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On the Optimization of Sinogram-based Calibration

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Abstract

Sinogram-based calibration in Magnetic Particle Imaging using a 3D field free line trajectory offers high-quality system matrices. This approach involves repeating the imaging trajectory at multiple trajectory offsets in sinogram domain. However, transitions between these repetitions can introduce unwanted spectral components (USCs), potentially overloading transmit electronics. This work investigates and compares three strategies, namely stop & go, circularly-shifted, and all-ramp, for their impact on spectral purity. Simulations demonstrate that the circularly-shifted design maintains trajectory stability and significantly suppresses USCs, while the all-ramp approach achieves the shortest calibration time and minimal USCs at the cost of a slight infidelity to the actual trajectory. These results highlight trade-offs between spectral purity, trajectory accuracy, and efficiency, providing practical guidelines for optimizing sinogram-based calibration.

I. Introduction

High-fidelity system calibration is essential in Magnetic Particle Imaging (MPI) to ensure accurate image reconstruction [1]. In the case of sinogram-based system calibration for 3D field free line (FFL) sinusoidal trajectories, the base imaging trajectory is repeated with varying trajectory offsets in sinogram domain, determined by the in-plane spatial resolution Δ_{xy} [2, 3]. As this is a field-based procedure, the point source is positioned solely at the center of the field of view (FOV).

While this approach yields high-quality system matrices, the calibration process is potentially limited by the transition inefficiencies between repetitions. Abrupt transitions may result in unwanted spectral components (USCs), and thus, potentially overload transmit electronics. Furthermore, the non-ideal frequency response of power amplifiers and transmit filters can degrade the field fidelity. To address these challenges, this work proposes and evaluates three transition strategies aimed at minimizing USCs: Stop & Go, Circularly-Shifted, and All-Ramp.

II. Methods and Materials

Three transition strategies were simulated using a custom Python program with parameters: $T_{\mathrm{acq}} = 100\,\mathrm{ms}$, $f_{\mathrm{tra}} = 180\,\mathrm{Hz}$, $f_{\mathrm{rot}} = 50\,\mathrm{Hz}$, $N = 61$, $N_a = 1$, FOV = 60 mm, $\Delta_{xy} = 1\,\mathrm{mm}$, $G = 4\,\mathrm{T\,m^{-1}}$. f_{tra} and f_{rot} are the translational and rotational frequencies of the FFL, respectively. The number of repetitions $N = N_z N_{xy}$ defines the overall measurement duration $N_a T_{\mathrm{acq}} N$, excluding transition times between repetitions (T_{acq}: base trajectory duration, N_z: Number of voxels in the z-direction, N_a: Number of averages). They were illustrated using a simplified trajectory model ($N = 3$) in Figs. 1a-c. Their performance were evaluated based on the Fourier spectrum of the simulated magnetic fields in the x-direction.

