THE EU FRAMEWORK V PROJECT "GEMCAR": EFFICIENT SIMULATION STRATEGIES

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Abstract: This document considers different ways to improve system level calculations in order to improve operational simulation strategies. A modeling methodology is proposed followed by a discussion on the different aspects of modeling EMC performance. The capabilities of currently available numerical techniques are presented with their advantages and drawbacks, hence offering several ideas to improve their efficiency. One of the main conclusions is to encourage the combination of different methods, which is the basis of the strategy suggested at the end of the document.

1. Introduction

The objective of this paper is to present strategies for improving the efficiency of vehicle level EMC simulations. The scope of this work is limited to the calculation element only: no consideration is given here to the equally important model building aspects of the problem (eg. geometric descriptions, mesh generation, identification of material properties) or the engineering processes that are required to integrate EMC modeling with wider vehicle engineering tasks. These elements are addressed in other parts of the GEMCAR project.

In the context of this activity the notion of improved "efficiency" includes:

- the capability to perform a calculation that is perhaps not achievable with a single tool or technique;
- improvements in the accuracy of the results;
- approaches allowing easy modification of parameters associated with the model;
- reductions in the duration, scope and number of models that are required.

These goals can be achieved by working on three main areas:

- optimizing the algorithms used in the simulation software;
- combining numerical techniques to exploit the strengths of different approaches;
- improving the modeling methodology to obtain the maximum benefit from each simulation.

Within the GEMCAR project, it will not be possible to investigate all possible types of improvements. Nevertheless, the main ones applied in the project will be described in detail as illustrations of the enhancements that can be achieved. Other ideas will also be mentioned even if not specifically addressed in the project.

2. Modeling methodology

The approach that is used in building and exploiting EMC models can have a significant impact on the computer resources that are required, and hence the efficiency of the modeling activity. This is particularly true where full 3D field computations are to be carried out, as these calculations are extremely demanding in terms of computer time and resources. Nonetheless, there are opportunities for reducing these requirements, depending on the exact purpose of the modeling activity.

For 3D simulations, the complexity of the model determines the required memory and run-time to complete the necessary calculations. Such models should therefore be made as simple as possible in order to ensure their computational tractability. For validation purposes, it is generally essential to include a realistic representation of the antenna that is used to illuminate the real system in order to replicate the test conditions effectively. This requires the geometry of the antenna, which may be quite intricate in itself, to be added to the model at the correct position relative to the test object. This inevitably adds considerably to the size of the model and the resources required for the simulation. However, it is not anticipated that model validation will be a mainstream modeling activity. The primary aims of adopting numerical modeling are to:

- reduce reliance on physical testing;
- improve understanding of physical tests;
- facilitate the analysis of "un-testable" scenarios;
- provide a source of objective information that can be used to guide design choices, even before any physical hardware is available for test.

Thus, although model validation is without doubt an extremely important activity, the true benefits of modeling only become available when the simulation results are trusted without reference to practical measurements. In addition, direct simulation of physical test conditions is unlikely to provide the most efficient route for generating useful simulation data. However it is likely that EM modeling may have a strong impact on the definition of the test conditions of the following domains of interest:

- radiated immunity,
- illumination antenna,
- optimization of on-board antenna,
- radiated emissions;
- intra-system EMC.

3. Modeling functional EMC performance

An electromagnetic (EM) model is not the same as an electromagnetic compatibility (EMC) model. Nonetheless, accounting for the 3D electromagnetic interactions that determine the coupling from or to cables and equipment within their housing (ie. a geometrically complicated vehicle bodyshell for GEMCAR) is an essential element of the wider analysis that is needed in order to predict functional EMC effects. A single monolithic simulation for such purposes is not a practicable proposition, so a combination of appropriate modeling techniques represents the most viable approach to developing a functional EMC model. There are, however, a number of points at which hybridization can be considered.

