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► **To cite this version:**

Lounès Mokhtari, Benoît Delinchant, Thierry Chevalier, Jean-Louis Coulomb. Comparing Weak and Strong PEEC-MoM Coupling. COMPUMAG 2009, Nov 2009, Florianopolis, Brazil. pp 83-84. hal-00440316

HAL Id: hal-00440316

<https://hal.science/hal-00440316>

Submitted on 21 Jan 2019

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Comparing Weak and Strong PEEC-MoM Coupling

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Abstract—The aim of this paper is to compare strong and weak coupling of the PEEC and MoM methods applied to the modeling of magnetoharmonic problem, and to generalize the weak coupling approach. MoM and PEEC are dedicated to the modeling of specific parts of the overall device. As an example of validation, we have chosen the modeling of a simple transformer. Resolutions of several weak couplings are compared to the strong coupling approach. A new strategy of weak coupling is proposed to improve the time of resolution.

Index Terms—PEEC method, MoM method, weak/strong coupling, iterative methods.

I. INTRODUCTION

THE MODELING of multiphysic systems needs powerful modeling tools and simulation methods. In this context, a specialized electric and magnetic method will be coupled in order to model an electromagnetic device.

The PEEC (Partial Elements Equivalent Circuit) approach has been proved to be excellent for the modeling of many ranges of cabling and interconnections in electric structures. The ferromagnetic materials can be modeled by FEM or integral method like Method of Moments [1][2]. Couplings of these methods have been done successfully in [3][4][5].

In the following sections, different coupling strategies of PEEC and MoM method will be compared. The figure below (Fig.1) shows the strategies commonly used for coupling programs.

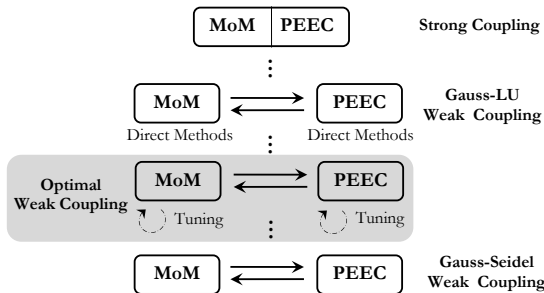


Fig. 1. Coupling strategies.

We have proposed an *Optimal Weak Coupling strategy* based on tuning models to improve the simulation performances. Both iterative and direct methods will be used to solve each of strong and weak coupling.

II. PEEC AND MoM METHOD

A. The PEEC method

The principle of the PEEC method is to decompose electric circuits into several parts, then calculate the mutual between them also the contribution of each of these elementary circuits to the total inductance [5]. The partial mutual between two electric conductors i and j is calculated as follows (1)

$$Mp_{ij} = \frac{\mu_0}{4\pi} \cdot \frac{1}{S_i S_j} \int_{V_j} \int_{V_i} \frac{1}{r_{ij}} \cdot dV_i \cdot dV_j \quad (1)$$

From (1), we build the impedances matrix (2)

$$Z_m = \begin{bmatrix} R_1 + j\omega L_1 & j\omega M_{12} \\ j\omega M_{21} & R_2 + j\omega L_2 \end{bmatrix} \quad (2)$$

The impedances matrix can be obtained directly with using software as INCA3D to the modeling of the conductors and a specific solver to extract the impedance matrix [6].

The source voltage formulation is defined as follows (3)

$$U = Z_m \cdot I + fem \quad (3)$$

where fem is the well known electromotive force induced by the electric current I in the conductors.

B. The Method of Moments

The MoM is an integral approach well adapted to the modeling of magnetic and radiating regions with simple geometries [1]. The global elements magnetic field is given by (4)

$$H = H_{ext} + H_{red} \quad (4)$$

where H_{ext} and H_{red} are respectively the external magnetic field generated by the source field and the reaction of the material to the source field. In case of linear and unsaturable material, the discretization gives us the magnetic field in any point P of the material (5).

$$H(P) = H_{ext}(P) + \frac{1}{4\pi} \iiint_{V_{mag}} \left(3 \frac{\vec{M} \cdot \vec{r}}{r^5} \vec{r} - \frac{\vec{M}}{r^3} \right) \cdot dV_{mag} \quad (5)$$

With making M (Magnetization of the element P) out of the second term of the equation (5), we write the formulation of the magnetic field for all mesh elements (6)

$$[H] = [H_{ext}] + [g] \cdot [M] \quad (6)$$

The matrix $[g]$ is called the magnetostatic matrix, it represents the interactions between the material elements. It can be obtained directly with using some softwares specialized in the modeling of magnetic devices like LOCAPI [6].

