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Implementation of a gradiometer receive coil for a single-sided FFL MPI scanner

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Abstract

A single-sided MPI scanner holds a great promise for a variety of clinical applications. In such a scanner the SPIOs response to the excitation is detected by a planar receive coil on the surface of the device. Due to a single-sided geometry, differentiating a small signal on a strong excitation background becomes a challenging task and further impinges the potential sensitivity gain, thus we implemented a new planar gradiometer receive coil configuration for our MPI scanner. The preliminary results imply the improved sensitivity of the device over the traditional single coil design.

I Introduction

Magnetic Particle Imagining (MPI) is the new frontier of medical imaging modalities, capable of imaging the distribution of superparamagnetic nanoparticles (SPIOs) in an expeditious and highly sensitive manner [1]. For instance, the accumulation of SPIO in tumor tissue, serving as tumor markers [2] presents the MPI device as a practical means of imaging for in vivo cancer detection [3]. The single-sided design may be beneficial for this application allowing for imaging of regions of interest in larger subjects [4]. In our design of a scanner we utilize a field-free line (FFL) geometry of the magnetic field zero [5], which has a potential advantage of an increased sensitivity over the traditional approach with field-free point (FFP) [6]. Our prototype device uses a single primary coil to generate a magnetic excitation field [7].

A notch filter is routinely used to reject most of the drive frequency component, however, a significant part of it remains and contributes to the saturation of the receive chain, thus reducing the overall sensitivity. Solenoid gradiometer receive coils have been exploited in conventional MPI scanners for their ability to reduce feed-through from the drive field, thus improving scanner performance. Unlike cylindrical bore scanners, single-sided scanner cannot accommodate a solenoid receive coil. Here we present the first implementation of a gradiometer receive coil in a single-sided MPI device and show the results from the numerical simulations and experimental data that imply the improved sensitivity of the device over the single receive coil design.

II Material and methods

The first order gradiometer coil is designed to cancel directly induced voltage from the excitation field (H_d) and detect only the response from the SPIO located on the top surface of the scanner. It is composed of two identical hollow centered planar Rx coils. The dimensions of the Rx coils were simulated to optimize the spatial sensitivity profile 10 mm above the center of the coil. Each coil has an inner diameter of 25 mm and an outer diameter of 60 mm. The coil is constructed of dual layer 38 total turns of Litz-wire (AWG 22, 40/38), with an inductance of 62.5 uH.

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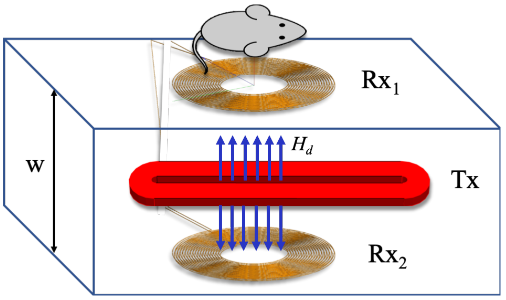

Figure 1: Scanner setup showing gradiometer coils: Rx1 and Rx2; Tx coil centered between two Rx coils, w - vertical separation between two Rx coils.

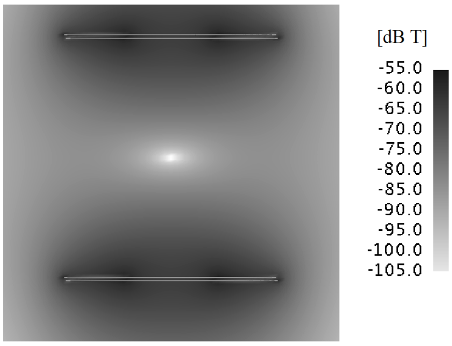

Figure 2: Simulations of the magnetic flux density showing the spatial sensitivity profile (in dBT units).

