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MPI field-free line scanning with dual electromagnet current adjustment

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Abstract

Magnetic particle imaging (MPI) is a technology that directly detects the nonlinear response of magnetic nanoparticles (MNPs). It has garnered significant attention in medical imaging. MNPs are saturated except near a specific point known as the field-free region, which is established by applying a static magnetic field [1]. Recent research has emphasized using the field-free line (FFL) method for scanning the field-of-view to enhance MPI sensitivity [2-4]. This paper reports on a performance evaluation of an MPI system that employs two pairs of electromagnets capable of scanning the FFL by finely adjusting the distribution of the current flowing through each electromagnet.

I. Introduction

Magnetic particle imaging (MPI) is an innovative medical imaging modality designed to directly detect the nonlinear responses of magnetic nanoparticles (MNPs). Spatial encoding is achieved by employing a static magnetic field, effectively saturating the MNPs across a vast area, except near a special point known as a magnetic field-free region (FFR) [1]. A recent study demonstrated the remarkable potential for enhancing MPI sensitivity by scanning the field-of-view (FOV) by applying the field-free line (FFL) method, which creates a field-free region along a designated line [2][3][4]. In a previous study, we tailored an MPI system for small animal imaging with a permanent magnet and an iron yoke to establish an FFL for imaging by physically moving the target object [5]. However, expanding this MPI system for medical imaging in humans poses practical challenges due to the need for enlarging the permanent magnet and iron yoke, resulting in increased weight and cost. An alternative method generates FFLs using electromagnets [6]. An MPI with electromagnets operates on the principle of the superposition of magnetic fields (those within the same region are vectorially summed) to displace the FFLs. Achieving this situation involves introducing a static, spatially varying-gradient magnetic field to a spatially homogeneous, temporally varying magnetic field (a drive field), which spatially shifts the FFR. Generally, a bipolar or a DC-stabilized power supply, in combination with an amplifier (for AC conversion and amplification), generates the drive field using electromagnets [6]. However, when scaling up MPI devices, the increased size of the electromagnetic coil leads to a greater load and increased power supply capacity demands, resulting in a larger and costlier power supply. Consequently, we developed a novel MPI system capable of scanning FFLs using two pairs of electromagnets. This solution eliminates the need for a bipolar power supply and relies on the fine-tuning of the current distribution to each electromagnet for control. This report comprehensively evaluates the FFL shift, the magnetic field uniformity, and the imaging results acquired from a sample containing MNPs.

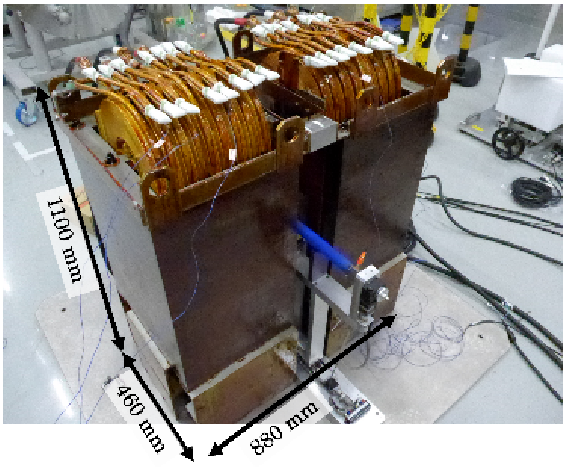

Figure 1: Photograph of MPI system with FFL generated by two sets of electromagnets.

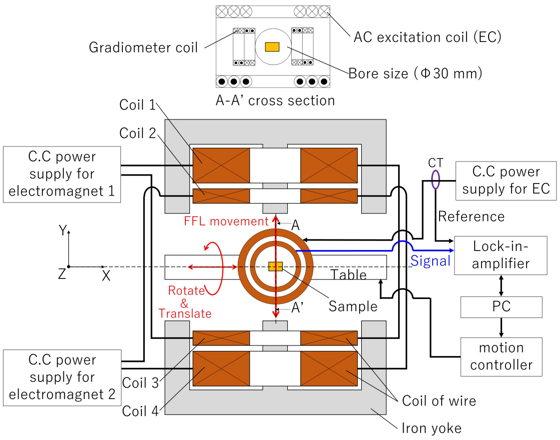

Figure 2: Schematic of MPI system with FFL: Gradient magnetic field and FFL were produced by electromagnet 1, connected to coils 1 and 3, and electromagnet 2, connected to coils 2 and 4.

