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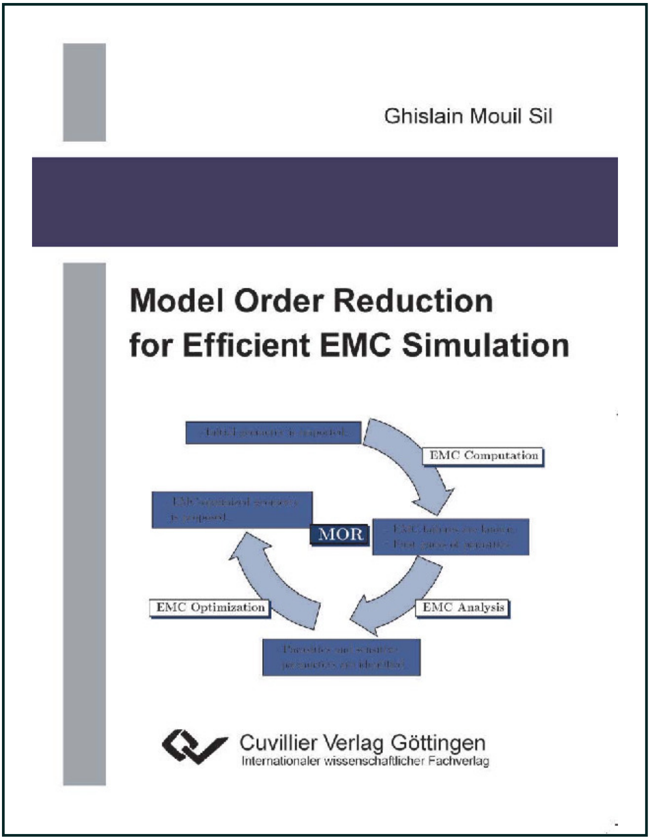
Model Order Reduction for Efficient EMC Simulation



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1 Introduction

1.1 Motivation

1.1.1 Introduction to EMC

Electromagnetic compatibility (EMC) is the ability of a device or system to function without error in its intended electromagnetic environment, without influencing this environment inadmissibly [1]. This is of great importance as transfer of electromagnetic energy induces interferences between electronic devices which could in the context of e.g. automobile safety lead to severe damages.

EMC standards are set today by international CISPR (comité international spécial pour les pertubations radioélectriques) recommendations from which European standards are derived by the European standardization institute for civil applications CENELEC (comité européen de normalisation electrotechnique). The institute which is responsible for the national DIN standard in Germany is the DEK (Deutsches Elektrotechnisches Komitee) [1].

There are two main trends observed in the last years which enhanced the interest on EMC in automobiles:

- In order to meet the demand for telecommunication services and improve the safety standards, faster and more sophisticated electronic systems are provided.

- The implementation of electromobility requires the integration of more electronic devices.

Summing up, those trends lead to more devices and thus a higher electromagnetic susceptibility. In order to guarantee the safety while providing more comfort and possibilities for the passengers, the EMC norms have got more and more restrictive. This progress has contributed to put EMC engineering in the focus of electronic product development.

For EMC validation, it can be distinguished between electromagnetic emissions of the device under test (DUT) and its immunity against interferences from its environment which are related to *external EMC*, whereas the interferences of components within a product or system are related to *internal EMC* [2]. In the scope of this work, the focus will be on internal EMC and electromagnetic emissions. For a detailed insight into this topic, refer to [2–5].

1.1.2 EMC Simulation in this Work

EMC simulation has grown in the last years to an indispensable tool for EMC engineering. In fact, it allows a reduction in time and resources in early design stages as well as later in the development process. Tremendous advances in hardware and computational methods have contributed to this progress. This interest has increased the demand on model accuracy which ramped up again computation time and model complexity. Improving the underlying computational methods is thus of great importance for a better efficiency of EMC simulations.

The electronic devices analyzed in this work are subdivided into two categories:

- **Control units** are impregnated in printed circuit boards (PCBs) which are multi-layered and miniaturized ($\sim \mu$m details). These devices become more and more indispensable especially for transmission control and safety issues in cars[1]. In this work we analyzed the board of an electronic stabilization program (ESP) system.
- **DC/DC-Converters** have gained interest in the last years due to its application in hybrid and electrical cars which constitute the megatrend electromobility. The dimensions of the devices here are larger compared to PCBs ($\sim$mm).

The numerical modeling of these problem types which contain nonlinear elements[2] requires the coupling of three dimensional (3D) field- and circuit simulation. The high frequency (HF) couplings occurring on the PCB or converter are captured by a transfer function computed with a field solver. From the transfer function a reduced model is derived for the circuit simulation, which additionally considers nonlinear elements.

