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Optimizing shimmability for gradiometric feedthrough suppression using linear programming

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Abstract

Magnetic particle imaging (MPI) is a tracer imaging modality that detects superparamagnetic iron oxide nanoparticles (SPIOs), enabling sensitive, radiation-free imaging of cells and disease pathologies. The arbitrary waveform relaxometer (AWR) is an indispensable platform for developing magnetic nanoparticle tracers and evaluating tracer performace for magnetic particle imaging applications. One of the biggest challenges in arbitrary waveform excitation is direct feedthrough interference, which is usually six orders of magnitude larger than the signal from magnetic nanoparticles. Direct feedthrough is often mitigated with a gradiometric cancellation coil which requires extremely precise placement in order to achieve adequate decoupling from the transmit excitation coil. This work will showcase a coil design of a transmit coil that meets excitation capability requirements with an order of magnitude more forgiving mechanical tolerance.

I. Introduction

Magnetic particle imaging (MPI) is a tracer imaging modality that detects superparamagnetic iron oxide nanoparticles (SPIOs), enabling sensitive, radiation-free imaging of cells and disease pathologies. Tracer development and evaluation is crucial to optimizing MPI performance. The arbitrary waveform relaxometer (AWR) is an indispensable platform for developing magnetic nanoparticle tracers for magnetic particle imaging (MPI) applications. By characterizing the point spread function (PSF) of a specific magnetic nanoparticle, the AWR can evaluate the performance (e.g. SNR and spatial resolution) of the magnetic nanoparticle for MPI [1]. The design of wideband (DC-400 kHz) and arbitrary waveforms enables rapid optimization of pulse sequence design.

One of the biggest challenges in arbitrary waveform excitation is direct feedthrough interference due to the drive field, which is usually much larger than the signal from magnetic nanoparticles. The flux induced by the excitation coil couples into the receive coil, contaminating the magnetic particle signal. In MPI and conventional magnetic particle spectrometers (MPS), a high-pass filter and tuned filter are applied to filter out the single tone interference, which cannot be done for arbitrary waveform excitation. The AWR uses a very fine shimming system, which employs a cantilever and duplicated gradiometer receive coil. This mechanism currently achieves over 60 dB of direct feedthrough attenuation, but is senstive in mechanical placement, with nearly 10 dB feedthrough attenuation per 50 µm near the ideal placement point [1]. Other feedthrough attenuation techniques include pas-

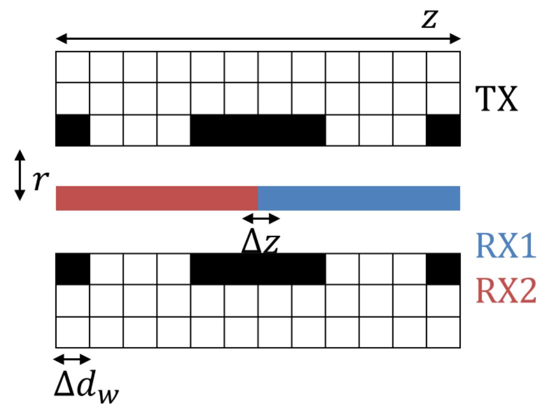

Figure 1: A possible solution for the wiring/current distribution of an optimal transmit coil design. The black filled in grids are windings and the rest is air. Blue and Red are locations of the receive coils relative to the transmit coil in the axial direction z

sive shimming by applying a second order gradiometer [2], secondary finer mechanical shimming [3] and active compensation by feeding back the drive feedthrough signal [4].

A challenge in mechanical coil shimming of a gradiometer is that it is highly sensitive to spatial variations. This requires a shimming process that is done before each scan to ensure the highest possible feedthrough rejection. This abstract will show results for a design of an optimally shimmable excitation coil for a given gradiometric coil design using L_1-norm minimization formulated as a linear programming problem. Linear programming is a power optimization tool that has been used to design RF and gradient coils for MRI[5, 6].

II. Methods and Materials

To best understand how to optimize the mechanical tolerance of the transmit/receive (TX/RX) coil pairs, we must formulate direct feedthrough as a function of axial placement of the RX coils Δz. Feedthrough is directly proportional to the net mutual inductance of the TX/RX coil pairs which can be calculated by the Neumann formula for mutual inductance [4, 7]

$$M(\Delta z) = \frac{\mu_0}{4\pi}\Big[\oint_{C_{RX1}}\int_{C_{TX}} \frac{d\mathbf{z_{TX}}\cdot\mathbf{z_{RX1}}}{\mathbf{z_{TX}}-\mathbf{z_{RX1}}} - \oint_{C_{RX2}}\int_{C_{TX}} \frac{d\mathbf{z_{TX}}\cdot\mathbf{z_{RX2}}}{\mathbf{z_{TX}}-\mathbf{z_{RX2}}}\Big] \tag{1}$$

where $M(\Delta z)$ is the net mutual inductance of the transmit coil with the anti-series combination of the receive coil (RX1) and cancellation coil (RX2). Using the fact that mutual inductance is directly proportional to flux, we can relax Equation 1 into a more digestible form by calculating the total flux of concentric solenoids with current loops $i_{tx}(r,z)$ illustrated in Figure 1, which are the values of the currents at radius r and axial location z. For our problem we assume the radius for the TX and RX coils are the same.

For a single winding of a transmit coil, the on-axis field generated per unit current is

$$\frac{B_{turn}(z)}{I} = \frac{\mu_o r^2}{2(r^2+z^2)^{\frac{3}{2}}} \tag{2}$$

by Biot-Savart law. The total flux can then be written as a dot product of the RX winding pattern coil area with the spatial convolution of the TX current loops with the field of a single turn:

$$M = \int \pi r^2 i_{rx}(z)\cdot\Big(\frac{B_{turn}(z)}{I} * i_{tx}(z)\Big)dz \tag{3}$$

where $i_{rx} = i_{rx1} - i_{rx2}$.

