International Journal on Magnetic Particle Imaging
Vol 6, No 2, Suppl 1, Article ID 2009064, 3 Pages

Proceedings Article

Design of a doubly tunable gradiometer coil

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Abstract

In a magnetic particle imaging (MPI) scanner, utilizing a tunable gradiometer receive coil can aid in achieving greater degree of decoupling of direct feedthrough signal. However, such a coil can be hard to tune since a very precise positioning of the compensation segment is necessary for excellent decoupling. In this work, we present a doubly tunable gradiometer coil capable of fine tuning without loss of tuning range. We show with experimental results this design can achieve an effective 81.4 dB decoupling in comparison to an identical coil with no gradiometric compensation.

I Introduction

Due to the simultaneous excitation and reception in Magnetic Particle Imaging (MPI) [1], the drive field (DF) directly feeds through to the receive coil. This coupled direct feedthrough signal is usually orders of magnitude larger than the MPI signal from the magnetic nanoparticle (MNP). Due to the limited dynamic range of the analog-to-digital converter (ADC) of the receive chain, feedthrough signal must be decoupled to not saturate the ADC. A commonly utilized method to overcome this problem is winding the receive coil in a gradiometer configuration, where a portion of the receive coil windings are wound in reverse direction to cancel out the direct feedthrough signal. There is a reverse winding ratio that, in theory, perfectly decouples the transmit and receive coils. However, this ratio depends on many factors, and slight positioning errors in the windings can easily degrade the performance of the gradiometer coil. Previous work on gradiometer coil design also addressed the issue of fine-tuning the decoupling of the drive/receive coils [2,3], but those designs came with a tradeoff of tuning range vs. sensitivity. In this work, we present a doubly tunable gradiometer coil design, which features a high tuning sensitivity while retaining a wide tuning range.

II Materials and Methods

Field sensitivity of the finite-length DF coils in MPI decrease as distance from the center of the coil along the z-axis increases. Tunable gradiometer configurations usually utilize this feature by allowing one of the gradiometer segments to move along the bore axis, therefore achieving a variable cancellation on the induced direct feedthrough voltage. There are several factors determining the effectiveness of this variable cancellation, such as the position, turn count, and length of the cancellation segment. The relationships between these factors and the amount of decoupling achieved is quite nonlinear. Therefore, a finite-element approach is suitable for designing a gradiometer coil. However, there is a hard-to-strike balance in design of a gradiometer coil. Having a wide tuning range (i.e. the ability to compensate for a large set of changes in the system, such as imperfect placement of windings on DF and/or receive coils, imperfections in manufacturing of components, or changes in

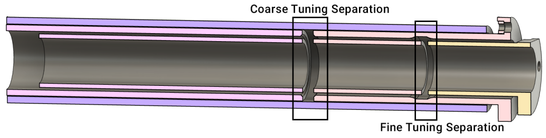

Figure 1: The proposed doubly tunable gradiometer coil design. The position of the coarse-tuning segment is referenced to the DF coil, and the position of the fine-tuning segment is referenced to the coarse-tuning element via plastic screws.

temperature) conflicts with the ability to fine-tune with ease. In this work, we propose to overcome this problem by bisecting one of the gradiometer segments. As shown in Fig. 1, the segment closer to the coil center provides coarse tuning, allowing one to quickly locate the decoupling region. The other segment provides the fine-tuning capability, to chase the perfect decoupling spot.

II.I COMSOL Simulations

As the gradiometer was to be used with our in-house FFP scanner, our scanner's existing DF coil and copper shield parameters were transferred to COMSOL. Then, the doubly tunable gradiometer receive coil shown in Fig. 1 was simulated. The inner/outer diameters of this coil were selected to match our previous untunable gradiometer receive coil (d^{in} = 20 mm, d^{out} = 23.7 mm). Important design parameters were the number of turns on each segment, as they cannot be tuned after construction. The lengths of the segments were set to be proportional to the number of turns, assuming dense packing during winding. The tunable parameters of the designed coil were the separation gaps of each tuning segment, resulting in a 2D "tuning parameter space". COMSOL simulation had two goals: To find the parameters which provide a homogenous sensitivity profile (> 90 % homogeneity in > 12.5-mm region at the scanner isocenter) and a region of excellent decoupling within the tuning parameter space. Design parameters were found with a combination of grid search and manual adjustment. Resulting turn counts of fixed compensation segment, center receive segment, coarse tuning segment, and fine-tuning segment were 83, 56, 55, and 28, respectively. The simulated sensitivity profile of the designed coil is shown in Fig. 2.

II.II Decoupling Experiments

Once the design parameters were set, a coil former to house the coil and the adjustment mechanism was designed in Fusion360 and 3D printed. The constructed gradiometer receive coil was inserted into the existing DF coil of our FFP scanner. Then, 9.7 kHz excitation pulses of 1 V amplitude were continuously applied to the DF coil, while the received signal was monitored in real time.

