

Computational Electromagnetics for Automotive Problems using Equivalent Circuits

OR:

How to include a chassis in your SPICE simulations

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IEEE EMC Society, Sweden chapter & SNRV-E, Borås

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1. Introduction

1.1. Background

- Work within automotive technology is performed at LTU:s Center for Automotive System Technologies and Testing (CASTT).
- The ever increasing electronic systems in automobiles to ensure customer satisfaction \Rightarrow more and more complex electronic systems, antennas, information flow, etc.
- The progress in computational electromagnetics (CEM).
- The need for faster evaluation of early stage designs, concept testing, electromagnetic compatibility through CEM.
- However, it is crucial to use the right CEM method (FEM, FDTD, FIT, MoM, TLM, MTL, PEEC) for the right problem (close or open space, TD or FD, H and B or V and I, etc).

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2. The Partial Element Equivalent Circuit Method

2.1. Basic theory

The theoretical derivation starts from the expression of the total electric field in free space as

$$\vec{E}^T(\vec{r}, t) = \vec{E}^i(\vec{r}, t) - \frac{\partial \vec{A}(\vec{r}, t)}{\partial t} - \nabla \phi(\vec{r}, t). \quad (1)$$

If the observation point, \vec{r} , is on the surface of a conductor, the total electric field can be written as $\vec{E}^T = \frac{\vec{J}(\vec{r}, t)}{\sigma}$, in which $\vec{J}(\vec{r}, t)$ is the current density on a conductor. To transform into the electric field integral equation (EFIE), the definitions of the electromagnetic potentials, \vec{A} and ϕ are used.

$$\vec{A}(\vec{r}, t) = \sum_{k=1}^K \mu \int_{v_k} G(\vec{r}, \vec{r}') \vec{J}(\vec{r}', t_d) dv_k \quad (2)$$

$$\phi(\vec{r}, t) = \sum_{k=1}^K \frac{1}{\epsilon_0} \int_{v_k} G(\vec{r}, \vec{r}') q(\vec{r}', t_d) dv_k \quad (3)$$

Combining results in the well known electric field integral equation.

The EFIE to be solved

$$\vec{E}^i(\vec{r}, t) = \frac{\vec{J}(\vec{r}, t)}{\sigma} + \mu \int_{v'} G(\vec{r}, \vec{r}') \frac{\partial \vec{J}(\vec{r}', t_d)}{\partial t} dv' + \frac{\nabla}{\epsilon_0} \int_{v'} G(\vec{r}, \vec{r}') q(\vec{r}', t_d) dv' \quad (4)$$

Interpreting the EFIE as KVL

It is possible to interpret each term in the above equation as KVL since

$$V = RI + sLpI + Q/C \quad (5)$$

This results in interpreting:

- The first RHS term as Resistance,
- The second RHS term as Partial inductance
- The third RHS term as Coefficient of potential

The resulting equivalent circuit

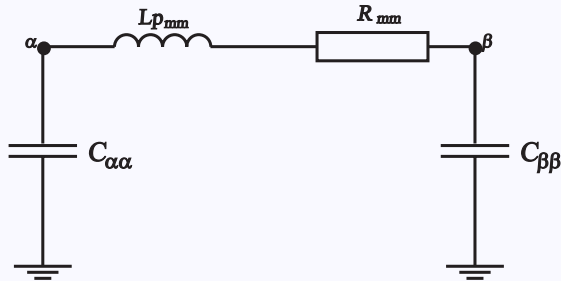


Figure 1: One way of visualizing the interpretation of the EFIE as a partial element equivalent circuit (quasi-static approximation).

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The resulting equivalent circuit (FW)

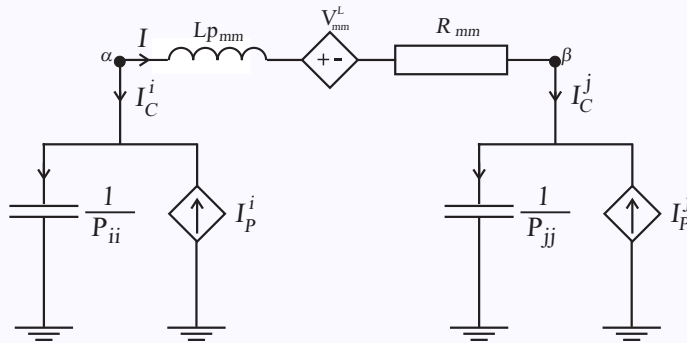


Figure 2: One way of visualizing the interpretation of the EFIE as a partial element equivalent circuit (full-wave).

