A NEW ACCURATE FEM BASED OPTIMIZATION METHOD FOR BIRDCAGE COIL DESIGN AT HIGH FIELD STRENGTH

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Target Audience: MR technicians, RF engineers and the researchers with an interest in design and simulation of RF coils.

Introduction: Designing RF birdcage coils at high field strength is a challenging task. As the operation frequency increases, wavelength becomes comparable with the coil dimensions and the size of the human body. Therefore, using lumped element circuit models, which are based on the quasi-static field approximations, will not be appropriate for the accurate design and simulation of the coil. In this study, we present an accurate method and a software tool for the capacitance calculation of low-pass and high-pass birdcage coils using a Finite Element Method (FEM) based optimization algorithm. For the verification of the algorithm, we have constructed 8-leg low-pass and high-pass birdcage coils (Fig. 1) and capacitance values used in the experiments are compared with the capacitance values calculated using our algorithm and also with the capacitance values obtained by the widely used software BirdcageBuilder[1] which is based on a lumped element circuit model.

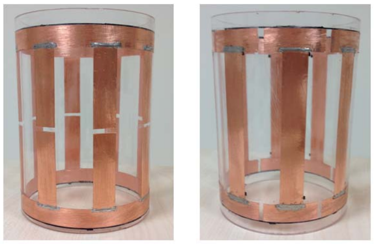

Figure 1. *8-leg low-pass (left) and high-pass (right) birdcage coils with a diameter of 11.5 cm and length of 16.5 cm. (without capacitors)*

Methods: FEM models of low-pass and high-pass birdcage coils are built in COMSOL Multiphysics (COMSOL AB, Stockholm, Sweden).[2] Optimum capacitance value is calculated for the given resonance frequency by using two different objective functions: magnitude of the port impedance ($|Z_{11}|$) and the variance of $|H^+|$ ($Var(|H^+|)$). We know that $|Z_{11}|$ of the coil reaches its maximum values at the resonant modes and $Var(|H^+|)$ is supposed to have minimum value at the desired resonance frequency in order to generate a homogenous magnetic field in the region of interest. From the optimization point of view, we can find the optimum capacitance value that maximizes the $|Z_{11}|$ of the coil or minimizes the $Var(|H^+|)$ in the square region inside the coil (shown in Fig. 2) for the given frequency. By investigating these objective functions for different capacitance values (Fig. 3), we see that $|Z_{11}|$ makes a sharp peak, whereas the $Var(|H^+|)$ forms a shallow minimum at the desired frequency. Therefore, using $|Z_{11}|$ as an objective function seems more appropriate than using the $Var(|H^+|)$ because the minimum of a shallow region cannot be found accurately due to the numerical errors in the computations. On the other hand, since we use the gradient-based optimization method SNOPT[3] in COMSOL Multiphysics, using only $|Z_{11}|$ as an objective function may also give wrong results since the objective function may have more than one maximum point. Hence, we define a feasible region by looking at the $Var(|H^+|)$ graph (Fig. 3) since it has only one minimum point and make optimization using $|Z_{11}|$ as an objective function in this defined region in order to find the optimum capacitance value. Finally, we have developed a software tool using MATLAB GUI (Fig. 4) which connects to the COMSOL Multiphysics server, makes all the FEM based design and simulation calculations according to the user-specified parameters and calculates the optimum capacitance value automatically.

