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Design and numerical simulation of a RF coil using the COMSOL Multiphysics software

Abstract. *The main purpose of numerical modelling of coils is the influence of a specific RF coil model (radio frequency) on medical imaging diagnostics system, resonance modes, currents and magnetic field distribution in resonance conditions, as well as identification of dielectric losses or noise sources. The article presents individual stages of RF coil design based on the example of a birdcage type volumetric coil with the use of COMSOL Multiphysics software. The article also contains simple electromagnetic simulations taking into account the material parameters of the conductive medium. (**Projektowanie i symulacje numeryczne cewki radiowej przy użyciu oprogramowania COMSOL Multiphysics**).*

Streszczenie*. Głównym celem modelowania numerycznego cewek jest wpływ określonego modelu cewki RF (o częstotliwości radiowej) na system medycznej diagnostyki obrazowej, tryby rezonansowe, prądy i rozkład pola magnetycznego w warunkach rezonansowych, a także identyfikacja strat dielektrycznych czy źródeł szumów. W artykule przedstawiono poszczególne etapy projektowania cewki RF na przykładzie cewki objętościowej typu birdcage przy użyciu oprogramowania COMSOL Multiphysics. Artykuł zawiera także proste symulacje elektromagnetyczne uwzględniając parametry materiałowe ośrodka przewodzącego. (**Design and numerical simulation of a RF coil using the COMSOL Multiphysics software).***

Słowa kluczowe: symulacje, częstotliwość radiowa, cewka, rezonans magnetyczny.
Keywords: simulations, radio frequency, coil, magnetic resonance.

Introduction

The MRI technique focuses on improving image quality, achieving the best possible tissue contrast, and maximising the SNR (signal-to-noise ratio). The SNR can be increased by using scanners with increasing values of magnetic field induction and contrast media, but it is the use of better RF coils which often provides much greater benefits.

In recent years, research on device design has been carried out to improve the contrast of the image. Most often, these studies are aimed at the construction of magnetic resonance systems that use progressively higher values of constant magnetic field. The compatibility of the coil with the system determines the quality of imaging, which is still a big challenge when choosing the right RF coil [4,5].

The design of the coil is constantly improved to provide the highest signal ratio and the best possible sensitivity. One of the most commonly used coils in magnetic resonance imaging is the birdcage type volumetric coil due to its wide homogeneous field production and ability to transmit/receive with a high SNR. [6-8].

Crucial for most preclinical studies is the imaging of small animals (mainly using birdcage coils). [9-11]. The paper presents a low-pass RF coil designed to operate at 297 MHz (high field MRI system, 7 Tesla).

Methods

The design and simulation of the coil was carried out in the COMSOL Multiphysics (COMSOL Inc.) environment. It is a simulation package solving systems of nonlinear partial differential equations, using finite element methods in one, two or three dimensions. In the case of RF coil design, three-dimensional modelling is the most appropriate.

Use was made of the RF Module, dedicated to the design of RF coils. The first step was to determine the appropriate parameters (Global Parameters), the definition of which greatly facilitates the introduction of possible changes in the model at any stage of design. The advantage of global parameters is the fact that in addition to the sizes associated with the geometry of the system, these can also be parameters for passive elements of the electrical circuit. In the case of a designed volumetric coil, global parameters include e.g. coil radius, coil height or the value of capacitors used.

The simulation coil used is an example of a volumetric coil consisting of 8 legs located symmetrically between two end rings, as shown in Figure 1. There are 3 capacitors on each leg of the coil, 24 in total. Two of them act as lumped ports.

After introducing the geometry of the system, the next step is to determine the materials of the individual elements. They can be selected from an extensive library of materials or defined the material on one's own. In the case of the RF coil, the main material is copper, from which the thin-film conductive medium is made. This material was selected from the library and its most important parameters are presented in the table below.