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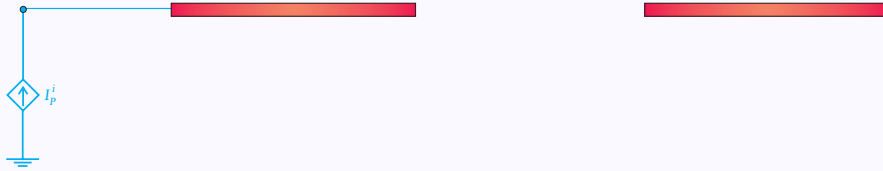
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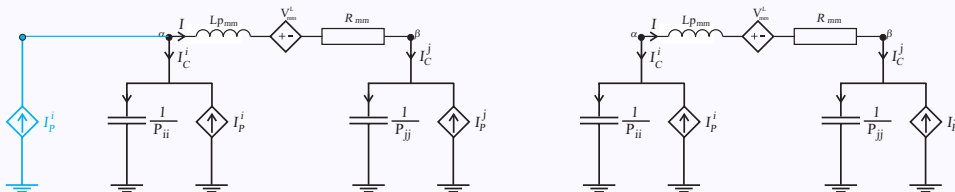
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2.2. Simple PEEC model for two wires in free space



(a)



(b)

Figure 3: PEEC model for two conducting wires (a) using controlled voltage- and current- sources to account for the electromagnetic couplings (b).

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3. Non-orthogonal formulation

1. Developed in 2003¹.
2. Enables the modeling of geometrically complex structures.
3. Consistent with the orthogonal formulation.
4. More complex partial elements. Compare:

$$Lp_{nonort} = \mu \int_a \int_b \int_c \int_{a'} \int_{b'} \int_{c'} (\hat{a} \cdot \hat{a}') h_{a'} G[\vec{r}_g(a, b, c); \vec{r}_g(a', b', c')] da' db' dc' h_a da db dc \quad (6)$$

with

$$Lp_{ort} = \frac{\mu}{2\pi} \left[\ln \frac{2l/w}{1+t/w} + 0.5 + \frac{2}{9l/w(1+t/w)} \right] \quad (7)$$

¹A. E. Ruehli, G. Antonini, J. Esch, J. Ekman, A. Mayo, A. Orlandi, "Nonorthogonal PEEC Formulation for Time- and Frequency-Domain EM and Circuit Modeling," *IEEE Transactions on EMC*, 45, pp. 167-176, 2, 2003.

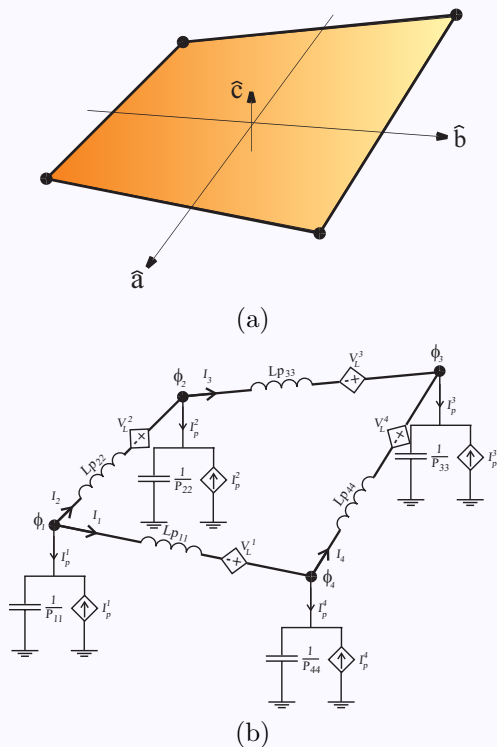


Figure 4: Nonorthogonal metal patch (a) and PEEC model (b).