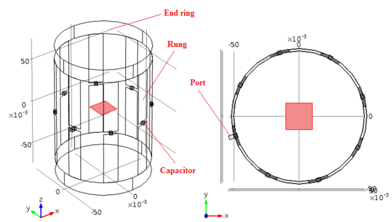

Figure 2. *8-leg low-pass birdcage coil model*

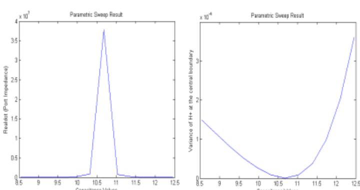

Figure 3. *$|Z_{11}|$ (left) and $Var(|H^+|)$(right) versus capacitance values*

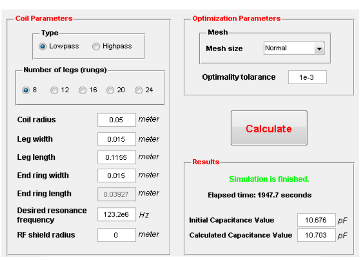

Figure 4. *GUI of the software tool*

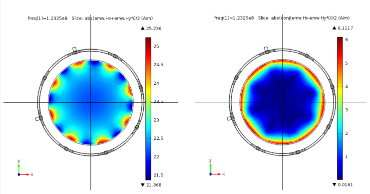

Figure 5. *$|H^+|$ (left) and $|H^-|$ (right) images for quadrature excitation*

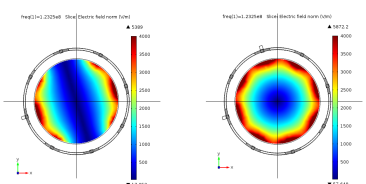

Figure 6. *$|E|$ field images for linear (left) and quadrature (right) excitation*

Results: Electromagnetic fields (H^+, H^-, and electric field (E)) at the central slice of the unloaded birdcage coil for the optimized capacitance value are shown in Fig. 5 and Fig. 6. As expected |H+| has uniform distribution and |H-| is close to zero in the central region of the coil for the quadrature excitation. Additionally, linearly and circularly polarized fields can be seen from |E| field images in Fig.6. For the experiment, resonance frequencies corresponding to the m=1 mode of each coil is determined by investigating the S_{11} graph using Agilent Technologies E5061A Network Analyzer for five different capacitance values (Dielectric Laboratories High-Q Multi-Layer and Broadband Blocking Capacitors). For these resonant frequencies, capacitance values are calculated using FEM based optimization tool (FEM-OPT) and BirdcageBuilder. Results for low-pass and high-pass birdcage coils are given in Table 1 and 2, respectively. The percentage error rate of the results of these two software tools relative to the values used in the experiment are illustrated in Fig. 7 and Fig. 8. It is observed that for both software tools, calculated capacitance values are almost same for the lower frequencies and error in the results increases as the desired frequency increases. However, increase in the error of BirdcageBuilder results is significantly greater than the increase in the error of FEM-OPT results. For the worst case scenario (f≈335 MHz, 7.87T), for instance, FEM-OPT calculates the capacitance value within 20-25% error whereas BirdcageBuilder calculates 45-50% error for both low-pass and high-pass birdcage coils.

Table 1. *Used and calculated capacitance values for low-pass BC*

Frequency (MHz)	Experiment (pF)	BirdcageBuilder (pF)	FEM-OPT (pF)
60.75	47	43.87	44.42
122.11	10	10.86	10.42
211.3	3.3	3.63	3.51
255.2	1.8	2.49	1.92
335.7	1	1.44	0.84

Table 2. *Used and calculated capacitance values for high-pass BC*

Frequency (MHz)	Experiment (pF)	BirdcageBuilder (pF)	FEM-OPT (pF)
75.25	100	99.27	100.34
131.4	30	32.56	32.3
182.5	15	16.88	16.03
245.0	7.5	9.36	8.65
334.26	3.3	5.03	4.2

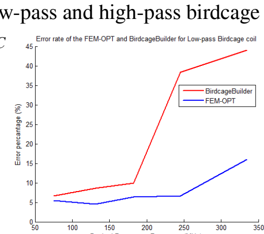

Figure 7. *Percentage error of the software tools for low-pass BC*

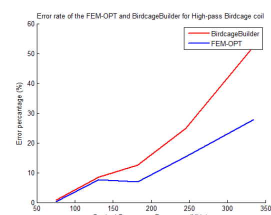

Figure 8. *Percentage error of the software tools for high-pass BC*

Discussion and Conclusion: Using the proposed algorithm for designing a birdcage coil, will reduce the duration of tuning and matching procedures by calculating a more accurate initial capacitance value, especially at higher frequencies. Additionally, this algorithm can be applied for loaded birdcage coils and using more than one control variable (capacitor values may not be equal) in order to achieve a homogenous magnetic field in a local region inside the coil. Furthermore, instead of optimizing the capacitance values, we can optimize the geometry of the coil to generate a desired field in the region of interest. This possibility for shape optimization will allow coil designers to build their own RF or gradient coils in the simulation environment. At present we are focusing on different RF and gradient coil designs in the light of optimization techniques.

References: [1] C. L. Chin, et al. Concept Magn. Res, 15 (2002). [2] N. Gurler and Y.Z. Ider, COMSOL Proc. (Milan, 2012). [3] P. Gill, et. al. SIAM, 47 (2005).

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