For building an EMC model, we can consider a range of modeling techniques operating at a number of different levels as outlined in Table 1. The clearest requirement for combining models of different types is the integration of circuit behavior (a “class D” model) with the electromagnetic performance of the vehicle installation (a class A model). It is possible to include cable models within some 3D field modeling schemes (the “self-consistent” approach), which should provide a more rigorous solution, but an approximation that treats the behavior of the cables separately (the “separated” method) may offer some advantages in terms of computational efficiency. The latter approach, however, requires the introduction of class B (2D) and class C (1D) models in order to determine the transmission line parameters for the various elements of the network and the propagation characteristics of its branches. The separated approach is only valid for those cases where the harness is located close to the vehicle structure. However, in some areas, such as the engine bay and dashboard regions, the harness may not meet these requirements.

The most computationally expensive elements of such models (in time and computing resources) are the full 3D electromagnetic field computations. Thus, there may also be advantages in linking different class A models in order to maximize the efficiency of the 3D field calculation, particularly for electrically large systems such as vehicles at high frequencies. A representative scheme for modeling functional performance using the separated method is illustrated in Fig. 1, which outlines the necessary interactions between various model types.

Table 1: Classification of model types required to predict functional EMC performance for vehicle systems

Model class	Model order	Model nature	Objectives
A	3D + time or frequency	Electromagnetic - volume or surface meshing	3D electromagnetic field distribution and related parameters (eg. antenna characteristics)
B	2D static	Electrostatic - planar or peripheral meshing	Lumped circuit models of transmission line segments (valid for small spacing)
C	1D + time or frequency	Transmission line - linear meshing	Accounting for wave propagation effects on transmission lines (length and load dependent)
D	0D + time or frequency	Circuit simulation – lumped element behavioural models	Device physics in circuit models, but no account of physical layout

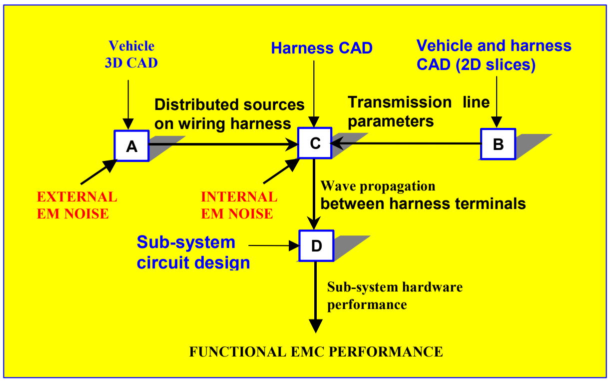

Fig. 1: Strategy for functional EMC performance prediction using separated methods

At present, all of the model types outlined in Table 1 are possible, and the integration of some of these techniques has been demonstrated to some degree. However, comprehensive modeling for systems of realistic complexity is still relatively untried.

4. Capabilities of numerical techniques

The purpose of this section is to provide an overview of the main capabilities of the numerical techniques that can be employed in the analysis of vehicle level EMC. As it is not possible to exploit a class C model without input from a class B model (using the designations illustrated in Fig.1), the combination of these two can be described more conveniently as “cable network” simulation [1]. To avoid describing each technique in detail the methods are classified in terms of the following two criteria:

- the operational domain of the simulation (ie. time or frequency);
- the nature of the simulation (3D field, cable network and electrical circuit codes).

4.1 Time and frequency domain techniques

The relative merits of simulations in the time and frequency domains are summarized in Table 2 below. It can be seen that both time and frequency domain techniques offer advantages, and that neither provides an ideal approach for all types of problems.

Table 2: Relative merits of simulation techniques

Operating domain	Advantages	Disadvantages
Time	Good description of transients and non-linear problems (eg. sparks, non-linear components) Entire frequency spectrum from a single simulation Calculation time depending on the size of the mesh	Difficult to account for frequency dependence of materials (cables, absorbers, soils) Difficult to have a multiple excitation problem Accommodating multiple-domain approaches (signal processing requirements) Calculation time for resonant structures
Frequency	Accounting for frequency dependent materials Simultaneous application of multiple sources Analysis of restricted frequency ranges	Calculations made at single frequencies Frequency step required to generate a detailed frequency response

4.2 Types of simulations

4.2.1 Three-dimension numerical codes

These are numerical codes that solve some form of Maxwell's equations for an approximate representation of the scattering geometry. This geometry is represented in a discrete form, generally described as a "mesh". Numerous methods have been developed to solve Maxwell's equations, in both time and frequency domains. In principle, they can solve any kind of problem since Maxwell's equations account for the overall coupling within the geometry in a global sense.