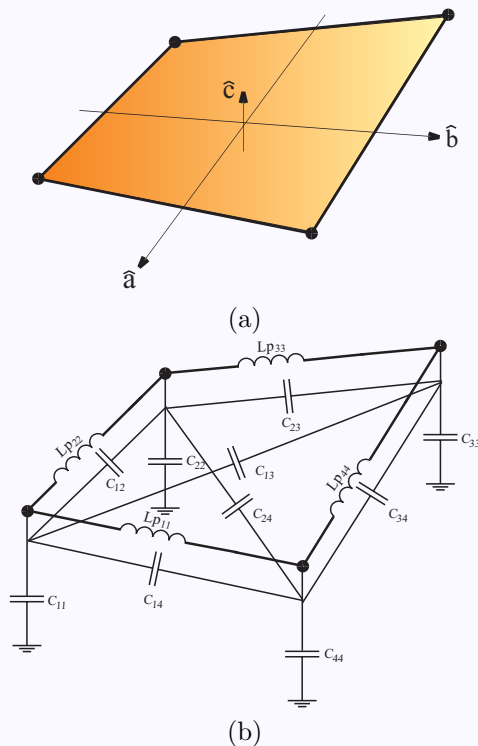
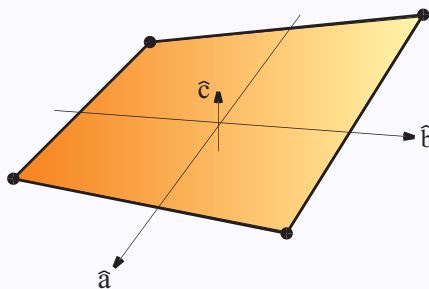


Figure 5: Nonorthogonal metal patch (a) and QS-PEEC model (b).



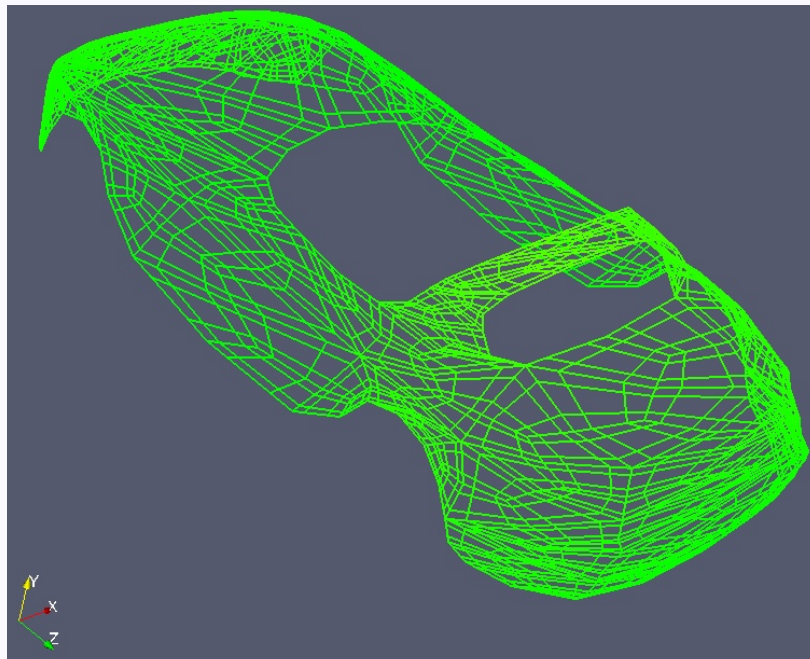
(a)

Lp11 1 4 {Lp11_value}	C11 1 0 {C11_value}
Lp22 1 2 {Lp22_value}	C22 2 0 {C22_value}
Lp33 2 3 {Lp33_value}	C33 3 0 {C33_value}
Lp44 4 3 {Lp44_value}	C44 4 0 {C44_value}
K13 Lp11 Lp33 $\sqrt{\frac{\{Lp13_value\}^2}{\{Lp11_value\}\{Lp33_value\}}}$	C12 1 2 {C12_value}
K24 Lp22 Lp44 $\sqrt{\frac{\{Lp24_value\}^2}{\{Lp22_value\}\{Lp44_value\}}}$	C13 1 3 {C13_value}
	C14 1 4 {C14_value}
	C23 2 3 {C23_value}
	C24 2 4 {C24_value}
	C34 3 4 {C34_value}

(b)

Figure 6: Nonorthogonal metal patch (a) and SPICE .cir-file in (b).

