Directional Hybrid FEM-MoM for Automotive System level Simulation

Bibhu Prasad Nayak*†, Sreenivasulu Reddy Vedicherla†, Dipanjan Gope*
*Department of Electrical Communication Engineering
Indian Institute of Science
Bangalore, India
†EED Department, Robert Bosch Engineering Business Solution Limited, India
Bibhu.Nayak@in.bosch.com, SreenivasuluReddy.Vedicherla@in.bosch.com, dipanjan.gope@gmail.com

Abstract—**Electromagnetic compatibility (EMC) issues are becoming increasingly important for the automotive industry. An accurate system level analysis is required from an early design stage for optimal performance. The major difficulty encountered in automotive simulation is to deal with different geometric scales, ranging from fraction of wavelengths to multiple wavelengths. In many cases, a domain decomposition method using Finite Element Method (FEM) and Method of Moments (MoM) may be effective by computing each domain separately and stitching them together using equivalent boundary currents. However, when the problem size becomes larger, this method loses its efficacy as calculation of domain interactions become computationally costly. In this paper a new method is proposed for multi-domain problems in EMC radiation emission (RE) test, based on the fact that when two domains are electrically far apart, the back scattered field from the receiving antenna to DUT is quite minimal and can be neglected. The proposed method demonstrates a substantial reduction in memory requirements and computational time when compared to traditional multi-domain hybrid FEM-MoM with acceptable accuracy.**

Keywords— *Electromagnetic compatibility (EMC); Hybrid FEM-MoM*

I. Introduction

In recent years, there has been a significant increase in electronics components introduced into the car. The trend seems to be growing, fueled by research in safety, reliability, communication and car-entertainment towards advanced driver assistance systems (ADAS) and a connected car environment. Electromagnetic noise inside the car is ever increasing with more number of components and coupling between each sub-system. With such a complex system, it becomes very difficult to accurately predict potential EMC problems. To mitigate this issue, each component has to meet CISPR 25 standard [1] used in the automotive industry to characterize the electromagnetic radiation and to make sure that radiation is under the prescribed limit. The test setup is comprised of a source domain consisting of the device under test (DUT), cable harness and metallic table, and a victim domain consisting of the measuring antenna. Physical dimensions vary from a couple of meters for cables to fractions of a millimeter for interconnect structures on the printed circuit board (PCB). As the measurement can only be carried with availability of the DUT prototype, it becomes imperative to use numerical simulation methods to predict electromagnetic compatibility at the early design stage.

Volume-based numerical methods like FEM or Finite-Difference Time Domain (FDTD), are well suited for the PCBs, but computationally ineffective to handle the large free space between measurement table and antenna. On the other hand, use of MoM avoids meshing the free space. Therefore, in recent times much work has been devoted in combining FEM with MoM to leverage the relative advantages of each method. In such a hybrid approach, the problem space is divided into sub-domains separated by free space. FEM efficiently deals with problems consisting of inhomogeneous and arbitrarily shaped objects in each sub-domain. This is coupled with a boundary integral (BI) technique such as MOM, which introduces an exact termination to numerically truncate the FEM computational domain and yields powerful and versatile FE-BI hybrids, e.g. [2, 3]. However, all existing, hybrid FEM-MoM methods become time and memory inefficient in case of electrically large problems, to compute interaction of all boundary elements using integral equations. It becomes essential to re-compute these terms with any modification in the mesh elements due to change of DUT.

The proposed method takes advantage of the directional property of radiation in a typical EMC RE test setup for automotive applications. Here, the domains are well-separated and radiation efficiency of the source domain (Fig. 2) is quite small. Hence, back scattering from the victim domain, comprising of the measuring antenna, can be ignored. In the proposed Directional hybrid FEM-MoM method, the source domain is computed using the normal FEM-MoM hybrid method. Radiated field on the victim's boundary is calculated from electric and magnetic currents on the source domain boundary using Green's function. With the calculated field on the boundary as source, the victim domain is solved using FEM. Numerical experiments demonstrate a speed-up of around 5-10x using the proposed Directional Hybrid FEM-MoM over normal Hybrid FEM-MoM and around 20x over commercial tools.

