Complex Approaches for the Calculation of EMC Problems of Large Systems

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***Abstract*—Large and complex systems from the EMC point of view are objects that contain different structures and requiring individual composed methods for modeling as well as calculation. Automobiles, aircrafts, or PCB's with devices are large and complex systems. This paper describes activities that were done to handle automotive EMC problems with computer simulations. A set of methods was compiled to allow in a first stage the fast calculation model generation, and to apply in a second stage with minimum user interaction accurate and fast multi step hybrid methods. The focus of this paper is less on the methods itself but more on the completeness of the process chain that is required to do successful simulations of automobiles or other large systems.**

I. Introduction

Systems like automobiles, aircrafts, ships or PCB's need special treatment to estimate the EMC behavior. If different structures like antennas, antenna amplifiers, cable bundles, integrated circuits, or large metallic scatterers should be treated together, the numerical solution of the wave equations will not give a satisfying result in most cases.

Large systems are from the computational point of view systems, that can not be modeled straight forward and can not be calculated with a single calculation method. Such systems require complex models that reflect all important properties of the system, but do not contain unnecessary information, for limiting the calculation time. Looking on an automobile the following 4 main objects can be identified:

- car body – metallic structure
- cable harness
- electronic/electric components
- antennas

The car body can be treated up to very high frequencies as an ideal conductive surface object. The cable harness in modern cars can have a length of more than 3 km. It is the most critical structure from the EMC point of view. The cable harness radiates and receives electromagnetic fields. For most purposes it is sufficient to consider the extensions of the electronic/ electric components as small compared to wavelength. This means they can be treated as lumped element terminations. Antennas in modern cars are by far more than just simple rod structures. Complex arrays of up to 4 switched antennas for one and the same frequency but different polarization directions give significant performance improvements. Modeling of structures and amplifiers is necessary.

This paper describes the complex process chain of an EMC calculation. The chain starts with preprocessing aiming to generate a computational model. Then combination of different computational algorithms needs to be applied. Developed computer codes were integrated into the program package EMC Studio [1]. Integration into one single package was necessary as otherwise the complexity of the needed methods can not be handled any more. Integration of EMC calculation into the development process would have been impossible with a large number of separate tools.

II. Calculation Model Generation Process Chain

A successful EMC computation that is integrated into the development process and gives valuable information for product improvement needs to be aligned to the product development process. Calculation model generation must be an issue of some minutes and can not last some days. Available data must be adjusted fast for EMC calculations to meet time schedule demands.

Synergy effects between different CAD/CAE groups, also groups doing mechanical engineering, need to be maximized. Component measurements results that are generated independent from the EMC computation activities must be included.

The initial data for the generation of the calculation model needs further processing. The next section describes how the available data in automotive industry can look like and how processing is done.

A. Car Body Model Preprocessing

An analytical CAD car body model is not suitable for numerical computations. But triangle-meshes that are processed for the mechanical analysis of a car body are a good base for the generation of a suitable car body model for EMC computations. As mechanical analysis groups calculate the internal mechanical tensions in a structure the FEM method is widely used here. The surrounding space needs not to be modeled for the mechanical calculation. Due to the sparse equation system of FEM, the calculation models of the car body can contain 200000 up to 400000 triangle elements.

In Figure 1 the initial car model represented with a dense mesh containing 334421 elements is shown.

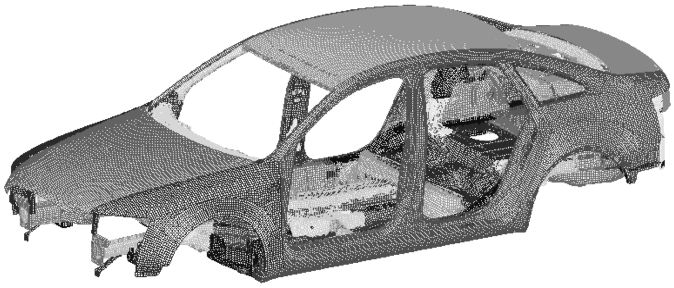

Figure 1: Initial model of the car (334421 elements)

For electrodynamic surface current and field calculations with large structures it was found that the Method of Moments, MoM, is most appropriate. Due to the dense matrix that needs to be solved, the number of unknowns must be much smaller than for mechanical FEM calculations. Reasonable models contain between 10000 and 50000 triangle elements.