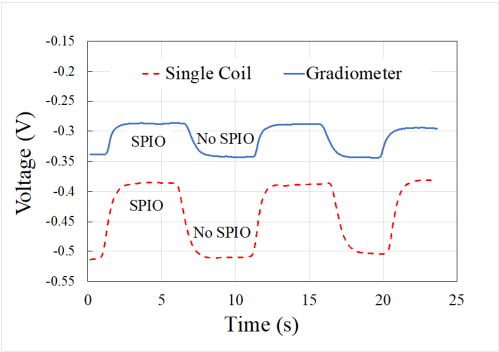

Figure 3: Detection of 5 mg (Fe) SPIO, 1 ml sample, at $I = 1.55A$ for single Rx and gradiometer coils.

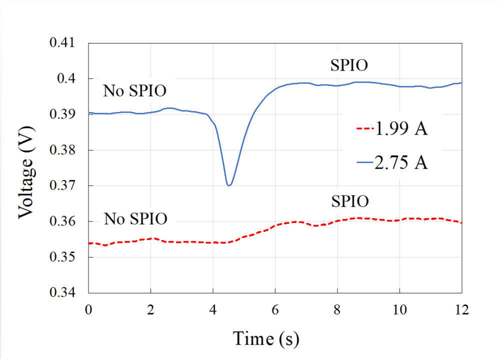

Figure 4: Detection of 9 μg (Fe) SPIO, 18 μl sample, by gradiometer coil at $I = 1.99A$ and $I = 2.75A$, here the negative spike corresponds to a mechanical transient.

The coils are connected with the opposite polarity in series and equidistant from the primary drive coil inside the scanner's enclosure, as shown in Fig. 1, with one coil positioned on the top surface, for the SPIOs detection, and the other coil positioned on the bottom of the device separated by w = 70 mm in the vertical direction.

A numerical simulation of the spatial magnetic field profile in the proposed gradiometer configuration was done in hybrid EM solver Altair FEKO (Altair Engineering, Inc).

The experimental validation tests were carried out at a drive frequency of 23 kHz generated by a function generator (AFG3022C, Tektronix) with various excitation currents from the power amplifier (EP4000, Behringer). The detected signal was additionally filtered by a 3rd order Butterworth band-stop filter to reject the drive frequency and match to transmit the 3rd harmonic. The signal was fed to a Lock-In Amplifier (SR830 DPS, Stanford Research Systems). The time series signal is then recorded with a GPIB card by a LabView (National Instruments) interface. In these validation tests the selection gradient was not applied. The gradiometer coils were shifted off-center from the drive coil to achieve best results. In the SPIO detection experiment we used a series of diluted sample phantoms containing 18 μl of Precision MRX (Imagion Biosystems) nanoparticles with iron core $d_c = 25nm$, $c(Fe) = 5mg/ml$.

III Results and discussion

Figure 2 shows the simulations of the magnetic flux density generated by the two coils in the gradiometer configuration showing a cylindrically symmetric spatial sensitivity profile. The sensitivity profile has zero in the geometrical center corresponding to the point drive source. Although this profile matches well the magnetic field lines from the elongated drive coil across its short axis, it has a geometrical mismatch in the cross-section along long axis, which limits the efficiency of the gradiometer coil in the current setup.

In the sensitivity studies we used five drive current amplitudes I =0.87, 1.41, 1.55, 1.9, 2.75 A. In two different experimental runs we used either a single Rx or the gradiometer coil. Figure 3 shows an example of time series data at $I = 1.55A$ for the undiluted 1 ml SPIO sample with single Rx and gradiometer coils. For the large sample at relatively low current there was no significant background present, thus the single Rx coil provides better results. Starting from $I = 1.9A$, we were able to suppress feedthrough background by a factor of 10 with the gradiometer coil, as compared to a single Rx, and increase the detection gain, and at $I = 2.75A$ only the gradiometer coil was able to detect the signal from the diluted SPIO of 9 μg (Fe) with obtained signal-to-noise-ratio (SNR) of 9 and 15, respectively, as shown in Fig. 4.

IV Conclusions

We implemented a novel gradiometer receive coil for a single-sided FFL device. Demonstrated increased sensitivity with experimental data validates the gradiometer coil concept. The obtained preliminary sensitivity results imply a new detection limit of our device of a few μg. Improvements in the coil geometry will be sought for further optimization of the design.

Author's Statement

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Conflict of interest: Authors state no conflict of interest.

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