Software-based optimization of coil geometries for decoupling a pair of loop and Fo8 elements: does separation between coil elements matter?

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Introduction: MRI data acquisition that uses radio frequency (RF) coils with multiple elements has been utilized for about 25 years [1]. It is used widely used in today's scanners. In some of these RF coil arrays, a traditional loop element is combined with a figure-of-eight (Fo8) (aka. butterfly) element to increase sensitivity. The two elements are inherently decoupled and their orthogonal field profiles in the region of interest provide higher signal-to-noise ratio (SNR) by quadrature detection [2]. In practice, there is some degree of coupling between the elements, which affects the performance of the RF coil array. It can be expected that the relative dimensions of the elements are critical for minimal coupling. Moreover, we anticipate that the dimensions required for minimum coupling will change when the distance between the two elements change (e.g. thickness of the coil former). Therefore one needs to find the optimal dimensions for those coils for specific designs before building the actual probe. For that purpose, accurate simulation of these RF coil arrays would be needed to maximize the coil's performance. Quasistatic approximation (Biot-Savart calculations) does not provide the required accuracy, especially for high field MRI systems in which the wavelength of electromagnetic fields within the human body becomes comparable to the dimensions of the body. One way of solving the problem is to derive closed forms of Maxwell's equations analytically, but these solutions can only be found for specific geometries. For complex heterogonous objects and sophisticated coil configurations, a numerical technique such as Finite Element Method (FEM) would provide a solution yielding sufficient accuracy. In this study we developed a software that uses FEM-based RF electromagnetic field modeling to simulate the coils and a least squares approach to automatically calculate the optimal geometries of a pair of loop and Fo8 coil elements to minimize coupling. We also investigated how the coil dimensions should change for maximum decoupling when the distance between those elements was increased.

Method: In this study we have used FEM-based RF simulation methods implemented by the HFSS software (High Frequency Structure Simulator, ANSYS Inc, Canonsburg, PA, US). Salon et al [3] reported that FEM-based simulation techniques in RF simulations provided better accuracy for high quality factor structures, such as MRI RF coils. In addition, the s-parameters for all ports are calculated in a single run. For our optimization algorithm, a realistic parametric model of overlapping loop and Fo8 elements was created in the HFSS program. The coil conductors were simulated as copper foils (width: 6.35mm, thickness: 0.04mm) and distributed capacitors were implemented for tuning and matching. The operating frequency was selected as 127.73MHz (f_0), which corresponds to proton imaging at 3T. The coil was loaded with a two-layer spherical phantom that mimicked human head. The electrical properties of the inner compartment were selected as the weighted sum of white matter, gray matter and CSF values at f_0 (radius:8.1cm, σ:0.57S/m, loss tangent:1.19, permitivity:$63.4\varepsilon_0$) [4]. For the outer layer, weighted sum of skull's and scalp's properties were used (radius:8.8cm, σ:0.57S/m, loss tangent:0.97, permitivity:$35.8\varepsilon_0$). In order to find dimensions of the two coil elements to achieve minimum coupling, the dimensions of the loop coil were varied using a least squares approach while the size of the Fo8 element was fixed to 7cm in x and 17cm in z directions. Before simulating the combined coil system, the Fo8 coil was first tuned and matched to 50Ω terminal impedance (S_{11}=-24.5dB @ 127.73MHz) in the absence of the loop element. Then, the combined loop and Fo8 elements were simulated to calculate RF field distributions and the s-parameters. Note that the loop was terminated with 50Ω but it was not tuned or matched until the final geometry for minimum coupling was obtained. This eliminated the need to readjust matching and tuning of the loop every time the dimensions were changed by the least squares technique. Using the loop size in x and z directions as variables, the Quasi-Newton method [5] was implemented to optimize the loop size with respect to the Fo8 element. Equally weighted Euclidian norm of forward transmission coefficient (S_{12}: Fo8 to Loop) and input reflection coefficient (S_{11} of Fo8) at f_0 was used as the cost function. The rationale behind choosing this cost function is that the coupling between the coil elements causes both S_{12} and S_{11} parameters to increase at f_0. If there is significant coupling between the elements at the resonance frequency, S_{12} increases and results in a frequency split in S_{11} parameter [6]. Therefore, both S_{11} and S_{12} have to be minimized for maximum decoupling. The proposed dimension-optimization procedure was applied to three different cases where the distance between the loop and Fo8 elements (i.e. coil separation) was increased to investigate the effect of distance on the optimal coil dimensions for maximum geometrical decoupling. The tested coil distances were 0.2cm, 0.4cm and 0.8cm. The dimensions of the loop coil were allowed to vary between 4.2cm and 12.5cm in x direction and 8.5cm and 26cm in z direction to find optimal dimensions within a practical range.

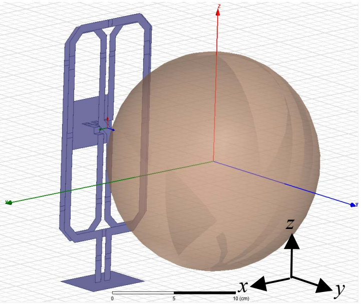

Figure 1. Fo8, Loop coils and head model.

Results: A single iteration for optimization took about 40 minutes with an i7 CPU and 16GB RAM PC. A sketch of the optimal coil geometry for 0.2cm separation is shown in Fig.1. The relative position of the phantom is also shown in the figure. For each case, the dimensions calculated by the optimization program, the s-parameters and the number of iterations to reach the optimal solution are listed in Table 1.

Table 1. Coil separation vs optimized coil

Coil Sep.	***x size***	***z size***	***S_{11}***	***S_{12}***	***#of iter.***
0.2cm	8.28cm	18.16cm	-24.2dB	-27.3dB	16
0.4cm	8.13cm	20.02cm	-34.5dB	-27.4dB	19
0.8cm	7.43cm	22.16cm	-31.4dB	-30.6dB	15

Conclusion: In this study we demonstrated the feasibility of an algorithm that can calculate the dimensions of a pair of coils automatically to achieve maximum decoupling. The details in the simulations were implemented to reflect the actual physical setup as close as possible. Using this technique, we showed that precise dimensions of the coil elements in a loop-Fo8 combination are critical in minimizing coupling and improving overall coil performance. Moreover, we demonstrated that even small changes in the separation between the coils require significant changes in coil dimensions to achieve the best geometric decoupling. For instance, the loop has to be approximately 1.2cm larger in both directions for 2mm separation. However, as the coil separation increases, the dimensions of the loop coil decreases in x direction by 0.15cm – 0.7cm and increases in z direction by almost 2cm for each step of increase in separation. This serves as a convenient tool in finding optimal coil geometry automatically before building a coil array. It should be noted that this framework can be used not only in decoupling coils but also in optimizing different cost functions such as maximizing SNR in a target region, or minimizing g-factor or specific absorption rate.

References:

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