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Single-harmonic-based narrowband MPI: Effect of different harmonics

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Abstract

Single-harmonic-based narrowband magnetic particle imaging (MPI) is one of the most promising approaches, which only measures a single harmonic to visualize the spatial distribution of superparamagnetic iron oxide nanoparticles (SPIONs). In this paper, we investigate the effect of different harmonics, e.g. the 3^{rd}, the 5^{th} and the 7^{th} harmonic, on the spatial resolution of single-harmonic-based narrowband MPI. The point spread functions of different harmonics at an excitation magnetic field of 4 mT and 10 kHz are simulated and evaluated by comparing the full width at half maximum (FWHM). The 3^{rd}, the 5^{th}, and the 7^{th} harmonics are used to reconstruct MPI images to investigate their effects on the spatial resolution. Simulation results indicates that with increasing harmonic order, the FWHM get narrower and the spatial resolution gets improved.

I. Introduction

Magnetic particle imaging (MPI) is an emerging imaging modality which can visualize the spatial distribution of superparamagnetic iron oxide nanoparticles (SPIONs), which allows for high spatiotemporal resolution and high sensitivity [1]. These advantages, along with its non-invasive nature and lack of ionizing radiation, make MPI a promising approach for biomedical applications, including cancer detection, vascular imaging and targeted drug delivery. In most of these applications, spatial resolution is one of the most important metrics. Improving the spatial resolution is one of the most challenging topics in MPI research field.

MPI was firstly developed by Gleich and Weizenecker in 2005 [1], which measures the full spectra of the SPIONs in the frequency range from a few 10 kHz to about 1 MHz. Another approach called narrowband MPI that only measures a single harmonic has been reported for the imaging of the SPIONs. For instance, Goodwill *et al.* introduce narrowband MPI which offers the benefit of reducing bandwidth requirements and increasing the signal-to-noise ratio (SNR) [2]. Janssen *et al.* reported on a single harmonic based narrowband MPI, demonstrating promising performance in terms of spatial resolution and limit of detection (LOD) [3].

This study investigates to use different harmonics, e.g. the 3^{rd}, the 5^{th}, and the 7^{th} harmonics, to realize single-harmonic-based narrowband MPI, especially, the effect of different harmonics on the spatial resolution. The point spread function (PSF) is simulated with an ac magnetic field of 4 mT and 10 kHz. Two dot samples with a distance of 0.4 mm are simulated to investigate the spatial resolution.

II. Method

The amplitude of a specific harmonic of a dot SPION sample versus position of field free point (FFP) is considered as the PSF of narrowband MPI. Taking the 3^{rd} harmonic as an example, the relationship between measured 3^{rd}

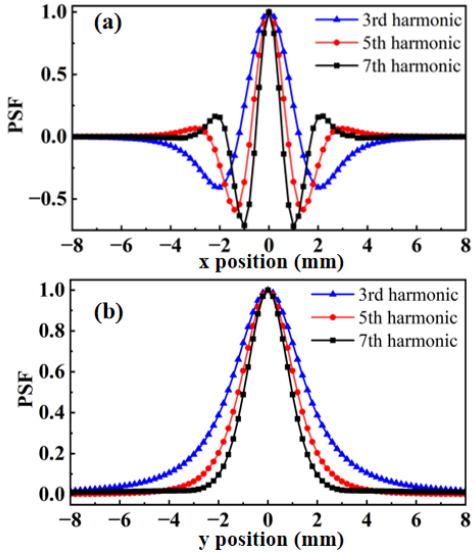

Figure 1: (a) 1D PSF of different harmonics in x-direction. (b) 1D PSF of different harmonics in Y-direction. The FOV for the PSF measurement is 8 mm × 8 mm.

harmonic $u_3(\boldsymbol{r})$ at different FFP position and the PSF of the 3^{rd} harmonic PSF($\boldsymbol{r}$) can be expressed as:

$$u_{3rd}(r_{\mathrm{FFP}}) = h_{3rd}(\mathrm{r}) * PSF_{3rd}(\mathrm{r_{FFP}}), \tag{1}$$

where $h(\boldsymbol{r})$ is the 3^{rd} harmonic generated by the local SPIONs at position $\boldsymbol{r}$.

