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Characterization of noise and background components in MPI raw signals

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Abstract

Interfering noise and background signals deteriorate the image quality of magnetic particle imaging (MPI). In this work, we present the detailed characterization of noise and background factors interfering the acquired MPI raw signals. Empty scanner measurements were obtained to analyze the temporal variations in the short-, mid- and long-term regime. These results form the basis to improve the mandatory understanding of these unwanted signal components to become able to remove or minimize their impact on image reconstruction.

I Introduction

Magnetic particle imaging (MPI) relies on the detection of a magnetic response generated by magnetic nanoparticles (MNP). This magnetic response, also called the MPI raw signal, is further processed to reconstruct a spatial MNP distribution. One of the limiting factors of MPI is the distortion caused by contributions of random noise and systematic background signals to the MPI raw signal. Previous studies presented methods aiming to remove these components or include additional information in the image reconstruction to minimize their effects [1]–[4]. These methods make assumptions about the characteristics of the detected noise and background signals during an MPI measurement (noise "color", influence of hardware components, temporal stability, ...), whereas a fundamental characterization of MPI-noise has not been published so far. Here, we present a first approach of a noise characterization using measurement data acquired from a commercial, preclinical MPI scanner (Bruker MPI 25/50 FF). Empty scanner measurements were acquired using varying measurement parameters to study their influence on the MPI raw signals. In particular, the temporal stability of background signal components was investigated. We hypothesize, that a detailed characterization of the MPI-noise can pave the way for improved image quality, and a better understanding of MPI physics in general, and thus is a crucial consideration for the design of future scanner generations.

II Material and methods

Characterization of noise is a common task in multiple analytical modalities. A typical way to start is by introducing a mathematical model, including different kinds of signal sources. A model for the MPI raw measurement data $\hat{u}$ is given by:

$$\hat{u} = \hat{u}_{\mathrm{MNP}} + \hat{u}_{\mathrm{N}} + \hat{u}_{\mathrm{BG}} \tag{1}$$

$\hat{u}_{\mathrm{MNP}}$ is the signal generated by MNP, $\hat{u}_{\mathrm{N}}$ describes contributions generated by random processes, $\hat{u}_{\mathrm{BG}}$ is caused by systematic background signals generated externally or by the MPI hardware itself. Multiple measurements of the empty scanner were performed to characterize each component of equation (1).

In the following we will focus on the influence of background signals, only. The main contributions of background signals in MPI are caused by the drive fields used

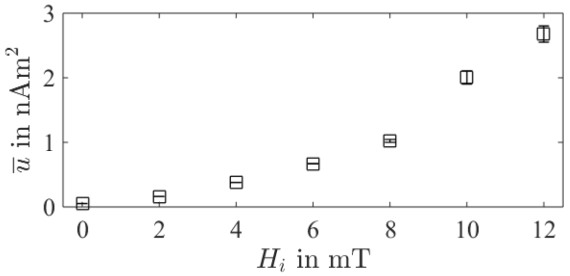

Figure 1: Mean MPI signal amplitude as a function of drive field amplitude. Displayed are mean values with the standard deviation presented as error bars.

to generate the MNP response. To this end empty scanner measurements with varying drive field amplitudes ($H_i = 0$ - 12 mT, $i = x, y, z$) were performed. A straightforward way of removing these background signals is by subtraction of a separate/additional empty measurement. This requires the signals to be stable over time, which was analyzed in three different time regimes: short-term variations (seconds up to minutes), mid-term variations (minutes up to hours) and long-term variations (days up to weeks). The empty scanner measurement data were analyzed for the real and imaginary part of each frequency component, individually. In addition, the mean signal amplitude of all frequency components ($\bar{u}$) generated by a mixing order of <20 was used to quantify the average impact on a single measurement.