For classification purposes, a useful distinction can be drawn between volume and surface meshing techniques.

- Volume meshing techniques such as FDTD, TLM, FEM or FVTD are based on computing fields over the entire object and its surrounding environment (in theory, the entire universe). The advantage of these methods is that they easily account for complex spatial variations in the electrical properties (permittivity, conductivity etc.) of the modeled volume. However, special techniques (absorbing boundary conditions) are required to truncate the workspace to ensure computational tractability. In the past ten years the "perfectly matched layer", introduced by J.P. Berenger, has demonstrated considerable promise. Nevertheless, this approach still presents instabilities in specific conditions that could perhaps be overcome with more sophisticated schemes.

- Surface meshing techniques such as BEM and MoM are based on computing parameters only over the surfaces of the objects of interest. They are very well suited to the solution of integral equations, in either the frequency or time domains, and automatically take into account radiation effects. The main limitation of these techniques is in the memory requirement, because a dense matrix containing the interactions between the different cells has to be stored. Modeling dielectric materials is also a greater challenge in surface meshing techniques than is the case for volume meshing techniques. Recently, the fast multipole method (FMM), which is based on optimizing the product of matrices and vectors, has shown dramatic improvements for Radar Cross Section (RCS) calculations ([2], [3]). However, the application of this method for EMC applications at high frequencies is not obvious with the current forms of integral equations that are used (EFIE - Electric, MFIE - Magnetic, CFIE – Combined Field Integral equations).

4.2.2 Cable network codes

Cable network codes are numerical codes that determine the response of a network under different excitation and termination conditions. Versions are available that operate in both the time and frequency domains. Substantial efficiency gains can be obtained when the branches can be approximated as multiconductor transmission lines. The gain compared to 3D codes mainly comes from the avoidance of time-consuming field computations.

In this case, the calculation is made not on the geometry but on equivalent electrical models of cables (per-unit-length impedance and admittance parameters), connections (electrical circuits) and sources (equivalent voltage and current generators). The field distribution local to the cable is determined from an electrostatic model and the subsequent calculations are then essentially limited to longitudinal propagation and reflection effects.

4.2.3 Electrical circuit codes

Electrical circuit codes are computer codes able to calculate the response of an electric circuit. Such codes operate both in time and frequency domain. Public domain versions like the famous SPICE software developed at Berkeley University and commercial products are available throughout the world.

5. Improving efficiency of simulation techniques

In this section we propose several enhancements to either the implementation or use of EM simulation techniques.

5.1 Mesh optimization

Mesh optimization is concerned with more efficient spatial sampling of the geometry in 3D codes. In current techniques, the cell must be small compared to the wavelength λ. In free space, a widely accepted criterion is that the size of the cell must be smaller than $\lambda/10$. However, even if this criterion is respected, the discretized model is often a coarse representation of the real geometry, which may lead to errors in the field calculation in key areas. In GEMCAR, this is the case for the illuminating antenna when modeled using a structured mesh (Fig. 2). As the antenna is a broadband device (operating up to 1 GHz in GEMCAR) all of the details of the geometry are important. For methods based on a structured mesh it is important to define a grid parallel to the main directions of the antenna in order to avoid "staircases" in the feeder bars.

