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Wireless power transfer in magnetic resonance imaging with a detuned birdcage coil

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Abstract. In this work, we develop an application of a transmit birdcage coil for wireless power transfer during the receive phase within a magnetic resonance imaging (MRI) scanner. The study includes numerical simulations and an experimental verification of a numerical model with a clinical birdcage coil. We simulate numerically magnetic fields inside the magnetic resonance imaging scanner with a phantom, the specific absorption rate distributions with a human voxel model, and the resulting voltage on receiving system coils. Therefore, we characterize possible distortions in MR images, demonstrate safety of the setup for a patient, and evaluate the RF-RF efficiency numerically, respectively. Finally, we outline potential devices placed in MRI bore which can provide a wireless power supply with the detuned birdcage coil and receive system.

Keywords: MRI, magnetic resonance imaging, birdcage coil, WPT, wireless power transfer, resonators

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Материалы конференции
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Беспроводная передача энергии в магнитно-резонансной томографии с использованием отстроенного резонатора типа «птичья клетка»

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Аннотация. В данной работе рассмотрена концепция беспроводной передачи энергии с помощью отстроенного резонатора типа «птичья клетка» для магнитно-резонансной томографии (МРТ) во время фазы приёма сигнала от ядер атомов. Было проведено численное моделирование, а также верификация численной модели в эксперименте с помощью резонатора от клинического аппарата МРТ. В частности, рассчитаны картины магнитного поля для такого резонатора с фантомом, распределения удельного коэффициента поглощения электромагнитной энергии внутри воксельной модели человека, а также напряжение на системе приёмных антенн. В результате, оценены возможные искажения на МР-изображениях, безопасность такой системы, а также коэффициент полезного действия. Разработанная схема беспроводной передачи энергии может быть использована внутри тоннеля аппаратов МРТ со встроенным резонатором типа «птичья клетка» и системой приёма энергии, что позволит обеспечивать электроэнергией большинство видов приёмных локальных катушек (ближнепольных антенн с предусилителями и системой отстройки), а также медицинских датчиков.

Ключевые слова: МРТ, магнитно-резонансная томография, резонатор типа «птичья клетка», БПЭ, беспроводная передача энергии, резонаторы

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Introduction

Magnetic resonance imaging (MRI) is an important method of medical diagnostics for the diseases including cancer and injuries. Near field antennas (called local coils) are used in MRI bore to enhance the functionalities of an MRI scanner and require a wire connection to the scanner during the scanning process. However, wire connection of local coils has many disadvantages, including patient discomfort, lowered speed of the patient positioning by medical staff, periodic replacement required by connectors and wires, and wrong cable positioning within MRI bore which can cause an additional heating of the patient [1]. The cable provides data transfer and power supply.

These issues can be resolved with wireless power transfer [2, 3]. Power supply without any cables between a local coil and an MRI scanner can be realized with energy harvesting at the scanning (Larmor) frequency, and with wireless power transfer at the frequency, different from Larmor frequency [4]. The main drawback of energy harvesting is low transmitted power (above 500 mW) [5, 6] which can supply only limited types of receive local coils. However, wireless power transfer requires an additional antenna [7–10]. Otherwise, the power transfer takes place during a very limited time of the nuclei excitation (the excitation phase) [11], which is much lower than the time of receiving the signal from the nuclei (the receive phase). As we demonstrate, this problem can be solved by performing wireless power transfer during the receive phase without an additional transmitting antenna. In particular, we use Siemens Avanto Body Coil with a modified detuning system as the transmitting structure.

Materials and Methods

We apply CST Microwave Studio 2022 software package for numerical simulations. The numerical model includes a birdcage coil with a modified detuning system, a radio frequency (RF) screen, a receive system, and a phantom or the human voxel model. The Gustav voxel model from CST Bio models library which was used for numerical simulations consists of $2\times2\times2$ mm^3 voxels with permittivity, conductivity, permeability, density, and heat capacity corresponding to those of specific human tissues and organs (for example, grey matter of the brain, skin, bones, etc.), making it possible to study the specific absorption rate (SAR). The numerical model of the birdcage coil is based on Siemens Avanto Body Coil with two ports and includes a matching circuit. Moreover, the diodes in the birdcage coil model are replaced by inductors to implement the detuning system. The RF screen is modelled as a cylinder surface made of an annealed copper. The receive system consists of two identical orthogonal loop coils with a port including a matching circuit in each of them. The body phantom is implemented as a cylinder with the diameter of 300 mm and the length of 500 mm filled with a salted water.

The voltage on the dummy load and the magnetic fields within the birdcage coil are simulated with the frequency domain solver (implementing a modified finite element method), while the time domain solver (a modified finite difference time domain method) was used to obtain the (SAR) of the voxel human model.

The permittivity and conductivity of the Siemens Test Phantom liquid for 1.5 T MRI scanners used in numerical simulations were measured by SPEAG DAK 12 probe and Planar S5048 vector network analyser. Besides, Planar S5048 was used for measuring the scattering parameters of Siemens Avanto Body Coil.

