: *p* (3%), *d* (3%), *l* (3%), *w* (80%).

We can note that even for 4 RV and at a few frequencies, the SE remains almost independent from these RV.

3.3 A Dielectric Resonator Antenna

The Finite Difference in Time Domain (FDTD) simulation [4] of a strip-fed Dielectric Resonator Antenna (DRA) (Fig.9) will allow a stochastic study. The antenna is simulated by a probe feeding: a 1mm gap is left between the ground plane and the strip, and a voltage source is placed in this gap.

Fig.10 shows the mean value of the input port return loss (S11) as well as ± one standard deviation computed by collocation method for an uncertainty of 4% on the relative dielectric permittivity ε_r. Its strong influence on resonances was predictable and once again, considering only the central value is not an accurate and sufficient solution. Here the SC method is used jointly with commercial software [4] but thanks to its non intrusive property no deep modifications have to be done. Nevertheless, each simulation took about 105mn on a PC (IntelXeon W3530, 2.80GHz, 12GoRAM) and MC simulations will not be accessible for a reasonable cost. Since the third and fourth statistic moments (respectively skewness and kurtosis) require higher polynomial approximations, the SC method convergence is hardier to obtain but remains reachable at an acceptable cost (Fig.11 and Fig.12). Thus, a complete stochastic study for each parameters of the antenna with the computation of higher statistical moments and the estimation of the probability density function will be helpful for antenna design. Indeed, the convergence of the SC method is obtained straightforward (3 points) for the S11 mean (Fig.10) whereas its skewness (Fig.11) and kurtosis (Fig.12) need 5 SC values at least. This remains particularly efficient comparing to the thousands of MC simulations expected.

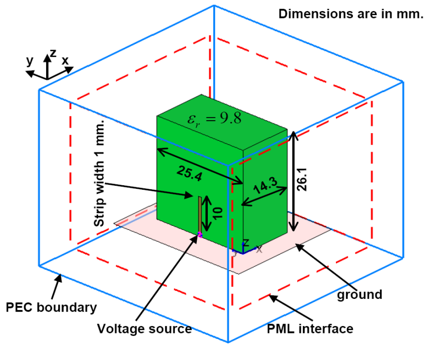

Fig.9: A strip-fed dielectric resonator antenna [4].

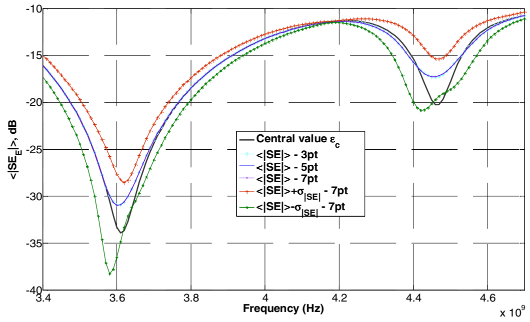

Fig.10: Return loss (mean) of the Fig.5-a DRA.

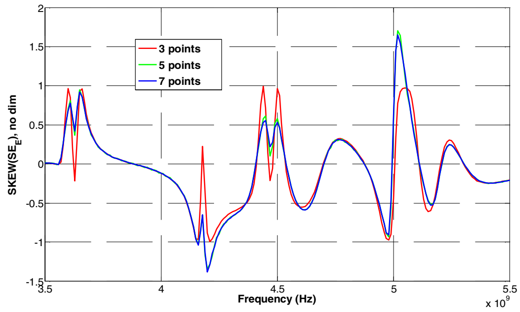

Fig.11: Skewness from return loss computed by SC method with 3/5/7 points.

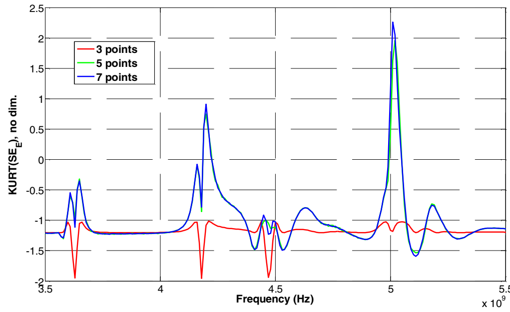

Fig.12: Kurtosis from return loss computed by SC method with 3/5/7 points.

4. Conclusion

The problems considered in this paper can appear as ‘classical’ and ‘simple’ EMC issues but the complexity lies on uncertainty. Simulations of real systems must take into account the randomness of parameters. A solution of this challenging modeling issue is brought by the stochastic collocation method presented in this paper. It is one approach among many others (e.g. kriging, experimental design, Unscented Transform method, polynomial chaos) but its simplicity, efficiency and non intrusive characteristic made it very interesting to obtain a probabilistic model [5] useful for advanced EMC reliability studies.

5. Acknowledgments

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6. References

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