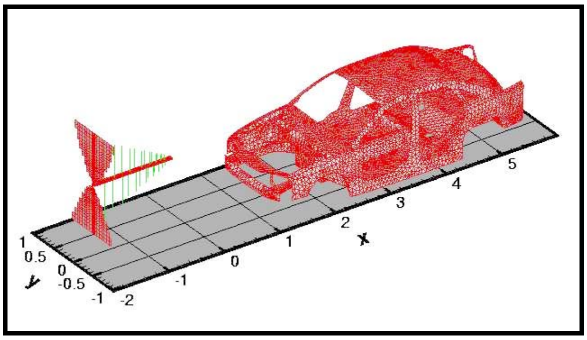

Fig. 2: Non structural mesh of the VOLVO S80 car (simple test case geometry) with the biconilog antenna

The use of high performance absorbing boundary conditions may also help in reducing the size of the workspace in 3D codes. As an example, Fig. 3 shows the big calculation volume required in FVTD to treat the GEMCAR plane-wave excitation problem (note the two different layers required).

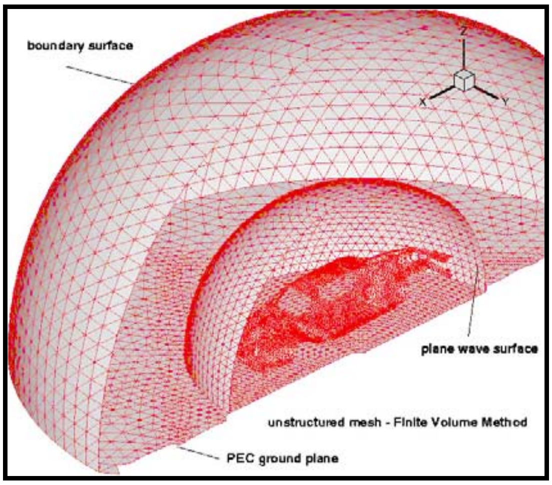

Fig. 3: Example of the calculation volume required in FVTD to treat the GEMCAR plane wave excitation problem

5.2 Accounting for geometry sensitivity

The objective is to use an implementation of the source code in such a way that it may account for geometrical variations during the calculation, thus allowing for limitations in our knowledge of the real geometry in 3D codes. This technique is based on the computation of a Taylor polynomial used to approximate and optimize a solution.

From an initial design made with a CAD system (for example I-DEAS from SDRC), one or a small number of polynomials are built and integrated back into the CAD representation in order to allow the EMC specialist to manipulate the design and determine the optimal solution. The automatic computation of the Taylor polynomial is based on the inversion of a complex matrix and on higher order differentiation of the same matrix.

5.3 Different EM-states formulation

The idea is to structure a calculation in order to account for different EM-states configurations (different source excitations, different materials) within the same calculation, whereas a direct approach would require several runs to obtain the response of the system under different conditions. The linear equation can be written under the form:

$$[A]\cdot[X_1,X_2,...,X_n]=[S_1,S_2,...,S_n] \qquad (1)$$

Generally, this kind of approach is well suited for methods based on the resolution of linear systems. This capability is particularly suited for numerical techniques working in frequency domains, such as integral equation codes, cable network codes and electric circuit codes.

A typical application of this kind of technique is the BLT equation used in EM Topology [4] for network resolutions ([5], [6]):

$$([1]-[S])\cdot\left[W_1^u,W_2^u,\ldots,W_n^u,W\right]=[S]\cdot\left[Ws_1^u,Ws_2^u,\ldots,Ws_n^u,Ws\right] \qquad (2)$$

5.4 Exploiting reciprocal formulations of problems

A further approach is based on the application of the reciprocity theorem. Therefore, two EM states must be defined judiciously. The choice of the two problems is made in order to make possible a calculation that would not be possible in a single step. Two applications have been investigated:

- Calculation of the response of a wiring system in an EM field environment. Particularly, let us mention that the approach is appreciable when the incident EM field is decomposed in a series of plane waves [7]: in this case, the response of the cable may be obtained by a projection of analytical plane waves on numerically-calculated currents in an emission state [8].

- Calculation of the field in an enclosure. This is useful when the inner field is close to the noise level. In this case, reciprocal formulations allow one to solve the outer and inner problems separately.

6. Combining different methods

In this section, two approaches will be discussed:

- the multiple-domain approach;
- the hybridization approach.