II. Material and methods

Fig. 1 illustrates our proposed system, and Fig. 2 provides a schematic representation of the developed MPI system. Electromagnet 1, connected to coils 1 and 3, and electromagnet 2, connected to coils 2 and 4, generated the gradient magnetic field and the FFL. Coils 1 and 4 have 217 turns; coils 2 and 3 have 310. Electromagnets 1 and 2 are connected to separate CC power supplies. The FFL was produced by the superposition of the magnetic fields generated by each electromagnet at the position of a coil system that combined the excitation coil and receiving coil (gradiometer coil), both of which are centrally positioned within the system. Adjusting the current balance between these two magnets facilitates FFL scanning along the Y-axis. Simultaneously, the table bearing the sample was translated and rotated for scanning in the X-axis direction, acquiring projection data, and reconstructing a cross-sectional image. The table, which was moved and rotated by a motor managed by a motion controller, moves at a maximum of 2 mm/s and rotates at 24 deg/s. The gradient magnetic field strength can be continuously adjusted within a range of 0-3 T/m by regulating the current flow through the magnets. The power supply connected to magnets 1 and 2 was a WP250-180E (NF Chiyoda Electronics Co., Ltd.). A main feature of this system is its ability to calculate the phase difference in the measured MPI signal by referencing the energizing current of the excitation coil with a lock-in amplifier. The phase difference data are contingent on the time constant of the measurement device and the relaxation time of the MNPs; consequently, the phase difference can be used to distinguish noise and assess variations in the relaxation time of the MNPs. Fig. 3 shows a cross-sectional view of the simulation model. We used electromagnetic field analysis, employing the finite element method, to calculate the shift in the FFL concerning changes in the gradient field strength and the current balance.

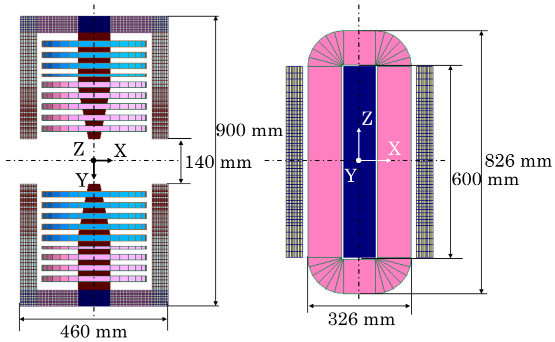

Figure 3: Simulation model of two sets of electromagnets to calculate gradient magnetic field.

III. Results and discussion

Next we compared the simulated and measured FFL shift quantities and discuss them. Fig. 4 shows the time evolution of the currents in magnets 1 and 2 with a gradient field strength of 1.5 T/m. As the current in magnet 1 increased, the current in magnet 2 decreased. Maintaining an equal change in each current led to a shift in the FFL along the Y-axis. Fig. 5 shows the time variation of the FFL center position in the $Z = 0$ plane along the Y-axis. The FFL center position changed with time variation (a change in the current balance between the two magnets). Specifically, when $T = 0.1$ [a.u.], the FFL was located at both ends of the Y-axis; when $T = 0.5$ [a.u.], it was positioned at the center. The simulation data closely aligned with the experimental results, affirming that FFL's position shifted linearly with the change in the current. The FFL exhibited a range of movement spanning approxi-

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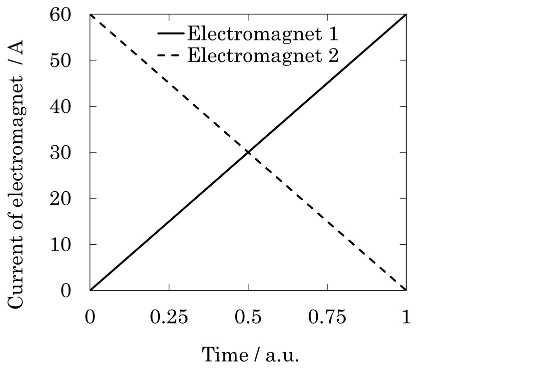

Figure 4: Time sequence of energizing currents of each electromagnet.

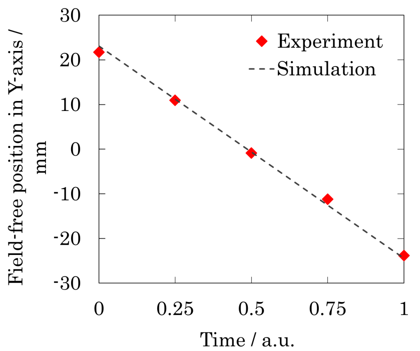

Figure 5: Center position shift of field free in Y-axis at Z = 0 plane over time: Note that balance of energizing currents for two sets of electromagnets changes with time.

mately ±25 mm from the center.

An assessment of the gradient magnetic field uniformity is presented below. In this evaluation, the gradient field strength remained fixed at 1.5 T/m, and the current was adjusted to the FFL position at the center of the magnet (X = 0, Y = 0). Fig. 6 shows the gradient field components along each axis of the FFL magnet. The gradient magnetic field showed uniformity along both the X- and Y-axes, approximately at 1.5 T/m, with maximum deviations of 4.3% and 3.1%. The magnetic field demonstrated uniformity along the longitudinal direction of the FFL (Z-axis) at approximately 0 T/m, with a maximum deviation of 1.2%.

