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Advanced assessment of the risk of underestimating EMC conducted tests for satellites "in-flight" conditions

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Abstract

This proposal deals with the assessment of the statistical risk of underestimating conducted electromagnetic levels in the framework of electromagnetic compatibility (EMC) testing for "in-flight" satellites' configurations. In the following, the context of this study is briefly described. Then, the theoretical foundations are presented including: deterministic models for grounding and bonding networks, and the framework for uncertainty propagation. Indeed, noticeable differences exist between "test" and "in-flight" configurations that may lead to overestimating and/or underestimating EMC confidence margins. In this context, a particular focus is given for Monte Carlo (MC) and Stochastic Collocation (SC) methods: the use of the two techniques is illustrated through Multi-conductor Transmission Line (MTL) simulations. The MTL method allows taking into account "uncertain" grounding of an equivalent MTL system including screening and straps bonding. A final discussion is proposed with EMC recommendations.

1 Introduction

For the last years, considering the expansion of nano-satellites, space programs are looking for competitiveness in terms of programs' costs and time schedule. This leads to a strong motivation for decreasing the time (and, as a consequence, the number) of EMC tests, specifically at satellite's scale (system) and subsystems (platforms, payloads for instance). Thus, it is more and more important to ensure the goodness of fit of EMC testing at equipment's level. Furthermore, it has become crucial to anticipate downgrading due to the differences between "test" and "in-flight" (i.e. real and final one) setups, with risking to lately identify drastic incompatibilities. Generally, one may find various sources for the differences existing between "test" and "in-flight" configurations:

- grounding (e.g. straps for grounding purposes with different number of bonding wires and various network topologies),
- harnesses' structures (cable's layout with standard heights, ideal or not?),
- screening (e.g. electrical (dis-)continuity depending on the different configurations, apertures, ...),
- probes (e.g. standardized distances for "test" measurements, not assigned for "in-flight" configurations).

Obviously, it should be necessary to exhaustively list the different sources of uncertainties, and then to separately assess the impact of each of them about EMC coupling. In this work, we will focus on different grounding straps configurations as exposed in the following. Considering the case of an unitary cable (e.g. 1-meter length here), it is recommended to settle grounding straps with a distance of 20 cm. Due to layout constraints (system's complexity, obstacles, ...), it is often difficult to respect this simple recommendation. Moreover, the electrical quality of the straps may vary from one system to another (electrical quality and length of the straps in the following).

2 Statement of the problem

This section is dedicated to a brief overview of the numerical test cases provided in this work. It has been proposed to highlight the effect of conducted emissions in common mode over a multi-wires screened harness. In this proposal, it is assumed that the generic issue of a harness of cables may be modelled with an equivalent coaxial wire as illustrated in figures 1 and 2:

- the wire is located at height $h = 5$ cm above grounding, the core is given at height $h+1$ cm from the grounding plane,
- the equivalent cable radius is $r_2 = 1$ cm,
- the core radius is $r_1 = 0.3$ mm,
- the coating is characterized by its equivalent dielectric permittivity $\varepsilon_r = 1.5$.

Table 1 gives a short description of the deterministic parameters chosen in this proposal. Tables 2 and 3 detail the assumption regarding for different test cases (in the following labelled #1 and #2).

Table 1. Deterministic parameters description (it is assumed that the transfer impedance of the screen is given with $R_t = 10$ mΩ and $L_t = 1$ nH ; ω stands for pulsation).

Physical output	**Variable**
Terminal bonding	$L_b^0 = L_b^L = 40$ nH
Grounding inductances	$L_g^0 = L_g^L = 60$ nH
Grounding capacitances	$C_g^0 = C_g^L = 200$ pF
Load resistance (Z_c)	$R = 10\ \Omega$
Load inductance (Z_c)	$L = 25,5$ nH
Load capacitance (Z_c)	$C = 500\ \mu$F
Screen transfer impedance (in Ω)	$Z_t = R_t + j\omega L_t$

Test case #1 (see table 2 and figure 1) is focused on a 5-strap testing configuration. The straps are located at fixed positions but with varying electrical (poor) quality of bonding (i.e. varying length of the purely-inductive straps). It is to be noticed that fixed positions are assumed (arbitrarily chosen but almost respecting the recommendation for 20-cm distance between each of them): $\mathbf{x} = [x_1, x_2, x_3, x_4, x_5,]^T$, with $x_1 = 15$cm, $x_2 = 35$cm, $x_3 = 45$cm, $x_4 = 65$cm, and $x_5 = 85$cm; respectively for straps #i ($i = 1, \ldots, 5$).