Tab.1. Material parameters of copper

Copper *(mat3)*

Property	Value	Unit
Relative permeability	1	1
Electrical conductivity	5.998e7[S/m]	S/m
Coefficient of thermal expansion	17e-6[1/K]	1/K
Heat capacity at constant pressure	385[J/(kg*K)]	J/(kg·K)
Relative permittivity	1	1
Density	8960[kg/m^3]	kg/m³
Thermal conductivity	400[W/(m*K)]	W/(m·K)
Young's modulus	110e9[Pa]	Pa
Poisson's ratio	0.35	1
Reference resistivity	1.72e-8[ohm*m]	Ω·m
Resistivity temperature coefficient	0.0039[1/K]	1/K
Reference temperature	298[K]	K

In order to be able to perform any simulation of the electromagnetic coil, it was necessary to introduce lumped ports into the system. For a volumetric coil, the coils are placed at an angle of 450 to each other as shown in the following figure. The birdcage coil was designed as a low-pass version, i.e. one in which the capacitors are placed on the legs of the coil and not on the end rings, as in the case of the high-pass version. [11]

The next step was to build a grid on all elements of the system involved in numerical calculations. The more dense the grid, the more accurate the calculations become, but at the same time the longer they take. The following figure (Fig. 2) shows a grid with medium density, completely sufficient for the simulations. In the analysis, apart from the coil (external cylinder), the cylinder inside the coil, which acts as a phantom, is also involved.

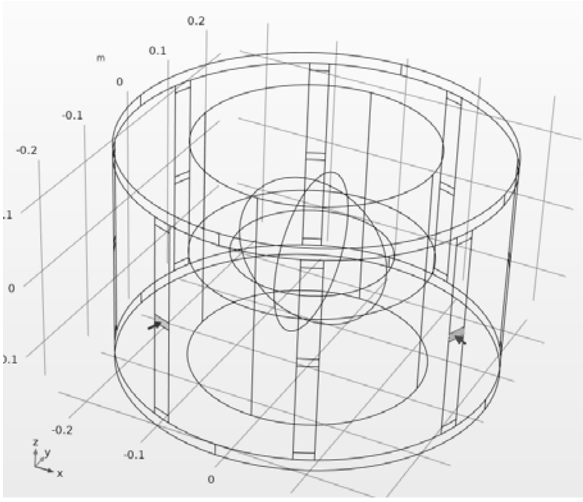

Fig. 1: Arrangement of concentrated ports marked with arrows.

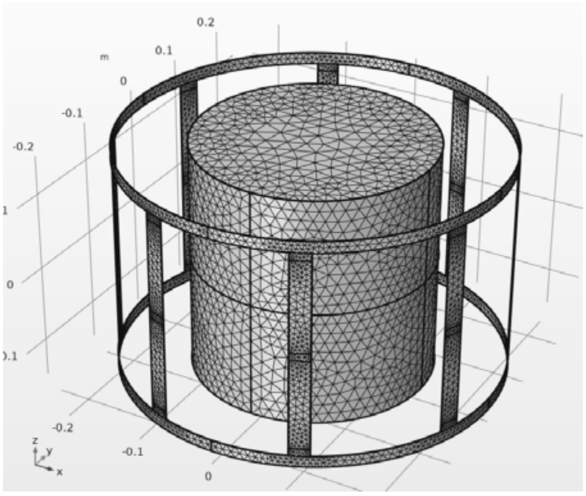

Fig. 2: Medium density grid created.

The last step before electromagnetic simulation is to determine what kind of analysis has to be performed. The COMSOL environment offers a wide range of possibilities. In this case, the Electromagnetic Waves group, Frequency Domain (emw) has been chosen, located in the Multiphysics tab. Here it is possible to select appropriate physical equations, which must be taken into account in the simulations and to provide basic parameters, such as e.g. reference impedances Z_{ref} = 50Ω.

Results

Coils of complex shape or spatial configuration already at the design stage require complex numerical simulations, based on the formulation of equations difficult for analytical solution.