Reducing the number of triangle elements and keeping all important information is a time consuming and complex task. To solve this task numerous mesh handling algorithms were implemented and combined into a program for better usability [2]. This developed program is called ReMesh [3] and is partially integrated into EMC Studio. Steps, necessary for preparation of suitable model of car body are described below.

1) "Healing" of data

Besides the need of reducing the number of mesh elements, frequently models, which are transformed from large FEM models, contain various errors. Such input data should be corrected either manually, or by an appropriate computer algorithm. Numerous healing functions were implemented in ReMesh.

2) Removing of redundant surfaces

Before preparing a coarsened car model, first it needs to be determined which surface can be considered as redundant from the electrodynamical point of view. The reason for such decision can be either small size of the surface area or a surface, completely surrounded by the other ones. Functions for the detection of redundant areas were developed and implemented.

3) Partition

In most cases the initial model is too large and complex, that the creation of a coarse mesh in one step overstrains the computational resources. To overcome this problem each part represented by individual property is re-meshed separately with new mesh size and then assembled back into the model.

4) Re-meshing

When surface is re-meshed, different methods can be applied. The implemented methods are:

- Delaunay triangulation
- Advanced front method
- Tri-mesh (division on quads and splitting of quads on triangles)

5) Correction of errors

After re-meshing there may be errors in the model like redundant elements, elements with bad quality or single free elements. Mesh quality can be visualized by different methods. Errors can be corrected by special functions. It is common, that mesh cells on boundaries of adjacent surfaces are not matched after meshing. After healing of incorrect areas, the meshes must be fitted and compiled together. Special functions to support this process were implemented.

6) Final model

Finally the car body is represented with a coarse mesh. Figure 2 shows an example of a mesh containing 11014 elements (mesh size: 5-7 cm, upper frequency limit: 430 MHz) that is ready for electrodynamical calculations.

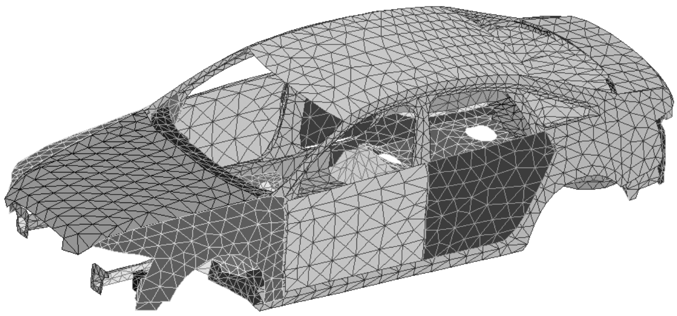

Figure 2: Coarsened model of the car (11014 elements, valid up to 430 MHz)

For fast calculations at different frequencies it is useful to have a number of meshes with different mesh sizes. Such models can be easily generated having a coarsened basic model.

B. ECU Model Generation

ECU (Electronic Control Unit) model generation is a critical task. Modern ECU contains a very large number of complex transistor circuits and can by far not be modeled in each detail within a complete automobile calculation model. Single pins of an ECU or structures were proposed to be handled with e.g. IBIS models [4]. Nevertheless there are no usable methods yet showing how to overcome the dynamic range problems of the needed time domain measurements or how to model EMC effects within an IC model. Black box models generated in the frequency domain are more promising [5]. Here new component testing methods are used to generate an ECU model that contains all important EMC properties of a model without suffering of dynamic problems or being difficult to handle. Figure 3 shows a setup for identifying equivalent parameters for radiation calculations of a complex setup to substitute this setup by a simple one-wire configuration. Common mode currents and common mode voltages with respect to the car body are measured at different locations of a cable bundle. A simple one wire model for further calculations can be derived from the measurement results. This one-wire-model (Figure 3) is terminated with frequency dependent complex impedance fed by a frequency dependent voltage or current source. The one-wire-substitution-model can be easily integrated into an automobile simulation setup for calculating the behavior of the combination ECU, cable harness and loads in an automobile model.