3.1. Example of nonorthogonal structure not possible to study with orthogonal PEEC formulation



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3.2. Summary of approach

- Pros:
 - + Same time- and frequency- domain model.
 - + Direct inclusion of other SPICE circuit elements.
 - + Solvable with SPICE-like solvers.
 - + Inductance, capacitance, and resistance calculations.
 - + SPICE-like approach.

- Cons:
 - Large number of partial elements (speed-up, approximations).
 - Not for RCS,

- The PEEC method is equivalent to a Method of Moments solution (if the Moment Method is formulated in a special way).

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3.3. LTU/UAq PEEC Solver

- A PEEC implementation developed by Luleå University of Technology, Sweden, and University of L'Aquila, Italy, is used in this project.
- The sequential PEEC-solver is written in C++, uses the GMM++ template library for matrix computation. The code is suitable for electromagnetic analysis in the time- and frequency- domain of combined conductor and dielectric structures.
- The structures are described in a text-file by specifying hexahedral regions, material parameters, PEEC model type, and analysis options.
- The output is given as node voltages and/or volume cell currents in a text-file. Output can be given to enable post processing for visualizing current- and voltage- distribution.
- A parallel version is running at High Performance Computing Center North (HPC2N) at Umeå University, Sweden, on 190 dual AMD nodes, 120 dual Athlon, or 100 P4 nodes.
- Further information at: www.csee.ltu.se/peec

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4. Automotive Computational Electromagnetics

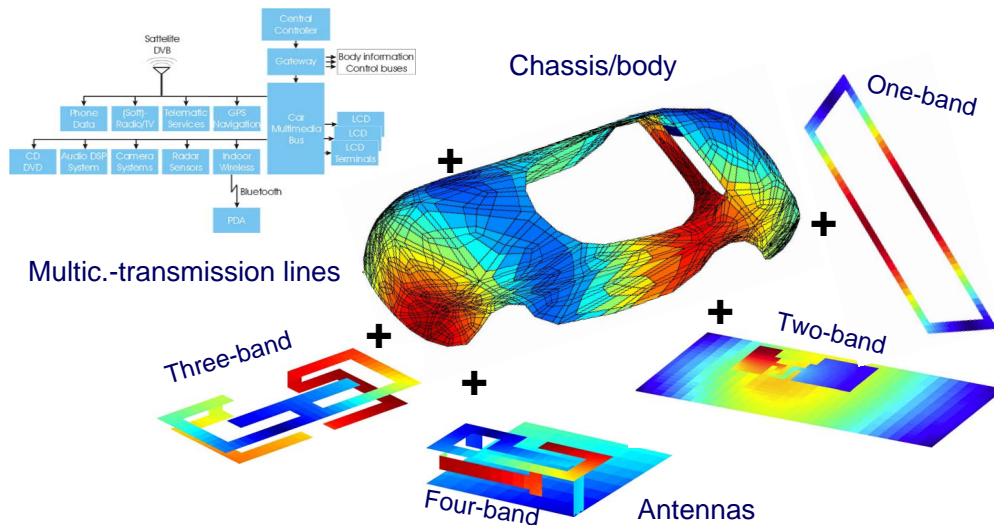
Typical problems:

1. Radiated fields from current distribution in cable bundles/harnesses.
2. Design and positioning of electrical and electronic units.
3. Induced voltages and currents from radiated fields.
4. Integrated antenna analysis.
5. Intra system EMC/Cross-coupling.

All these different types of problems require many different methods!!

With PEEC, we target the following:

- Integrated antenna performance analysis.
- Chassis and multi conductor transmission lines.
- Chassis analysis in the time and frequency domain.



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4.1. Integrated antenna analysis

The reason for this type of study is to ensure the correct operation for the increasing number of antennas in automobiles.

