Validation of Electromagnetic Field Simulation for MR Coil Design at 3 Tesla

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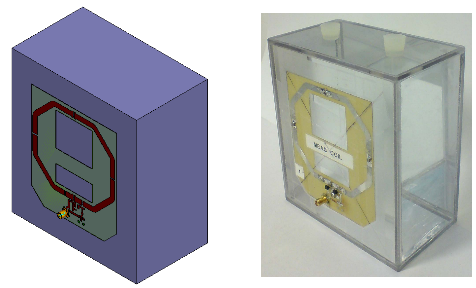
Introduction

RF Coil development and design is a difficult engineering task due to its iterative nature. Electromagnetic field simulation programs are a promising tool to simplify and shorten development-, design-, and tune-procedures of coils. For design procedures accurate simulation results are key. Therefore, special care needs to be taken to incorporate the proximity to dielectric media and the frequency dependent behavior of the media. Additionally lumped elements and their electrical representation at high frequencies needs to be taken into account. In this work, electromagnetic field simulation software was evaluated for usage as a design-supporting tool. Key simulation parameters were identified. Then the software was optimized to match actual network parameters and an experiment was designed for comparison and measurement on a 3T GE Excite HD system.

Materials and Methods

For simulation and measurement, a simple setup was chosen, depicted in Figure 1. The setup contained a rectangular Lexan phantom filled with 0.9 % saline solution. The phantom measured 150.9 mm x 140.0 mm x 80.0 mm, with a wall thickness of 4.0 mm. Two holes were drilled at the top of the phantom for filling. A coil was placed directly onto the phantom. The Printed Circuit Board (PCB) with the coil traces had the dimensions of 112.0 mm x 95.0 mm. A regular FR4 substrate with a thickness of 350 µm was chosen. On the inner side of the conductor the PCB had cut outs. The coil had an octagonal shape. The conductor had a total thickness of 75 µm. Capacitors (33 pF, 47 pF, 51 pF) with a tolerance of ±1 % were equally distributed around the octagonal shaped coil. Two 5 nH inductors with ±2 % tolerance were added for matching to 50 Ω. This setup was implemented into HFSS Version 11 (Ansoft Inc., Pittsburgh). For the simulation a Design of Experiment (DOE) with six factors using a fractional factorial design was performed, including five unbalanced pseudo center points. These factors were: i) equivalent circuit for the capacitors, ii) capacitor tolerances, iii) inductor tolerances, iv) number of meshed tetrahedra, v) conductivity of the saline solution, and vi) dielectric constant of the medium. The coil sensitivity was analyzed in a plane 20.0 mm below the coil. Network measurements were performed with an Agilent 4593A Vector Network Analyzer (VNA). Calibration of the VNA was done with a Rosenberger RPC-3.50 Calibration Kit. Coil imaging was performed on a 3T GE Excite HD system with a 16-channel TEM transmit body coil [1].



a) **b)**

Figure 1: **a)** Simulation setup: all components are designed three-dimensional instead of the lumped elements. They are modeled as sheet object **b)** Measurement setup

Results

The circuit and model components were analyzed in detail to determine which had the most significant impact on the simulation results. Additionally the DOE provided the interaction between the significant parameters, depicted in Table 1. The final simulation settings for the six factors were: an equivalent circuit, -1 % capacitor tolerance, -2 % inductor tolerance, numerous meshed thetrahedra, 1.55 S/m conductivity, and a dielectric constant of 77.53. Simulation settings and results for matching were calculated in advance. A resonance at 126.8 MHz was found for measurement and simulation. At resonance, the impedance 52.0415 Ω and -j0.4296 Ω was simulated and 53.6370 Ω and -j0.5365 Ω was measured. In Figure 2 measurement was compared to two simulation setups: one with optimized parameters, the other with default parameters (idealized components). Receive sensitivity maps were measured with correction for the non-uniform transmit sensitivity [2] in Matlab for comparison, Figure 3.

Conclusion and Discussion

In summary, a very good agreement between simulation and measurement could be achieved. Therefore, simulation parameters were adopted to match actual measurement results using a DOE approach. The factorial fit analysis provided insight in the interactions of the different factors that influence coil frequency and impedance. Therefore, it was possible to calculate the optimal simulation setting and the simulation results in advance, increasing efficiency of the coil tuning. A deviation of about 3 % in the peak impedance and zero deviation in the resonance frequency could be achieved. A sensitivity shift off-coil-center was found in the simulation and experimentally measured [3], depicted in Figure 3. The comparison of the results received from simulation and measurement showed a small deviation in the field patterns. Potential error sources were: geometrical uncertainty in the slice position and orientation, interaction with the body coil and RF shield, and different excitation setup. Analysis of different geometrical designs as well as different lumped element configurations is a work-in-progress to conclusively confirm the validity of the simulation. Noise parameters like temperature dependency were not considered.

Term	P-Value for	
	Frequency	Real Part
Equivalent circuit capacitors	0.000	0.002
Capacitor tolerances	0.000	0.443
Inductor tolerances	0.161	0.112
Number of mesh	0.000	0.000
Conductivity	0.000	0.000
Dielectric constant	0.236	0.000
Equivalent circuit capacitors * Capacitor tolerances	0.008	0.039
Equivalent circuit capacitors * Number of mesh	0.000	0.000
Number of mesh * Dielectric constant	0.016	-
Equivalent circuit capacitors * Capacitor tolerances * Inductor tolerances	0.040	-

Table 1: DOE results for significant terms. Significant terms with p-value < 0.05

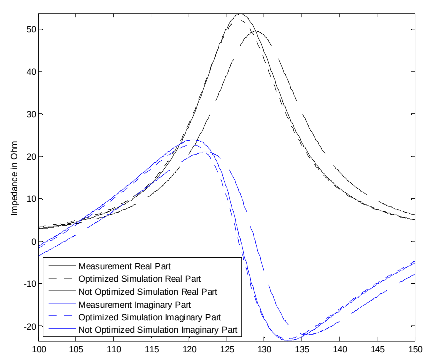


Figure 2: Comparison of complex impedance over frequency between measurement and simulation.

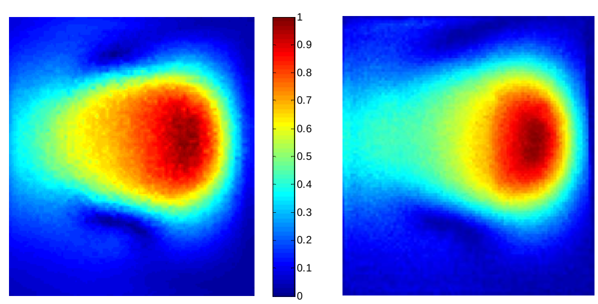


Figure 3: Normalized sensitivity maps for simulation (left) and MR-image (right) taken from a plane 20.0 mm below the coil.

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