International Journal on Magnetic Particle Imaging
Vol 10, No 1, Suppl 1, Article ID 2403018, 4 Pages

Proceedings Article

Super-resolution pulsed magnetic particle imaging using shape anisotropic nanoparticles

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Abstract
Pulsed magnetic particle imaging (MPI) allows the use of long relaxation time magnetic particles to achieve high-resolution images. In this study, we proposed a super-resolution imaging method for pulsed MPI, which can further enhance its spatial resolution. We validated our approach using autonomously synthesized long relaxation time shape anisotropic nanoparticles on our in-house-built 1D MPI system. The results demonstrate a spatial resolution of 1.0 mm under a gradient field of 1.2 T/m.

I. Introduction

Pulsed magnetic particle imaging (MPI) is a novel imaging method distinct from traditional sinusoidal excitation MPI[1][2][3]. Tay et al. mentioned that pulsed MPI could overcome image blurring caused by relaxation, allowing the larger magnetic particles to enhance MPI resolution [1]. In this study, we utilized the relationship between relaxation time and bias field (provided by the gradient field), employing a super-resolution algorithm further to differentiate the central and outer regions in the field free point (FFP). We validated our approach using autonomously synthesized long relaxation time shape anisotropic magnetic nanoparticles (MNPs) on our in-house-built 1D pulsed MPI system. The results demonstrate a spatial resolution of 1.0 mm under a gradient field of 1.2 T/m.

II. Theory

Various factors can influence the relaxation time. In addition to the inherent characteristics of magnetic nanoparticles, different applied magnetic fields can result in varying relaxation times. This process can be described by the Fokker-Planck equation [4].

Moreover, interactions between MNPs under the external magnetic field may cause adjacent particles to respond collectively, leading to changes in relaxation time [5].

In MPI, the gradient field can be considered a static bias field related to position. As the position approaches the center of the FFP, the bias field decreases. Therefore, magnetic particles can have different relaxation times under the same excitation magnetic field because of different static biases. In pulsed MPI, the signals (in the flat segment of the square wave) of MNPs with varying relaxation times are nonlinear. Therefore, we can decompose signals from various bias fields using pre-acquired prior signals. In other words, we can further shrink the FFP region to achieve super-resolution imaging.

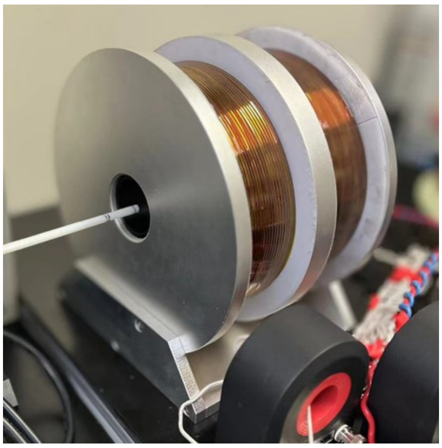

Figure 1: 1D In-house-built pulsed MPI scanner

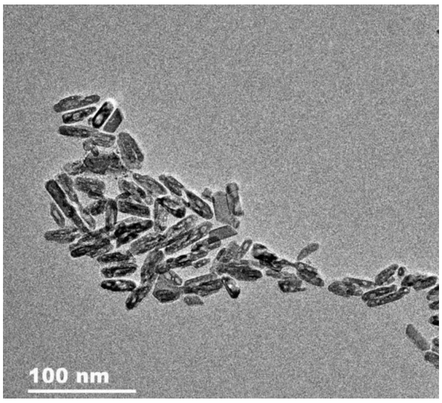

Figure 2: Shape-anisotropic MNPs

III. Material and methods

III.I. 1D In-House-Built Pulsed MPI

We used a 1D in-house-built pulsed MPI scanner to validate our work (fig. 1). The Maxwell coils generate a variable gradient field from 0 to 3 T/m. The gradient field was fixed at 1.2 T/m during the experiments. The excitation field is generated by a solenoid, which can produce a square wave with a peak value of 7 mT at 1 kHz.

III.II. MNPs and Phantom

We used autonomously synthesized shape-anisotropic MNPs for imaging. According to the TEM, the major axis of the core diameter is about 40nm, and the minor axis is about 18nm. The tested hydration kinetics results in a diameter of about 60nm. The iron concentration of MNPs is about 60 percent, with about 2mg of iron per milliliter of solution. Its TEM images are presented in Fig. 2. The line pair phantom was used for resolution testing.

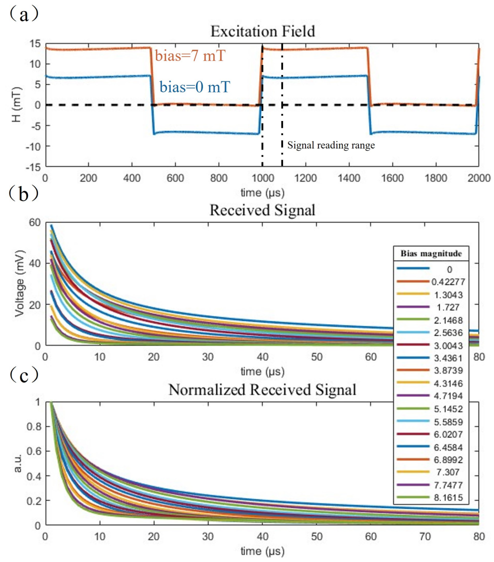

Figure 3: The relationship between the bias field and relaxation (experimental data). (a). Excitation field; (b)Received signal; (c) Normalized received signal

III.III. Super-resolution system matrix

We measured 19 groups of signals as a super-resolution system matrix within the bias range of 0-7 mT.