6.1 Multiple-domain approach

The term "multiple-domain" describes techniques where different tools are applied to different parts of the problem. With the multiple-domain approach, the calculation of each part can be achieved separately at different times. In order to re-create the entire problem, the link is made through data files calculated by the elementary tools. The interest of the approach is in the parametric analysis that it permits. In the following sections, two main types of linking techniques have been identified.

6.1.1 Link through scattering matrices

Each part of the problem is characterized by S, Z or Y matrices. A network formulation is then used to describe the full wave interactions between the different parts. This technique leads to a network resolution such as the BLT equation.

The technique may be applied to decompose a 3D geometry as illustrated in Fig.4 below for a simple cavity with an aperture and internal wire.

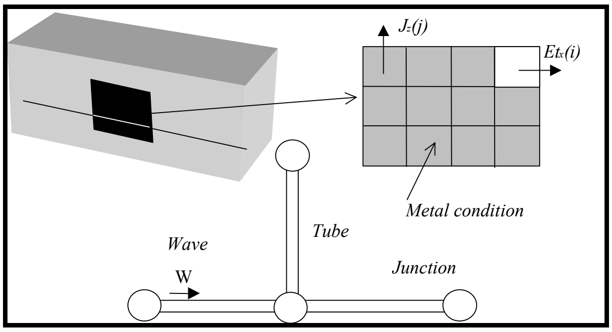

Fig 4: Example of a multiple domain decomposition to treat the coupling on a wire in an enclosure

The problem in that case is that large files have to be stored. Interpolation in space, time or frequency is needed to make the different files compatible with each other and with the specifications of the global calculation. All these considerations may explain why this approach has not been serriously developed in the operational context. However, the network approach may also be applied to describe very complex cable bundles topologies. Applications in the past 10 years have fully demonstrated the value of this technique ([9], [10]).

6.1.2 Link through incident fields

The link through incident fields is based on the field-to-transmission-lines formalism ([11], [12], [13]). Its interest is for calculating the response of a complex wiring system illuminated by an incident field (the field in the absence of the wiring). This technique has been successfully applied in different applications [14] and in GEMCAR [15].

6.2 Hybridization approach

The word "hybridization" is used to describe different numerical techniques that are merged within a single source code. This technique is currently applied in 3D codes, as for example in GEMCAR between FDTD and FVTD [15] (see Fig. 5). In these techniques the calculations must be made at the same time. Compared to the multiple-domain technique approach, the advantage is that no large files have to be stored in order to exchange data. Nevertheless, the entire calculation has to be repeated for any local modification to the geometry, which is not the case with a multiple-domain approach.

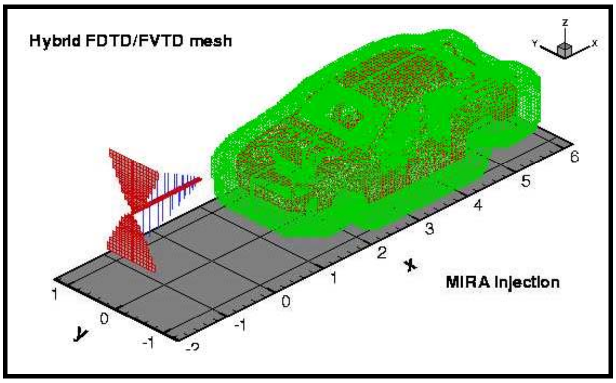

Fig. 5: Example of hybrid FV/FDTD mesh for the illumination configuration used in measurements at MIRA

7. Suggestions of an operational strategy

7.1 The topological decomposition

The suggested strategy is based on a good understanding of the topology of the problem. This topological approach will certainly not guarantee that the system is perfectly designed, but it will at least ensure that it is possible to analyze the system in the future ([16] [17], [18]). To make this analysis possible, one has to design the system in such a way that the frontiers between different domains are well defined. The boundaries of these domains correspond essentially with the points of entry of EM interference. In EM Topology, depending on the hierarchy of coupling, the problem is decomposed in terms of "shielding levels" defining several volumes. The coupling from one shielding level to the other is oriented, which means it goes from an upper level to a lower level, but no retroaction is taken into account. Within a given shielding level, a full EM interaction analysis is required. This means that a modification within a particular shielding level always has an influence on all the other components at that shielding level. The three shielding levels that we suggest for automotive and similar applications are the following (Fig.6):