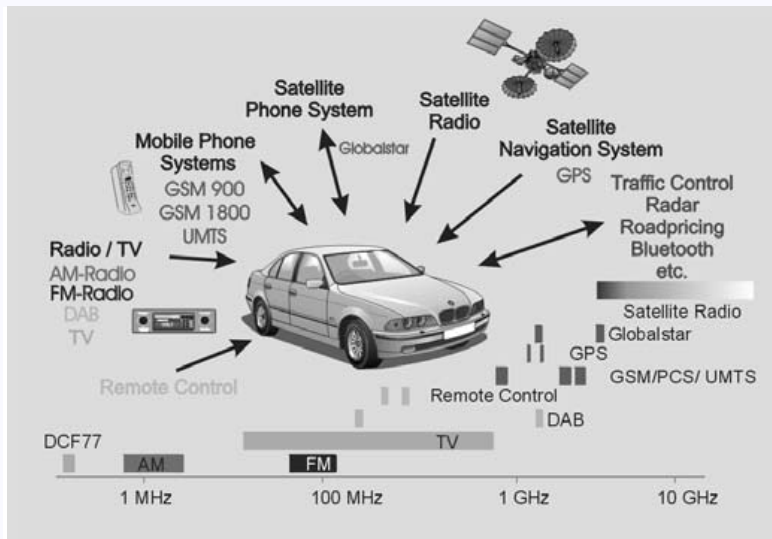


Figure 7: Required communication services to meet customer demand.

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- Complex (multi-band, 3D, complex materials) antenna simulations are demanding. Usually performed using Method of Moments, Finite elements, etc.
- Chassis + complex antennas are even more demanding due to the high frequency analysis required for antennas, resulting in an extremely fine mesh. Example: $f_{max} = 3 \text{ GHz} \Rightarrow l_{max} = 0.5 \text{ mm}$ cells.
- Chassis + complex antennas are complex due to large differences in cell dimension². This is not handled well in all methods since requirements on cell aspect ratios exist (L-to-W, L-to-T, T-to-W).
- One strength with PEEC is the ability to handle both large and small cells in the mesh. Therefore, chassis+complex antennas should be feasible. But, no results at this moment.

²Entire chassis can not be meshed into $0.5 \text{ mm} \times 0.5 \text{ mm}$ cells (40 000 cells / m²).

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4.2. Chassis and multi conductor transmission lines

- Several kilometer of cables in modern automobiles, often in bundles/harnesses.
- Since the PEEC method resorts on the solution of circuit equations, the simultaneous solution of the multi conductor transmission line equations (very efficient) is possible.
- Transmission in MTL can be modelled using the Method of Characteristics (MoC), Delay Extraction-Based Passive Compact Transmission-Line Macromodeling Algorithm (DEPACT), macromodels, etc.
- MTL are implemented as macromodels in the solver.

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4.3. Chassis analysis

Chassis, or body-in-white, analysis in the time- and frequency- domain enabled by the nonorthogonal formulation. We can study:

- fields inside and outside the chassis created by internal and externally applied fields (plane wave, mobile telephone, fixed antennas, etc.),
- resonances in the chassis,
- the propagation of transients through the chassis.

When this part is verified, we can continue with *Integrated antenna analysis*.

5. Results from chassis analysis

5.1. Time domain

Computational model:

1. Front bumper excited using a unitary, 50 ns, Gaussian, unitary current source.
2. Back bumper grounded by a 50 Ω resistor.
3. Transient analysis from 0 to 500 ns using 300 steps.
4. Lp-matrix = 3 816 x 3 816, (7 279 020 mutual inductances).
5. P-matrix = 2 862 x 2 862, (4 094 091 mutual coefficients of potential).
6. (Lp, C, R)PEEC model. MNA-method. Serial code using GMM++.
7. 1 hour to calculate Lp and P matrices.
8. 10 minutes to solve the circuit equations.
9. Total solution time: 1 hour and 10 minutes.