For the discretization in field solvers, we distinguish between

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[1] They are used for steering, anti-lock bracking, suspension and engine management systems.

[2] Nonlinear in system view, e.g. micro controllers, transistors, ...

- **Surface discretization methods**: In this set of methods (e.g. *Boundary element method, BEM* [6]), only the conducting structures surfaces inside of homogeneous bodies and dielectrica are discretized as the wave propagation in air is compted with help of Green functions.

- **Volume discretization methods**: These methods limit the number of state variables by considering only a part of the whole domain as computational domain in which the field values are solved for nodes defined on a grid. In this regard, the *finite element method* (*FEM*) approximates the requested functions of the fields through superpositions e.g. of functions which are each defined on small areas. The wave equation can be transformed in the following system [7]

  $$(\mathbf{A} + \frac{\mathrm{d}}{\mathrm{d}t}\mathbf{D} + \frac{\mathrm{d}^2}{\mathrm{d}t^2}\mathbf{K})\mathbf{e} = \mathbf{b}, \tag{1.1.1}$$

  where $\mathbf{e}$ is the unknown field vector and $\mathbf{b}$ the excitation vector. The stiffness matrix $\mathbf{A}$, the damping matrix $\mathbf{D}$, and the mass matrix $\mathbf{K}$ are all sparse. On the other side, the *finite differences* (*FD*) computes the fields on each node where the partial differential form of Maxwell's equations is transformed in discrete differences. The finite integration technique (FIT) which on its part consists on applying the integral form of the Maxwell's equations on the the nodes of the grid can also be seen as part of this group.

In the scope of this work, volume based techniques are more suitable, especially considering PCBs as volume elements (air, dielectrics, ...) dominate surface elements (traces, layers, ...). The volume discretization of PCBs yields generally 10^6 to 10^7 unknowns whereas only 10^5 unknowns are needed for converters. We used FIT as discretization method in this work, but it should be stated that the methods implemented can be easily extended to FEM systems.

After having discretized the DUT, the computation of its transfer function resulting from the Maxwell equations may be performed with one of the following methods:

- Time domain: This method has a low complexity as only matrix-vector multiplications[3] are performed. It is appropriate for problems with wide frequency range but gets less inefficient for resonant structures[4] and in presence of a lot of ports[5] [8].

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[3] Only in combination with FIT or FD which allow efficcient explicit time domain methods.

[4] The energy in the system would decay slower and thus lead to longer computation times.

[5] The computation time grows linearly with the number of ports, except in combination with Graphic process units (GPU)

- Frequency domain: The complexity of this method is high as several matrix-inversions should be performed to determine the transfer function in a wide frequency range. However, it may get more efficient as time domain in presence of a lot of ports[6] and for narrow band computations.

The main challenges for field computation for EMC purposes can be stated as follows:

- wide frequency range,
- large model size,
- resonant behavior,
- and large number of ports.

The limits in circuit simulation are:

- accuracy of extracted models,
- number of ports,
- guarantee for passivity and stability.

1.2 MOR

Model order reduction methods (MOR) [9] which consist on computing reduced order models have been first used in the field of control theory. They have been since then introduced to systems resulting from nodal analysis and discretization of Maxwell's equations. They generally consist on generating a reduced model which captures the dependance of a function on one or several parameters. By this way, the complexity of recomputations is lowered and the coupling with other models is made easier.

MOR methods which have already been identified as robust for efficient field simulation [10–12] and especially for EMC simulation [13] present the following advantages:

- fast computation,
- wide frequency range,
- efficient for resonant structures,

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[6] Once the matrix has been inverted, it can be applied at all ports.

