Numerical and experimental methods for the comparison of radiated immunity tests in EMC sites

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Thesis subject

Simulation of electromagnetic wave propagation into electrically large sites.

Actual subject of the simulations: anechoic chambers used in electromagnetic compatibility measurement and testing.

Notoriously difficult problem: most numerical schemes (even in commercial software) fail on huge propagation simulations like this.

Why this kind of simulations is useful?

Electromagnetic compatibility is a central topic in the development of every electronic product.

Two actors in EMC, facing different issues:

The manifacturer:

- Must comply with regulations
- No recipes to meet required standards
- Lab time to debug the products is very costly

The test lab:

- Must be sure about the efficiency of the measurement chain
- Must be confident about the correctness of the procedures

Simulation can help dealing with these issues.
Actual demand of simulation tools by the industry.

Work areas

The thesis deals mostly with issues faced by the laboratory.

Accurate EMC measurements are not easy at all: simulation can help to check correctness. This is why industry demands it.

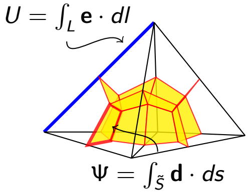
The work consists in

- a theoretical part: novel numerical tools developed
- a numerical code implementing the developed numerical tools
- an experimental part to validate the numerical tools

Simulation tools

Simulation tools developed in this thesis are based on the *Discrete Geometric Approach*, which allows to write Maxwell's equations in an algebraic form suitable for computers.

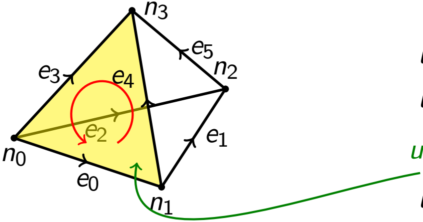
Space is discretized in two grids: primal grid $\mathcal{G}$ and dual grid $\tilde{\mathcal{G}}$



Circulations and fluxes of EM quantities are associated to lines and surfaces of the grids.

Faraday–Neumann law

With this discretization writing the Faraday–Neumann law is easy.
Sum of voltages on the edges around a face = flux across the face multiplied by $-i\omega$



$$u_1 + u_5 - u_4 = -i\omega\Phi_0.$$
$$u_2 + u_5 - u_3 = -i\omega\Phi_1.$$
$$u_0 + u_4 - u_3 = -i\omega\Phi_2\ .$$
$$u_0 + u_1 - u_2 = -i\omega\Phi_3.$$

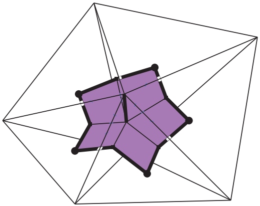
Or, using the face-edge incidence matrix $\mathbf{C}$:

$$\mathbf{C}\mathbf{U} = -i\omega\boldsymbol{\Phi}.$$

We just obtained the *Discrete Geometric Faraday–Neumann law*!

Ampère–Maxwell law

Doing same on the dual mesh, the *Discrete Geometric Ampère–Maxwell law* is obtained.



- Magnetomotive forces F_i on dual edges
- Electric fluxes Ψ_k on dual faces

$$\mathbf{C}^{\mathsf{T}}\mathbf{F} = i\omega\boldsymbol{\Psi}.$$

Constitutive relations

Faraday–Neumann and Ampére–Maxwell laws work on a single grid.

The two grids need to be "connected" and this is done using constitutive relations:

- $\mathbf{d} = \boldsymbol{\epsilon}\ \mathbf{e}$ which becomes $\boldsymbol{\Psi} = M_{\epsilon}\mathbf{U}$
- $\mathbf{h} = \boldsymbol{\nu}\ \mathbf{b}$ which becomes $\mathbf{F} = M_{\nu}\boldsymbol{\Phi}$

The discrete constitutive relations are obtained using the *Energetic Approach*.