Table 2. Uncertain inductances of the straps (test case #1, five independent Random Variables, RVs)

Physical parameter	Straps' inductance
Random variables	L_s^i $(i = 1, \ldots, 5)$
Reference value	80 nH
Distribution law	Uniform
Level of uncertainty	± 30 nH

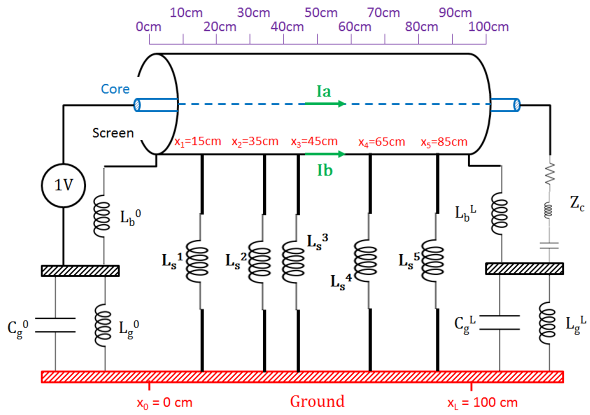

Figure 1. Numerical setup for test case #1: focus on parameters L_s^i $(i = 1, \ldots, 5)$.

In parallel, an alternative configuration is depicted in table 3 and figure 2. Test case #2 aims to characterizing the effect of one purely resistive single strap (higher quality than in case #1), with unknown and uncertain location between positions $p_1 = 15$cm and $p_2 = 85$cm along the line.

Table 3. Uncertain position of the resistive strap ($R_s = 2$ mΩ; test case #2, one RV)

Physical parameter	Strap's location
Random variable	*pos*
Reference value	50 cm
Distribution law	Uniform
Level of uncertainty	± 35 cm

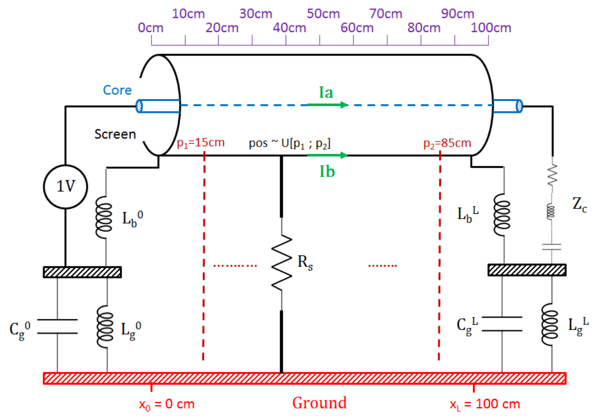

Figure 2. Numerical setup for test case #2: focus on the location of the resistive R_s-strap (parameter *pos*).

3 Theory

In this work, the two configurations (see tables 2 and 3) were deterministically modeled using MTL technique [1]. The core of the method is particularly well-fitted in this context regarding the layout of the harness (uniform transmission line, maximal height of the line is below $\lambda_{min}/10$ criterion, with λ_{min} the minimum wavelength under consideration) and the requirements for multi-conductor modeling (see figures 1 and 2). This theoretical content was previously successfully used by the authors for flexible interconnects and the interested reader may find details about the foundations of the deterministic technique in [2].

As previously exposed in the introductory part, the infinite knowledge of the different input parameters (see tables 1-3) is unrealistic and it was necessary in this work to assume parameters (here grounding inductance of straps as described in tables 2 and 3). As a reference, the Monte Carlo method is useful since it is non-intrusive and straightforward (feeding the previous deterministic model with data sampled from statistical assumptions) [3]. However, its convergence rate is known as a major bottleneck (i.e. it requires a huge number of simulations; classically, thousands to tens of thousands only for first statistical moments expectations). In this context, various alternative techniques exist to improve the sampling rate. Without exhaustiveness to the state-of-the-art, the Stochastic Collocation method [4] has demonstrated its high fidelity to the reference results (for instance MC method) with improved convergence rates (i.e. number of simulations needed). The principles of the method were detailed in [4] regarding electromagnetic applications. The next section will be devoted to a selection of numerical results obtained jointly with MTL simulations and stochastic methods (here MC [3] and SC [4]).