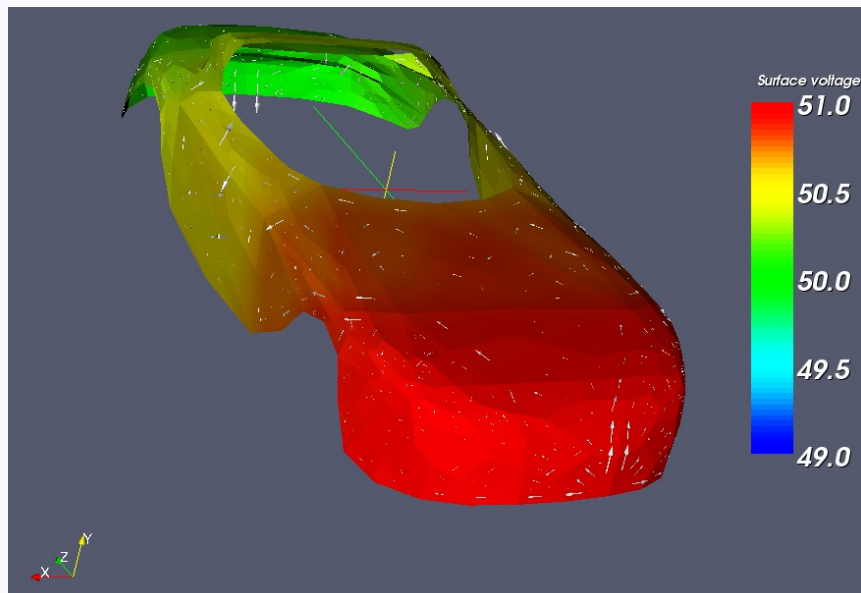


Figure 8: Screenshot from 50 ns, Gaussian, current source excitation at the front. Arrows indicate the current distribution.

5.2. Frequency domain

Computational model:

1. Front bumper excited using a unitary pulse current source.
2. Front bumper grounded by a $100\ \Omega$ resistor (parallel to I_{IN}). Back bumper grounded by a $50\ \Omega$ resistor.
3. Frequency domain analysis from 0 to 75 MHz using 75 steps.
4. L_p -matrix = $3\ 816 \times 3\ 816$, (7 279 020 mutual inductances).
5. P -matrix = $2\ 862 \times 2\ 862$, (4 094 091 mutual coefficients of potential).
6. (L_p, C, R)PEEC model. MNA-method. Serial code using GMM++.
7. 1 hour to calculate L_p and P matrices using FMF-approach.
8. 3 hours to solve the circuit equations.
9. Total solution time: 4 hours.

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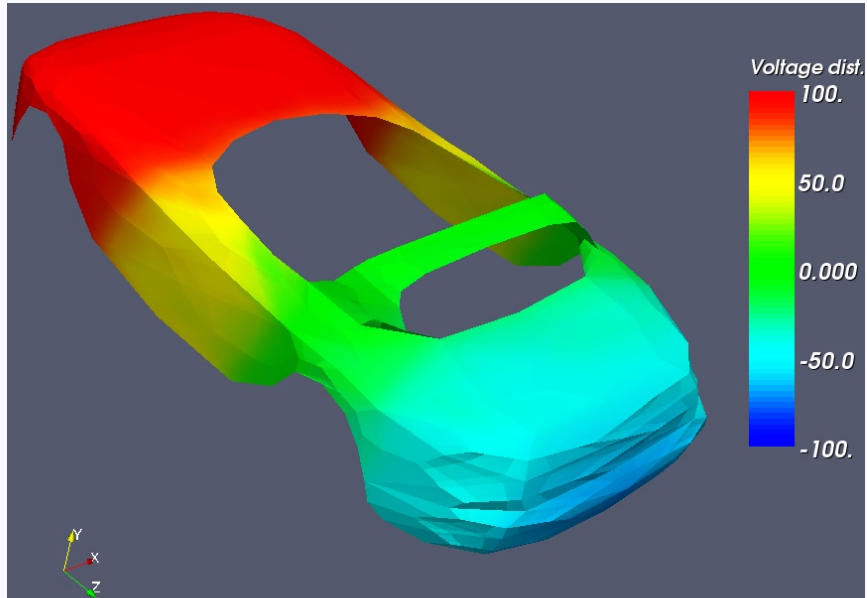


Figure 9: Voltage distribution at 22 MHz.