C. Coupling terms

Lenz-Faradays law

The impact of the material magnetization $[M]$ on the conductor is the induced electromotive force $[fem]$. The vector potential created by $[M]$ is given by (7)

$$\vec{A} = \frac{\mu_0}{4\pi} \iiint_{V_{mag}} \frac{\vec{M} \times \vec{r}}{||r||^3} \cdot dV_{mag} \quad (7)$$

The link between the potential vector and the electromotive force is given below (8)

$$fem = j\omega \int_{l_c} \vec{A} \cdot dl_c \quad (8)$$

The matrix formulation of (8) is

$$[fem] = [LF] \cdot [M] \quad (9)$$

where $[LF]$ is calculated with the geometric parameters of the system r and V_{mag} .

Biot-Savarts law

The impact of the conductor current I on the material is the excitation magnetic field H_{ext} . The magnetic field created by the electric current I is given by (9)

$$H_{ext}(P) = \frac{1}{4\pi} \iiint_{V_{cond}} \frac{\vec{J}_s \times \vec{r}}{||r||^3} \cdot dV_{cond} \quad (10)$$

where \vec{J}_s is the uniform density of the electric current I in the conductor. The expression of H_{ext} in (10) becomes

$$[H_{ext}] = [BS] \cdot [I] \quad (11)$$

where $[BS]$ is calculated with the geometric parameters of the system.

III. THE PEEC-MoM COUPLING

The modeling of electromagnetic devices requires the modeling of the electrical and magnetic part, but also the interactions between them. This interaction is usually called "Coupling".

A. Weak Coupling

In this coupling, each method is available separately (Fig.2). The electric and magnetic systems are solved successively, the resolution of one is injected into the other and so that until achievement of the accuracy requirements.

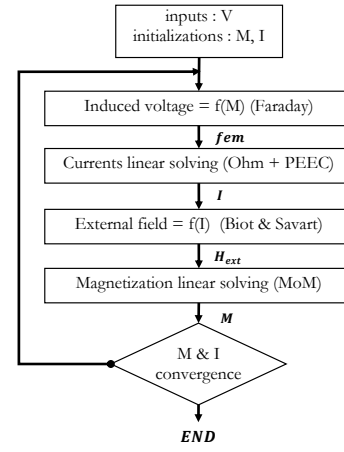


Fig. 2. Algorithm of weak coupling iterative approach.

B. Strong Coupling

The strong PEEC-MoM coupling developed in [2] aimed at grouping in one global matrix the overall modeling as detailed below.

We replace H_{ext} in (6) by its formulation in (11), we obtain

$$[H] = [BS][I] + [g][M] \quad (12)$$

The material law says that $(\mu_r - 1)H = M$ so if we multiply the equation (12) by $(\mu_r - 1)$, we obtain

$$([I_d] - (\mu_r - 1)[g])[M] - (\mu_r - 1)[BS][I] = 0 \quad (13)$$

$$\text{Lets consider : } \begin{cases} ([I_d] - (\mu_r - 1)[g]) = [MM] \\ -(\mu_r - 1)[BS] = [BS_m] \end{cases}$$

then (13) becomes

$$[MM][M] + [BS_m][I] = 0 \quad (14)$$

The electric model (15) is built by replacing the formulation of fem in (3) by that of (9)

$$[LF][M] + [Z_m][I] = U \quad (15)$$

Now, it is possible to group the magnetic (14) and electric (15) model in one global matrix system, which represents the overall model of the system (16)

$$\begin{bmatrix} MM & BS_m \\ LF & Z_m \end{bmatrix} \cdot \begin{bmatrix} M \\ I \end{bmatrix} = \begin{bmatrix} 0 \\ U \end{bmatrix} \quad (16)$$

The resolution of the system (16) gives as $\begin{bmatrix} M \\ I \end{bmatrix}$ vector of unknowns composed by magnetizations of the material elements and the electric currents in the conductors, according to the sources vector $\begin{bmatrix} 0 \\ U \end{bmatrix}$.

