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A heating coil insert for a preclinical MPI scanner

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Abstract

Magnetic particle imaging (MPI) is a rapidly developing imaging modality, which determines the spatial distribution of magnetic nanoparticles. Magnetic fluid hyperthermia (MFH) is a promising therapeutic approach where magnetic nanoparticles are used to transform electromagnetic energy into heat. The similarities of MPI and MFH give rise to the potential of integration of MFH and MPI. In our previous work, a heating coil insert for the preclinical MPI scanner is designed, which can be utilized to generate a high frequency magnetic field suitable for MFH. The current development of the heating coil insert is presented in this paper.

I Introduction

Magnetic fluid hyperthermia is a method for heating nanoparticles by exciting them with an alternating magnetic field. The magnetic nanoparticles (MNPs) are used to couple magnetic energy into the body to heat tissue via hysteresis power loss. MPI is a new imaging modality that makes use of the nonlinear magnetization of the MNPs [1]. The physical principle of MFH and MPI are similar, and the magnetic nanoparticles are used for both. Furthermore, in MPI, the gradient fields saturate the nanoparticles everywhere except in the vicinity of a field-free region (FFR). In the saturated regions, the particle magnetizations are effectively locked in value and only the MNPs in the FFR can respond to an AC excitation field and generate heat, which makes the spatially selective MFH possible. MPI and MFH may be integrated together in a single device for simultaneous MPI–MFH to allow for seamless switching between imaging and therapeutic modes [2].

The challenge of integrating the heating coil insert for MFH into the MPI scanner lies in the minimization of its effect on the MPI receive chain. The voltage induced in the receive coil of the MPI system caused by the insert will damage the low noise amplifier (LNA). In our previous work, we proposed a modified version of the algorithm Differential Evolution Particle Swarm Optimization (DEPSO) to optimize the geometry of the coil [3]. The heating coil insert is composed of a heating coil and a compensating coil. The modified DEPSO algorithm is used to optimize the structure of the compensation coil to minimize the induced voltage in the MPI scanner. In this work, the insert is tested under high power. When carrying large current, the increase in temperature of the Litz wire will lead to an increase of the coil resistance, which results in a load mismatch and loss of power transfer. To monitor the temperature of the coil, a temperature sensor is implemented.

II Material and methods

The design of the coil is identical to the prototype described in [3]. It is beneficial to have a good visibility of both the heating coil and the compensating coil when assembling the cooling unit. The main parts of the cooling unit are manufactured using transparent materials (PMMA and Clear Resin, Formlabs, Massachusetts, USA).

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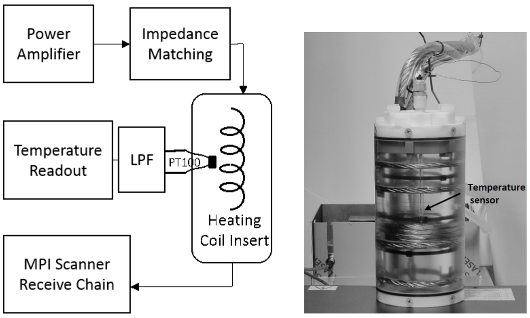

Figure 1: Left: Block diagram of the heating coil insert with the temperature sensor. Right: Heating coil insert cooled with oil. The box in the background is the air-cooled impedance matching circuit.

The state of the Litz wire is clearly visible (Fig. 1), which makes it possible to keep the cooling system free of air bubbles by visual inspection.

To test the heating coil insert with high power, a power amplifier AG 1012 (T&C Power Conversion, Inc., New York, USA) is used to generate and amplify the 700 kHz sinusoidal signal. An impedance matching circuit is designed to match the load to 50 Ohm. The current through the coil is measured by a current probe (MiniFlex MA200, Chauvin Arnoux, France), which is capable to measure the current with frequency up to 1 MHz. In order to monitor the temperature of the coil during the test, a platinum resistance temperature detector (RTD) PT100 (C220, Heraeus Nexensos GmbH, Kleinostheim, Germany) is placed beside the heating coil through a 3D printed holder. When measuring in the alternating magnetic field (AMF), optical rather than electronic temperature sensors are often used to avoid eddy current self-heating in conducting parts. However, eddy current heating is strongly dependent on the size and geometry of the conducting part [4]. The PT100 used in this work is a thin-film RTD with the size of 2.3 mm × 1.9 mm × 1 mm and is placed parallel to the magnetic field generated by the heating coil insert to minimize the eddy current heating caused by the AMF. In addition, a low pass filter (LPF) is designed to eliminate the induced alternating signal to ensure an accurate measurement of the resistive value of the PT100.

