

Efficient Optimal-Numerical-Analytical Computation: Segmented Spiral Coil at High Field

X. Chen¹, X. Shou¹, Y. Wu¹, M. Zhu¹, M. A. Griswold², H. Fujita^{1,3}, and R. W. Brown¹

¹Department of Physics, Case Western Reserve University, Cleveland, OH, United States, ²Department of Radiology, University Hospitals of Cleveland, Cleveland, OH, United States, ³Quality Electrodynamics LLC, Mayfield Village, OH, United States

Introduction: RF field non-uniformities caused by shortened RF wavelengths in human tissue significantly affect the image quality, especially for high-field MRI [1]. Spiral coils [2, 3] have been put forth to improve field homogeneity. In addition, RF shimming based on a TEM coil [4] or an RF transmit array [5] is an efficient method to address such non-uniformities. In this work, we combine these approaches and present a modeling of a spiral coil utilizing an efficient computational numerical-analytical optimization to achieve RF shimming. The results are encouraging even at the rather high RF frequency of 400MHz, which corresponds to 9.4T Hydrogen imaging.

Methods: A model is constructed to simulate the spiral coil presented in [3]. As illustrated in Figure 1, 16 circumferential and 15 axial segments are distributed on a cylindrical surface with a diameter 25cm and a length 40cm. Each circumferential segment spans approximately 102 degrees in azimuthal angle. All the segments are assumed to be infinitely thin wires with negligible cross sections. Each segment (either circumferential or axial) carries an independent current source. (While it is omitted for simplicity, the RF shield has been incorporated in similar modeling and can serve as a current return path.) We further assume an average dielectric medium with zero conductivity and a constant dielectric permittivity value of 50 chosen to represent the average human head properties at 400MHz [6]. In this case, the RF wavelength in the dielectric media is approximately 10.6cm. The assumption is also made that this medium fills all space; numerical simulations for similar segmented coils have shown that the air gaps can be accounted for by introducing a nonzero effective conductivity [7]. The RF magnetic field produced by a single segment, which carries a current with magnitude I_0 and phase δ_0 , is given by:

$$\mathbf{A}(\mathbf{r}) = \frac{\mu_0 I_0 e^{i\delta_0}}{4\pi} \int \frac{e^{-ik|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|} d\mathbf{l}' \approx \frac{\mu_0 I_0 e^{i\delta_0}}{4\pi} \sum_{n=1}^N \frac{e^{-ik|\mathbf{r}-\mathbf{r}'_n|}}{|\mathbf{r}-\mathbf{r}'_n|} d\mathbf{l}' \quad \mathbf{B}(\mathbf{r}) = \nabla \times \mathbf{A}(\mathbf{r})$$

The vector potential $\mathbf{A}(\mathbf{r})$ is approximately calculated by dividing the segment into a number of elements $d\mathbf{l}'$, and summing all their contributions. The RF field produced by the whole spiral coil model $\mathbf{B}_{coil}(\mathbf{r})$ is then determined as the superposition of the fields of all individual segments $\mathbf{B}^{(i)}(\mathbf{r})$:

$$\mathbf{B}_{coil}(\mathbf{r}) = \sum_i \mathbf{B}^{(i)}(\mathbf{r})$$

A function is then constructed to impose the constraint of a homogeneous RF field at $M=197$ constraint points in the central transverse plane:

$$W(I_1, \delta_1, I_2, \delta_2, \dots, I_N, \delta_N) = \sum_{i=1}^M [B_{coil}(r_i) - B_t(r_i)]^2$$

where $B_t(r_i)$ is the (uniform) target field at the i th constraint point. The function is then minimized with respect to current amplitudes and phases $I_1, \delta_1, I_2, \delta_2, \dots, I_N, \delta_N$, and the optimal RF field profile is thereby produced.

Results and Discussion: Figure 2 shows the RF field profile in the central transverse plane for the optimized spiral coil. Compared with a conventional birdcage coil model with the same size, the RF field inhomogeneity, estimated as the maximum RF field magnitude deviation from the isocenter, is reduced from 90% to 20%. It has been previously demonstrated that the spiral coil can improve the RF field homogeneity significantly at 170MHz (4T proton imaging) using a current phase oscillation along the axial direction resulting directly from the spiral geometry [3]. Nevertheless, recent simulations [8] have shown that at ultra-high RF frequency (400MHz), the improvement of the RF homogeneity with an unsegmented spiral coil is limited. We therefore combine the advantages of the spiral coil geometry and RF shimming to feed each segment with an independent current source. The RF field homogeneity is improved significantly even at the ultra-high RF frequency 400MHz. Furthermore, the circumferential current flow on a spiral coil, which produces a significantly different EM field profile compared with axial current flow, provides more flexibility for RF field optimization. The proposed “target-field” optimization approach is very efficient (computation can be done within a few minutes on today’s personal computers), and can be applied to different kinds of RF coil geometries. Further studies are in progress to find effective conductivity parameters and an optimized RF shield.

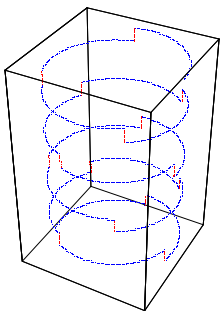


Figure 1: A spiral coil model. The circumferential segments are in blue, and the axial segments are in red. Note that each segment is driven by an independent current source.

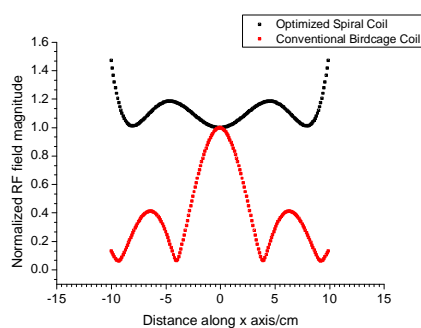


Figure 2: Normalized RF field magnitude plotted along x axis in the central transverse plane for an optimized spiral coil (black) and a conventional birdcage coil (red).

References:

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