4 Numerical results

This section is dedicated to the different results obtained for the assessment of the common mode current (I_{CM}) statistics along the cable. Currents I_{CM} were computed each $\Delta_x = 5$ cm. Next, with a view of simplification, the results will be presented in the bidimensional (2-D) plane (position x, frequency f), assuming one elementary cell (from (x, f) to $(x+\Delta_x, f+\Delta_f)$) of the 2-D plane will be characterized by one statistical moment (mean, or mean + three standard deviations) of I_{CM} (sampling of the current along the cable). It is to be noticed Δ_f is referring to the sampling frequency (here 500 frequencies from 5 kHz to 500 MHz with logarithmic scale).

4.1 Multiple straps (poor quality, case #1)

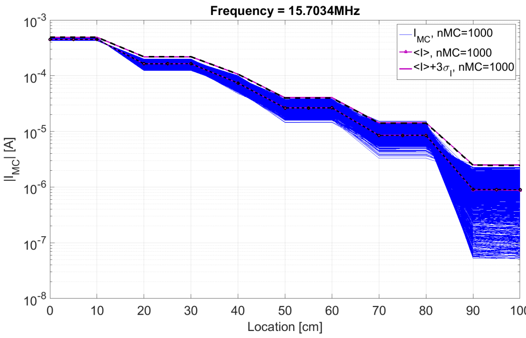

Figure 3. "Current mean" and "current mean +3 standard deviations" for test case #1 at $f \approx 15$ MHz.

Figure 3 shows the results obtained for the mean current along the cable. The mean statistics are obtained from 1,000 MC simulations: pink curves for the mean value $< |I_{CM}| >$ (with markers) and the mean value + three standard deviations (stds) (without markers) at frequency $f \approx 15$ MHz. For the purpose of notation (and abusively), the quantity "mean + three stds" represents an expectation of the maximum (for each location over the cable and for each frequency) due to random variations of the straps' inductance (see table 2). The results derived from $2^5 = 32$ SC simulations are added in figure 3 with black curves (mean, and mean + three stds). It is to be noticed the great accordance between the data from 1,000 MC simulations and 32 SC simulations. Finally, each of the 1,000 deterministic I_{CM} results are given in blue to check the prediction of the "maxima" from the results obtained with "mean + three stds" (especially for SC data). This shows also the huge variability of results along the cable at frequency $f \approx 15$ MHz.

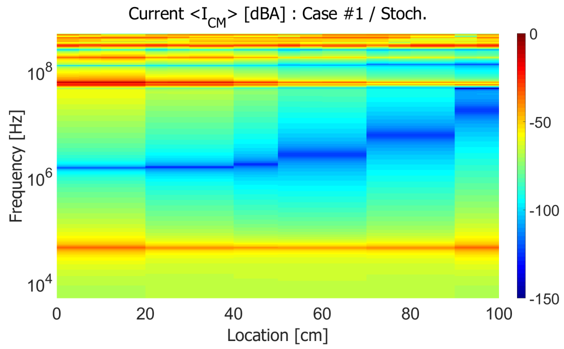

Figure 4. Current mean for test case #1 with respect to the location over the line and frequency.

Figure 4 shows the common mode current mean in 2-D view (i.e. along the line and for different frequencies) given from SC simulations (here, $243 = 3^5$ realizations were necessary). This offers an overview of the first-order statistical moment (i.e. mean) of the current.

4.2 Single resistive strap (case #2)

Similarly to test case #1, we are interested in the assessment of the statistics of current I_{CM} (common mode current) along the cable. Figure 5 gives an overview of the distribution of the current relatively to the location over the line and the frequency. Comparatively to previous case, differences occur regarding the mean value of the current (see figures 4 and 5), due to the intrinsic nature of the uncertain parameters (quality and location of strap(s) respectively for test cases #1 and #2). It has been demonstrated (data not shown here) that the statistics given by SC method are in accordance with reference values obtained from the use of MC technique (as pointed out in figure 3 for test case #1).

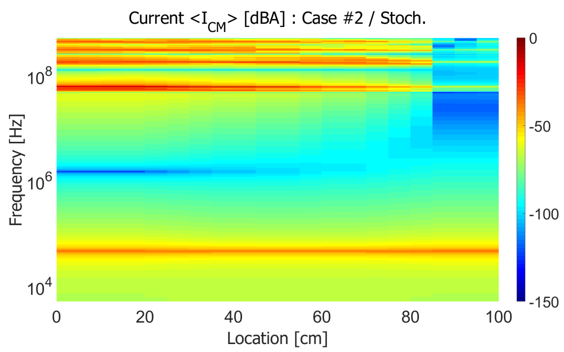

Figure 5. Current mean for test case #2 with respect to the location over the line and frequency.