Wave propagation in frequency domain

Combining the equations and the constitutive relations we get

$$(\mathbf{C}^{\mathsf{T}}\mathbf{M}_{\nu}\mathbf{C} - \omega^2\mathbf{M}_{\epsilon})\mathbf{U} = \mathbf{0},$$

where the unknowns are the electromotive forces $\mathbf{U}$ on the edges.

Equation is solved subject to usual boundary conditions.

- Dirichlet: enforced by fixing values of the entries of $\mathbf{U}$ corresponding to boundary edges ($\mathbf{U}^b$)
- Neumann: requires a little trick.

Neumann BCs

We need to introduce the *boundary dual grid*.

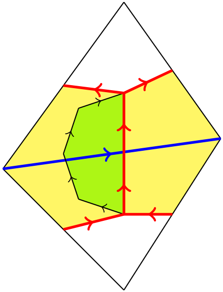
Dual boundary edges allow us to rewrite the Ampère–Maxwell law as:

$$\mathbf{C}^{\mathbf{T}}\mathbf{F} - \mathbf{F}^{b} = i\omega\boldsymbol{\Psi}.$$

We re-derive the wave equation and we get

$$(\mathbf{C}^{\mathbf{T}}\mathbf{M}_{\nu}\mathbf{C} - \omega^{2}\mathbf{M}_{\epsilon})\mathbf{U} = -i\omega\mathbf{F}^{\mathbf{b}}.$$

Entries of $\mathbf{F}^{b}$, which correspond to dual boundary edges, allow us to impose Neumann BCs.



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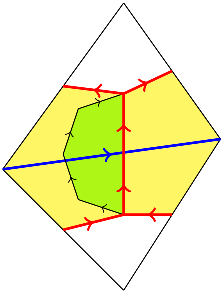
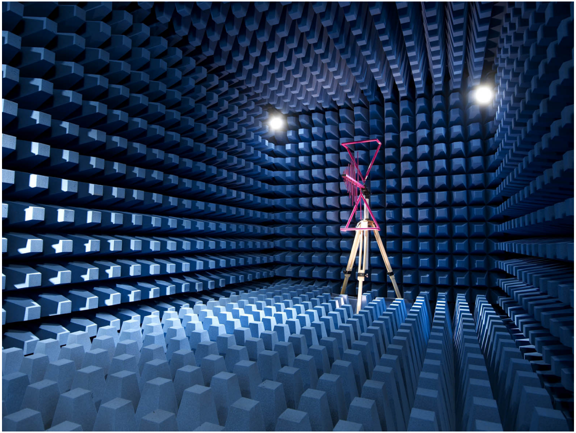


Moreover, introducing a matrix $\mathbf{M}_Y$ between primal and dual boundary edges such that $\mathbf{F}^b = \mathbf{M}_Y\mathbf{U}^b$, we obtain the *admittance boundary condition*.

Simulation of anechoic chambers

We want to solve our equation in the domain depicted in the photo.



Simulation of anechoic chambers

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State-of-the-art Intel MKL Pardiso direct solver & 32 GB of RAM: no more than 1.3M equations.
Definitely unacceptable, but we must live with this.

Limiting computational requirements

How to limit computational requirements?

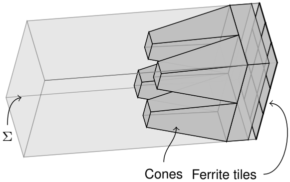
One of the objectives of the thesis was to develop strategies for this.

First equivalent model: anechoic walls

A wall is composed by cones and the ferrites. Idea: remove them and substitute them with an impedance boundary condition!

To do this we only need to study the basic unit of an anechoic wall, the *unitary cell*.