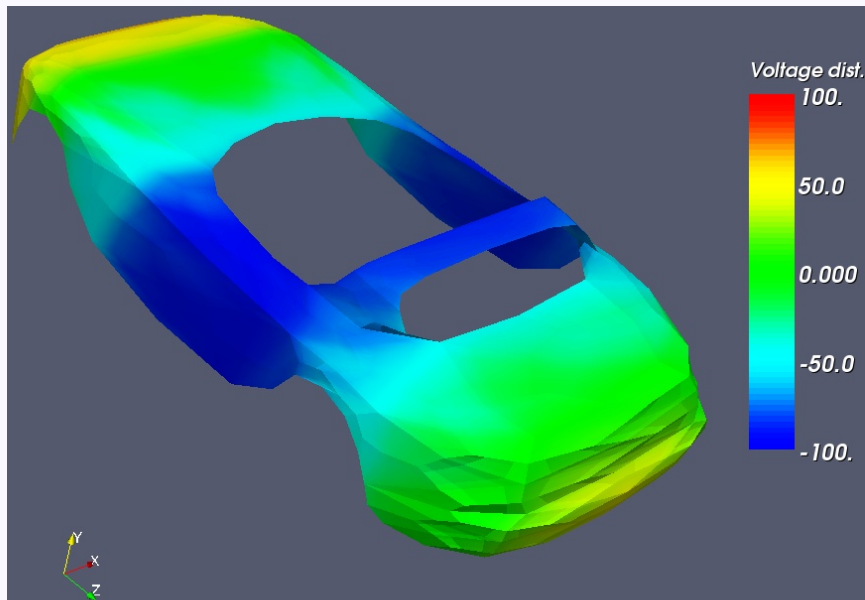


Figure 10: Voltage distribution at 50 MHz.

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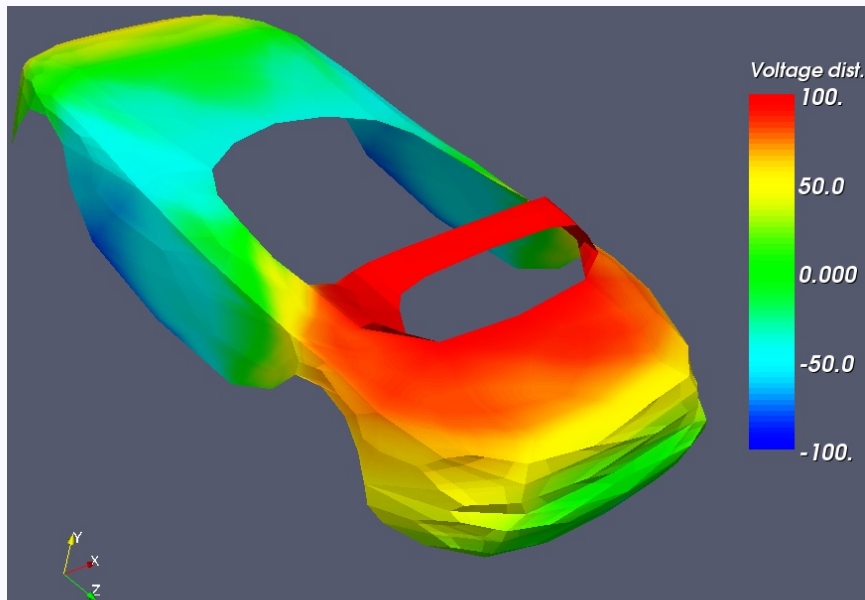


Figure 11: Voltage distribution at 72 MHz.

6. Conclusions

- **The PEEC method offers a framework for creating electric equivalent circuit models for arbitrary (3D) structures. These models can then be solved in, for example, SPICE to model the electronic and electromagnetic behavior for a structure/design.**
- The Nonorthogonal PEEC formulation is of great importance for EM analysis of complex structures.
- The circuit formulation utilized in PEEC makes the formulation suitable for automotive EM analysis. Easy inclusion of (any) additional passive and active circuit elements.
- The possibility to handle large aspect ratio cells is of importance when combining antennas and chassis structures \Rightarrow less cells.
- To tackle all the (upcoming) EM problems within automotive engineering, many different methods are needed.

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