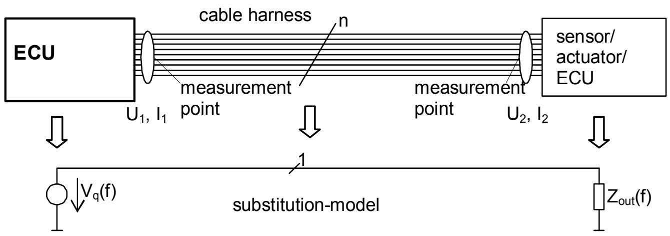

Figure 3: Substitution model determination setup of a complex configuration

A similar approach can be used to generate approximate models for susceptibility. Using BCI in a bench setup together with current and voltage measurements gives equivalent impedances and failure currents for further immunity calculations with a complete automotive model.

C. Cable Harness Processing

The modern CAD process for the cable harness leads to a database, containing nearly all information about the automotive cable harness. What this database not contains, is distinct information about the location of each cable in the cross-section of a harness bundle. This information is not available and not required for the cable harness production process. Location of each cable within a bundle can be only determined by statistic means.

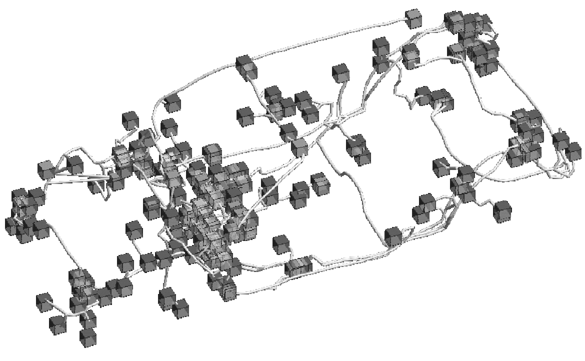

Figure 4: EMC Studio view of a complex cable harness of an automobile, the boxes represent the devices

There is also no information about how cables are passing from one segment to another. The aim of pre-processing here is to determine distinct placement of cables for further calculation. This can be only done randomly, based on rules of wire routing. It is also necessary to extract from the large data bases, containing between 10 and 3000 cables, the needed cables for a calculation model. For EMC simulations data base extraction and routing of cables is performed using a special module of EMC Studio.

D. Antenna Modelling

Antennas in the car can have very different shapes and follow different concepts. Most important in modern automobiles are glass antennas. Here the following important aspects must be considered:

- topology of antenna structures
- glass permittivity and resistivity of conductors
- models of amplifiers and antenna terminations

Topology of antennas either can be provided as a given model, or there is knowledge about desired general features of antenna and topology must be optimized to obtain these features. For termination/ amplifier linear models need to be generated. With providing experimental data it is possible to adjust the termination/ amplifiers models and glass model parameters. Influence of glass permittivity is considered using equivalent impedance approach within the MoM. According to this approach, it is possible to determine equivalent impedance parameters for metallic structures on a dielectric like glass.

III. THE CALCULATION METHODS

Several solvers are used to provide the needed analysis methods. First the solvers are described. Later it is shown how the solvers can be combined in hybrid methods to handle even very complex problems.

A. 3D Electrodynamic Field Solver

A three-dimensional field solver program TriD [6] based on MoM is part of the program package EMC Studio. Currents on metallic structures consisting of arbitrary shaped wires and surfaces (both open and closed) can be calculated with TriD. From currents near and far fields can be calculated. The program allows finite conductivity of wire segments by specifying their resistance, inductance and capacitance. Values can be frequency dependent. Complex impedances (frequency dependent) as a load to any wire segment can be used. Any linear time invariant passive circuit can be incorporated into the calculation with a unique SPICE link. Different types of excitation sources are available in TriD including incident plane waves, voltage sources over a wire segment, current sources, impressed currents, electric and magnetic dipoles as well as any arbitrary combination of sources. Sources can operate in frequency or in time domain. For transient problems multifrequency approach (based on FFT) combined with adaptive frequency sampling, AFS, is applied. Different fast solvers (out-of-core version, parallel cluster version) are used in TriD for solving the resulting systems of linear equations to obtain the coefficients of the current expansion. The out-of-core and parallel solvers allow the calculation of large problems. Special algorithms to estimate the accuracy of a calculation are included ensuring a high quality of a result [7].