- 2 $\times$ 2 cones
- 3 $\times$ 3 ferrite tiles



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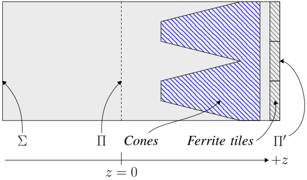

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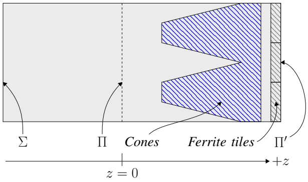

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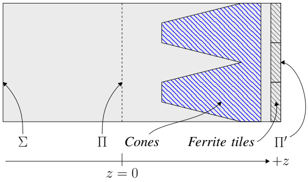
- calculate wave impedance on a plane far away from cones
- translate impedance on the rightmost end of the cell



$$Z_{\Pi'}(z) = Z_c \frac{Z_\Pi - iZ_c \, tan(\beta z)}{Z_c - iZ_\Pi \, tan(\beta z)},$$

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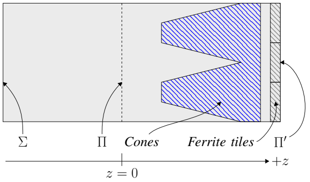

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- substitute cones and ferrites with that equivalent impedance

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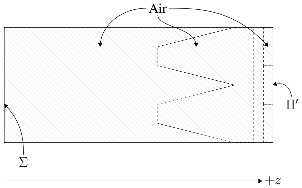
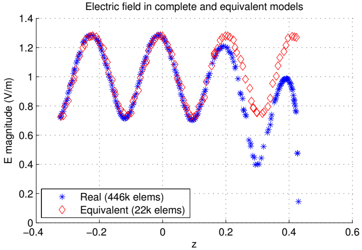
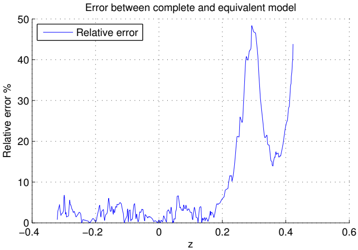


Equivalent model for anechoic walls: results

The proposed equivalent model gave very good results

- number of elements reduced by 20 times
- in the area of interest (away from cones) the relative error was below 5%





The problem given by the details of the walls is solved...

Second model: equivalent radiating elements

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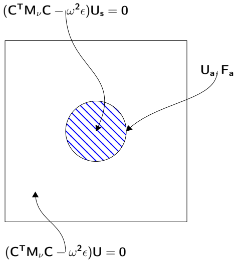
Modelling of equivalent source done via a total field/scattered field decomposition developed in this thesis [2].

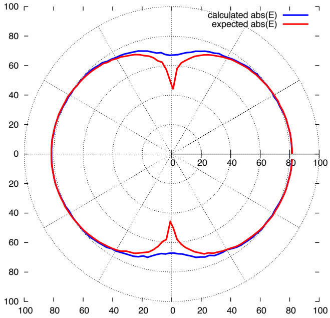
- it allows to compute also field scattered by environment
- useful (and used) to model waveguide ports [4]



Equivalent radiating elements: results

Equivalent model for antennas appear to have a good performance.

Real half-wave dipole field vs. equivalent model:



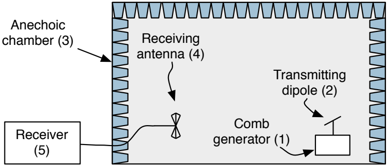
Also the problem of the antennas appears to be solved.

However, do these models work on real-world problems?

Validation

The models were validated against real-world meausurements [2]

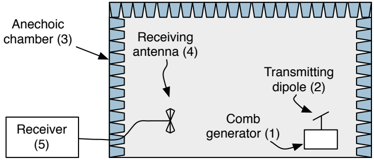
Extensive measurements made at Emilab SRL, an EMC laboratory. Two experiments were of particular significance:



CE room, 558 comparison points

Automotive room, 30 comparison points

CE room experiment: description



Some preliminary steps required:

- Comb generator characterization
- TX antenna characterization
- Antenna current measurement

About the setup:

- RX at $h = 1m, 1.5m, 2m$
- TX at $h = 1m, 1.5m, 2m$
- Horizontal and vertical polarizations
- From 90 to 390 MHz at 10 MHz steps

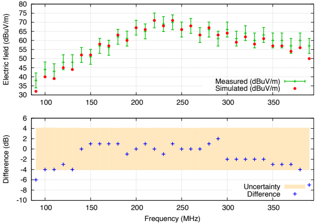
A total of 558 comparison points!