II. Standard EMC Measurement Setup

A standard test bench for radiated emission test according to CISPR25 is shown in Fig. 1. Some observations from the measurement setup which motivated the proposed method is explained below:

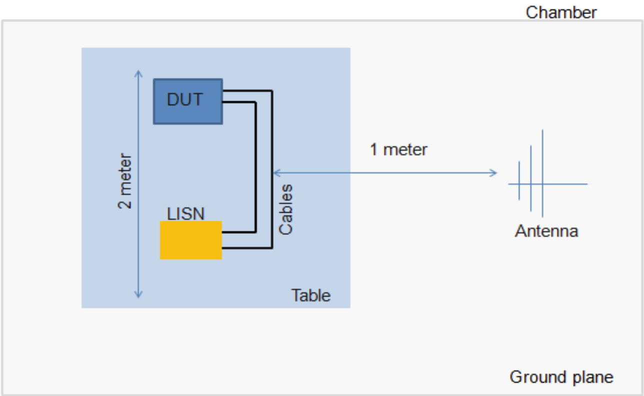

Fig. 1. Radiated emission test bench according to CISPR 25 standard

A. Source and Probe are well-separated

The radiated field from differential pair of length L at a distance of r can be analytically estimated as shown below:

$$E(r) = \frac{\eta k^2 L I e^{-jkr} \sin(\theta)}{4\pi} \times \frac{s}{r} \qquad (1)$$

where η and k are intrinsic impedance and wave number of free space respectively, s represents the separation between the cables and θ the angle subtended by the center of the cables to the observation point. In a typical automotive EMC case, the separation between cables is in the order of mm and r is 1 meter, the field intensity goes down by a factor of one thousand. It can be inferred that field at the antenna is mainly due to common mode current on the cables as radiation from the differential current is minimal.

B. Radiation efficiency

In the CISPR setup, cables lie above the measurement table. It is a well-known fact that the radiation efficiency of current carrying conductor goes down when placed horizontally above the metallic body due to the image current. Therefore it will also absorb less of the back-scattered radiation from the measuring antenna.

The distance between the source and the probe/victim domains, and the poor radiation efficiency of the source domain leads to a directional property that can be exploited to reduce the cost of a typical hybrid FEM-MoM approach.

III. Directional Hybrid FEM-MoM

The general structure of interest is shown in Fig. 2. The complete domain is divided into two parts. Volume *1* represents the source domain and radiation is monitored through antenna in domain *2*.

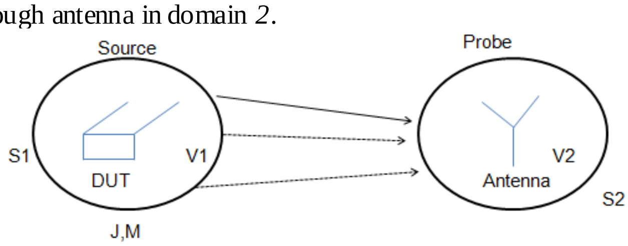

Fig. 2. Source and victim domain in typical EMC measurement setup

Domain 1 contains the device under test and excited by the internal source. As mentioned earlier, this is discretized using tetrahedrons.

A. Solution of domain 1 with FEM

The weak form of FEM equations can be expressed as in terms of electrical field (E) as shown below:

$$\int_{V1} \left[(\nabla \times E) \bullet (\nabla \times w) - \omega^2 \mu \varepsilon E \right] dV = j\omega\mu \int_{S1} (\vec{n} \times H) \bullet w dS - j\omega\mu \int_{V1} J \bullet w dV \qquad (2)$$

where ω is the angular frequency, μ and ε represent the permeability and permittivity of the tetrahedron, w is a weighting function, which in this case, is same as the basis function. J is the applied current source in volume $V1$. The term $(\vec{n} \times H)$ is the unknown quantity which represents Huygen's surface current on $S1$. This can be found out using MoM as described in the next sub-section. The basis functions proposed in [4] are employed. Each basis function is defined within a tetrahedron and is associated with one of the six edges. The electric field E within the volume of the tetrahedron can be expanded as:

$$E = \sum_{n=1}^{N} E_n w_n \qquad (3)$$

where N is the total number of edges and E_n is the coefficient of the unknown electric fields within the FEM volume.