- Source and structure of the vehicle. At this level, the source and structure are in close interaction. Of course, the antenna illuminates the car, but the car also interacts with the antenna. The source comprises the whole antenna system, including the generator and if possible the driving cable. The structure comprises the body shell and all parts other than cabling and electronic equipment within the vehicle (ie. the data from the CAD model).
- Wiring harness. The cable paths must be designed in order to reduce EM coupling, which generally requires the cables to be close to the structure (hence allowing the use of network methods based on transmission lines).
- Electronic modules. The design of the equipment should not allow direct coupling from the field to the circuit paths or radiation from these circuits. Thus the coupling path for interference to and from the equipment is limited to the wiring alone.

Associated to this decomposition is of course the nature of the calculations that are to be performed with the available codes. Indeed, if large and fast enough computer codes were available, direct calculations could be performed on the entire model, without any decomposition. However, even if feasible, this approach would still remain poorer than a decomposed one in that sense that it would be very difficult to identify the sub-system that is "responsible" for the problem.

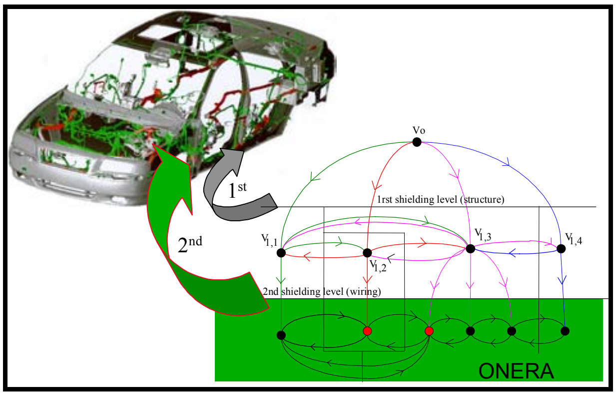

Fig. 6: Identification of topological shielding levels on the Volvo S8O car

Let us emphasize that this design approach is equally useful for experimental analysis. Without this approach the identification of the origin of a problem remains difficult, and sometimes impossible. The statement of such design principles may sound straightforward. Nevertheless, it is very easy to break these rules, thus producing a system decomposition that is not amenable to any form of EM analysis, either numerical or experimental.

7.2 The link between the topological levels

From the analysis of the topology leading to shielding levels, the link between each level is achievable through equivalent generators allowing the calculation of the response of the shielding level directly below it in the hierarchy (see Fig.7).

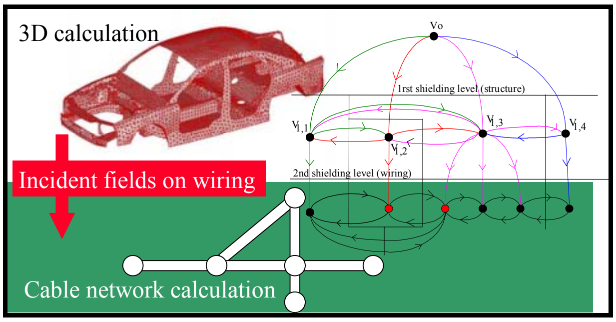

Fig. 7: Calculation strategy as related to the topological level decomposition

First shielding level

If the penetration points in the structure are small compared with the wavelength (e.g. small apertures), it is possible to separate the external problem (outside the structure from the internal problem (inside the structure). Equivalent sources may therefore be applied at aperture levels. These may be derived by short-circuiting the apertures, which provides complete separation between external and internal volumes.

This kind of decomposed approach is generally well suited for EM hardened military systems. Nevertheless, it cannot be applied on a car because the openings are too large. So both external and internal volumes must be calculated at the same time using a 3D code, solving Maxwell's equations ([17], [18]). This calculation must provide the equivalent generators distributed along the wiring, which are obtained by collecting the incident fields on the wiring path. It should be noted that the wiring is not present in this calculation.

