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An 101 kHz – narrowband magnetic particle imaging scanner

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Abstract

Magnetic particle imaging (MPI) is an emerging medical imaging modality for quantitatively visualizing the spatial distribution of superparamagnetic iron oxide nanoparticles (SPIONs). In this study, we develop a narrowband MPI scanner with an excitation frequency of 101 kHz. In x-direction, a solenoid coil is used to generate the 101 kHz ac magnetic field with amplitude of 4 mT for the SPIONs excitation. In y-direction, a saddle coil is used to generate a low-frequency ac magnetic field to scan a field free point. A gradiometric detection coil is used to only measure the 3rd harmonic at 303 kHz for the SPIONs visualization. Phantom experiments are performed with SynomagD-70 SPIONs. It indicates that reconstructed images have a spatial resolution of 1.5 mm and 1 mm for a gradient field of 0.56 T/m and 1.12 T/m in x- and y-direction, respectively.

I. Introduction

Magnetic particle imaging (MPI) is an innovative imaging technique that is capable of visualizing superparamagnetic iron oxide nanoparticles (SPIONs) with exceptional temporal-spatial resolution and sensitivity [1], [2]. MPI has shown significant potential for various biomedical applications, such as cancer detection, drug delivery and cell tracking.

To date, various MPI approaches have been developed with different imaging methodologies and scanner designs. In 2005, Gleich and Weizenecker have demonstrated a wide-bandwidth MPI system [1]. In 2009, Goodwill et al. proposed the methodology of narrowband MPI with multi-harmonics [3]. In 2022, Janssen et al. investigated and designed a single harmonic based narrowband MPI with an excitation frequency of 5 kHz, showing promising performance in terms of spatial resolution and limit of detection (LOD) [2].

In this study, we develop a narrowband MPI scanner at 101 kHz and 4 mT by measuring only the 3rd harmonic at 303 kHz. SynomagD-70 SPIONs are used as the experimental samples. The point spread function (PSF) was measured and phantoms experiments were performed to evaluate the spatial resolution.

II. Method

For the narrowband MPI scanner, a pair of permanent magnets generate a selection field, with a main gradient of 1.12T/m along the y-direction. A saddle-shaped coil saddle coil generates the scanning field in the y-direction and a solenoid coil generates the excitation field in the x-direction. A gradiometric detection coil is used to only measure the 3rd harmonic at 303 kHz for the SPIONs visualization. For the signal chain, the nearly identical circuit is as described in literature [2].

In this study, the measured 3rd harmonic $u_3(\boldsymbol{r})$ at the FFP position is an integration over the imaging field of view (FOV) and can be written as a convolution of $h(\boldsymbol{r})$

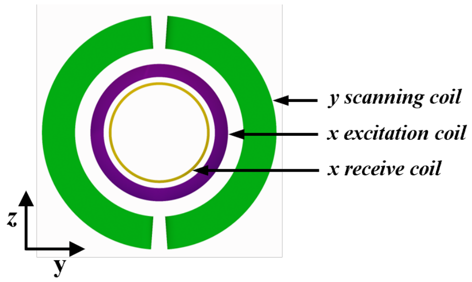

Figure 1: Coil configuration of narrowband MPI scanner.

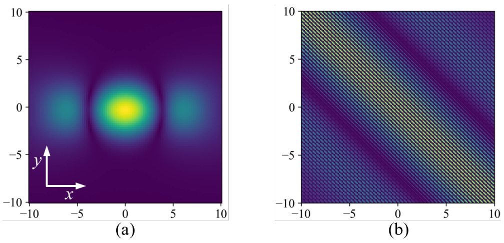

Figure 2: (a) Measured 2D image of PSF at 4 mT. (b) System matrix based on the measure PSF. The FOV for the PSF measurement is 20 mm × 20 mm.

and the PSF of the third harmonic PSF($\boldsymbol{r}$):

$$u_3(r_{\mathrm{FFP}}) = h(\mathrm{r}) * \mathrm{PSF}(\mathrm{r})|_{\mathrm{r}=r_{\mathrm{FFP}}}\,, \qquad (1)$$

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

As the FFP moves across the entire FOV, a series of measurement signals can be obtained. Thus, Eq. (1) can be rewritten as

$$\mathrm{u} = \mathrm{S} \cdot \mathrm{c}, \qquad (2)$$

with $\boldsymbol{u}$ is the measured raw image of the 3rd harmonics, $\boldsymbol{S}$ is the system matrix converted from the PSF, and $\boldsymbol{c}$ is the spatial distribution of the SPIONs concentration. The solution of Eq. (2) allows to image the spatial distribution of the SPIONs.

III. Results

III.I. Experimental description

In this study, SynomagD-70 plain SPIONs are used as experimental sample. The iron concentration of the stock sample is 10 mg/mL. The single dot sample was used to measure the PSF and experiments on two dots were performed to evaluate the spatial distribution. Each dot with a depth of 3 mm in the z direction and a diameter of 1.5 mm in the x-y plane was filled with 4.2 µL synomag SPIONs. The excitation field was a sine wave with an amplitude of 4 mT and a frequency of 101 kHz. The scanning field was a triangular wave with an amplitude of 11.2 mT and a frequency of 1 Hz. The measurement time of one line in y-direction amounts to 1 s (1 s data acquisition). Each pixel of all the measured images has a dimension of 0.2 mm × 0.2 mm. Three replicate measurements were performed for PSF measurements and 2D phantom imaging experiments.

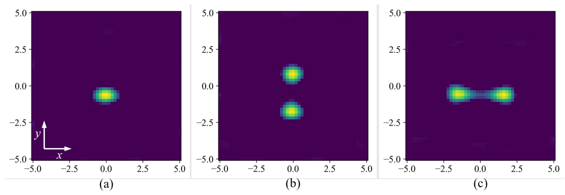

Figure 3: (a) One dot phantom. (b) Two dots phantom with a distance of 1.0 mm along the y-axis. (c) Two dots phantom with a distance of 1.5 mm along the x-axis. The image intensity is normalized to 1.

III.II. PSF measurement

The narrowband MPI scanner utilizes the system matrix for image reconstruction. A dot sample was used to measure the PSF at 4 mT, as shown in Fig. 2(a). The FOV for the PSF measurement is 20 mm × 20 mm in x- and y-direction. The movement of FFP caused by the excitation magnetic field was ignored. Based on the 2D measured PSF, the 2D system matrix was constructed, as illustrated in Fig. 2(b).

III.III. Phantoms imaging

The 2D phantom experiments were performed to evaluate the spatial resolution. The distance between two dots is defined as the edge-to-edge distance. The Kaczmarz algorithm was employed for image reconstruction, as shown in Fig. 3.

IV. Conclusion

We developed a narrowband MPI scanner that utilizes a single harmonic. Specifically, it measures only the 3rd harmonic at 303 kHz of the SPIONs signal induced by an excitation magnetic field of 101 kHz. To evaluate the spatial resolution of the newly designed narrowband MPI scanner, we conducted PSF measurements and 2D phantom imaging experiments. The Kaczmarz algorithm was employed for image reconstruction, followed by normalization of the reconstruction intensity values. Experimental results demonstrate that the narrowband MPI scanner achieves a spatial resolution of 1.5 mm and 1 mm for a gradient field of 0.56 T/m and 1.12 T/m in the x- and y-direction, respectively, under an excitation magnetic field of 4 mT. In the future, we plan to enhance the

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narrowband MPI scanner by extending its capabilities to 3D imaging for mouse imaging.

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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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