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Recovering higher harmonics when increasing the frame rate in MPI

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Abstract

The frame rate of an MPI measurement can be increased by splitting the receive signal and reconstructing the split signals separately. Thus, motion artefacts can be reduced. Splitting the signal results in a decreased spectral resolution and a mismatch of higher harmonics. In this contribution, an approach for recovering the spectral resolution and higher harmonics is shown that is based on mirroring the split signals.

I. Introduction

Magnetic Particle Imaging (MPI) visualizes the spatial distribution of iron oxide nanoparticles. The nanoparticles are excited by a periodical sinusoidal magnetic field and the change in magnetization can be measured as a voltage signal in a receive coil. An image showing the spatial distribution of the nanoparticles is then reconstructed from the voltage signal. Usually, one image per full period of the excitation signal can be obtained. It would be beneficial to increase the frame rate of an MPI measurement without further changes to the measurement setup. Then, highly dynamic biological processes could be monitored without motion artefacts.

A method has been proposed that splits the receive signal of an MPI measurement into a first and second half [1, 2]. Both halves are reconstructed separately resulting in two images per excitation signal period. Related work was presented in [3], where the temporal resolution was enhanced by splitting the voltage signal into subframes which are multiples of the excitation frequency. The authors in [4] introduced a framework, which reduced motion artifacts that occurred at the interaction of movement and signal detection.

Using the approach presented in [1, 2] it has been shown that both static and dynamic measurements can be reconstructed successfully. Cosine-based 2D excitation signals have been used as the spatial sampling of the field of view which is the same for the first and second halves of the receive signal. However, splitting the time signal in two halves results in a decreased spectral resolution of the signal, which may lead to a decreased spatial resolution within the reconstructed image.

In this contribution, the method presented in [1, 2] is extended and reviewed regarding the recovery of periodicity of the halved signals, of spectral resolution and spatial resolution in the reconstructed images.

II. Methods

Similar to [1, 2] the magnetization signal that is to be reconstructed into an image is split after the first half of the excitation signal, which results in a decreased spectral resolution of the signal (see Figures 2 and 4). Furthermore, the splitting may result in a non-periodic magnetization signal that is being Fourier transformed and reconstructed with a system-matrix based approach.

In order to recover both the original spectral resolution and periodicity of the magnetization signal, it is mirrored. Periodicity of the signal is important to avoid a high noise level at higher frequencies due to a jump

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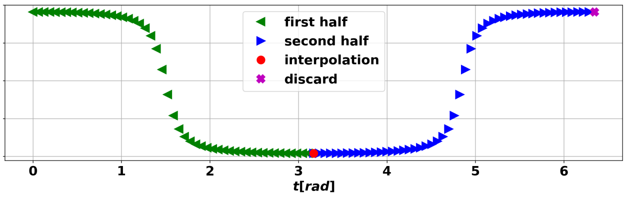

Figure 1: Mirroring procedure of the first half of the magnetized cosine signal. By discarding the last point it has the interval of $[0, 2\pi)$.

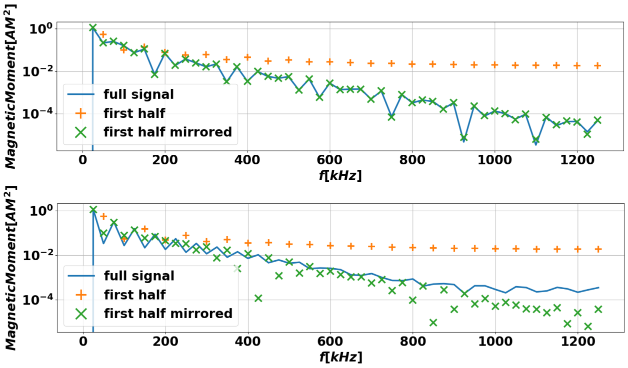

Figure 2: Amplitude spectra of a static phantom (top row) and a dynamic phantom (bottom row) generated using a 1D cosine-based excitation signal. The spectral resolution and the higher harmonics can be recovered by mirroring the signal. In case of the dynamic phantom, the recovered higher harmonics do not match precisely.

within the signal. Code-wise the mirroring is performed by copying the halved signal, flipping it left to right (y-axis) and in the case of a sine signal up to down (x-axis) and appending it to the raw halved signal. For a cosine-based excitation signal, mirroring is performed along the y-axis, which is the magnetization (see Figure 1). To avoid a duplication of one sample, an additional interpolated sample point of the magnetization signal is inserted. Then, the last sample of the signal needs to be discarded as it is a duplication of the first sample.