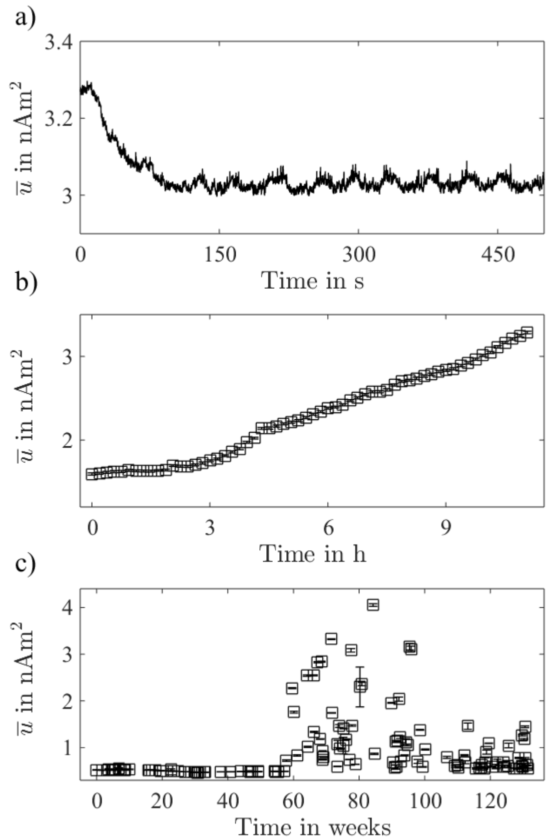

Figure 2: Signal deviation of the mean MPI signal amplitude in the short- (a), mid- (b) and long-term (c) regime respectively. b) and c) display mean values with the standard deviation presented as error bars.

III Results and discussion

Figure 1 shows the influence of the main signal amplitude $\bar{u}$ (without any MNP sample, $\hat{u}_{\mathrm{MNP}} = 0$) generated by the drive fields. With increasing drive field amplitudes, $\bar{u}$ increases from 0.05 nAm^2 to about 2.7 nAm^2. These signals should be removed before image reconstructions are performed, either by subtracting empty scanner measurement data or by using gradiometric receive coils to minimize the influence of the drive fields [5], [6].

Figure 2 displays the temporal variation of $\bar{u}$ in the short- (a), mid- (b) and long-term (c) regime, respectively. The short-term variation showed a reproducible drift during the first 90 s after the start of each measurement, caused by heat-induced changes in the properties of the drive field coils. Hereafter, the signal stays almost constant with smaller variations of about 13 pAm^2, which were correlated to fluctuations of the drive field amplitudes.

The mid-term regime showed significant differences over the course of 12 h with changes of the mean signal amplitude up to 1.6 nAm^2, which were attributed to thermal drifts of the MPI hardware components of the receive chain. These findings demonstrate the importance of considering the temporal variation of MPI raw signals in the background correction technique to avoid misinterpretation of changing background signals as MNP signals.

Long-term variations were acquired over a period of 2.5 years. During the first 60 weeks, small signal fluctuations of about 0.1 nAm^2 were detected. Starting after the 60th week, much stronger differences of up to 4 nAm^2 were observed. The exact reason for a sudden change in the scanner resulting in these higher signals are presently unknown. Possible explanations include damage of hardware components in the transmission/receive-chain, contamination or external electromagnetic interference (e.g. new high-power devices in the clinical environment near the scanner site). Although the exact cause needs still to be identified, the results demonstrate the strength of using the information gained from the MPI-noise characterization to check the system performance over long time periods.

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IV Conclusions

The minimization of noise and background signals is a mandatory purpose for further MPI improvement since these unwanted signals crucially determine the sensitivity, quantification, and spatial resolution limits of this technology. First, it is necessary to identify and analyze the main influencing features in the MPI raw signals; which then permits to develop tailored methods to remove or minimize these signal components.

In this work, we presented initial progress towards a full characterization and understanding of contributions from noise and background signals to the MPI raw signal. We identified that major background signal contributions are caused by the drive fields. By analyzing the temporal stability based on empty scanner measurements, possible hurdles were determined that need to be considered when these contributions are removed. The results of the long-term analysis demonstrate the empty scanner measurements can be a useful tool to analyze the conditions of the scanner and detect possible wear or damage of hardware components.

In this abstract, only the influence of background signals was presented for a single conventional transmit/receive-coil. The results obtained by gradiometric coils and the influence of other contributions on the MPI raw signals will be presented at the conference. For the near future, inter-site comparisons of the temporal stability of background signals acquired from multiple MPI scanners are anticipated and might bring useful insights.

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