Taking into account many factors influencing the final form of the coil, such as the environment in which the coil will eventually work or the heterogeneity of the sample, numerical methods are used to design the coils [1-3]. They can be classified according to whether the calculations are performed in the time domain or in the frequency domain, and whether the method concerns differential or integral equations.

The Fig. 3.a-d show the effect of capacitance values of the capacitors used (from 22.5 pF to 30 pF) on the distribution of the electric field generated inside the coil (perspective projection).

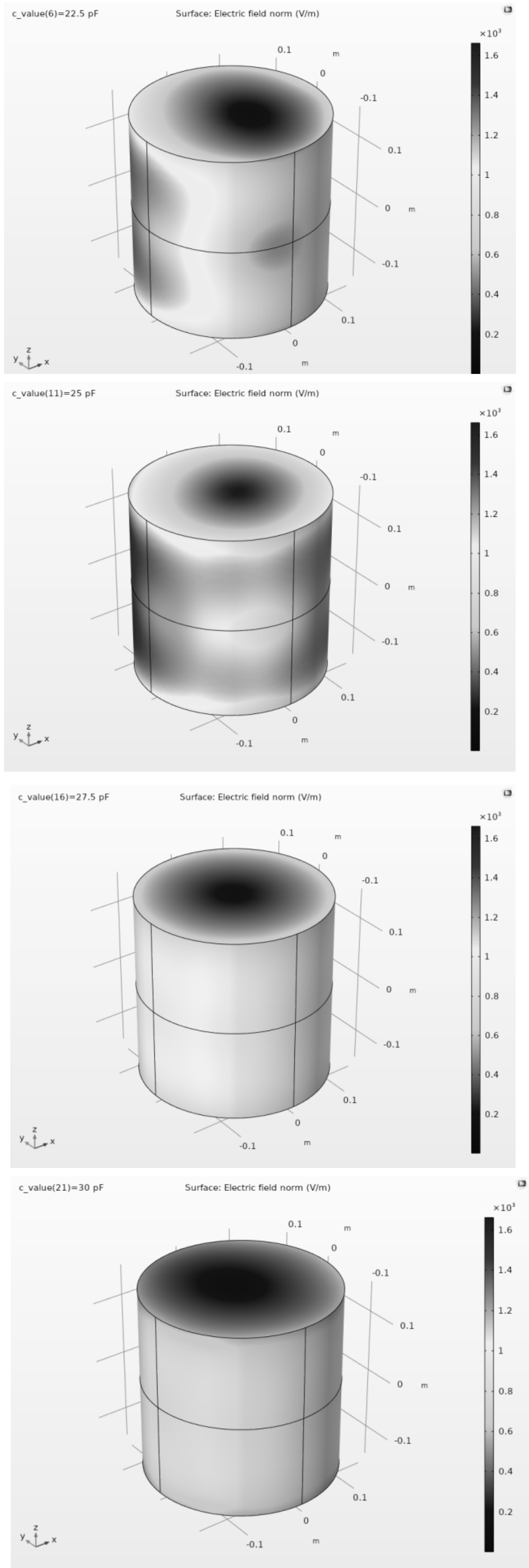

Fig. 3: Electric field distribution on the surface of the phantom for capacitors placed on a coil with a capacity of a) 22.5 pF, b) 25 pF, c) 27.5 pF and d) 30 pF.

It can be concluded that with the increase in capacitance of capacitors (placed at the ends and in the middle of each leg of the coil) the value of the field strength produced by the coil decreases and at the same time the homogeneity of the field inside the coil increases.

Figure 3 below shows the distribution of the electric field on the surface of the conductive elements of the coil for 30 pF capacitors.