When mirroring a sine-based excitation signal, the mirroring is performed along both the x- and y-axis, which is time and magnetization.

III. Simulations

In this work, system matrices and both static and dynamic phantoms are generated using a Langevin function-based simulation (see Eq. (1)) without introducing noise. In the equation, M_S is the saturation magnetization, H the magnetic field, T the temperature and k_B the Boltzmann-constant. The particle core diameter is set to 25 nm, while the excitation field has an amplitude of 20 mT and the sample rate is at 2.5 MHz. The excitation field frequency for 1D is at 25 kHz while for 2D the excitation frequencies have been 26.04 kHz and 25.51 kHz.

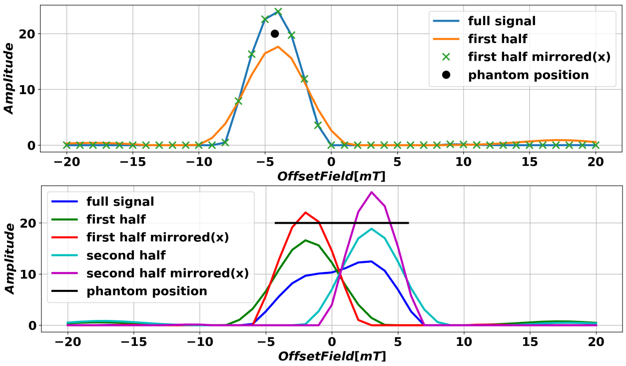

Figure 3: Reconstructed images of a static phantom (top row) and a dynamic phantom (bottom row) generated using a 1D cosine-based excitation. After mirroring the magnetization signal, the original spatial resolution can be recovered for the static phantom. In case of the dynamic phantom, motion artefacts can be reduced by splitting the magnetization signal. The ground truth positions of the phantoms have been added as a ground truth with an arbitrary amplitude value.

$$L(\xi) = coth(\xi) - \frac{1}{\xi}, \xi = \frac{M_S|H|}{k_B T} \tag{1}$$

First, one-dimensional simulations are carried out using a cosine-based excitation signal. Here, the field of view is sampled fully within both the first and second half of the excitation signal period. A static one-dot phantom is generated at an offset field strength of −4.25 mT. Further, a dynamic one-dot phantom is generated that shifts from −4.25 mT to 5.75 mT within one full period of the excitation field.

Second, two-dimensional measurements are simulated using cosine-based and sine-based excitation signals. Again, both static and dynamic one-dot phantoms are generated. Motion is simulated along the y-axis (top to bottom in Figure 5).

IV. Results

When calculating the spectrum of one period of a 1D magnetization signal using only the first half of the signal, the spectral resolution decreases and higher harmonics do not match the full signal anymore (see Figure 2). After mirroring the signal, the spectral resolution is recovered.

In case of the static phantom (top row), the original signal is fully recovered. This is also reflected in the metrics. Where full and mirrored signals have the same values for center of mass (COM) at $-4.192 mT$ and full-width-half-maximum (FWHM) at $4.525 mT$, the halved ones differ (COM: $-3.2 mT$, FWHM: $5.3 mT$). Also with the phantom being at -4.25mT the center of mass of the halved signals is further away. The sum squared error