Results and Discussion

For numerical simulations, we measured the permittivity of 80 and the conductivity of 1 Sm/m for Siemens Test Phantom for 1.5 MRI scanners. Then, we verified our numerical model by comparing the scattering parameters of the Siemens Avanto Body Coil and the model. When converting the scattering parameters into Z-parameters, we obtained that the difference between the frequencies in the numerical model and the experiment for five modes does not exceed 4%. After that, we added a detuning system with inductors to the model, and calculated scattering parameters (Fig. 1) of the birdcage coil. We obtained the resonance frequency of the fundamental mode (59 MHz), and higher-order modes (41 MHz, 31 MHz, 26 MHz) after converting the scattering parameters into Z-parameters. We convert the real and imaginary parts of the S-parameter of the first port (S11) to Z-parameters. The resulting frequency dependence of impedance features a maximum whose position corresponds to the frequency of a certain mode. Finally, for all studied modes (59 MHz, 41 MHz, 31 MHz, 26 MHz) we characterize the safety, the RF-RF efficiency, and the distortion of MR-images by calculating the specific absorption rate for the voxel human model, the voltage on dummy load within the receive coils, and the magnetic fields, respectively. We established that the optimal mode for wireless power transfer is the one at the frequency 31 MHz with RF-RF efficiency of 49%. Safety is the key limiting factor for the birdcage coil input power since a human body is heated during scanning. The heating for any part of the human body must be less than 2 W/Kg [12]. However, the received power (116 W) is sufficient for supplying many types of receiving local coils and medical sensors, while providing the safety of the scanning procedure. Moreover, the magnetic fields do not demonstrate any considerable distortion at Larmor frequency (63.6 MHz) within the phantom volume, facilitating that the proposed wireless power transfer system with a detuned birdcage coil will not decrease the MR-images quality.

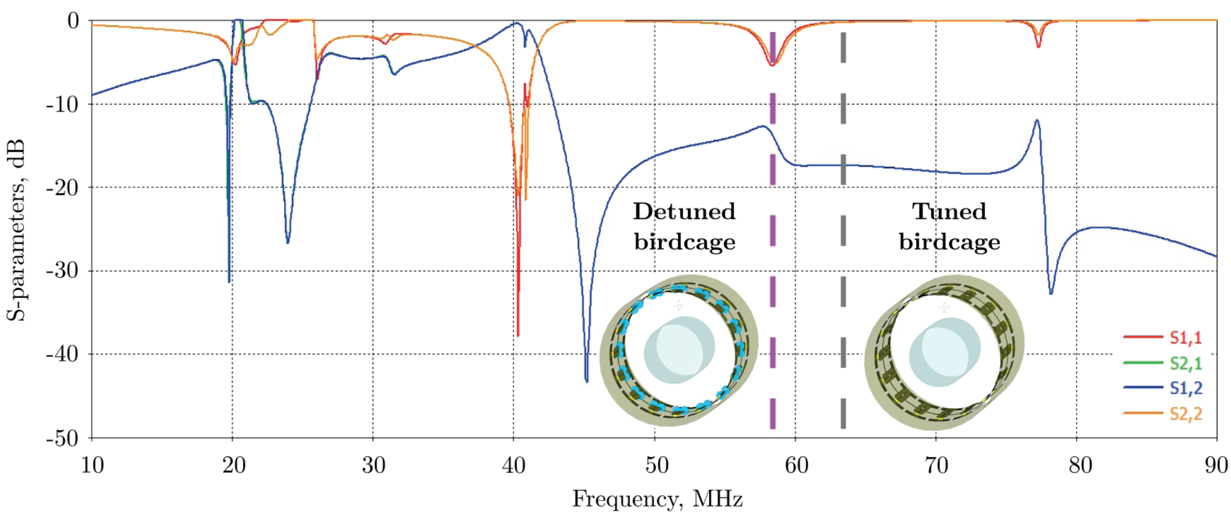

Fig. 1. S-parameters of the birdcage coil. Grey dashed line indicates the fundamental mode frequency 63.6 MHz of the tuned coil (right inset). Purple dashed line shows the fundamental mode frequency of the detuned coil (left inset). Blue markers in the inset indicate inductors used for detuning

Conclusion

In this work, we demonstrated a principle of wireless power transfer with a detuned birdcage coil, which allows providing power supply wirelessly during the phase of receiving the signal from atomic nuclei. It allows power transfer with minimal pauses (tens of ms during several seconds). For this purpose, a numerical model of the Siemens Avanto Body Coil has been developed and verified. Then, a detuning system and a receiving antenna system were added to the model. Magnetic field profiles for several birdcage modes were obtained, which facilitate that higher-order modes, rather than the fundamental one, should be used for wireless power transfer since their fields are concentrated on the surface of the phantom instead of its bulk. We demonstrate that the optimal mode for wireless power transfer has the frequency of 31 MHz. Simulations with a human voxel model show that the efficiency of wireless power transfer is 49%, and the maximal transmitted power is 116 W, which is sufficient supply the majority of modern multichannel receive coils and medical sensors. The developed system can be implemented in Siemens Avanto setups, and the principle itself can be used for any MRI scanners with a birdcage coil.

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