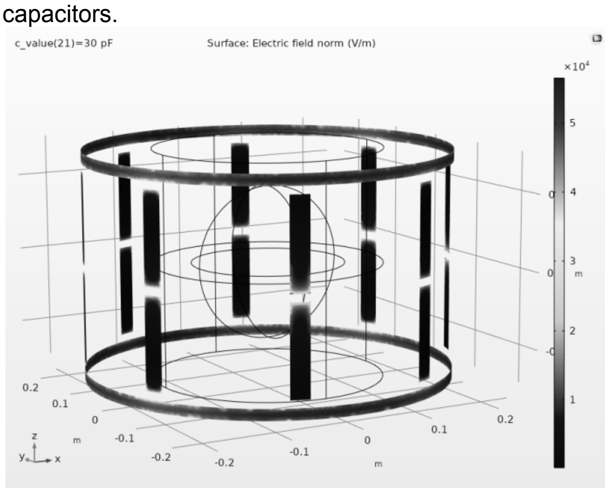

Fig. 4: Distribution of the electric field in the coil.

The value of the electric field strength in most areas of the copper tape shall not exceed 104 V/m. The highest field strength can be observed at the edges of the copper tape, which is directly adjacent to the capacitors located in the middle of each leg of the coil. In this case, the field strength is approximately three times greater than in the other areas of the coil, and the point value is as high as 5*104 V/m. This is related to a potential hazard that may suggest an improvement in the geometry of the locations where the capacitors are soldered to the copper tape. It can be concluded that rounding the edge of the copper tape would reduce the electric field strength at these locations [4-6].

In addition to the results presented above in the 3D Results group, the COMSOL environment also offers results in the form of graphs. The above simulation resulted in a graph illustrating the sphericity of magnetic flux in the phantom environment, depending on the capacitor capacity (Chart 1) and a graph showing the standard deviation of the electric field depending on the capacitor capacity (Chart 2).

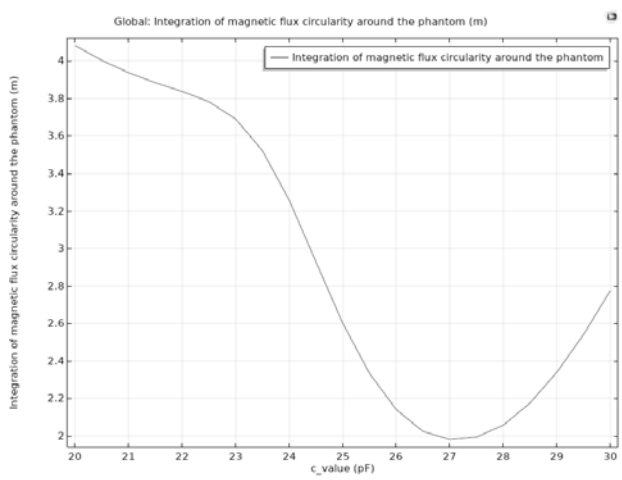

Chart 1: Integration of magnetic flux density around the phantom [m]

The following figures (Fig. 5. a and b) show the density of the magnetic flux (using arrows) produced in the environment of the coil using 30 pF capacitors (top view, side view). The magnetic flux density is illustrated by a cylinder inside the coil and is the highest near the conductive medium (coil). The greater the distance from the

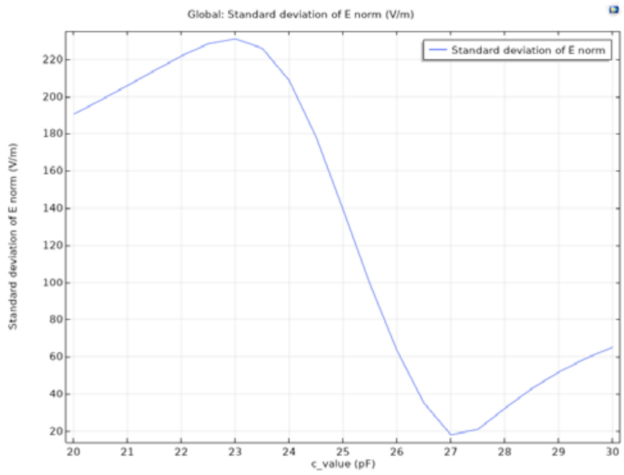

Chart 2: Standard deviation of E [V/m]

coil, the smaller the magnetic flux density.