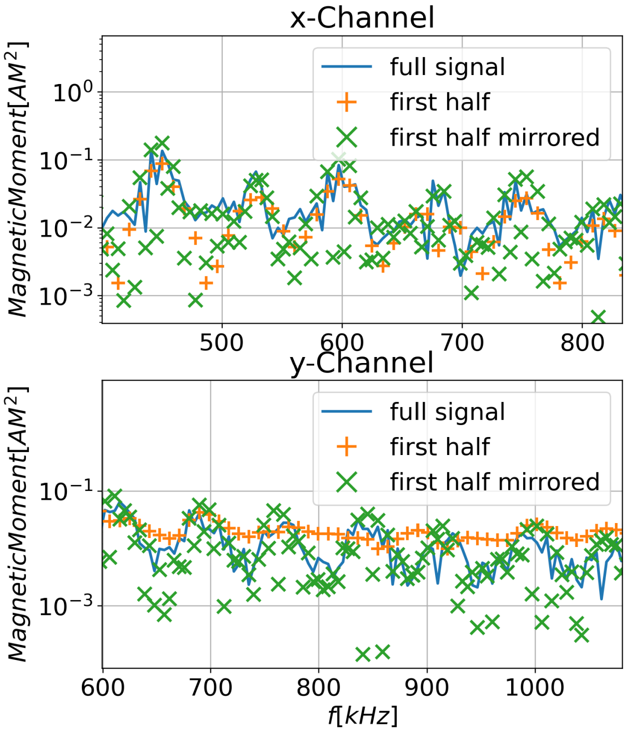

Figure 4: Amplitude spectra of a dynamic phantom generated using a 2D cosine-based excitation signal. Most of the harmonics can be recovered when mirroring the magnetization signal.

Metric	full signal	1st half	1st half mirr.	2nd half	2nd half mirr.
COM	0.697	−1.492	−1.849	2.424	3.041
FWHM	8.929	5.526	4.725	5.125	4.324

Table 1: Center of mass (COM) and full-width-half-maximum (FWHM) of the reconstruction of the dynamic 1D phantom.

(SSE) between full and mirrored signal spectra being at $2.36E-10$ (second half: $1.34E-09$) is also smaller than between full and halved signal at 0.36 (second half: 0.37).

For the dynamic phantom (bottom row), most of the frequencies can be recovered. However, the accuracy decreases with the higher harmonics. This is due to the fact that because of the movement the signal becomes non-periodic and therefore, the mirrored signal won't match the original anymore. Comparing the FWHM here (see table 1), the halved signals should be around half of the full signal since they each only capture half of the movement. Therefore, the mirrored signals are closer. Also, the center of mass should be around -1.75mT for the first half since the halved movement is 5mT and starting at -4.25mT. For the second half therefore, it should be at 3.25mT. In both cases mirroring shows improvement. The SSE also provides evidence of an enhancement, since it is at $4.08E-2$ (second half: $4.07E-2$) when comparing full and mirrored signal and at 0.38 (second half: 0.36) for the difference between full and halved signal.

The reconstruction results of the static and dynamic 1D phantom are shown in Figure 3. The spatial resolution decreases when using only half of the magnetization signal for reconstruction. Corresponding to the full recovery of the spectrum shown in Figure 2, the spatial resolution can be recovered by mirroring for the static phantom. Motion of a dynamic phantom can be split up into two reconstructed images (bottom row) after splitting the magnetization signal.

Figure 4 shows the amplitude spectra of the cosine-based 2D simulation for a dynamic phantom. Same as for the 1D case, the spectral resolution decreases when using only half of the magnetization signal but is recovered by mirroring. Mirroring recovers most of the higher harmonics. In the bottom row it is shown, that at higher frequencies, the noise level of the first half signal is too high to be able to follow the full signal. The corresponding image reconstruction results are shown in Figure 5 (top row) and Figure 6 (top row). Motion artefacts are reduced when reconstructing the first and second half of the magnetization signal separately. After mirroring, imaging artefacts are reduced further.

In Figure 5, for both cases the shape is improved comparing the first half with it's mirrored equivalent. Regarding the second half a minimization of background noise is visible.

V. Discussion

When mirroring one half of the magnetization signal of a dynamic phantom, the harmonics cannot be fully recovered (see Figure 2). As non-periodic motion is encoded in the entire magnetization signal in time domain , information is lost when splitting the magnetization signal. However, the goal of this approach was to show different states of the motion in two separate images as well as the improvement of information in comparison to a signal half which has been successful (see Figure 3).

In case of a 2D cosine-based excitation (see Figure 4), the amplitude spectrum of the first half of the magnetization signal differs much more for the y-channel than for the x-channel due to the motion being simulated along the y-axis. As the excitation signal of the x-channel features an even multiple of the excitation frequency, also the halved signal holds periodicity. For the y-channel with an uneven multiple of the excitation frequency, periodicity is not fulfilled after splitting, but can be restored by mirroring.