Second shielding level

With the distributed generators, the response of the wiring may be derived using a cable network code. The calculation provides currents and voltages everywhere on the network, along each wire and particularly at the wiring terminals. If a precise linear description of the terminal circuit is available, this may also be included in the model. Otherwise, or if the circuit is non-linear, it is worth connecting a reference load at the terminals (typically 50 Ω) since the voltages on this load enable the derivation of Thévenin equivalent generators. For this the input impedance matrix of the wiring is required. This is obtained by an additional calculation resulting from compaction of the cable network to provide its equivalent S, Z or Y parameters. It should be noted that both the equivalent parameters and the Thévenin generators can be obtained from a single calculation on the network ([6], [19]).

In practice it is found that, the greater the complexity of the network, the higher the quality of the simulations. This is because modeling a single wire is more demanding than a whole multiconductor network, in terms of precision. Moreover, even if the local incident fields that are used to excite the cable network model are not perfect, the coupling onto the wiring provides a summation of the incident fields and so reduces the significance of the field errors on the computed response of the network.

Third shielding level

In GEMCAR, the third shielding level is associated with the circuitry at the wiring terminations. Thanks to the Thévenin equivalents calculated in the previous step with the cable network code, it is possible to calculate the response of each termination independently. If the termination is a linear circuit, the calculation may be directly performed with the cable network tool, using its network modeling capability. If the circuit is non-linear, a convolution approach is generally required because of the wideband analysis. In all cases, the method suggested is to use electrical circuit codes with the Thévenin equivalents as inputs (see Fig. 6).

7.3 Approximations made

Except for the approximations made within the numerical models, no approximation is made in this methodology. In particular, the retroaction between shielding levels is implicitly taken into account in the equivalent generators. The retroaction could be calculated if necessary, but the order of magnitude of this retroaction is small compared to the direct excitation. For instance, once the response at the terminal is determined, it is possible to calculate the distribution of currents on the network and make them radiate in the 3D geometry to obtain the total field (ie. incident plus scattered) inside the vehicle.

This kind of approach must not be compared with the "good shielding approximation" which is suggested in the theory of EM Topology [4]. In this approximation, the retroaction is neglected, which makes the approach more suited for norm determinations than for precise calculations.

8. Conclusion

In this document, we have presented a number of strategies for maximizing the efficiency of electromagnetic simulations, and we have emphasized the value of combining different numerical methods. After having presented specific aspects of modeling the EMC performance of a system, we have also outlined the capabilities of currently available numerical techniques. This led us to analyze how to improve the efficiency of the calculations made by one technique and how to combine those techniques. Consequently, a modeling methodology and a strategy of EM simulation of the coupling on a system have been suggested.

Nowadays, we can say that many numerical tools are mature enough to treat complex local problems, but they are still limited in their ability to treat large systems. In this case, one must consider combining different tools that are particularly well adapted to the resolution of specific problems. Typically, three types of numerical codes suitable for three types of problems have been identified. Firstly, 3D codes allow the calculation of 3D fields everywhere in a complex 3D structure. Secondly, the cable network codes calculate the response of a complex network, including the incident field along its paths. Thirdly, the electrical circuit codes allow calculation of the response at complex circuit terminations, including those with non-linear characteristics.

The strategy that we suggest for automotive and similar problems is based on the determination of equivalent generators at each shielding level (with respect to an EM topology terminology). It is important to note that different ways may lead to the determination of those generators. Some come from direct methods, but it can be also interesting to use indirect methods (based on reciprocity, for example).

The value of a decomposed approach is also that it is well suited for parametric analysis, since each level is calculated independently from the other. This also means that different partners in different companies can carry out the calculations. This may be of great interest if confidential information is needed concerning the vehicle geometry or the detailed design of an electronic system. The calculation may also be carried out on different computers. Concerning this point, only the 3D calculations require access to a high performance computer, whereas the cable network calculation and the electrical circuit calculation may be performed on more modest computers.

9. Acknowledgements

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