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Hybrid harmonics projection reconstruction for magnetic particle imaging

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Abstract

X-space is a rapid reconstruction method based on time domain signals for magnetic particle imaging (MPI). However, due to particle relaxation effect, signal distortion and image blur will inevitably occur in high drive field. In this work, we present a hybrid harmonics projection (HHP) reconstruction technique, which uses the response harmonic amplitude in a short time for continuous projection reconstruction. In addition, a 3D simulation model of HHP MPI scanner was constructed. Simulation and reconstruction results show that HHP has the advantage of realizing high resolution in high drive field compared with time domain projection.

I. Introduction

The main reconstruction methods in magnetic particle imaging (MPI) include system matrix (SM) and x-space. SM methods have the potential to achieve higher image quality [1], but SM acquisition process is very expensive, requiring long time measurement and repeated calibration [2]. In contrast, x-space is a rapid reconstruction method, which grids the time domain signals into field of view according to the drive trajectory [3]. However, due to the relaxation effect of particles, signal distortion and image blur will be caused under high drive field [4].

In this work, we present a hybrid harmonics projection (HHP) reconstruction method for MPI. The combination of high-order harmonics in the frequency domain is used to replace the time domain signal for imaging. The feature of this method is that the image blur caused by high drive field is compensated by narrow point spread function (PSF) of high harmonic. In addition, a preliminary HHP MPI scanner model was established in this work, and 3D dynamic magnetic field distribution was obtained by finite element simulation, then particle signals were simulated based on Langevin model. The results show that HHP has higher resolution than direct time domain projection.

II. Material and methods

II.I. HHP MPI scanner simulation model

The HHP MPI scanner moves the FFP with a focus field perpendicular to the direction of the drive field, which is only used to excite the particle signal.

In order to better simulate the real dynamic magnetic field, we established the 3D model of HHP MPI scanner in the finite element analysis software COMSOL, as shown in Fig.1(a). The cascade gradient coil group can be used to arbitrarily adjust the gradient size from 0 to 4T/m. The drive coil is used to generate an excitation field of 25kHz

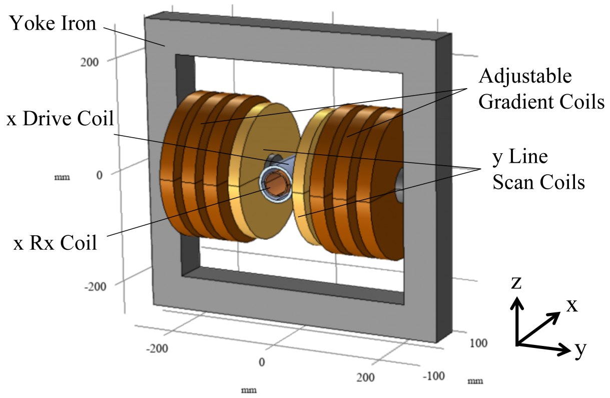

Figure 1: Structure diagram of HHP MPI scanner.

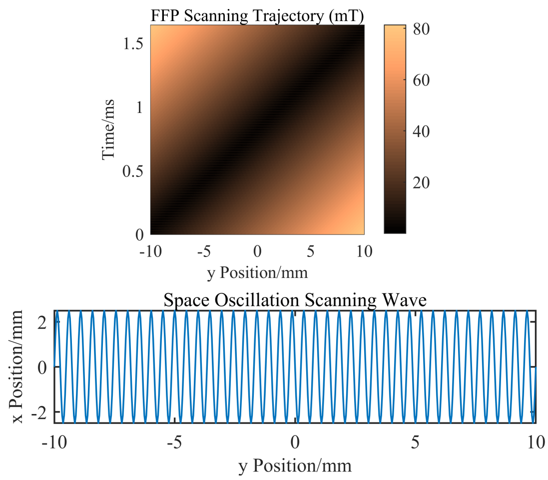

Figure 2: FFP scanning trajectory. FFP scans along the y direction under the action of the focus field, the 1D scan time is 1.6ms. Due to drive field, FFP oscillates rapidly in the x direction while scanning in the y direction.

and 0∼15mT, and the scan coils are used to generate a low-frequency focus field of 1∼600Hz. Yoke iron is used to further increase the magnetic field, and in practice its ferromagnetic nonlinear interference can be avoided by adding copper shielding.

Dynamic FFP scanning trajectory is shown in Fig.2. The scanning direction of FFP is along the y direction, and FFP also moves repeatedly in the x direction to excite particle signals. The drive coil is excited by sine wave and the scan coils by triangle wave.

II.II. Principle and formulas

According to Langevin theory of paramagnetism, without considering the relaxation effect of particles, the magnetization response M can be expressed as follows:

$$M(\bar{H}) = \rho m_0 L(\beta \bar{H}) \tag{1}$$

where, β is the particle characteristic coefficient. $\bar{H}$ is a composite field, a function of space and time. ρ is the number of particles per unit volume, m_0 is the magnetic moment of a single particle, and L is the Langevin function. According to the reciprocity theorem, particle signals u_p detected by the receiving coil can be expressed as:

$$u_p(t) = -\mu_0 \int_V \frac{\partial M_x(r,t)}{\partial t} s_R(r) dV \tag{2}$$

where $M_x(r,t)$ is the x component of magnetization, $s_R(r)$ is the sensitivity distribution of the receive coil, μ_0 is the vacuum permeability.