B. 2D Electrostatic Field Solver

To handle complex cable harnesses used in automobiles multi conductor transmission line methods, MTL, need to be included. 2D LC-parameters must be calculated taking into account the dielectric insulation of the cables. Using these parameters it is possible to represent cable harness with a lumped circuit transmissions line (LCTL) model and finally solve cross-talk, immunity, and radiation problems involving a circuit network simulator like SPICE.

To calculate LC-parameters a solver based on Method of Auxiliary Sources (MAS) and MoM with special adaptive to geometry discretization was developed. Approach realized in this solver, has advantages against both, FEM and pure MoM methods. A priory knowledge about static field behavior, which is used on pre-processing phase, gives possibility to avoid big number of iterations, which are normally needed for adaptive FEM schemes in order to achieve desired accuracy. Peculiarities of cross-talk problems for automobile harness system, i.e. presence of wires with very small radiuses (0.3-0.6 mm) close to the metallic contours of 1-3 m length, with big number of sharp edges, cause FEM adaptive schemes to generate big number of intermediary meshes before given accuracy is reached. The same peculiarities of geometry pose a problem for MoM based algorithms. Using special discretization, which is done automatically, very fast convergence can be reached. Ideas of MAS are used to reduce number unknowns for cables. Details are described in [8].

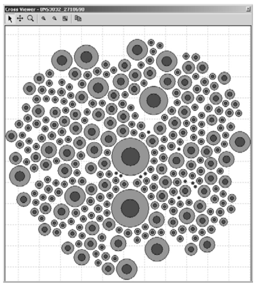

Figure 5: Cross-section of a bundle of a complex cable harness

C. 3D Electrostatic Field Solver

As numerous problems of large system EMC occur in the low frequency range, special quasi-static approaches can simplify the model and shorten the calculation time. Low frequency means in the case of automotive EMC frequencies of up to 10 MHz.

Low frequency interactions can be described as a quasi-static process, where parameters (capacitances and inductances) of the resulting equivalent circuit can be obtained from static potential calculations. Such problems can be modeled with a number of conductive objects, some of which are surface objects and others are wire objects. When applying equivalent circuit approach, all interconnections (due to electronic devices) have to be removed. To each object a static potential has to be assigned. For 3D capacitance/inductance calculations, different methods are used. But the most powerful and promising results were obtained by integral equation techniques, MoM, for example.

The program Static3D, which is part of the EMC Studio package, was developed based on a MoM approach. The equivalent circuit approach was tested to ensure the correctness of the calculations [9]. The proposed approach is much faster compared to direct MoM calculations and can be used in time as well as in the frequency domain. Due to the link to circuit simulation programs, complex, nonlinear terminating devices can be included into the calculation model.

D. SPICE Network Analysis

To include complex terminations and for applying hybrid methods a SPICE 3f5 core is included. This core is adjusted to provide better stability. Frequency and time domain analysis is supported. Also frequency dependent variables for circuit elements are supported. That way sweeps including frequency dependent measurement data can be done.

E. Hybrid Radiation Calculation

To handle the radiation of complex cable bundles direct methods like MoM are not appropriate. Inhomogeneous charge distribution over the cable cross sections due to close proximity can spoil the accuracy. Hybrid methods combining MTL-theory with MoM are much more appropriate for such problems. These methods make the user free from many limitations of pure EM-field solvers. Termination circuits are not restricted to be linear or passive. Any termination can be treated, that can be modeled with a SPICE like network-analyzer-program.

The so called hybrid radiation engine of EMC Studio handles arbitrary complex cable structures terminated with lumped linear, nonlinear, passive or active circuits. The current distribution along the multi conductor transmission line, MTL, is calculated. The sum currents along the cable structures are converted to impressed sources and can be used within full wave EM-field solvers. The accuracy of this method was checked with numerous applications.

F. Hybrid Immunity Calculation

The calculation of the immunity of complex cable harnesses demands also decomposition methods. From the immunity point of view an automobile can be subdivided into three “sections”:

- The car body; i.e. all large metallic parts
- The cable harness; this is the receiving structure for the fields
- The electronic components; i.e. all terminations of the cable harness

Based on these subdivisions the automobile can be decomposed and the field coupling calculation can be done. A hybrid method for immunity is based on two main steps:

1. The field that illuminates the wire system is calculated without the wire system. The field distribution within the car body can be calculated with MoM.
2. Once the fields are determined, the coupling into the wire system can be considered by an extended transmission line theory. MTL-theory can be extended with forcing

functions that consider field to line coupling. With this extended MTL-theory the line termination voltages can be calculated.