To formulate M as a function of axial placement of the RX coils Δz, we perform another spatial convolution with respect to the RX winding pattern.

$$M(\Delta z) = \int \pi r^2 i_{rx}(z-u)\cdot\Big(\frac{B_{turn}(u)}{I} * i_{tx}(u)\Big)du \tag{4}$$

This formulation can be more easily understood as a series of convolutions, which are linear operations and represented as matrices. The current loops and winding patterns can be represented as vectors. The mutual inductance can therefore be represented as a resultant vector of the following matrix operations:

$$\mathbf{b_{tx}} = C_{B_{turn}}\mathbf{i_{tx}} \tag{5}$$

$$\mathbf{m} = C_{rx}\mathbf{b_{tx}} \tag{6}$$

where $\mathbf{i_{tx}}$ is a vector denoting the current loops spaced by Δd, and C_{rx} and $C_{B_{turn}}$ are convolution matrices for the RX winding patterns and the field of a single current loop, respectively. To design for a given mechanical tolerance of the coil, we impose a shimmability constraint ϵ_{dM} on the difference of the mutual inductance m for a symmetric displacement of $+z_{disp}$ and $-z_{disp}$ similar to how a field homogeneity constraint can be placed:

$$\Big|\mathbf{m}(+z_{disp}) - \mathbf{m}(-z_{disp})\Big| \leq \epsilon_{dM} \tag{7}$$

To ensure a symmetric design we must impose a constraint that the mutual inductance when the coils are placed in the ideal spot is close to zero ϵ_M and that the field at the symmetric displacements are the same as well:

$$\Big|\mathbf{m}(z=0)\Big| \leq \epsilon_M \tag{8}$$

$$\mathbf{b_{tx}}(+z_{disp}) = \mathbf{b_{tx}}(-z_{disp}) \tag{9}$$

To prevent a trivial solution, we must also impose a field strength constraint on the coil design:

$$\mathbf{b_{tx}}(z=0) \geq B_{min} \tag{10}$$

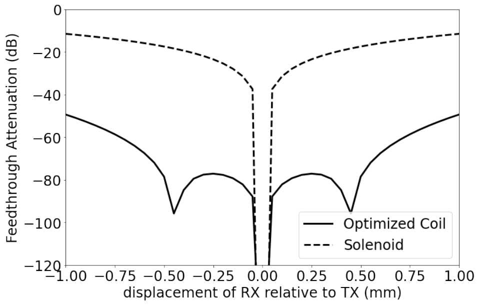

Figure 2: Compared to a regular solenoid design, our procedure generated a coil design that had tremendously better mechanical tolerance.

We impose the mechanical tolerance as opposed to minimizing for it and instead minimize the sum of the absolute value of currents in the transmit coil subject to these constraints, similar to [5]:

$$\begin{aligned} \text{Minimize: } & \sum |i_{tx,n}| \\ \text{Subject to: } & -\epsilon_{dM} \leq \mathbf{m}(+z_{disp}) - \mathbf{m}(z_{disp}) \leq \epsilon_{dM} \\ & -\epsilon_M \leq \mathbf{m}(z=0) \leq \epsilon_M \\ & -\mathbf{b_{tx}}(z=0) \leq -B_{min} \\ & \mathbf{b_{tx}}(+z_{disp}) = \mathbf{b_{tx}}(-z_{disp}) \end{aligned} \tag{11}$$

This is an L_1-norm minimization problem which is a convex optimization problem. This formulation is powerful because it not only is tractable, but it promotes sparsity in the coil solution due to the L_1-norm constraint, meaning that the optimal coil will have very few windings, and the shimmability constraint ϵ_{dM} is met. The LP problem can be solved very efficiently with standard software packages. For example, MATLAB's `lp()` function or Python's `linprog()` method with SciPy (which was used in this work) can efficiently generate an optimal solution to this LP.

III. Results and Discussion

One candidate TX coil solution result is presented in Figure 2, showing the improvement in mechanical tolerance.

Because of the sparsity of the solution, it is helpful to bootstrap this optimization problem by superimposing the solution onto an existing solenoid coil design. For our problem, we define the radius $r = 1$ mm, the wire diameter $d_w = 0.5$ mm (100/44 served Litz Wire for reduced AC resistance), and $\Delta z = 50\,\mu$m. We define a 20-turn solenoid for the initial TX coil, a 10-turn RX1 coil, and a 10-turn RX2 (cancellation) coil, all tightly wound. The modified optimization problem then only has to account for the bootstrapped TX coil.

Preliminary results of the candidate coil design show a more forgiving mechanical tolerance of less than 80 dB direct feedthrough rejection from −500 µm to 500 µm displacement of the RX coils relative to the TX coils. This 1 mm of mechanical tolerance allows for more coarse shimming of the gradiometer without the need of a super fine screw or tuning mechanism.

IV. Conclusion

This excitation coil design procedure is promising for applications where direct feedthrough mitigation is important, generating a minimal power solution for a given mechanical tolerance and field constraint. However, this procedure assumes perfect placement of wires according to the solution grid and does not account for winding errors or partial windings in the construction of the coil. Future work will include further experimental validation post-construction.

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Author's statement

Conflict of interest: S. M. C. is a co-founder of an MPI company, Magnetic Insight, and holds stock in this company. The authors declare no other conflict of interest.

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