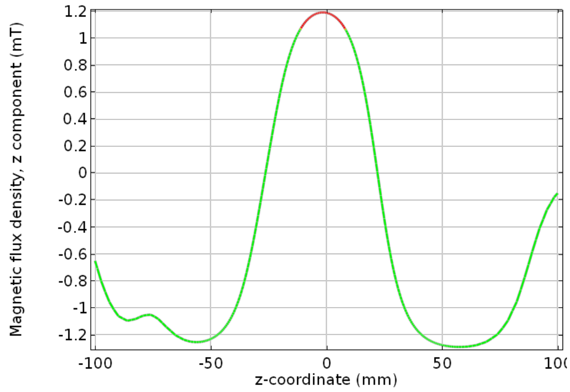

Figure 2: Sensitivity map of the proposed gradiometer coil. Shaded region in the center indicates the region with 90 % homogeneity, measuring 19-mm in length at the center of 44 mm long receive segment. The small local peak at -75 mm is caused by the separation of the coarse and fine tuning segments.

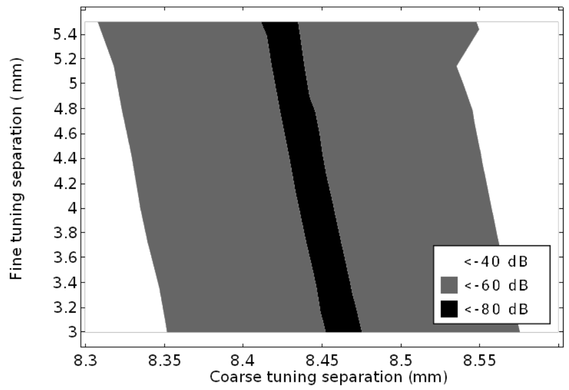

Figure 3: A region in the tuning parameter space, showing several different levels of decoupling performance. Notice how the width of 80 dB decoupling region is about 25 μm along the x-axis, while it is wider than 1 mm along the y-axis. This feature makes it easy to find the high decoupling region.

The feedthrough was minimized by adjusting both separations via M3 size screws. The measured decoupling was evaluated by comparing the received signal to the signal in the absence of the compensation segments.

III Results and Discussion

III.I Simulation Results

A region of the tuning parameter space is shown in Figure 3, which is a surface plot of the signal induced by the feedthrough on the receive coil for a sweep of both tuning separation parameters. Note that the width of the "-80 dB valley" is significantly greater (> 40x) along the y-axis than along the x-axis. This feature makes it easier to find and stay within the -80 dB valley. However, the decoupling in tuning parameter space is not always as

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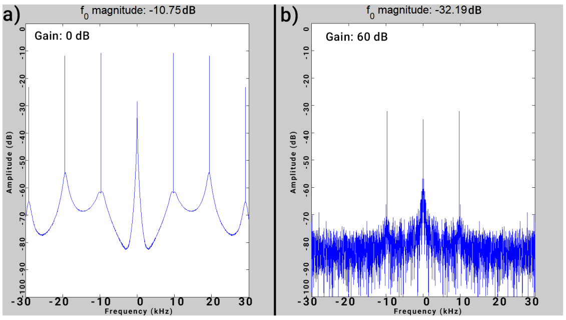

Figure 4: (a) Received spectrum of the reference coil with no compensation. Harmonics from the DF chain and transient artifacts are visible. (b) Received spectrum of the constructed and doubly tuned gradiometer coil. Artifacts and harmonics are well suppressed along with excellent decoupling of 81.4 dB with respect to the reference coil.

well behaved as in Fig. 3, due to imperfections. In that case, an estimate location for the well-behaving region can be found using a secondary simulation study.

III.II Experimental Results

Figure 4 shows the spectrum from the reference coil and the doubly tuned gradiometer coil, achieving -81.4 dB of decoupling with respect to the reference coil. After fine-tuning of the coil, an amplification of the direct feedthrough signal was needed to measure it. The signal amplitude of -32.1 dB shown in Fig. 4b was in the case of a gain of 1000 (i.e., 60 dB, confirmed experimentally) on the low-noise preamplifier. Considering -10.7 dB signal on the reference coil with unity gain, and -92.1 dB corrected signal on the designed coil, we deduce that the proposed coil achieves 81.4 dB decoupling with respect to the reference coil. In Fig. 4, it can be seen that any higher harmonics arising from nonlinearities in the DF chain that are present in the reference spectrum are also suppressed, along with the direct feedthrough at the fundamental frequency. The vibrations due to Lorentz forces during the drive field did not move the coil out of tuning.

IV Conclusions

In this work, we have shown that a doubly tunable gradiometer coil makes the tuning process easier, without loss of a wide tuning range capability. The proposed coil achieved 81.4 dB decoupling when compared to an identical coil with no gradiometric compensation, and has also helped suppress higher harmonics arising from nonlinearities in the DF chain.

Author's Statement

Research funding: This work was supported by the Scientific and Technological Research Council of Turkey (TUBITAK 115E677, 217S069). Conflict of interest: Authors state no conflict of interest.

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