VI. Conclusion

In this work, an approach for recovering spectral resolution, higher harmonics and spatial resolution in re-

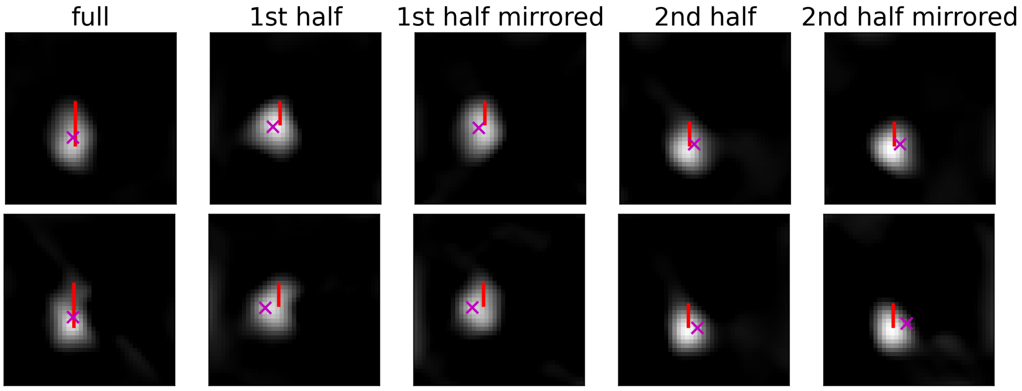

Figure 5: Reconstructed images of a dynamic generated using a cosine-based (top row) and sine-based (bottom row) excitation signal. Shown are the images reconstructed using (from left to right): the full magnetization signal, the first half, the mirrored first half, the second half, and the mirrored second half of the magnetization signal. The red lines are the ground truth lines along which the phantom moves. The magenta crosses show the center of mass of the reconstruction.

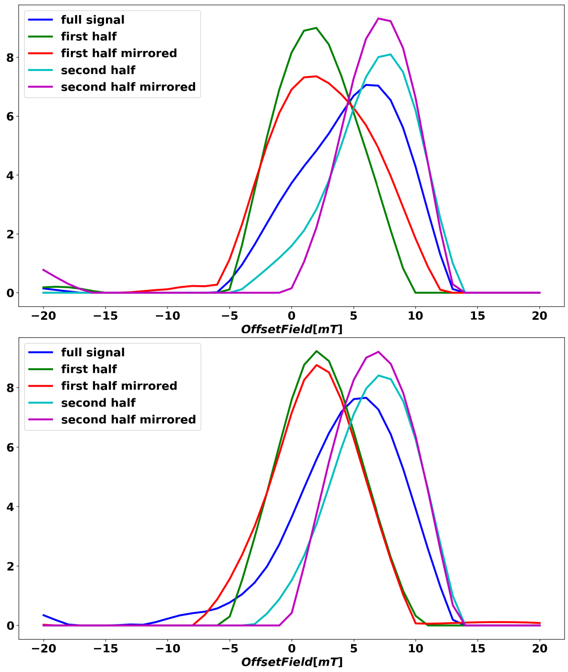

Figure 6: Line plots of the reconstructed images shown in Figure 5 along the pixel column where motion is expected most for cosine-based excitation (top) and sine-based excitation (bottom).

constructed images has been shown when splitting the magnetization signal of an MPI measurement for motion artefact reduction. By splitting and mirroring the magnetization signal, periodicity can be restored and both motion and image artefacts can be reduced in the reconstructed images.

Since the experiments were made with simulated data without consideration of noise or relaxation, the next steps would be to include these. The results should then be reevaluated.

Author's statement

Conflict of interest: Authors state no conflict of interest.

References

[1] A. von Gladiss, M. Graeser, and T. M. Buzug, Increasing the MPI Frame Rate by Excitation Signal Phase-Shifting and Receive-Signal-Splitting, in International Workshop on Magnetic Particle Imaging, 215–216, 2018.

[2] A. von Gladiss, M. Graeser, A. Cordes, A. C. Bakenecker, A. Behrends, X. Chen, and T. M. Buzug. Investigating Spatial Resolution, Field Sequences and Image Reconstruction Strategies using Hybrid Phantoms in MPI. International Journal on Magnetic Particle Imaging, 6(1), 2020, doi:10.18416/IJMPI.2020.2003004.

[3] P. Vogel, M. Rückert, P. Klauer, W. Kullmann, J. Peter, and V. Behr. Superspeed traveling wave magnetic particle imaging. IEEE Transactions on Magnetics, 51:6501603, 2015, doi:10.1109/TMAG.2014.2322897.

[4] N. Gdaniec, M. Schlüter, M. Möddel, M. G. Kaul, K. M. Krishnan, A. Schlaefer, and T. Knopp. Detection and compensation of periodic motion in magnetic particle imaging. IEEE Transactions on Medical Imaging, 36(7):1511–1521, 2017, doi:10.1109/TMI.2017.2666740.