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Phase-sensitive detection of third-harmonic magnetization signal using magnetoresistive sensor-coupled asymmetric gradiometer

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Abstract

Human-scale magnetic particle imaging demands a high sensitivity in acquiring weak magnetization signal from nanoparticle tracers. The standard receive chain usually includes high-order filtering, multistage amplification, and broadband noise matching in order to improve signal quality. We incorporate these features into a conventional flux transformer circuit which employs a magnetoresistive sensor coupled with a gradiometric head coil. This approach provides low noise level to map the third harmonic response of a 0.5 mL Ferucarbotran sample under 16 mT m^{-1} DC gradient and 1.5 mT/μ_0 excitation field at 2 kHz. However, high inductance of asymmetric gradiometer was responsible for a noisy output voltage of an empty bore, limiting the sensitivity up to 1 mg$_{\mathrm{Fe}}$. We later adopted lock-in method to differentiate the signal of a few µg$_{\mathrm{Fe}}$ sample. Although harmonic noises are signal-disruptive for higher excitation fields, this technique recognized a 10 µg$_{\mathrm{Fe}}$ sample under 2.5 mT/μ_0 in the current setup.

I. Introduction

Magnetic particle imaging (MPI) is a promising method for brain diagnostics to address the risk of neurovascular and neurodegenerative diseases by employing magnetic nanoparticles as tracers [1]. The development of human brain MPI scanner highlights a major issue in achieving sensitivity limit comparable to the amount of cellular uptake [2]. In terms of system hardware, large receive coils are inevitable to cover the dimension of human head within field of view (FOV) [3], thus leading to a proportional noise capture. MPI scanner relies on a sophisticated signal filtering and low-noise amplification to improve signal-to-noise ratio (SNR) [4]. A simpler signal-processing circuit with high SNR is preferable.

Previously, we reported a flux transformer-based receive chain using a magnetoresistive (MR) sensor for a magnetic particle spectroscopy system [5]. Flux transformer coupled with a magnetometer module principally detects magnetization signal of the tracers remotely [6]. For similar scenario, we exclusively report third-harmonic signal characterization of MR sensor-based receive chain using a standard lock-in method.

II. Methods and materials

We built a brain MPI scanner with a 168 mm×168 mm FOV, implementing an asymmetric gradiometer setup [Figure 1(a)]. A TDK Nivio xMR sensor was connected to the gradiometer output via flux transformer circuit. For preliminary test of imaging performance, we used a 0.5 mL Ferucarbotran sample with a high iron concentration of 56 mg$_{\mathrm{Fe}}$mL^{-1}. We recorded the third harmonic signal (V_3) for 5 s under low DC gradient of 16 mT m^{-1} and