The similar equations can describe the relationship between harmonic and PSF for 5^{th} and 7^{th}.

As the FFP moves across the entire field of view (FOV), the obtained magnetization response signals are discontinuous, and the convolution can be transformed into matrix multiplication form. Thus, we can obtain the following equation:

$$\mathbf{S} \cdot \mathbf{c} = \mathbf{u}, \tag{2}$$

with $\mathbf{S}$ denotes the system matrix converted from PSF, $\mathbf{c}$ denotes the distribution of SPIONs concentration, and $\mathbf{u}$ is the voltage vector.

III. Results

III.I. Simulation description

In this study, the static Langevin function is used to simulate the harmonics of the SPIONs induced in ac magnetic fields. An ac magnetic field with an amplitude of 4 mT and a frequency of 10 kHz is used to excite the SPIONs. The core diameter of SPIONs is 25 nm with a 15 nm coating without considering size distribution. The Gaussian noise is applied to the simulated signal according to the mean energy of different harmonics. Two-dot phantoms with 0.4 mm distance in x direction is used to evaluate the effect of different harmonics on spatial resolution.

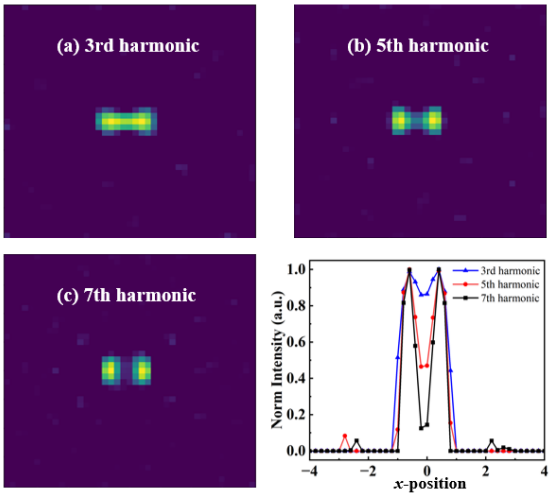

Figure 2: (a) Reconstructed by 3^{rd} harmonic. (b) Reconstructed by 5^{th} harmonic. (c) Reconstructed by 7^{th} harmonic. (d) Normalized image intensity vs position curves.

III.II. PSF simulation

To evaluate the spatial resolution, the magnetic response of a spot SPION sample was simulated in 0.2 mm steps through field of view (FOV). To compare the spatial resolution of different harmonics, normalized 1D PSFs in x- and y-direction are presented in Fig. 1. It's obvious that the PSF gets narrower with increasing harmonic order both in x- and y-direction. Figs. 1a and 1b shows the PSFs of the 3^{rd}, the 5^{th}, and the 7^{th} harmonics in x- and y-direction, respectively. With increasing the harmonic from 3^{rd} to 7^{th}, the FWHM in x-direction decreases from 2.0 to 1.0 mm while the FWHM in z-direction declines from 3.2 to about 2.0 mm.

III.III. Phantoms imaging

Images reconstructed by different harmonics using the algebraic reconstruction technique (ART) are shown in Fig 2. According to reconstructed images and intensity-position curves, two points can be distinguished by 7^{th} harmonic while artifacts appear between points in 3^{rd} harmonic.

IV. Conclusion

This study investigated the effect of different harmonics on the spatial resolution of single-harmonic-based narrowband MPI. According to the simulated PSF and reconstructed images of the 3^{rd}, the 5^{th}, and the 7^{th} harmonics, spatial resolution improves as the order of harmonic increases.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research does not involve any animal experiments.

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