The image reconstruction results using the MNP samples are detailed below. Fig. 7(a) shows a MNP sample prepared by encapsulating undiluted Resovist® (Fujifilm RI Pharma) in a cylindrical container with a diameter and a volume of 2 mm and 0.025 mL. Image reconstruction was performed using third-harmonic signal data at an excitation frequency of 500 Hz (corresponding to a magnetic field strength of 46 mTp-p). The time required to acquire the reconstructed image data was roughly 12 minutes. Fig. 7(b) presents reconstructed images of the

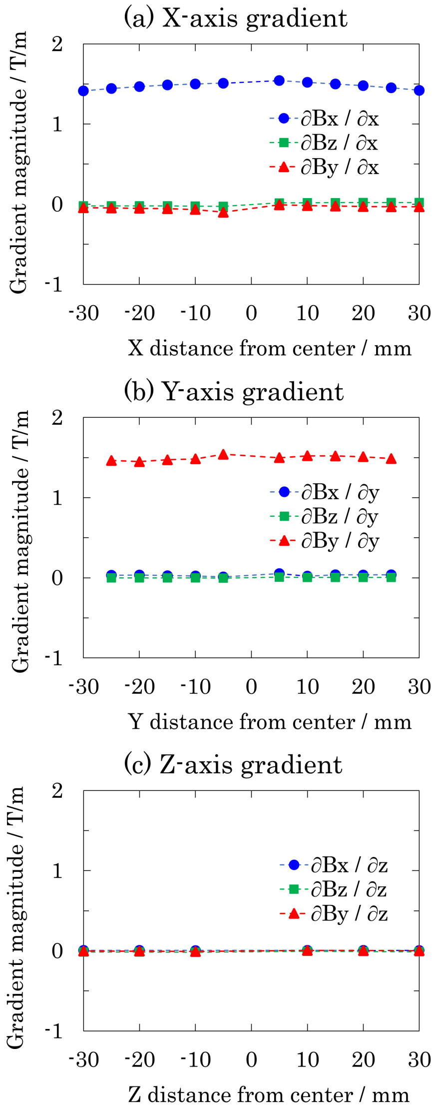

Figure 6: Experimentally measured gradient magnetic field along each FFL axis: Note that gradient remains uniform approximately at 1.5 T/m along both X- and Y-axes.

sample's central section at gradient field strengths of 1.5 and 2.0 T/m. The full width at half maximum (FWHM) of the signal intensity at each gradient field strength measured 8.2 and 11.3 mm. Specifically, the higher the gradient field strength was, the smaller the FWHM and the higher the spatial resolution.

IV. Conclusions

This paper describes a performance evaluation of an MPI system capable of scanning FFLs using two sets of electromagnets. It operated without requiring a specialized power supply, such as a bipolar power supply, and generated a drive field for FFL scanning. It was achieved by adjusting the balance of the current flowing through

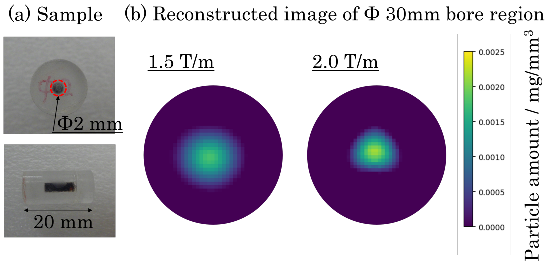

Figure 7: Reconstructed image of a sample containing encapsulated MNPs: (a) MNP sealed within a cylindrical container with a diameter and volume of 2 mm and 0.025 mL. (b) Reconstructed image of 3rd harmonic signal. Comparison between field gradient strengths of 1.5 T/m and 2.0 T/m.

each of the two sets of magnets. The magnets generated a uniform zero field along the FFL and a uniform gradient field perpendicular to it. In the future, we plan to optimize our MPI system to improve imaging speed and image quality.

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Author's statement

Conflicts of interest: The authors declare no conflicts of interest. Informed consent: Informed consent was obtained from all individuals included in this study.

References

[1] B. Gleich and J. Weizenecker, *Tomographic imaging using the nonlinear response of magnetic particles,* Nature, vol. 435, pp. 1214–1217, 2005.

[2] J. Weizenecker, B. Gleich, et al., *Magnetic particle imaging using a field free line*, J. Phys., D41:105009, 2009.

[3] K. Murase, S. Hiratsuka, R. Song, and Y. Takeuchi, *Development of a system for magnetic particle imaging using neodymium magnets and gradiometer,* Jpn J. Appl. Phys., vol. 53, pp. 067001, 2014.

[4] T. Knopp, M. Erbe, S. Biederer, T. F. Sattel, and T. M. Buzug, *Efficient generation of a magnetic field-free line*, Med. Phys., vol. 37, pp. 3538, 2010.

[5] K. Nomura, M. Washino, T. Matsuda, S. Tonooka, S. Seino, H. Yoshida, K. Nishigaki, T. Nakagawa, and T. Kiwa, *Magnetic-Particle-Discrimination Method Using Difference of Relaxation Time for Magnetic Particle Imaging*, IEEE Magn. Lett., vol. 14, pp. 8100105, 2023.

[6] E. E. Mason, C. Z. Cooley, S. F. Cauley, M. A. Griswold, S. M. Conolly, and L. L. Wald, *Design analysis of an MPI human functional brain scanner*, Int. J. Magn. Part. Imaging, vol. 3, 2017.

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