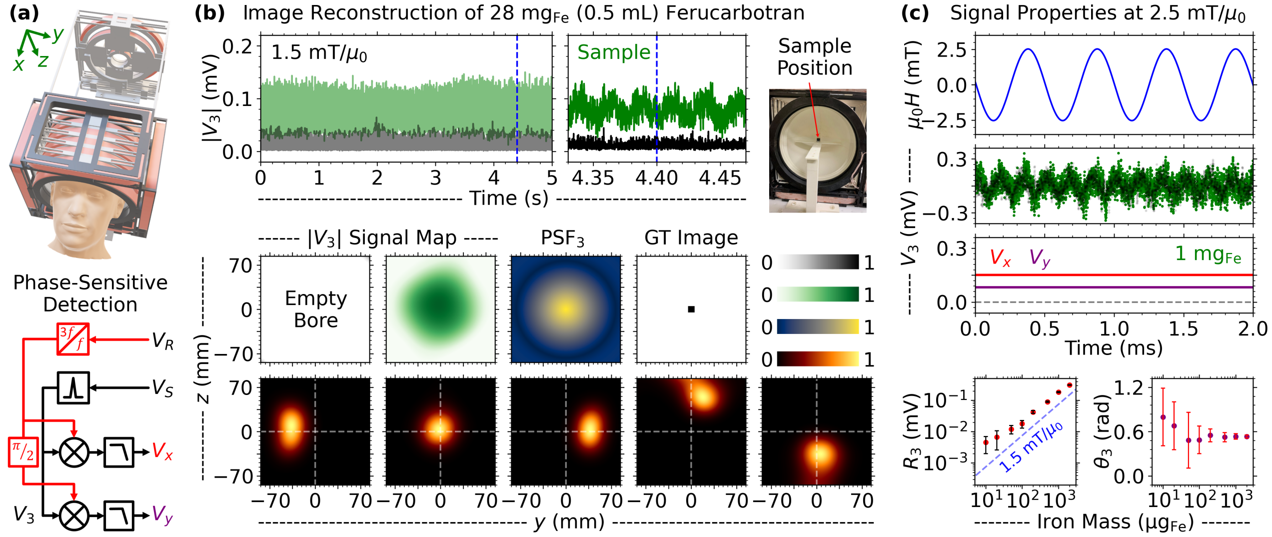

Figure 1: (a) Phase-sensitive detection scheme of raw MR sensor output (V_S) relative to a reference voltage (V_R). The filtered third-harmonic signal (V_3) is decomposed into V_x and V_y components. (b) Preliminary test of reconstructing a 0.5 mL liquid Ferucarbotran point-phantom under a 16 mT m^{-1} DC gradient. The time-varying $|V_3|(t)$ (before the lock-in detection) represents a broadening $|V_3|(y,z)$ signal map of 28 mg$_{\text{Fe}}$ sample, later correctable upon deconvolution over PSF$_3$. (c) Improved signal quality using lock-in method under 2.5 mT/μ_0. At a 1 mg$_{\text{Fe}}$ sample mass, V_x and V_y can be extracted from a noisy $V_3(t)$ to define its amplitude (R_3) and phase (θ_3). Light-blue dashed line represents the slope of R_3 at 1.5 mT/μ_0 which equals 75 nV/µg$_{\text{Fe}}$.

one-dimensional excitation field of 1.5 mT/μ_0 at 2 kHz. We later measured V_x and V_y components of V_3 for various iron mass at constant 0.1 mL volume.

III. Results and discussion

Figure 1(b) shows $V_3(t)$ acquisition from MR sensor output, which emphasizes the time-varying magnitude to map the signal distribution of 28 mg$_{\text{Fe}}$ sample at $|V_3|(y,z)$. Low DC gradient principally leads to a broad harmonic point-spread-function, PSF$_3$. It is responsible for a blurred $|V_3|(y,z)$ projection, while an empty bore produced a small artifact in the corner of $|V_3|(y,z)$. To reconstruct the phantom, we deconvolved $|V_3|(y,z)$ by a predetermined PSF$_3$, resulting in a less-blurred image as compared to the ground truth one. Accordingly, we were able to track the sample when moved within the FOV.

From Figure 1(c), $V_3(t)$ overlaps with background noises for sample mass reduced to 1 mg$_{\text{Fe}}$. Here, the lock-in method clearly recognizes $V_3(t)$ in terms of V_x and V_y. The calculated $R_3 = \sqrt{(V_x^2 + V_y^2)} \equiv |V_3|$ appears linear above 75 nV/µg$_{\text{Fe}}$ (obtained under 1.5 mT/μ_0) with constant $\theta_3 = \arctan(V_y/V_x)$. Extensively, these properties may be usable for developing a phase-contrast imaging protocol as a complement to the typical reconstruction using only the amplitude [Figure 1(b)].

IV. Conclusion

We demonstrated an improved sensitivity of brain MPI scanner by adopting lock-in method for third-harmonic signal differentiation. A flux transformer with MR sensor was used to measure magnetization signal from nanoparticle samples, where the sensitivity limit of the system currently reached 10 µg$_{\text{Fe}}$ for 2.5 mT/μ_0.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

References

[1] M. Graeser, F. Thieben, P. Szwargulski, F. Werner, N. Gdaniec, M. Boberg, F. Griese, M. Möddel, P. Ludewig, D. van de Ven, O. M. Weber, O. Woywode, B. Gleich, and T. Knopp. Human-sized magnetic particle imaging for brain applications. *Nature Communications*, 10:1936, 2019, doi:10.1038/s41467-019-09704-x.

[2] E. Mattingly, M. Sliwiak, J. Chacon-Caldera, A. Barksdale, F. Niebel, E. Mason, and L. Wald. A human-scale magnetic particle imaging system for functional neuroimaging. *International Journal on Magnetic Particle Imaging*, 10(1):2403016, 2024, doi:10.18416/IJMPI.2024.2403016.

[3] K. Nomura, M. Washino, T. Matsuda, S. Seino, T. Nakagawa, T. Kiwa, and M. Kanemaru. Development of human head size magnetic particle imaging system. *International Journal on Magnetic Particle Imaging*, 10(1):2403001, 2024, doi:10.18416/IJMPI.2024.2403001.

[4] F. Thieben, F. Foerger, F. Mohn, N. Hackelberg, M. Boberg, J.-P. Scheel, M. Möddel, M. Graeser, and T. Knopp. System characterization of a human-sized 3D real-time magnetic particle imaging scanner for cerebral applications. *Communications Engineering*, 3:47, 2024, doi:10.1038/s44172-024-00192-6.

[5] S. B. Trisnanto, T. Kasajima, T. Shibuya, and Y. Takemura. Low-concentration magnetic particle spectroscopy using gradiometric receive coil-coupled magnetoresistive sensor. *IEEE Transactions on Magnetics*, 59(11):10153680, 2023, doi:10.1109/TMAG.2023.3286415.

[6] T. Oida, K. Kato, Y. Ito, and T. Kobayashi. Remote detection of magnetic signals with a compact atomic magnetometer module towards human MRI–MPI hybrid systems. *International Journal on Magnetic Particle Imaging*, 5(1-2):1906001, 2019, doi:10.18416/IJMPI.2019.1906001.

