

High impedance MRI tunnel analysis with integral-equation methods

D. Tihon, H. Bui Van and C. Craeye

ICTEAM institute, Université catholique de Louvain, Place du Levant 3, 1348,
Louvain-la-Neuve, Belgium

E-mail: `denis.tihon@uclouvain.be`

Abstract. In MRI devices, the antennas used to generate the RF field are generally shielded from the rest of the device in order to limit the interference. A proper design of this shielding using metasurfaces is a promising way to improve the performances. In this paper, we propose a method to rapidly simulate metasurfaces whose behaviour is approximated using surface impedance boundary conditions. The method is based on the Method of Moments (MoM) and focuses on the rapid simulation of MRI devices for many different surface impedances, which is crucial for design and optimization. The results are validated using the CST commercial software.

1. Introduction

Magnetic Resonance Imaging (MRI) is an active field of research gathering researchers from many different areas, given the wide variety of challenges that it offers. Generally, in order to decouple the RF antennas problem from the rest of the device, a shielding is used. Most of the times, for simplicity reason, this shielding consists of a conducting plate. However, this shielding presents two major drawbacks. First, it greatly reduces the radiation efficiency of dipole-like antennas located close to it, thereby creating SAR hot-spots and reducing the penetration depth and the homogeneity of the magnetic field [1, 2, 3]. Second, such conducting boundary may support surface modes that may enhance coupling between antennas [3].

In [1, 2], the authors propose to use a High Impedance Surface (HIS) for the shielding. Such surface improves both the field penetration and homogeneity within the body. In [3], the HIS is also used to decouple closely packed antennas. In [4] the study is extended to a wider range of surface impedances. Such surface impedances may be implemented using well-designed metasurfaces.

In the first steps of the design of such a metasurface, its properties are generally modelled through an equivalent surface impedance [4, 7]. One crucial point is the ability to rapidly solve the electromagnetic problem for a given distribution of surface impedance. Methods to simulate such impenetrable sheets with boundary conditions described using surface impedances are known for long [5, 6, 7, 8].

This paper aims at providing a rapid tool to simulate such surface impedance using the Method of Moments (MoM). The method focuses on the rapid simulation of MRI shields for many different impedance distributions. The MoM simulation can be decomposed into two parts: the computation of the MoM matrices and the solution of the resulting system of equations. In the formulation presented here, the impedance matrices are computed only once. Then, these impedance matrices can be reused for any surface impedance distribution. The method is easy

to implement provided that one already has some code providing the classical MoM impedance matrices, and the computational overhead is negligible.

2. Description of the method

The MoM is based on the equivalence principle. Using equivalent electric ($\mathbf{J}$) and magnetic ($\mathbf{M}$) currents on the interface between homogeneous media, the electromagnetic problems on both sides of the interface are decoupled. The fields inside one material only depend on the sources located within this material and on the unknown equivalent currents on its boundary. In order to find the value of these unknown currents, boundary conditions are applied on the interfaces. In this paper, the Poggio-Miller-Chu-Harrington-Wu-Tsai (PMCHWT) formulation is used, so that the boundary conditions imposed for penetrable bodies correspond to the continuity of the tangential electric and magnetic fields [10].

In order for the computation to be tractable by a computer, the problem is discretized. The unknown currents are approximated as a weighted sum of predefined Basis Functions (BF) and the boundary conditions are imposed on average over some Testing Functions (TF). Doing so, the problem of finding the continuous currents distribution on the interfaces between different media is reduced to the problem of finding the unknown weights one has to attribute to the BF in order to find the electric and magnetic currents distribution. The system of equation to be solved then reads:

$$\underline{\underline{Z}} \begin{pmatrix} \mathbf{x}_J \\ \mathbf{x}_M \end{pmatrix} = - \begin{pmatrix} \mathbf{b}_E \\ \mathbf{b}_H \end{pmatrix} \quad (1)$$

with

$$\underline{\underline{Z}} = \sum_m \begin{pmatrix} \underline{\underline{Z}}_m^{EJ} & \underline{\underline{Z}}_m^{EM} \\ -\underline{\underline{Z}}_m^{EM} & \underline{\underline{Z}}_m^{EJ}/\eta_m^2 \end{pmatrix}, \quad (2)$$

$\underline{\underline{Z}}_i^{EJ}$ ($\underline{\underline{Z}}_i^{EM}$) whose (i, j) entry corresponds to the electric field on TF i generated by unitary electric (magnetic) currents on BF j through medium m , $\mathbf{x}_J$ ($\mathbf{x}_M$) the unknown coefficients one has to apply to the BF to find the equivalent electric (magnetic) currents, $\mathbf{b}_E$ ($\mathbf{b}_H$) the incident electric (magnetic) fields on the testing functions and η_m the impedance of medium m [10].