B. Discretization of boundary with MOM

Triangular mesh elements are used for discritization of boundary surface $S1$. Here, RWG basis function [5] is used as basis functions for both electric and magnetic currents. Huygen's principle is applied on $S1$ such that field inside $V1$ is assumed zero and outer field can be found out from surface currents on $S1$. Field distribution can be express using integral equation as:

$$\frac{1}{2} E_{S1} + \int_{S1} \left(M(r') \times G(r,r') + jk_0 \eta_0 J(r') G(r,r') - j\frac{\eta_0}{k_0} \nabla' \bullet J(r') G(r,r') \right) ds = 0 \qquad (4)$$

where both electric and magnetic currents are related to tangential field components as:

$$J(r') = (\vec{n} \times H) \qquad (5)$$

$$M(r') = (E \times \vec{n}) \qquad (6)$$

On surface $S1$, the MOM basis function f_{mom} and the FEM basis function w are related by:

$$w = \vec{n} \times f_{mom} \qquad (7)$$

After multiplying weighting function in (4), $J(r')$ can be expressed in terms of electric field as in [8] and replaced in equation (2).

C. E_{inc} on 2^{nd} domain

Incident electric field on the boundary edges on $S2$ can be found out using integral equation as shown below.

$$E_{inc} = \frac{1}{2} E_{S1} + \int_{S1} \left(M(r') \times G(r,r') + jk_0 \eta_0 J(r') G(r,r') - j\frac{\eta_0}{k_0} \nabla' \bullet J(r') G(r,r') \right) ds \qquad (8)$$

Both sides are multiplied by weighting function and Einc is formulated as in [6]. Here, weighting function is taken as RWG function on S2.

$$Einc = [A][J] + [B][M] \tag{9}$$

$[A]$ and $[B]$ represents the coupling matrix from the electric current and magnetic surface current on S1 respectively as in Fig. 3.

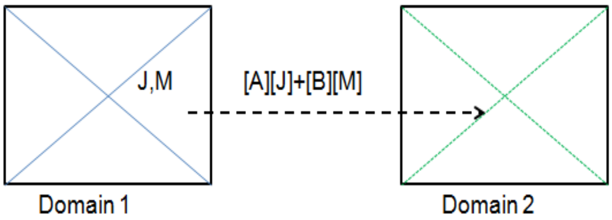

Fig. 3. Boundary to boundary interaction

In EMC application, victim domain, comprising of the measuring antenna, does not alter with different components inside domain 1. Also, if the boundary mesh elements can be kept fixed on domain 1, then [A] and [B] matrix can be used for multiple cases.

D. Einc to Antenna measurements

Once *Einc* is known on the boundary edges of domain 2, FEM is used for computing field inside domain 2 using Dirichlet boundary condition.

E. Computational Savings

Let the number of triangular edges on the surface S1 of source domain be N_{s_1} and that on victim domain be N_{s_2}. Let the number of FEM basis inside the source domain be N_{src}^V and that inside the victim domain N_{victim}^V. Let N_{fs}^V be the number of FEM basis in the free-space for a FEM-only analysis. Let N_{src}^S and N_{victim}^S be the number of surface MoM basis inside the source and victim domain respectively for MoM only solution. The computational complexity of different methods are tabulated in Table I.

TABLE I
COMPARISON OF COMPUTATIONAL EFFICIENCY

Method	Computational Complexity
FEM-only	$O(\left[N_{src}^V + N_{fs}^V + N_{victim}^V\right]^{1.5})$
MoM-only	$O(\left[N_{src}^S + N_{victim}^S\right]^3)$
Hybrid FEM-MoM	$O(\left[N_{S_1} + N_{S_2}\right]^3 + \left[N_{S_1} + N_{src}^V\right]^{1.5} + \left[N_{S_2} + N_{victim}^V\right]^{1.5})$
Directional Hybrid FEM-MoM	$O(\left[N_{S_1}\right]^3 + \left[N_{S_1} + N_{src}^V\right]^{1.5} + \left[N_{S_2} + N_{victim}^V\right]^{1.5})$

IV. NUMERICAL RESULTS

A simple case study was made for computing radiation from a microstrip line. The line was excited with 1 Amp current source and a dipole antenna was placed at a distance of 1 meter as in Fig. 4.