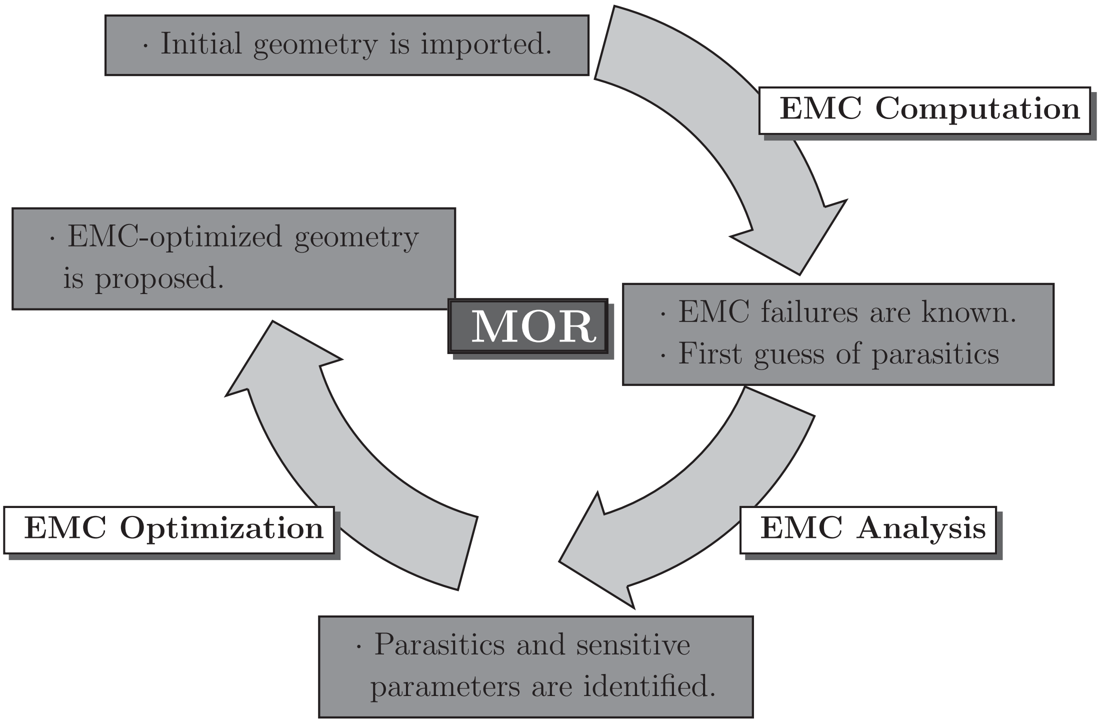

Figure 1.1: Overview of the EMC simulation concept implemented in the scope of this work

- high accuracy of the macromodels,
- guaranteed passivity of extracted models.

MOR has been implemented in a whole concept from EMC computation (prediction) through EMC analysis to EMC optimization as illustrated in Figure 1.1. This concept guarantees a better integration of EMC simulation in the development process of electronic devices.

EMC Computation

In this step, the EMC behavior of a given structure is predicted through simulation. It involves the coupling of field and circuit simulation already discussed above. MOR can be used to compute the transfer function more efficiently and/or to generate passivity preserving models for a stable circuit simulation if some system currents or voltages are of interest.

EMC Analysis

If some EMC failures have been predicted in the first step, an analysis is indispensable in order to understand their causes and thus derive proper EMC measures for improvement. In this step, we make use of the exact mathematical expression of the transfer function with MOR in order to generate equivalent circuits which retrieve the physics of the considered structure.

EMC Optimization

The EMC measures which typically influence the structure geometry are then parameterized and combined with a suitable optimization algorithm to retrieve an EMC-optimized geometry. Again, the efficiency of MOR can be used to reduce the overall optimization time.

1.3 Outline

After this introduction, the method FIT will be presented in Chapter 2. First, the discretization of Maxwell's equations will be addressed and afterwards, the discretized models will be derived to state space representations whose system properties are discussed.

The topic of Chapter 3 is model order reduction. After a brief introduction, different MOR methods are presented. Especially its passivity preserving variant which has been implemented in this work will be addressed.

The main contribution of this work is presented in Chapter 4 where the concept introduced in Section 1.2 is explicitly explained. The main concern in the EMC computation part is the efficient implementation of MOR. Particularly, an error control method for a reliable stop criterion is presented. A method for efficient order reduction in presence of a high number of ports is also proposed. Furthermore, an appropriate parallelization technique to enable the computation of more complex structures is introduced. The next section on EMC analysis presents a method to generate equivalent physical circuits by matching of the polynomial representations of the transfer functions resulting from MOR to proposed circuits. In the section related to EMC optimization, the computation of different variants is described along with the optimization workflow implemented in this work.

In Chapter 5, a method of matrix compression, the so-called Kronecker decomposition, is presented. Differently from parallelization which enables the computation of complex structures on several machines, this method allows to compute models of high order (10^7 unknwons) on standard computers with less memory requirements. It should be stated that the method requires cartesian grids and is thus suitable for FIT. On the other hand, this method has not been implemented in this work, as there are still some open issues to address on this field.

The methods implemented in this work are applied to solve real-life problems which are presented in Chapter 6. They consist of a measurement setup of the electronic stabilization program (ESP), and a DC/DC-converter.

Finally, Chapter 7 gives a conclusion to this work and an outlook to further improvements.