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OGF-based high-throughput spatial encoding for magnetic particle imaging

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Abstract

Enhancing the signal-to-noise ratio (SNR) is crucial for comprehensively improving the performance of MPI, as it can directly enhance detection sensitivity and indirectly improve spatial resolution due to the increase in the number of available harmonics. However, the strong gradient field in the existing MPI system inevitably leads to the loss of SNR. To deal with this problem, we introduce an oscillating gradient field (OGF) to achieve a high-throughput spatial encoding to improve the SNR of MPI. The time-varying gradient strength allows particle signals from both high and low gradient fields to be captured simultaneously over the sampling period. Preliminary simulation results show that the proposed spatial encoding scheme can generate unique intermodulation signals for particles at each position. And compared with static gradient field with the same peak gradient level, OGF can theoretically generate particle signals with higher SNR.

I. Introduction

Enhancing the signal-to-noise ratio (SNR) is crucial for comprehensively improving the performance of MPI, as it can directly enhance detection sensitivity and indirectly improve spatial resolution due to the increase in the number of available harmonics [1]. However, the strong gradient field in the existing MPI system inevitably leads to the loss of SNR. Although reducing the gradient intensity can be exchanged for high SNR, it will result in low spatial resolution [2]. To address this, we introduce an oscillating gradient field (OGF) for high-throughput spatial encoding to further improve the SNR of MPI.

II. Theory and methods

In this study, two types of magnetic fields are applied: 1) a rapidly varying homogeneous magnetic field for exciting the particle to produce a dynamic magnetization response, and 2) a relatively slow OGF for spatial encoding. First, we derive the formulas for magnetic fields starting from 1-D model. Considering the ideal magnetic fields, the total magnetic field H can be written as follows:

$$H(x,t) = H_0(t) + G(t)\,x \# (1)$$

where $H_0(t)$ denotes the homogeneous field, $G(t)$ denotes a time-varying gradient strength of the OGF. Assuming that both time-varying fields oscillated as cosine

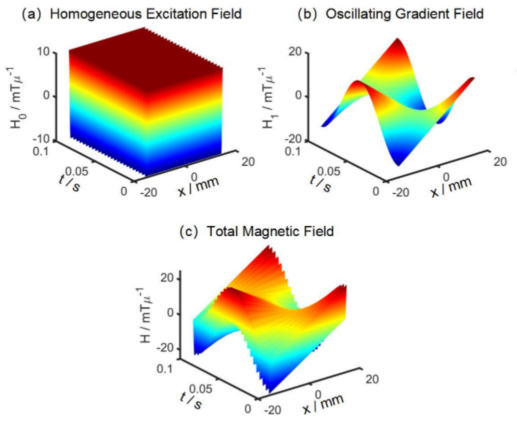

Figure 1: Simulation of the 1-D applied magnetic field. (a) The homogeneous excitation field is used to excite magnetic particles to produce dynamic magnetization response. (b) The oscillating gradient field is used for spatial encoding. (c) Total magnetic field.

functions, the total magnetic field can be further written as follows:

$$H(x,t) = A_0 \cos(2\pi f_0 t) + G_p x \cos(2\pi f_1 t) \#(2)$$

where A_0 is the amplitude of $H_0(t)$, G_p is the peak gradient strength of OGF, f_0 and f_1 are the frequencies of H_0 and OGF, respectively, and $f_0 \gg f_1$. The simulated magnetic field spatiotemporal distribution is shown in Fig 1. It can be seen from Fig. 1(c) that the total magnetic field at each position changes with time with a unique oscillation envelope, which will lead to the unique magnetization response of magnetic particles at each position.

From the given magnetic field distribution, it can be seen that the total magnetic field at each position contains two frequency components except the central position (x=0 mm). To further investigate the magnetization response signals characteristics of particles at different positions, simulation analysis is performed based on Langevin function.

III. Results and discussion

III.I. OGF-based spatial encoding

Fig.2. shows the simulated magnetic fields, particle signals and their spectra of the particles at three typical positions in the OGF. The farther away from the center position, the larger the proportion of low-frequency field component. Under the dual-frequency magnetic field excitation, the nonlinear response characteristics of magnetic particles will cause the Fourier spectra of magnetization signals to contain rich sideband harmonics. The mechanism behind this phenomenon is called intermodulation or frequency mixing [3], and the output signal is called mixing signal [4].

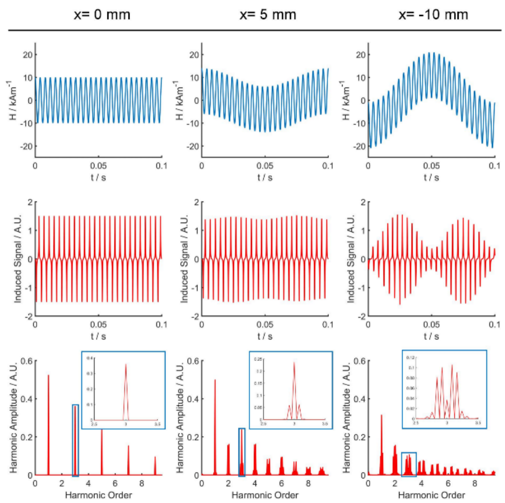

Figure 2: Simulated mixing signals at different positions under the OGF. The first row shows the total magnetic field at different positions (x=0, 5, -10 mm). The second row shows the induced signals generated by particles at different positions. The third row shows the corresponding Fourier spectra. The third harmonic and its sideband harmonics is shown in the blue box.

From the Fourier spectra, the position gradually deviated from the center, the amplitude of the low-frequency field gradually increased, and the proportion of the sideband harmonic component gradually increased. Therefore, the spatial position of the particles can be encoded using the variations of the harmonic components.

III.II. SNR enhancement using OGF

Fig. 3 shows the comparison of particle signals under OGF and static gradient field. The gradient strength of the static gradient field is consistent with the peak gradient strength of OGF. Here we consider a full field signal, which means that the particles fill the entire FOV. It can be seen from Fig. 3 that when the sampling time is set to $1/f_1$, there is a significant difference between the particle signals under the two types of gradient fields. The particle signal under static gradient field is kept at a relatively low level. The particle signal under OGF produces a peak when the gradient strength crosses zero. Assuming that the noise levels of the two are the same, it is expected that the OGF signal will have a higher SNR than the static gradient field.

IV. Conclusions

In summary, we propose a spatial encoding idea based on oscillating gradient field, which is high-throughput

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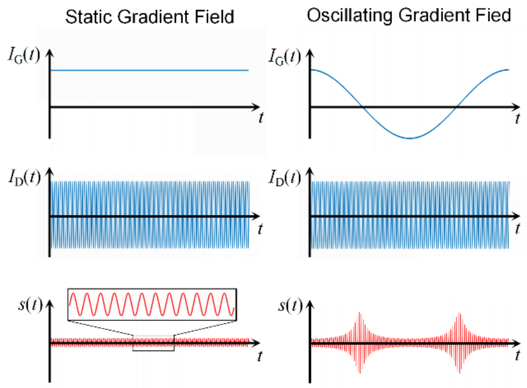

Figure 3: Comparison of OGF with a standard static gradient field signal in one sampling period. The first row shows the gradient coil current, the second row shows the drive coil current, and the third row shows the particle signal.

because it allows simultaneous acquisition of particle signals from the entire FOV. The preliminary simulation explains the spatial encoding principle of OGF and its advantages in SNR. Next, we will conduct experimental verification in the hardware system and further study the imaging issue.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

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