Now consider an infinitely thin impenetrable slab whose reaction to incident fields is described through Impedance Boundary Conditions (IBC) that links the total tangential electric and magnetic fields on each of its two sides:

$$\mathbf{E}_{t,1}^{\text{tot}} = Z_1 \hat{\mathbf{n}}_1 \times \mathbf{H}_{t,1}^{\text{tot}} \quad (3)$$

$$\mathbf{E}_{t,2}^{\text{tot}} = Z_2 \hat{\mathbf{n}}_2 \times \mathbf{H}_{t,2}^{\text{tot}} \quad (4)$$

with Z_i the impedance on side i of the slab, $\mathbf{E}_{t,i}^{\text{tot}}$ ($\mathbf{H}_{t,i}^{\text{tot}}$) the total electric (magnetic) field on side i of the slab at position $\mathbf{r}$ and $\hat{\mathbf{n}}_i$ the outer normal to the surface i of the slab. Note that since the slab is considered infinitely thin, both sides of the slab converge to a single surface, so that one position $\mathbf{r}$ may be on either side of the slab.

Using these boundary conditions and testing them on a given set of testing functions, considering that the fields vanish inside the slab and, following a reasoning similar to [5], one finally finds that equivalent currents on that slab are found imposing

$$\left[\underline{\underline{Z}} - \begin{pmatrix} \frac{Z_1 Z_2}{Z_1 + Z_2} \underline{\underline{G}} & \frac{Z_1 - Z_2}{Z_1 + Z_2} \underline{\underline{H}} \\ \frac{Z_1 - Z_2}{Z_1 + Z_2} \underline{\underline{H}} & \frac{1}{Z_1 + Z_2} \underline{\underline{G}} \end{pmatrix} \right] \cdot \begin{pmatrix} \mathbf{x}_J \\ \mathbf{x}_M \end{pmatrix} = - \begin{pmatrix} \mathbf{b}_E \\ \mathbf{b}_H \end{pmatrix} \quad (5)$$

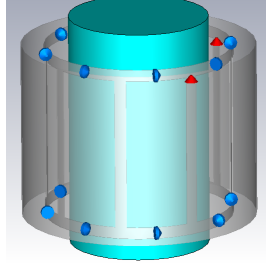


Figure 1. Geometry of the birdcage antenna studied. The blue arrows correspond to lumped capacitors, while the red arrows correspond to the two ports.

with

$$G_{ij} = \iint \mathbf{f}_j^B(\mathbf{r}) \cdot \mathbf{f}_i^T(\mathbf{r}) dS, \quad (6)$$

$$H_{ij} = \frac{1}{2} \iint \left(\hat{\mathbf{n}}_1 \times \mathbf{f}_j^B(\mathbf{r}) \right) \cdot \mathbf{f}_i^T(\mathbf{r}) dS, \quad (7)$$

with $\mathbf{f}_j^B$ ($\mathbf{f}_i^T$) being the j^{th} BF (i^{th} TF). Note that the above formula is only valid for constant surface impedance. If the impedance is varying over the surface, the factors involving the impedance in (5) should be included within the integral in (6) and (7). It is important to notice that the overhead for the computation of the $\underline{G}$ and $\underline{H}$ matrices is very small since the matrices are largely sparse and that the integrand is generally smooth. Moreover, if the impedance of the surface is constant by part and the meshing is conformal with respect to these parts, the $\underline{G}$ and $\underline{H}$ matrices only need to be computed once.

3. Numerical validation

In order to validate our results, we simulated a full 7T MRI device made of the 8-legs birdcage within a shielding surface presented in [9] (see Fig. 1). In order to mimic the presence of a body, a dielectric cylinder has been put inside the birdcage, with a relative permittivity $\varepsilon_r = 61$ and a conductivity of $\sigma = 0.8$ S/m. The birdcage is made of perfectly conducting strips with lumped capacitors of 11 pF located on the upper and lower rings, halfway between each leg. It is excited by two 50Ω ports linking the top of two legs to the upper ring. These legs are chosen to be separated by a $\pi/2$ angle in order to efficiently excite the birdcage. The radius of the shielding is 10 cm and its height is 15 cm. The birdcage is made of 1 cm wide PEC conducting sheets. Its height and radius are 15 cm and 8 cm, respectively. The phantom is 20 cm high and its radius is 6 cm.