IV. APPLICATION

A. Device description

The application example is the modeling of a simple transformer (Fig.2) with 2 current unknowns and a variable number of magnetization unknowns from 500 to 2000. Two square conductors are placed on two parallel planes and a magnetic core is placed through their center. The first conductor is powered by an alternative source voltage (1V, 1kHz). The second conductor is short-circuited.

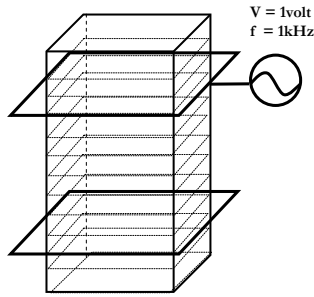


Fig. 3. Geometry of the test device.

Note that the coupling models have been validated by a finit element approach. For the same results of currents and magnetizations, the time resolution and convergence between the strong and weak coupling are compared.

B. First Results

The curves of the first results are plotted in the figure below (Fig.4).

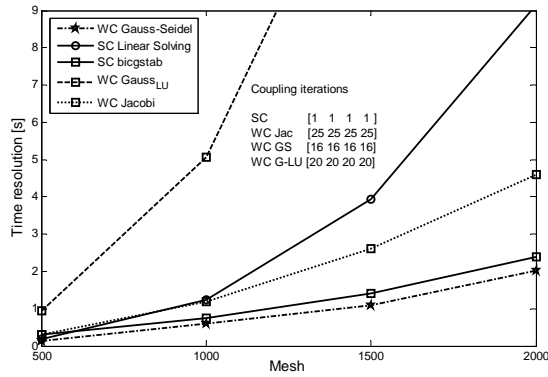


Fig. 4. Performances of the methods.

Conclusion 1

For a little mesh elements, the strong coupling using direct methods is a good solution but for a fine mesh, the iterative method like BiConjugate Gradient Stabilized Method is better adapted.

The Gauss Seidel method combined with the weak coupling shows very good performances comparing to the bicgstab method because the subsystems conditioning in the weak coupling is better than the conditioning of the overall system in the strong coupling.

C. Convergence Study

Here, the convergence and the stability of the different methods are studied and discussed.

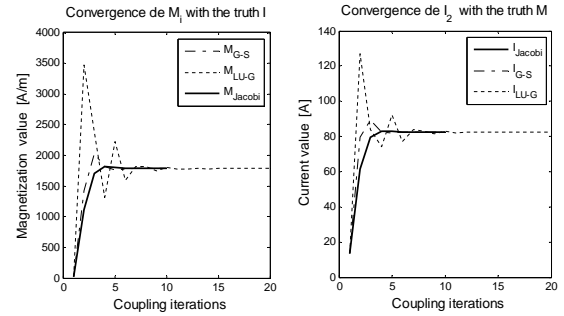


Fig. 5. Convergence of LU-Gauss, Jacobi and Gauss-Seidel method.

About the stability of the methods, oscillations appear when using the LU-Gauss method (Fig.4) and the convergence of the model is delayed until the 10th coupling iteration, unlike the Jacobi and Gauss-Seidel method. The oscillations persist even with using initial values very close to the truth values of magnetization and electric currents.

Conclusion 2

The weak coupling using iterative methods like Jacobi and Gauss-Seidel are more stable and converge faster than WC LU-Gauss method. The convergence of the WC LU-Gauss can be improved with using a parametric relaxation on the magnetization and current.

D. Optimal parameters

In the weak coupling built before (Fig.1), for each coupling iteration, we compute only once the electric and magnetic model. We add two tuned loops to solve more than once the electric and magnetic model (Fig.6). Now, for one coupling iteration, we make *iterM* and *iterI* iterations on respectively the magnetic and electric model.