Large discrepancies initially found on some points: analyzing the data, it turned out that I had a problem in the measurement setup.

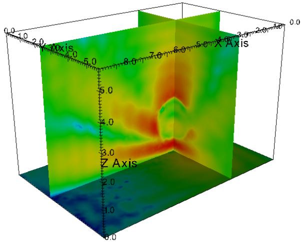
Simulation allowed to discover measurement problems already in this early validation phase!

CE room experiment: results

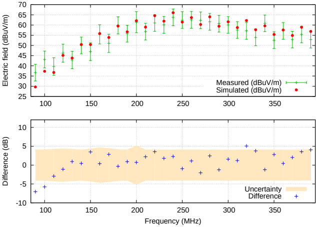
TX and RX @ 1m, horizontal



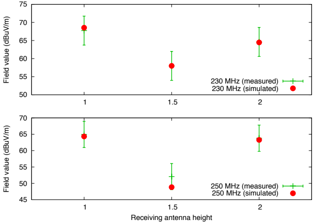
TX @ 1m horizontal, 230 MHz



TX and RX @ 1.5m, vertical



RX @ 1m, 1.5m and 2m



Automotive room experiment: description

Second experiment made inside an automotive test compliant room.

- Inside the room: table as prescribed by regulations
- Aim: evaluate its effect

Experimental procedure almost equal as the previous one.

Used a small dipole as receiving antenna $\Longrightarrow$ required careful characterization.

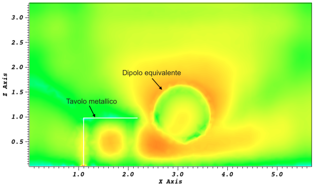
A transmitting dipole was placed at 1 meter in front of the table, in horizontal polarization.

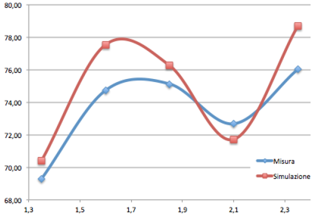
Automotive room experiment: results

An "unexpected" standing wave under the table was predicted by simulation: measurements confirmed its presence!

Automotive room is very busy, I had time for just 30 measurements.

Precise measurements in this setup were rather difficult.





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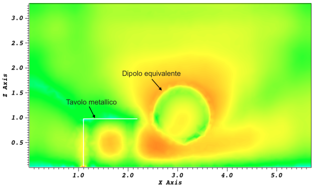
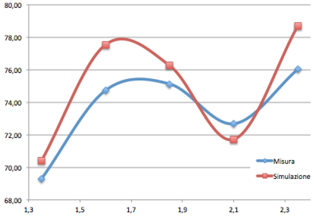


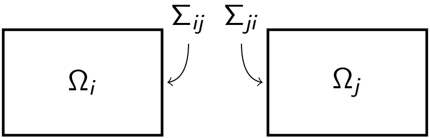


Despite the huge approximations introduced, the models we developed have a great predictive power. Moreover, simulation of large anechoic chambers become accessible on mid-range workstations.

