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Multi-dimensional harmonic dispersion x-space MPI

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Abstract

In magnetic particle imaging (MPI), standard x-space reconstruction requires partial field-of-view (pFOV) processing steps: speed compensation of the received signal and gridding the non-equidistant field free point (FFP) positions to a Cartesian grid. Moreover, due to direct feedthrough filtering, a DC recovery algorithm must be utilized, which requires pFOVs to overlap with each other. In this work, we propose an alternative x-space reconstruction technique that does not require pFOV processing or overlapping pFOVs. The proposed technique is applicable to rapid and sparse multi-dimensional scanning trajectories where standard x-space reconstruction cannot be applied due to non-overlapping pFOVs.

I Introduction

In magnetic particle imaging (MPI), standard x-space reconstruction requires partial field-of-view (pFOV) processing, such as speed compensation of the received signal and gridding signal on the non-equidistant field free point (FFP) positions to a Cartesian grid [1-4]. To determine the lost DC terms due to direct feedthrough filtering, a DC recovery algorithm must also be utilized, which requires pFOVs to overlap with each other [3]. We have recently proposed an alternative x-space image reconstruction, Harmonic Dispersion X-space (HD-X) [5]. HD-X does not divide the FOV into smaller pFOVs, and hence does not employ any pFOV processing steps. The simplified reconstruction pipeline increases robustness against relaxation and harmonic interferences compared to standard x-space reconstruction. HD-X was previously demonstrated for a line-by-line scan trajectory with each line reconstructed individually [5].

In this work, we extend HD-X to rapid multi-dimensional scanning trajectories. Importantly, we show that HD-X does not require the scanning trajectories to have overlapping pFOVs. We demonstrate with imaging experiments that HD-X is applicable to rapid and sparse multi-dimensional scanning trajectories where standard x-space reconstruction cannot be applied.

II Material and methods

II.I Theory

According to multi-dimensional x-space theory, assuming a 2D focus field in x–z plane, with 1D drive field (DF) and receive coil both aligned in the z-direction, the received signal $s(t)$ can be expressed as [2]:

$$s(t) = ||\dot{\mathbf{x}}_\mathbf{s}(t)||\, IMG(\mathbf{x}_\mathbf{s}(t)) \tag{1}$$

where

$$IMG(\mathbf{x}_\mathbf{s}(t)) = \rho(\mathbf{x}) *** \hat{\dot{\mathbf{x}}}_\mathbf{s} \cdot \mathbf{h}(\mathbf{x})\hat{\dot{\mathbf{x}}}_\mathbf{s}\, |_{x=\mathbf{x}_\mathbf{s}(t)} \tag{2}$$

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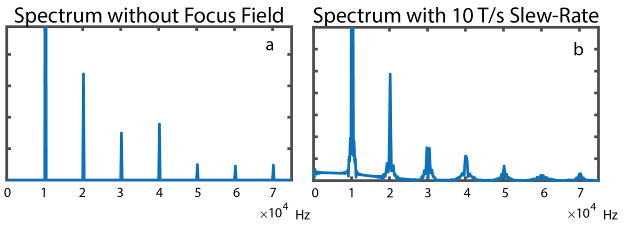

Figure 1: The dispersion of harmonics to nearby bands with the presence of a focus field. Simulations were for a point source sample, (-4.8, 2.4, 2.4) T/m selection field gradients, DF at 10 mT and 10 kHz along the z-direction.

Here, $\mathbf{x_s}(t)$ is the FFP position, $\dot{\mathbf{x}}_\mathbf{s}(t)$ is the FFP velocity and $\hat{\dot{\mathbf{x}}}_\mathbf{s}(t)$ is the unit vector along the same direction, $\rho(\mathbf{x})$ is the magnetic nanoparticle (MNP) distribution, and $\mathbf{h}(\mathbf{x})$ is the point spread function [2]. When DF is applied together with piece-wise constant focus fields in x-z,

$$\dot{\mathbf{x}}_\mathbf{s}(t) = \begin{bmatrix} x_i \\ \frac{W}{2}\cos(\omega_0 t) + z_i \end{bmatrix}. \tag{3}$$

Here, ω_0 is the DF frequency, W is the pFOV extent, and (x_i, z_i) is the central position of the i^{th} pFOV. This periodic $\mathbf{x_s}(t)$ yields a perfectly periodic $s(t)$, with components only at the harmonics of ω_0 [3] (see Fig. 1a). For this case, direct feedthrough filtering causes a DC loss that is *different for each pFOV,* mandating a DC recovery algorithm during image reconstruction [3].

In this work, we utilize a rapid multi-dimensional trajectory where the FFP scans the FOV continuously via a 2D focus field, while the DF is applied simultaneously. The time-varying focus field breaks the periodicity of the MPI signal. Hence, the spectrum is no longer contained in the discrete harmonics; instead the information disperses to nearby bands (see Fig. 1b). Importantly, the direct feedthrough is still restricted to ω_0. Therefore, a narrow-band band-stop filter followed by digital filtering makes it possible to eliminate the direct feedthrough, while removing only a small portion of the MNP signal.