III.IV. Reconstruction

First, we processed the signals using the method described in reference [1]. This will result in an initial image. Next, we apply the super-resolution algorithm to each non-zero pixel of the initial image. The super-resolution algorithm decomposes the signal into components from the central and outer regions of the FFP, and we discard the outer signal for each pixel. Finally, a high-resolution image (compared to the initial image) will be obtained.

We used the Alternating Direction Method of Multipliers (ADMM) to perform super-resolution on the images [5].

III.V. Simulation

We simulated the Brownian relaxation response of 20 nm MNPs in a two-dimensional FOV using the Fokker-Planck equation. The gradient field was set to 1 T/m.

IV. Results

IV.I. The relationship between the bias field and relaxation

By analyzing the data of the system matrix, the relationship between the bias field and relaxation can be visually

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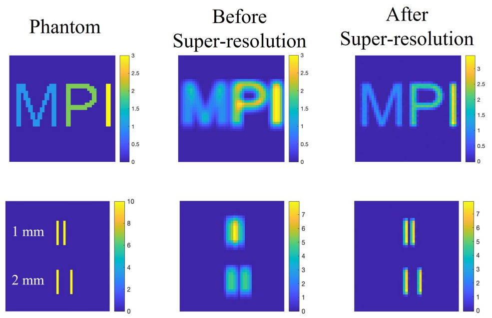

Figure 4: Simulated results.

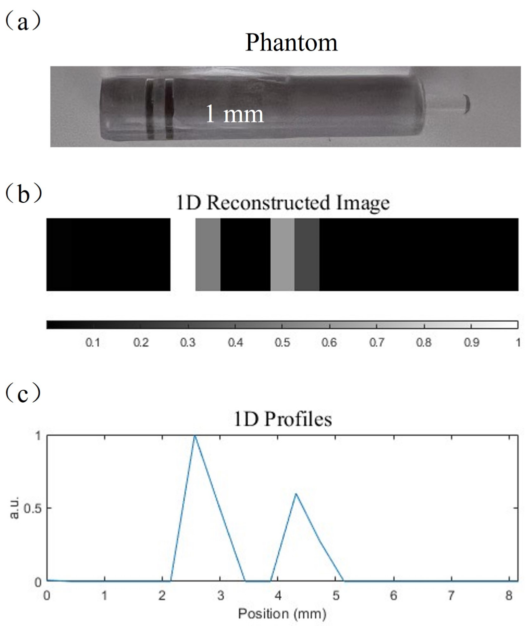

Figure 5: Line pair phantom and its reconstructed image.

visualized, as shown in Fig. 3.

From Fig. 3 (c), we can see that the normalized relaxation signals under different bias fields do not completely overlap, indicating their nonlinearity. This nonlinearity is crucial for the effectiveness of super-resolution algorithms.

IV.II. Simulation result

Fig. 4 shows the reconstructed results of the letter phantom and the line pair phantom. After super-resolution, the resolution has been improved. Numerically, the resolution has been improved from 2 mm to 1 mm (1 T/m).

IV.III. Spatial Resolution

Fig. 5 shows the experimental results of the line pair phantom. From the results, the phantom with 1 mm spacing is clearly resolved, which demonstrates that the proposed method achieves a resolution of at least 1 mm under a gradient field of 1.2 T/m.

V. Discussion

Our proposed work is based on pulsed MPI. Its advantage lies in the fact that during the signal acquisition stage, the FFP remains stationary. This allows us to analyze signals in specific locations. At the same time, pulsed MPI allows for better analysis of relaxation information compared to sinusoidal MPI.

Our work involves the use of a system matrix; however, our approach is distinct from traditional system matrix reconstructions. Before applying the proposed super-resolution algorithm, an initial image has already been obtained (using the method described in reference [1]). The super-resolution algorithm enhances the resolution of non-zero pixels in the initial image instead of reconstructing the image using the signals. The advantage of this approach is that the super-resolution system matrix does not need to be reacquired when changing parameters, and the size of the system matrix is independent of the size of the field of view (FOV). However, this approach requires decoupling the super-resolution system matrix from the hardware, necessitating distortion correction for the signals (which is not required in traditional system matrix reconstructions). At the same time, iterating pixel by pixel can consume a significant amount of computational resources.

In this work, we utilized autonomously synthesized long relaxation time shape anisotropic MNPs because conventional magnetic particles, such as Perimag, do not exhibit significant relaxation effects, resulting in weak signals during the square wave plateau period.

The experiments demonstrated a resolution of 1 mm under a gradient field of 1.2 T/m. However, this is not the limit of our algorithm. Some hardware issues have prevented us from conducting more in-depth tests. This work will be carried out in the future.

VI. Conclusion

We proposed a super-resolution method for pulsed MPI. The experimental results indicate that the resolution can reach at least 1 mm under a 1.2 T/m gradient field.

Author's statement

Conflict of interest: Authors state no conflict of interest.

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10.18416/ijmpi.2024.2403018