III Results and discussion

To evaluate the effectiveness of the compensating coil, the transmission coefficient from the insert to the LNA output is measured over a frequency range from 100 kHz to 1 MHz by the network analyzer (LF-RF E5061B, Keysight Technologies, California, USA). The same parameter of a 5-turn solenoid coil that has the same geometry of the heating coil but without compensation is also measured and showed as a comparison in Fig.2. The send power is set to make the two coil setups generate the magnetic field with the same strength. After compensation, the magnitude at 700 kHz of x and y channel decreases, especially on the x channel, the attenuation is 53 dB. The increase of the magnitude on z channel is due to the connection wire between the heating coil and the compensating coil. The magnitude of the transfer function can be used to calculate the residual induced power in the MPI receive chain after compensation. Since the LNA has a power-amplifying ratio of around 47 dB at 700kHz, the magnitude of the transfer function should be reduced by 47 dB to remove the amplifying effect of the LNA. Therefore, the damping of the insert at 700 kHz is 101 dBm, 88 dBm and 54 dBm for x, y and z channel respectively. Due to the good compensation result, the power level of the induced signal in the receive chain of the MPI scanner are all lower than the maximum input power of the LNAs in the three channels when the send power of the heating coil insert is below 1 kW.

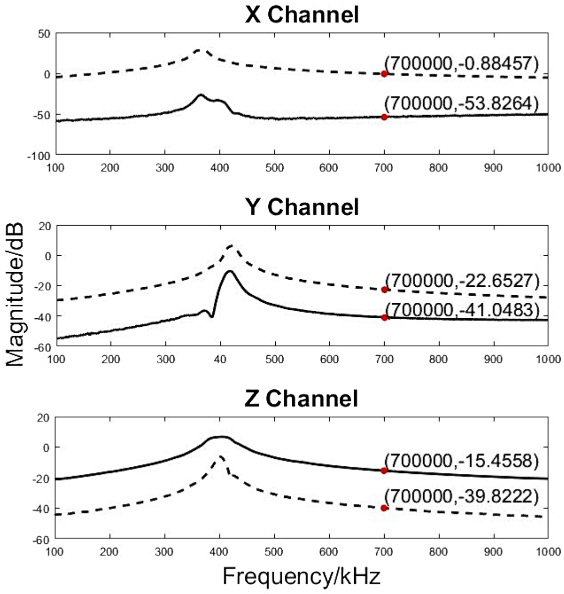

Figure 2: Transfer function of the MPI-MHF system of x, y and z channels. Dashed line: the result without the compensation coil. Solid line: the result of the heating coil insert with the compensation coil.

The magnetic field generated by the heating coil insert over an area of 22.5 mm × 18 mm × 12 mm around the center of the heating coil in steps of 1.5 mm in each direction is measured. The measured area is chosen according to [5] to imitate the size of a rat brain. The magnetic field is measured with 3 A DC signal, the field strength with 150 A current is calculated based on the measured 3 A results and shown in Fig. 3. The average field strength is 11.2 mT, with a standard deviation of $4 \cdot 10^{-4}$ mT.

The working frequency of the setup is tuned to 700.8 kHz in room temperature. With 650 W output power the current on the coil reaches 150 A_{rms}. The temperature

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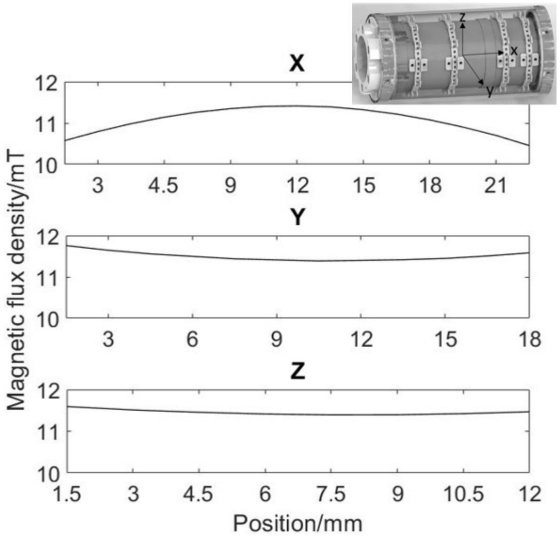

Figure 3: Magnetic flux density profile of x, y and z direction around the center of the heating coil with 150 A_{rms} current.

sensor shows the temperature at 650 W is 25 °C, which indicates that there is no significant heat up of the coil. Under high load, the series capacitor needs active cooling, as the resonance frequency can drift by several kHz if the capacitor heats up too much.

IV Conclusions

Within the scope of this work, the heating coil insert for the preclinical MPI scanner is implemented, which allows for the generation of a high frequency magnetic field suitable for MFH. A temperature monitor of the coil is also implemented and shows that the coil does not heat up under full power at 650 W. Nevertheless, it turns out that active cooling of the impedance matching is necessary. The next step will be to complete the safe integration of the insert into the MPI system.

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Author's Statement

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