4.3 Discussion

In order to better comment the results obtained from previous simulations (i.e. from test cases #1 and #2), a figure of merit is defined, for each current computation in the 2-D plane ("position"/"frequency"), as follows:

$$C_u(x,f) = \text{sign}\left(\left[I_{CM}^{case\#1}(x,f)\right]_u - \left[I_{CM}^{case\#2}(x,f)\right]_u\right) \quad (1)$$

where $u = 1,2$ relies on the "mean" $[.]_1$ of current $|I_{CM}|$ and its "mean + three stds" $[.]_2$. Function sign is defined as the sign of the difference computed in the equation (1): "+1", "-1" or "0" depending on the terms obtained from statistical computations. Relying on figures 4 and 5, the results in figures 6 et 7 show the distribution of the criterion C_u respectively for $u = 1$ and $u = 2$. Thus, yellow color is associated to $C_u = +1$ (i.e. currents computed for case #1 greater than values for case #2), whereas green color stands for $C_u = -1$ (i.e. currents for case #2 greater than values for case #1).

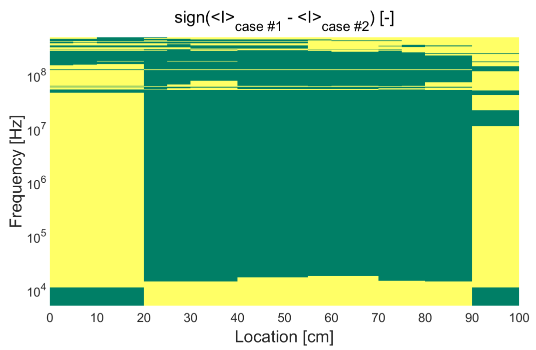

Figure 6. Figure of merit C_1.

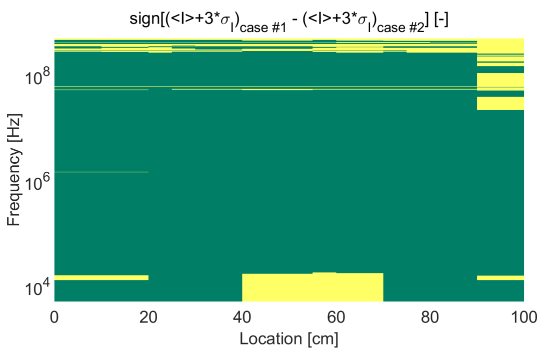

Figure 7. Figure of merit C_2.

The analysis of the deterministic test case (no uncertain parameter taken into account, all RVs from tables 2 and 3 are assumed to their initial reference value) shows that more than 53% of the cells (x, f) are yellow colored (data not shown here). Thus, it is quite difficult to recommend one configuration or another (case #1 or #2): it depends on the locations along the cable and the frequency. Figure 6 (mean of currents) is similar to the results obtained from the purely deterministic test case (regarding $C_1(x, f)$ distribution). Indeed, the distribution gives 42%/58% rates respectively for "+1" sign (yellow) to "-1" (green). The interest of the proposed methodology is illustrated in figure 7. Actually, the distribution of figure of merit $C_2(x, f)$ is far from the data in figure 6. Thus, case #2 seems far more disadvantageous than case #1 since the rate between yellow and green areas is 10%/90%. This may be explained by higher statistical dispersion of results for the test case #2, certainly due to the high impact of the parameter under consideration (location of the single resistive strap used here). Relying on the initial statistical assumptions, it seems test case #1 should be prefered in order to restrict the level of the common mode maximum current (abusively computed from "mean + three stds") along the cable and for the entire frequency bandwidth.

5 Conclusion

The aim of this proposal was to present a numerical methodology to assess the differences that may be observed between different cable harnesses layouts in an EMC aeronautical context. The combination of MTL technique and stochastic methods has been successfully used to compute the common mode current along a cable harness with uncertain conditions about grounding straps. The efficiency and accuracy of Stochastic Collocation was checked relatively to Monte Carlo simulation for a large frequency bandwidth (from 5 kHz to 500 MHz). The computation of the currents statistics along the cable harness and for different frequencies provided trustworthy complementary information regarding two different configurations. Indeed, the evaluation of the maximal currents showed a different behavior of the systems in comparison to deterministic or mean results. Finally, the analysis of the standard deviation of the currents (i.e. variance) could be efficiently extracted from SC simulations (i.e. without any additional costs), and might provide an overview of the sensitivity of the different random parameters.

References

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