It is assumed that the length T_{scan} of 1D signal $u_p(t)$ has the following relationship with the drive period T_{drive}:

$$T_{scan} = T_{drive} N \tag{3}$$

Let the central time of the n^{th} drive period be t_n, then the harmonic signal $\hat{u}_p$ in the n^{th} drive period is:

$$\hat{u}_p^k(t_n) = \hat{u}_p(k f_0, t)|_{t=t_n'}, \text{ for } n = 1, 2, \ldots, N. \tag{4}$$

where, f_0 is drive frequency, k is harmonic order.

According to Formula 4, a time-varying harmonic signal can be obtained. Then, the harmonic signal is projected to the spatial position at the corresponding time for imaging, as shown below:

$$\hat{u}_p^k(t_n) \rightarrow \hat{\rho}^k(y_n), \text{ for } n = 1, 2, \ldots, N. \tag{5}$$

where, $\hat{\rho}^k$ is the k^{th} harmonic projection image, y_n is the position of FFP at t_n.

The 2D harmonic projection image of different harmonics can be obtained by mechanical scanning or magnetic scanning, as shown in Formula (6), where M represents the number of scanned lines.

$$IMG^k(x_m, y_n) = \begin{bmatrix} \hat{\rho}_1^k(y_n) \\ \hat{\rho}_2^k(y_n) \\ \vdots \\ \hat{\rho}_M^k(y_n) \end{bmatrix} \text{ for } m = 1, 2, \ldots, M \quad \text{for } n = 1, 2, \ldots, N. \tag{6}$$

According to the simulation results, it is found that low-frequency harmonic projection images are more blurred, while high-frequency harmonic projection images have higher resolution but have additional artifacts. Therefore, we propose a preliminary hybrid harmonics projection formula (7) to remove artifacts and improve image resolution.

$$IMG_{HHP} = \sum_{k=3}^{K} IMG^k \tag{7}$$

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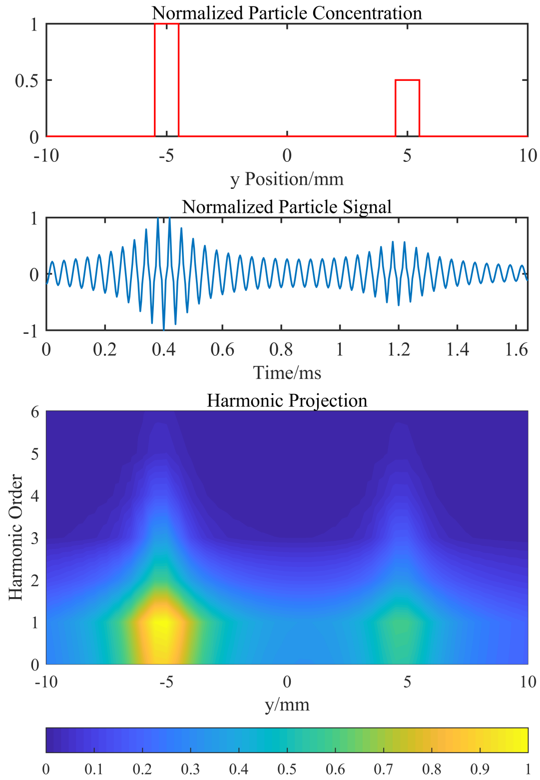

Figure 3: 1D simulation: harmonic projection reconstruction.

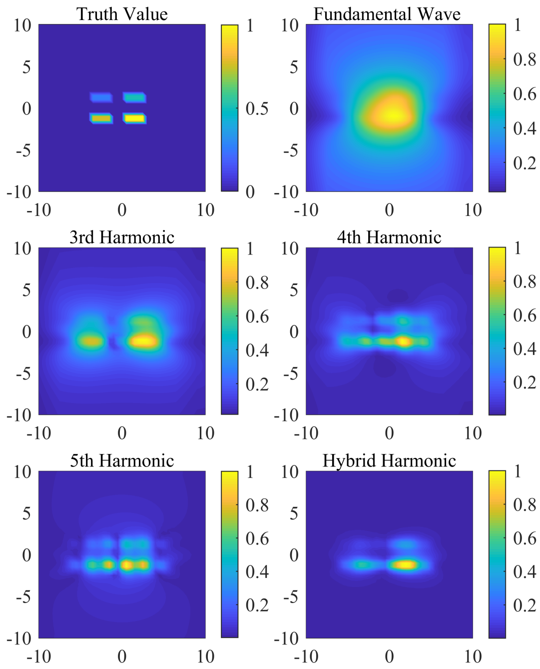

Figure 4: 2D Simulation: hybrid harmonics projection.

III. Results and discussion

The results of 1D and 2D simulation reconstruction are shown in Fig.3 and Fig.4 respectively.

Fig.3 shows the process from time domain signal to harmonic projection image. Harmonic projection images with different frequencies were spliced together for a clearer comparison. It can be seen from the results that the signal intensity of high order harmonics is weak but the spatial resolution is higher.

IV. Conclusions

In this work, we present a hybrid harmonics projection MPI reconstruction method, which uses short-time response harmonic amplitude instead of traditional time domain signal for projection reconstruction. The feasibility of this method is preliminarily proved by 2D simulation reconstruction. The results show that HHP can improve spatial resolution and reduce high order harmonic artifacts. The method will be further verified by experiments.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Not applicable.

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