Comparison of different simulation methods regarding their feasibility for MRI coil design

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Introduction: Loop antenna arrays are the major components for reception in magnetic resonance imaging systems. Typically they consist of copper conductors and a certain number of lumped capacitors, inserted in the resonant loop [1]. For the calculation of the corresponding field distribution and the resulting SNR (signal to noise ratio) or SAR (specific absorption rate) 3D full wave field calculation software is typically used. In order to additionally reduce simulation time, a co-simulation procedure, that includes matching of the antenna in a post-processing step, can be applied without significantly influencing the reliability of the results [2]. Simulation inaccuracies and variations of components, e.g. leading to incorrect capacitor values, can be compensated by further fine-tuning of the manufactured antenna setup. Other antenna design types are so called split ring resonator coils (SRR-coils) [3].On the contrary to the previous, tuning of the antenna after the manufacturing step is not feasible. This characteristic feature demands a highly accurate simulation method. Otherwise the measured resonance frequency might not match the simulation results (cf. Fig 1). In the following, different simulation methods are compared, including various meshing techniques in time and frequency domain simulations, regarding their suitability of accurately calculating these complex antenna structures. The focus is set on accuracy of the results (in this case resonance frequency) as well as simulation time and mesh density.

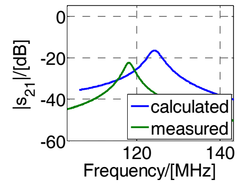


Figure 1 Simulated and measured $|s21|_{dB}$ of a self resonant loop placed 5cm above a conducting phantom

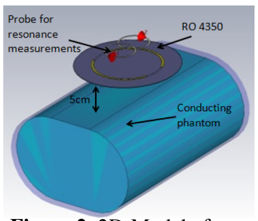
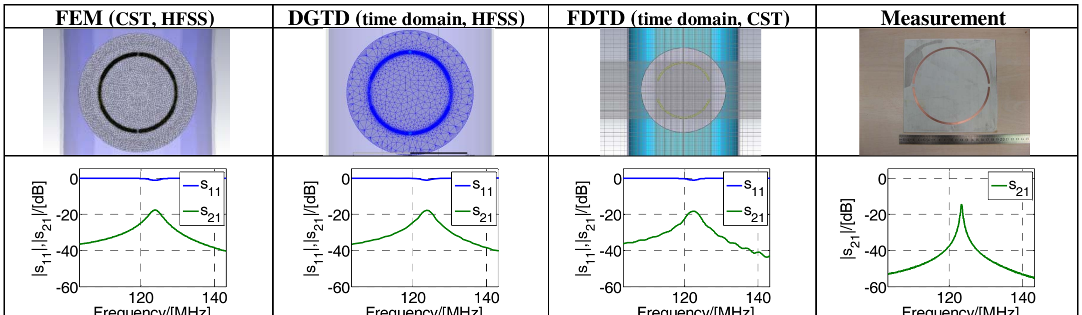


Figure 2: 3D-Model of simulation setup

Basic principle & Methods: The chosen simulation design consists of a pair of circular copper loops (diameter = 10cm, width= 5mm) on a dielectric substrate, placed on top of each other in a distance *d*. The thickness of the substrate as well as its characteristic features influence the resulting capacitance used for matching [3]. Each loop contains two discontinuities (gaps), which are oriented opposite to another. The adequate capacitance is defined by varying the size of the overlapping areas. What makes modelling difficult is that the substrate height of typically only a few hundreds of microns is orders of magnitude smaller than the overall dimensions of the copper structure. The grid has to be matched perfectly to the structure, as slight variations of the copper length or width can corrupt the results. Figure 2 illustrates the basic simulation model. The substrate for all calculations was RO4350 ($\varepsilon_r = 3.66$, thickness $d = 0.8$ mm, tan $\delta = 0.003$). It includes two decoupled PEC-loops, placed above the SRR-loops in order to determine the resonance frequency. Furthermore a liquid-filled phantom ($\sigma = 0.5$ S/m, $\varepsilon_r = 81$) was included in the simulation setups at a distance of 5 cm to the self-resonant loop. The main purpose of the conducting phantom is to reduce the inherently high Q factor of the self resonant structure and thereby help to meet convergence criteria in time domain simulations in an acceptable amount of time. Two simulation tools have been chosen for evaluation: Microwave Studio (CST, Darmstadt, Germany) and HFSS (Ansys, Canonsburg, USA), both offering time as well as frequency domain simulations. Each calculation method requires it own specific meshing procedure. For FEM simulations (frequency domain) a tetrahedral grid is advantageous and thus can be found in both simulation tools. However the tools use different meshing strategies in their time domain options: a hexahedral grid (FDTD) is used in Microwave Studio whereas HFSS also applies tetrahedral meshing (DGTD). All simulations have been performed on a 24 core dual Intel Xeon computer. In order to evaluate the simulation results, the loop has been manufactured on RO4350 substrate, using dimensions given by frequency simulations in HFSS. The resonance frequency is measured with a dual loop coil in a shielding box without phantom.