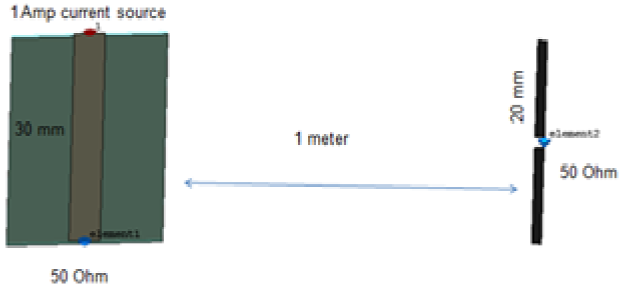

Fig. 4. Radiation from a microstrip line with substarte dielectric constant 4

Voltage is monitored at 50 ohm termination of the dipole and compared with commercial 3D solver in Fig. 5.

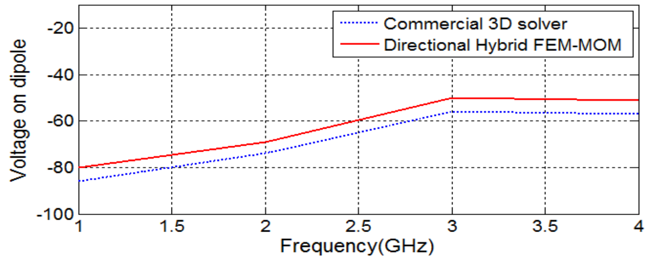

Fig. 5. Antenna voltage comparison of proposed method and commercial tool

The results show good agreement between the proposed method and a commercial 3D solver. Also the simulation time per sample is compared with hybrid FEM-MoM and the commercial 3D solver in Table. 2.

TABLE 2
COMPARISON OF SIMULATION EFFICIENCY

Type	Simulation time/frequency sample
Directional Hybrid FEM-MoM	8 min
Normal Hybrid FEM-MoM	45 min
Commercial 3D Solver (FEM)	>2 hours

V. CONCLUSION:

A directional hybrid FEM-MoM formulation is presented in this paper for automotive applications. The proposed method can handle EMC radiation problems with reduced time and memory requirements.

REFERENCES

[1] "CISPR 25: Limits and methods of measurement of radio distubance characteristics for protectionof receivers used on board veciles," third ed., 2008.

[2] K. D. Paulsen, D. R. Lynch, and J. W. Strohbehn, "Three-dimensional finite, boundary, and hybrid element solutions of the Maxwell equations for lossy dielctric media," *IEEE Trans. Mircrowave Theory Tech.*, vol. 36, pp. 682-693, Apr. 1988.

[3] J. M. Jin and J. L. Volakis, " A hybrid finite element method for scattering and radiation by microstrip patch antennas and arrays residing in a cavity," *IEEE Trans. Antennas propagat.*, vol. 39, pp. 1598-1604, Nov. 1991.

[4] M. L. Barton and J. Cendes, "New vector finite elements for three-dimensional magnetic field computation," *Journal of Applied Physics*, vol. 61, pp. 3919-3921, Apr. 1982.

[5] S. M. Rao, D. R. Wilton, and A. W. Gilsson, "Electromagnetic scattering by surfaces of arbitary shape," IEEE Trans. on Antennas and Propagat., vol. 30, pp.409-418, May 1982.

[6] M. W. Ali, T. H. Hubink and J. L. Drewniak, "A hybrid FEM/MOM technique for electromagnetic scattering and radiation from dielctric objects with attached wires," *IEEE Trans. on Electromagnetic Compatibility*, vol. 39, pp. 303-314, Nov. 1997.