Domain decomposition

Idea:

1. split Ω in multiple subdomains Ω_i
2. couple them, solve smaller problems in Ω_i and iterate



We have a new equation to solve in each subdomain:

$$(\mathbf{C}^\mathbf{T}\mathbf{M}_\nu\mathbf{C} - \omega^2\mathbf{M}_\epsilon)\mathbf{U}_j + i\omega\mathbf{M}_Y\mathbf{U}_{ji}^b = -i\omega\mathbf{G}_{ji}^b,$$

where

$$\mathbf{G}_{ji}^b = \mathbf{F}_{ij}^{b+} - \mathbf{M}_Y\mathbf{U}_{ij}^{b+}.$$

In plain english: we solve on each Ω_j but with an (additional) source, which represents the radiation coming from Ω_i.

Adaptive mesh refinement

Frequency domain wave propagation can be described mathematically in two ways

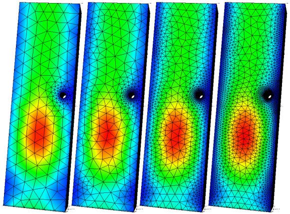
<u>the E-formulation</u>

$$\nabla \times \mu^{-1} \nabla \times \mathbf{E} - \omega^2 \epsilon \mathbf{E} = 0$$
$$\Downarrow$$
$$\mathbf{C}^T \mathbf{M}_{\mu^{-1}} \mathbf{C} \mathbf{U} - \omega^2 \mathbf{M}_\epsilon \mathbf{U} = 0$$

<u>the H-formulation</u>

$$\nabla \times \epsilon^{-1} \nabla \times \mathbf{H} - \omega^2 \mu \mathbf{H} = 0$$
$$\Downarrow$$
$$\mathbf{C}^T \mathbf{M}_{\epsilon^{-1}} \mathbf{C} \mathbf{F} - \omega^2 \mathbf{M}_\mu \mathbf{F} = 0$$

- Continuous formulations are equivalent, discrete ones are not!
- Solve both problems on a coarse mesh, compare them, refine only where needed [3]



Conclusions

Electromagnetic wave propagation is a difficult problem from the numerical point of view.

This thesis:

- extended DGA with previously unavailable features
  - plane wave, TF/SF, DomDec
- proposed techniques to alleviate computational effort to simulate electrically large environments
  - equivalent models, adaptive refinement, DomDec
- validated the proposed techniques against real-world problems
- confirmed the viability of the proposed approach
- addresses an increasing demand of simulation tools in EMC

Contributions (1)

Journal papers:

- [1] S. Chialina, M. Cicuttin, L. Codecasa, R. Specogna, and F. Trevisan, "*Plane Wave Excitation for Frequency Domain Electromagnetic Problems by Means of Impedance Boundary Condition*", IEEE Trans. Magn., vol. 51, no. 3, 2015.
- [2] SC, MC, LC, G. Solari, RS, and FT, "*Modeling of anechoich chambers with equivalent materials and equivalent sources*", IEEE Trans. EMC, in press
- [3] MC, LC, RS, and FT, "*Complementary discrete geometric h-field formulation for wave propagation problems*", IEEE Trans. Magn., vol. 52, no. 3, 2016.
- [4] MC, LC, RS, and FT, "*Excitation by scattering/total field decomposition and UPML in the geometric formulation*", IEEE Trans. Magn., vol. 52, no. 3, 2016.

Proceedings:

- [5] A. Affanni, MC, RS and FT, "*Fast uncertainty quantification of fields and global quantities*" [COMPUMAG2015]

Contributions (2)

A brand new code for the DGA method was developed.

- Commercial codes don't allow customization, impossibile to test reseach with them

The main features of the new code are

- Modern: it is written in C++14
- Modular, expandable and understandable
- Fast and highly parallel
- General: it is a framework for DGA, not only for frequency domain wave propagation

Further research

The work started with this thesis led us to more topics that need to be investigated. We're currently working on:

- efficient preconditioning techniques for the wave propagation problem (CEFC2016 conference)
- complementarity and adaptive refinement applied to eigenvalue problems (CEFC2016 conference)
- model order reduction and fast frequency sweeps

Thank you!

Thank you for your attention!

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