Results: Regardless of time or frequency domain method and the choice of the specific software, the initial mesh has to be carefully adapted to the structure. Otherwise simulation time will increase massively if adaptive meshing is used or on the other hand without adaptive meshing results will be incorrect. Automatic meshing is often not sufficient and should therefore not be used. For round structures tetrahedral meshing is the appropriate method and is used in both FEM and in the ANSYS GDTD simulation. The maximum grid size of the copper rings was set to 2 mm, so that convergence criteria ($|\Delta S| = 0.01$) in FEM is met after 8 passes and the number of mesh cells is only increased by 19%. A coarser initial mesh will deteriorate the results. This behaviour could be observed in both FEM simulations in HFSS and CST. The hexahedral grid (FDTD) required special attention since it is more difficult to approximate the round copper structure with squares. A suitable solution and compromise between accuracy and simulation time is a maximum grid length of 1mm. The often propagated use of sub gridding to reduce mesh cells and simulation time led to wrong results and thus should not be considered for these high accuracy problems. Figure 3 gives a summary of all setups. All calculated resonance frequency results differ only 1% to the measured one. FEM simulation techniques in a small frequency range enable an immense saving of time in comparison to time domain simulation. The number of mesh cells of the DGTD setup is comparable to the FEM simulation however simulation duration is increased by a factor of 3.5. Using a hexahedral grid also provides accurate results, however the long simulation time (more than 10 times longer than for the FEM simulations) might be impractical for fine tuning of a more complex SRR-loop array structure.



FEM (CST, HFSS)	DGTD (time domain, HFSS)	FDTD (time domain, CST)	Measurement
Meshcells: ~320 thousand	Meshcells: ~330 thousand	Meshcells:~3,8 mio	Res.frequency: 123.4MHz
Simulationtime: 40min	Simulationtime: 2h20min	Simulationtime: 9h10min	
Res. frequency: 123.9MHz	Res. frequency: 123.9MHz	Res. frequency: 122.5MHz	

Figure 3: Model, results, mesh cells and simulation time of the different calculation methods

Conclusion: Within this paper the feasibility of different numerical simulation approaches to design a self resonant loop antenna was shown by a comparison between different calculation methods and meshing techniques. The FEM or DGTD simulation method with a tetrahedral grid seems to be the method of choice for simulations, which require highly accurate results in a limited amount of time. FDTD simulation are more time consuming, however it could be shown, that a manually defined adequate mesh grid leads to sufficiently precise simulation results, too. This might be of particular interest if SAR calculations in combination with human body voxel models, which do not support tetrahedral meshing, have to be carried out. **References:** [1] Roemer P.B., et.al.: The NMR Phased Array, MRM 16, 192-225 (1990) [2] M. Kozlov et.al.: "Fast MRI coil analysis based on 3-D electromagnetic and RFcircuit co-simulation" JMRI, Vol. 200 147-152, 2009 [3] Fackelmeier A., Martius S.: Patent 2012E04548 DE [4] S. Martius, et. al. "Mutually decoupled self-resonant local coil array", BMT-Hannover 2014