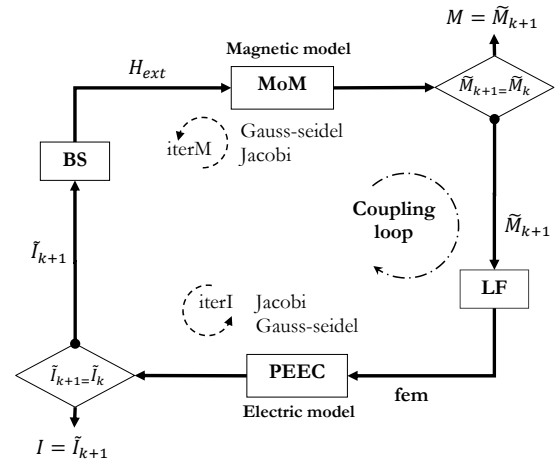


Fig. 6. Adjustable Weak coupling loop.

A test for 2000 mesh elements was performed to identify if there is an optimal number of iteration can be made locally on

the electric and magnetic model to reduce the time resolution.

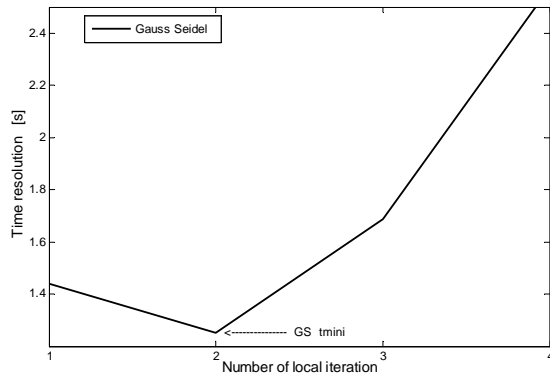


Fig. 7. Time resolution of WC G-S regarding the local iteration number.

From (Fig.7), the optimal number of iteration that reduces the most the time resolution is 2 for Gauss-Seidel. An algorithm was implemented to find these parameters so the overall model is automatically tuned with the optimal parameters.

E. Improvement of time resolution

The overall model of the system is tuned with the optimal parameters and solved. In the figure below (Fig.8), we have plotted the new curves of time resolution regarding the number of mesh elements and given the number of coupling iterations. In the same figure we have let appear the curves obtained before in order to compare between them.

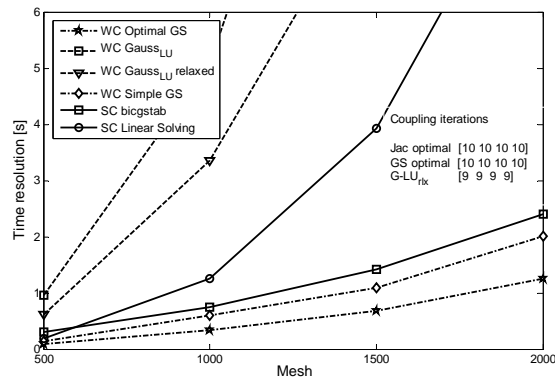


Fig. 8. Performances of the methods tuned with optimal parameters.

Conclusion 3

By using the optimal parameters, we have reduced the time resolution of the model comparing to the previous weak coupling.

We have also minimized the number of iterations on the coupling loop which is very important when coupling softwares on network and where an iteration on coupling takes a long time.

V. CONCLUSION

Different strategies of weak coupling of the PEEC and MoM methods have been compared with the strong coupling. A new strategy of weak coupling (Fig.6) is proposed, the results obtained prove that our weak coupling is:

- 1) better in term of time resolution than the strong one. We also improved the gain of the first weak coupling (Fig.2) by 27% and 17% for respectively Gauss-seidel and jacobi methods;
- 2) more stable than the weak coupling using direct methods; it speeds and relaxes the convergence of the model and
- 3) minimizes the iteration on coupling loop, which is very important in practice where we couple programs on network.

Adding to these gains, this strategy presents other advantages like, easy understanding because it repeats faithfully the evolution of physical phenomena in the system, more flexible, parallelizable tasks, and gives us the possibility to reuse the codes developed.

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