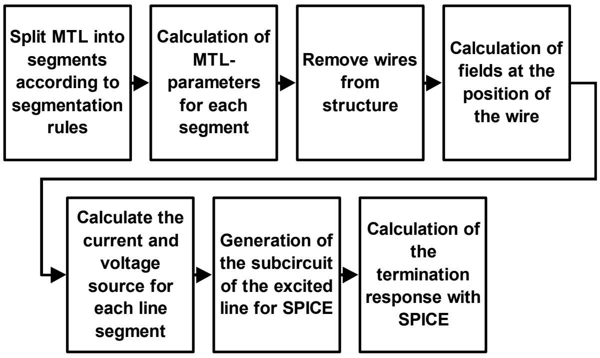

Figure 6: Flowchart for the calculation of the termination response of a field excited MTL

The single steps are shown in a flowchart (Figure 6). This Lumped Circuits TL - (LCTL) approach was tested on different configurations and checked against other methods. Details are described in [10].

G. *Virtual Component Testing Methods*

Virtual Bench is a collection of functions for the fast processing of simulation models for component investigations with EMC Studio. It allows the virtual testing with component testing models according to ISO 11452 (BCI, TEM, ALSE, Stripline) or the calculation of the radiation of devices in setups described in CISPR 25 (TEM, ALSE, Stripline). Devices are treated in the computer simulations similar to the hardware based development process. With Virtual Bench it is possible to check out if a component fulfills with a planed concept the given specifications and standards. Furthermore the electronic components can also be directly checked in the planed final environment like e.g. an automobile. At the moment the following modules are implemented:

- ALSE, Virtual Antenna
- BCI, Bulk Current Injection method
- TEM cell
- Stripline

H. *FFT-Engine*

EMC analysis requires often a change from time to frequency domain and vice versa. To realize this, a special FFT engine was implemented. It is possible to do time domain calculations with MoM by applying FFT to the time domain signal, calculating the transfer function, and coming back to time domain using IFFT.

As in many cases the excitation is given in the time domain but the result need to be evaluated in the frequency domain in a limited frequency range, special functions were implemented. Interesting frequency range is defined and calculation is done in the frequency range, giving the transfer function. When transfer function is given, different FFT-transformed time domain excitation signals can be easily convoluted with the transfer function. This way the emission spectrum is given directly.

IV. REALIZATION

To handle the complexity of the numerous required tools and methods all function and modules were integrated into one easy to use program interface. This interface combines all tools for model generation and methods for calculation.

Figure 7 shows a screen shoot of the program with an automobile model. Figure 8 shows a Virtual Bench Stripline configuration.

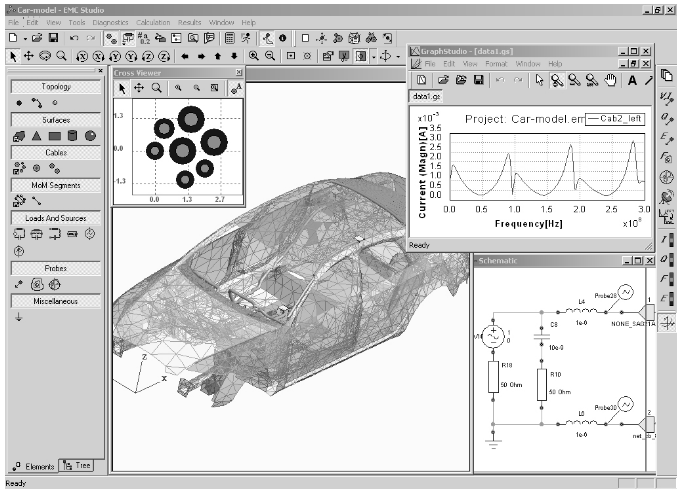

Figure 7: Screenshot showing model and a result of a hybrid EMC Studio calculation

For the calculation of large systems the following analysis types are necessary and provided by EMC Studio:

- **EM-Analysis** of linear electromagnetic field and current coupling problems in frequency and time domain with MoM. Electrical field integral equation for harmonic excitation is applied to the calculation model.
- **Circuit Analysis** of linear and non linear circuits in frequency and time domain with a SPICE 3f5 compatible calculation core.
- **Static Analysis** of linear and non linear low frequency problems in frequency and time domain with a quasi-static approach.
- **Cross Talk Analysis** of linear and non linear terminated complex cable structures in frequency and time domain. A circuit model of an arbitrary transmission line structure is generated. The included 2D field solver calculates the transmission line parameters with respect to the reference conductor. An arbitrary shaped metallic surface structure can be the reference conductor.
- **Radiation Hybrid:** Emission analysis of linear and non linear complex cable-antenna coupling problems in frequency and time domain. A circuit model of an arbitrary transmission line structure is automatically

generated. Common mode currents on transmission lines is calculated and converted to impressed current sources on MoM segments. Radiation and coupling to antenna is calculated by MoM.

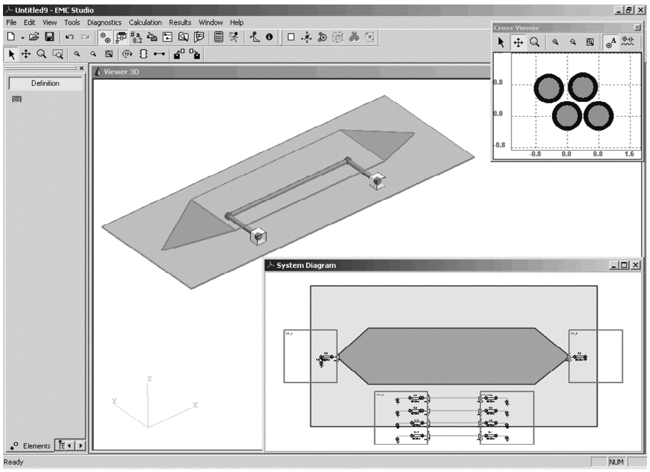

Figure 8: Virtual Stripline setup

- **Susceptibility Hybrid:** Immunity analysis of linear and non linear complex field-cable coupling problems in frequency and time domain. Field distribution along the cable structure is calculated. The transmission line circuit is supplemented with sources reflecting the incident field. Analysis model is calculated with a SPICE 3f5 compatible solver.

- **Virtual Stripline:** Analysis of immunity and emission problems in a Stripline according ISO 11452-5 with linear or non linear terminated complex cable structures in frequency and time domain. A circuit model of the complete Stripline model is automatically generated. The included 2D field solver calculates the transmission line parameters with respect to the reference conductor plate. Generated analysis model is calculated with a SPICE 3f5 compatible solver.

- **Virtual BCI:** Analysis of immunity problem in a BCI (Bulk Current Injection) configuration according ISO 11452-4 with linear or non linear terminated complex cable structures in frequency and time domain.

- **Virtual Antenna:** Analysis of immunity and emission problems in an Absorber Lined Shielded Chamber ALSE configuration according ISO 11452-2 and CISPR-25 with linear or non linear terminated complex cable structures.

- **Virtual TEM:** Analysis of immunity and emission problems in a TEM-cell configuration according ISO 11452-3 and CISPR-25 with linear or non linear terminated complex cable structures.

V. CONCLUSION

EMC model preparation of large systems is a complex task requiring special tools to allow preprocessing within reasonable time. Furthermore EMC calculation of complex structures needs combination of numerous calculation methods. Handling of many calculation tools and methods is time consuming and bears a high risk making mistakes.

This paper reports about the integration of different preprocessing and numerical calculation methods into one program to overcome the mentioned problems. Integration is required to solve EMC calculation problems of large systems. The following goals could be reached:

- minimum preprocessing time
- minimum sources of errors in preprocessing
- minimum sources of errors in the calculation chain due to automatic handling of many solvers
- maximum accuracy for typical metallic structure/ harness EMC problems
- minimum calculation time for typical metallic structure/ harness EMC problems

With the combination of the needed methods it is possible to reflect the development process of e.g. an automobile system in a simulation program. A set of analysis methods was presented and the applicability was discussed.

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