The 8-fold symmetry of the structure has been exploited in the simulations; details about the code used (symmetries, frequency sweep, etc.) can be found in [9] where the same geometry has been simulated for PEC shielding. In order to validate the presented method, the S parameter of the two ports have been computed for a very-low impedance surface ($Z_1 = 0.01 \Omega$ and $Z_2 = 0.01 \Omega$) and for high-impedance inner surface ($Z_1 = 1e5 \Omega$ and $Z_2 = 0.01 \Omega$), and the results compared with CST [11]. For CST, perfect electric conductor (PEC) and perfect magnetic conductor (PMC) have been used to mimick these extreme values of the impedance. The results can be seen in Figure 2. The phase-shift in the resonances (about 5%) is probably due to the differences in the model used for the simulations (implementation of the lumped elements, infinitely thin PEC sheet vs. 3D strips, etc.). Except for that systematic frequency shift, often encountered when comparing different methods with different meshings, the results are very similar. It can be seen that the presence of the PMC shielding is globally red-shifting the resonances. Adjusting the value of the capacitance, the second resonance can be blue-shifted

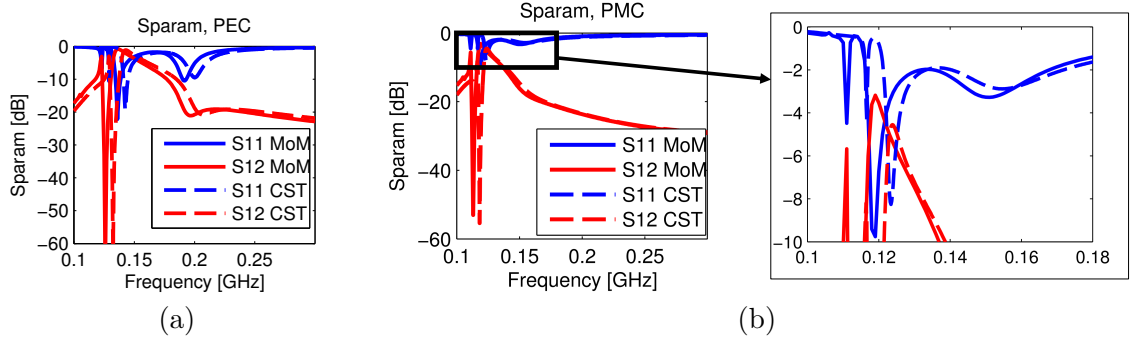


Figure 2. S-parameters of the birdcage antenna for (a) PEC and (b) PMC shielding. For the PMC case, a zoom on the results is provided for better readability.

back to 200 MHz. However, in this case, the homogeneity of the B_1^+ field remains better in the PEC case than in the PMC case. It is due to the fact that the whole geometry was originally designed for a PEC shielding. A complete redesign, with a possibly smaller radius for the shielding, should be conducted in order to provide a fair comparison, which is out of the scope of the present paper.

The CST simulations took about 30 minutes per graph, while the MoM code took about 12 minutes for the first graph, and then 90 additional seconds for every successive graph. Note that the MoM code has not been parallelized so far, so that it is running on a single CPU, while the CST software is using 4 CPU by default.

Conclusion

We presented a numerical method that rapidly simulates a birdcage MRI antenna with a shielding whose surface impedance can be varied at will. Dealing with surface impedances rather than PEC boundary conditions only involves a small overhead in the computational time. Moreover, once the simulation has been carried out for a given surface impedance, many terms can be reused for subsequent simulations, so that rapid sweeping can be achieved. It proves to be very useful in design steps, where simulations have to be run for a wide range of surface impedances. The results obtained using this method were compared with results from a commercial software.

Acknowledgements

This project has received funding from the European Union Horizon 2020 research and innovation program under grant agreement No. 736937.

The authors would like to thank Marc Dubois for the design of the birdcage used as an example.

References

- [1] Chen Z, Solbach K, Erni D and Rennings A 2015 *Microw. Conf. (GeMiC)* 111-4
- [2] Saleh G, Solbach K and Rennings A 2012 *European Conf. on Antennas and Propagat. (EuCAP)* 1399-401
- [3] Hurshkain A A *et al.* 2016 *J. Magn. Reson.* **269** 87-96
- [4] Chen Z, Solbach K, Erni D and Rennings A 2016 *IEEE Trans. Antennas Propag.* **64** 972-81
- [5] Bleszynski E, Bleszynski M and Jaroszewicz T 1993 *IEEE Trans. Antennas Propag. Mag.* **36** 14-25
- [6] Yan S and Jin J-M 2013 *IEEE Trans. Antennas Propag.* **61** 5533-46
- [7] Francavilla M A, Martini E, Maci S and Vecchi G 2015 *IEEE Trans. Antennas Propag.* **63** 2153-61
- [8] Glisson A W 1992 *Radio Science* **27** 935-43
- [9] Echeveste J I *et al.* 2018 *European Conf. on Antennas and Propagat. (EuCAP)*
- [10] Poggio A and Miller E 1973 *Computer techniques for electromagnetics* (Oxford UK:Pergamon Press)
- [11] (2018) CST *Microwave Studio* [Online]. Available: <https://www.cst.com>