Stop & Go: In this approach, the FFL rotation stops between repetitions. The offset to the next repetition is applied via a linear ramp. Transition durations are adjustable and constrained by the amplifier's current slew rate capabilities.
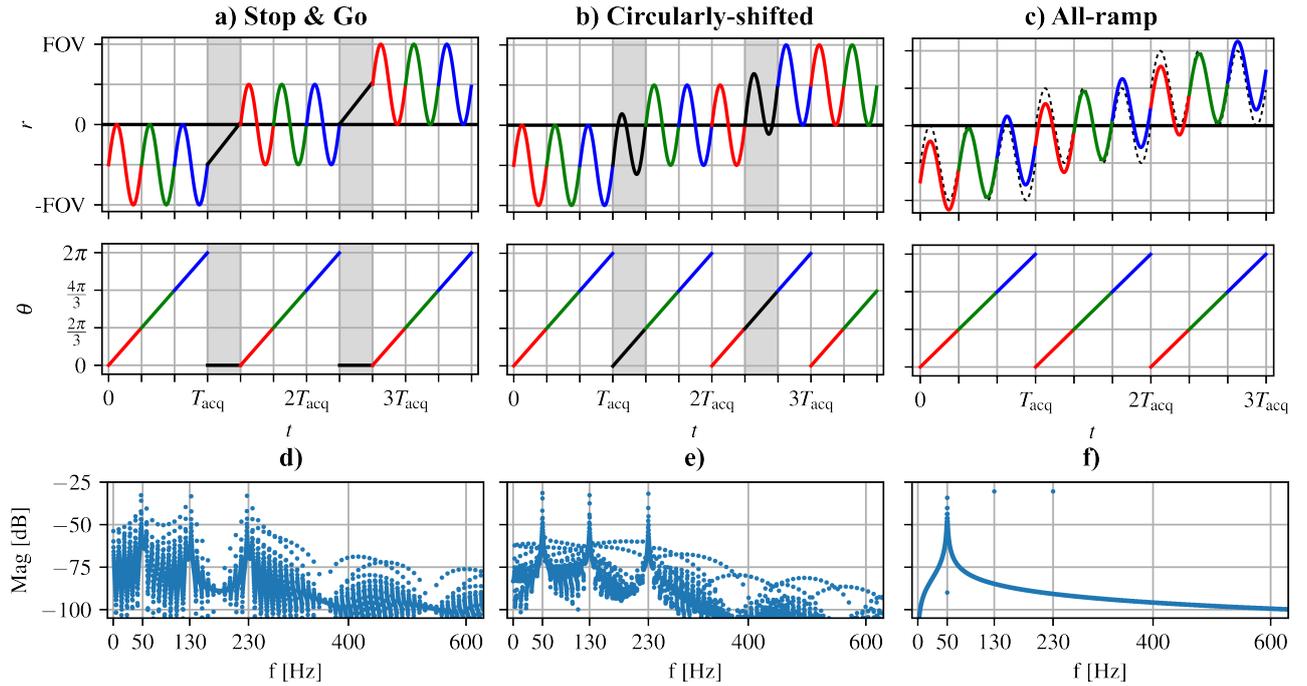
Figure 1: Simplified ($N = 3$) calibration trajectories in sinogram domain for **a)** stop & go, **b)** circularly-shifted, and **c)** all-ramp options with corresponding Fourier spectra in **d)**, **e)**, and **f)** for the magnetic fields in the x-direction (H_x) using realistic parameters ($N = 61$). Gray-shaded regions indicate transition phases, whereas the dashed curve in **c)** shows the ideal trajectory. In **a)** and **c)**, consecutive periods are color-coded (red, green, blue). In **b)**, each repetition is phase-shifted according to the accumulated phase during the previous transitions.

Circularly-Shifted: Here, the FFL continues rotating at a constant speed throughout the calibration process. Transition durations are synchronized with integer multiples of the offset trajectory period ($1/f_{\text{tra}}$) and the transition to the next repetition is applied sinusoidally at frequency f_{tra}. Each subsequent repetition is circularly-shifted by the corresponding accumulated phase during the transition.

All-Ramp: This method eliminates discrete transitions by ramping the entire calibration trajectory continuously. While it introduces a slight deviation from the original trajectory, it minimizes acquisition time and smoothens the waveform: $r = \frac{\text{FOV}}{2}\sin\left(2\pi f_{\text{tra}}t\right) + \frac{\text{FOV}}{N-1}\left(\frac{t}{N_a T_{\text{acq}}} - \frac{N}{2}\right)$, for $N > 1$. The maximum deviation occurs at the beginning and end of each repetition. The maximum trajectory error $E = \Delta_{xy}/2$.

III. Results and Discussion

Figures 1d-f show the Fourier spectra corresponding to each transition strategy. The circularly-shifted method significantly suppresses USCs compared to stop & go approach, exhibiting sharp trajectory edges that may degrade transmit performance and induce voltage spikes, which may potentially be mitigated by applying a low-pass filter.

The all-ramp method eliminates harmonics and mixing terms around 130 Hz and 230 Hz entirely, and offers the shortest acquisition time by removing transition phases. However, it introduces a minor deviation from the original trajectory ($E = 0.5$ mm for $N = 61$). When using multiple averages ($N_a > 1$), the effective error would be reduced, since the additional repetitions exhibit smaller deviations from the original trajectory.

IV. Conclusion

This simulation study compares three sinogram-based calibration strategies for MPI. The all-ramp method offers the best spectral purity and shortest acquisition time, albeit with slight trajectory distortion. The circularly-shifted approach balances USC suppression and trajectory fidelity, making it a strong candidate for practical implementation. Moreover, it allows maintaining the steady-state of magnetic fields during transitions. In contrast, the stop & go method may compromise spectral purity and system performance.

Author's statement

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