The signal from the entire FOV after direct feedthrough filtering can be formulated as:

$$s_{FOV}(t) = ||\dot{\mathbf{x}}_\mathbf{s}(t)|| IMG(\mathbf{x_s}(t)) - \gamma \sin(\omega_0 t + \theta) \tag{4}$$

where

$$\mathbf{x_s}(t) = \begin{bmatrix} \varphi_x t \\ \frac{W}{2}\cos(\omega_0 t) + \varphi_z t \end{bmatrix} \tag{5}$$

Here, φ_x and φ_z are the focus field slew rates for the x- and z-directions, respectively, and $\gamma \sin(\omega_0 t + \theta)$ is the loss due to filtering. We sample $s_{FOV}(t)$ with a sampling period $T = 2\pi/\omega_0$, such that

$$s_{FOV}[n] = s_{FOV}(nT + \Delta t) = \beta IMG(\mathbf{x_s}[n]) - \hat{\gamma} \tag{6}$$

where

$$\mathbf{x_s}[n] = \begin{bmatrix} \varphi_x nT \\ \Delta x + \varphi_z nT \end{bmatrix} \tag{7}$$

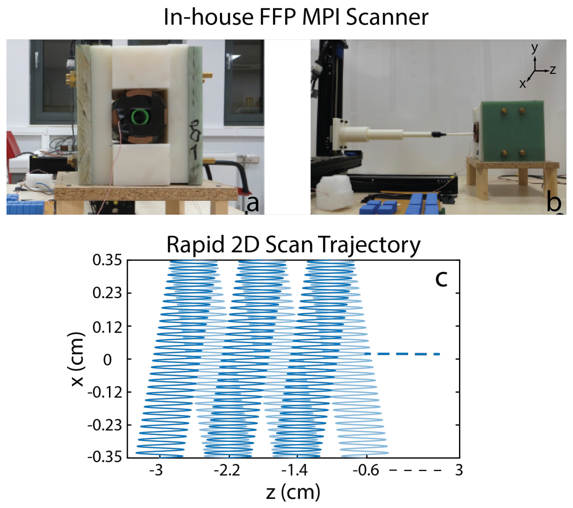

Figure 2: In-house FFP MPI scanner and the trajectory used in the imaging experiments. (a) Front and (b) side views of the scanner. (c) The rapid 2D scan trajectory with 6x0.7 cm^2 FOV.

Here, Δt is a potential timing offset in sampling, and Δx, β, and $\hat{\gamma}$ are constants. Note that, with this sampling strategy, the signal lost due to filtering becomes a DC term that is *constant for the entire FOV.* Assuming the FOV is wide enough, the minimum image intensity can later be set to zero to determine $\hat{\gamma}$. Then, the ideal MPI image can be easily obtained as:

$$IMG(\mathbf{x_s}[n]) = \frac{s_{FOV}[n] + \hat{\gamma}}{\beta} \tag{8}$$

We refer to this method as "Multi-dimensional Harmonic Dispersion X-Space MPI (Multi-dimensional HD-X)".

II.II Experiments

Imaging experiments were performed on our in-house FFP MPI scanner (see Fig. 2a-b) with (-4.8, 2.4, 2.4) T/m selection field gradients in (x, y, z) directions, with DF at 10 mT and 9.7 kHz along the z-direction. The entire FOV of 6x0.7 cm^2 was covered by a rapid 2D scan trajectory shown in Fig. 2c. Instead of electromagnetically driven focus fields, a robotic arm was used to continuously cover the entire FOV in 2D. The speed of the robotic arm was 2.54 cm/s. The resulting pFOV size along the z-direction was 8.3 mm, resulting in non-overlapping pFOVs outside the cental regions of the FOV (see Fig. 2c). The total scan time was 4.7 sec. The imaging phantom contained two 3-mm diameter vials separated at 2 cm distance (see Fig. 3a-b). Both vials were filled with Perimag nanoparticles (Micromod GmbH, Germany) with 5 mg Fe/mL concentration.

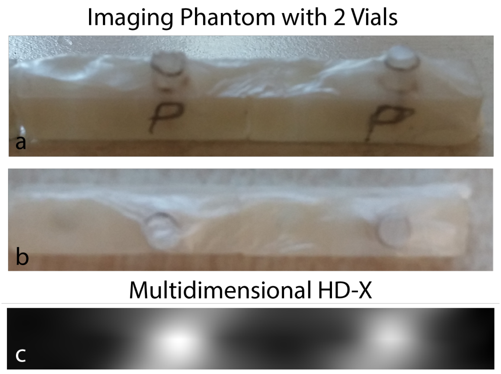

Figure 3: The imaging phantom and the imaging experiment result. (a) Side and (b) top views of the phantom. (c) MPI image using the proposed multi-dimensional HD-X reconstruction (6x0.7 cm^2 FOV).

III Results

Figure 3c displays the result of multi-dimensional HD-X reconstruction for the rapid 2D scan trajectory, showing high fidelity image reconstruction despite the usage of non-overlapping pFOVs. Note that, because the pFOVs do not overlap in certain regions, standard x-space reconstruction is not applicable for this trajectory. Hence, in contrast to standard x-space, HD-X is applicable to rapid and sparse multidimensional trajectories.

IV Conclusions

In this work, we presented an alternative x-space reconstruction technique called HD-X for multi-dimensional rapid scanning trajectories. HD-X features a simplified reconstruction pipeline, and the experimental imaging results show that it can be successfully applied to trajectories with non-overlapping pFOVs where standard x-space reconstruction cannot be applied.

Author's Statement

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