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Background-free reconstruction in magnetic particle imaging via differential offset fields

Penghua Zhai[a,b] · Zhongwei Bian[a,b] · Weixin Xu[a,b] · Jie Tian[a,b,*] · Wei Mu[a,b,*]

[a]School of Engineering Medicine, Beihang University, Beijing, China
[b]Key Laboratory of Big Data-Based Precision Medicine (Beihang University), Ministry of Industry and Information Technology of the People's Republic of China, Beijing, China
[*]Corresponding author, email: tian@ieee.org; weimu@buaa.edu.cn

Abstract
Magnetic particle imaging (MPI), an emerging molecular imaging technique with high sensitivity and spatial resolution, requires effective suppression of background interference. A common practice is to first measure the background and subtract it from subsequent MNPs signal acquisition. However, frequent background measurements not only reduce imaging efficiency but can also introduce additional noise and repositioning artifacts. To address these limitations, we propose a background-free reconstruction method to eliminate dedicated background measurements. Specifically, a pair of differential symmetric offset fields is sequentially applied to excitation field, and the differential signal between the two acquisitions yields a pure MNPs response. Simulation results demonstrate that the approach significantly enhances imaging quality compared to background measurement method.

I. Introduction

Magnetic particle imaging (MPI) is a novel tracer-based imaging technology that enables quantitative visualization of the spatial concentration distribution of magnetic nanoparticles (MNPs) [1]. However, the MNPs signal measured by MPI system is susceptible to background interference, such as electromagnetic distortion and mechanical vibration [2, 3], which can compromise the accuracy of quantitative MNPs assessment. To suppress such interference, a common practice is to first measure the background signal in the absence of MNPs and then subtract it from subsequent MNPs signal acquisition. This procedure typically requires repeatedly moving the MNPs in and out of the MPI scanner. Nevertheless, frequent background measurements not only prolong the overall measurement process but may also introduce additional interference and repositioning artifacts, which is especially pronounced in detection of low-concentration MNPs, especially for portable MPI systems [4].

Here, we propose a differential offset field-based background-free reconstruction that eliminates the need for dedicated background measurements to obtain pure MNPs signal. In this method, a pair of differential symmetric offset magnetic fields with identical amplitude but opposite phase is sequentially applied to the excitation field, and the differential signal between the two acquisitions is computed to extract pure MNPs response.

II. Methods and materials

The principle of the proposed method is illustrated in Figure 1. According to the basic principles of MPI, the relationship between the alternating magnetic field (H_{AC}) and the magnetization (M) of MNPs exhibits inherent nonlinearity. The nonlinear magnetization response can be described by the Langevin function ($L(\xi)$), expressed as:

$$M_{all}(H) = L(H_{AC}(t)) + \sigma, \tag{1}$$

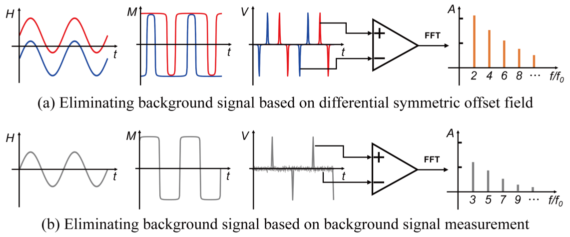

Figure 1: The principle of (a) the proposed offset field method and (b) background measurement method.

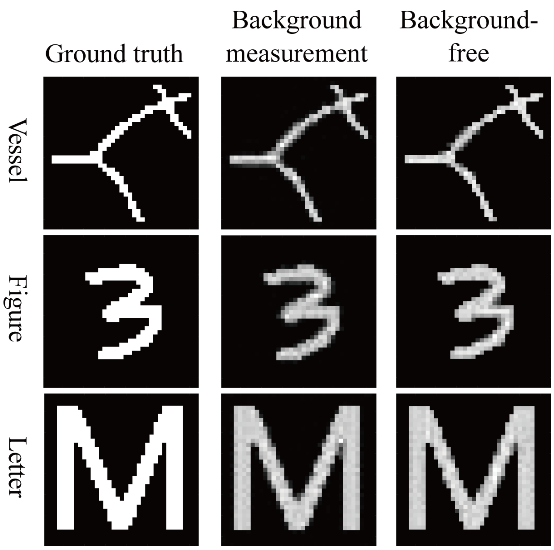

Figure 2: Reconstruction results based on system matrix.

where, σ denotes background signal, and $M_{all}(H)$ denotes the overall magnetization response in real MPI system.

For the proposed differential symmetric offset field method, the excitation is sequentially applied with a positive offset field (denoted as H_{DC}) and a negative offset field (denoted as $-H_{DC}$). The magnetization of MNPs is measured under each excitation, respectively.

$$M^{+}(H) = L(H_{AC}(t) + H_{DC}) + \sigma, \quad (2)$$

$$M^{-}(H) = L(H_{AC}(t) - H_{DC}) + \sigma, \quad (3)$$

where, $M^{+}(H)$ and $M^{-}(H)$ denote the magnetization of MNPs under a positive offset field and a negative offset field, respectively. Under the influence of offset field, MNPs exhibit different magnetization states (Eq. (2) and (3)). The magnetization of MNPs is reflected in the receive coil as a change in induced electromotive force, i.e., the measured voltage signal. Therefore, the voltage signal measured in the receive coil is generated by the H_{AC}, H_{DC}, and the σ. As the two excitation processes differ solely by a 180° phase shift of the offset field, a differential calculation effectively yields the final pure MNPs signal.

Furthermore, the MNPs signal spectrum obtained from the Fourier transform under the influence of an offset field exhibits even harmonics. In contrast, the Fourier-transformed signal contains only odd harmonics when no offset field is applied [5]. Therefore, the spatial distribution of MNPs is reconstructed through even-harmonic-based system matrix reconstruction.

Table 1: Quantitative results of image reconstruction based on system matrix. (nRMSE↓, PSNR↑, and SSIM↑)

	Background measurement			**Background-free**		
	nRMSE	PSNR	SSIM	nRMSE	PSNR	SSIM
Vessel	0.0869	21.22	0.9247	0.0660	23.61	0.9734
Figure	0.1106	19.12	0.9273	0.0874	21.46	0.9670
Letter	0.1354	17.37	0.9174	0.1120	19.01	0.9540

III. Results and discussion

The qualitative and quantitative imaging results for different phantoms are presented in Figure 2 and Table 1, respectively. The experimental phantoms include the letter "M", the figure "3", and a blood vessel phantom. Compared with the background measurement method, qualitative results indicated that the reconstructed images obtained by the proposed approach more closely resemble the ground truth, exhibiting reduced edge noise and smoother textures.

Furthermore, the quantitative comparison showed that the proposed method improves normalized Root Mean Square Error (nRMSE), Peak Signal-to-Noise Ratio (PSNR), and Structural Similarity Index (SSIM) for all phantoms. Collectively, these results demonstrated the superior performance of the proposed method in achieving high-quality image reconstruction.

IV. Conclusion

In this study, we propose a background-free reconstruction method based on a pair of differential offset fields with identical amplitude but opposite phase. This approach effectively removes background and repositioning artifacts, while eliminating the need for dedicated background measurement. Simulation results showed that the proposed method significantly improves imaging fidelity and quality.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

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