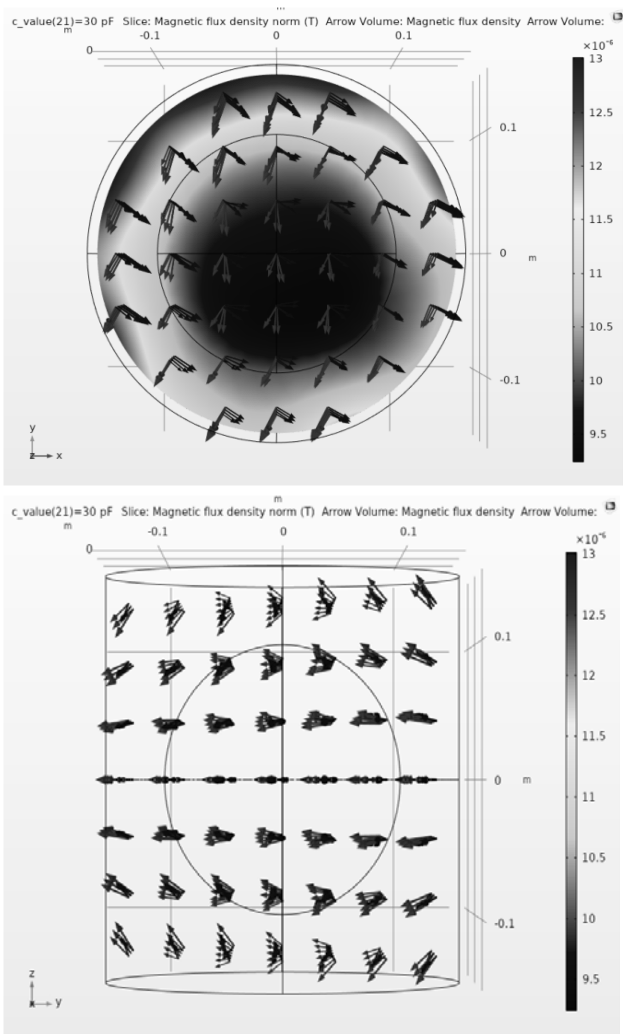

Fig. 5: Magnetic flux density a) top view, b) side view.

Numerical methods successfully help to simulate the behavior of a coil in a circuit coupled with a load model close to the real one or in space, as well as to test the coil efficiency at high values of magnetic field induction [7-10]. The use of numerical methods in the calculations also allows for taking into account the eddy currents occurring in the coil wires, which are caused by alternating magnetic fields [11-13].

Conclusion

The RF coil simulation allows to optimize the design process. More complex models based on electric and magnetic field calculations should be used, as the design of radio coils (RF) for MRI systems begins to fail at higher frequencies due to the use of techniques based on focused circuit modeling.

Numerical simulations are a very important part of the RF coil design process [14-16]. They are an essential tool for analyzing the behavior of the coil in the environment, the influence of fields appearing in space as a result of its operation, and for evaluating performance and safety. In addition, numerical simulations are also important in that they save time by eliminating possible errors at every stage of design.

Knowledge of the magnetic or electric field distribution that occurs in the RF coil environment is crucial for the designer in the context of safe operation of the device. Due to the fact that it is impossible to measure these fields in reality, it is necessary to conduct electromagnetic simulations.

The main purpose of this article is presenting the individual stages of RF coil design based on the example of a birdcage type volumetric coil. The simulations presented in the article were carried out using the COMSOL Multiphysics, RF Module software and form the basis for further calculations and numerical analyses.

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