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Initial imaging experiments with a direct-driven relaxation magnetic particle imaging setup

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Abstract

This contribution presents initial imaging experiments with a newly designed imaging setup that facilitates Magnetic Particle Imaging (MPI) by recording the step response of the tracer in contrast to its higher harmonic spectrum. Such a concept promises a greatly reduced complexity in hardware and enables a much simpler time-domain evaluation of the receive signals. The concept borrows from magnetorelaxometry (MRX) subjecting the tracer to a step change in excitation field to affect a relaxation of the particles' magnetization. For that reason, all experience from MRX data evaluation and modeling of the magnetization response apply to the imaging variant as well. The hardware design of the system opens a great deal of flexibility regarding excitation patterns and signal evaluation for future experiments.

I Introduction

In classical Magnetic Particle Imaging (MPI), the detection signal is generated by the tracer subjected to a sinusoidal oscillating magnetic excitation field [1]. Consequently, in order to detect the weak particle signal, analogue filters are typically inserted into the receive (Rx) chain to suppress the feedthrough of the fundamental frequency component from the transmit (Tx) side. The relaxation-based MPI method, initially introduced by Tay et al. in [2], on the other hand, records the step response of the tracer after a fast transient of the Tx signal. The Tx-Rx decoupling can then be achieved in time-domain because of a delayed response of the tracer due to its intrinsic relaxation time. The readout signal is essentially the exponential relaxation signal of the tracer particles, which introduces an induced voltage pulse in the receiving detection coils (hence the nickname 'Pulse MPI'). The exciting field step can use a small amplitude, e.g. around 2 mT, if the rise time of the step is steep enough to trigger a fast relaxation response. For that reason, the Tx signal is much easier to generate. We can feed a preformed voltage signal into the power amplifier which is directly connected to the Tx coil. No additional filters are required because here the detection principle does not aim for higher harmonics detection, but instead uses (but is not limited to) the linear M(H) magnetization range. Consequently, the power amplifier and other electronics (both on transmit and receive side) do not have to be very linear compared to a standard MPI setup. Also, since the bandwidth of the receive signal is dominated by the relaxation times of the tracer particles (and no harmonics are to be recorded), we can expect a much smaller required bandwidth for the receive path.

Another major advantage of the relaxation MPI concept, is the evaluation of the receive signal in time domain. By means of integrating the receive signal over

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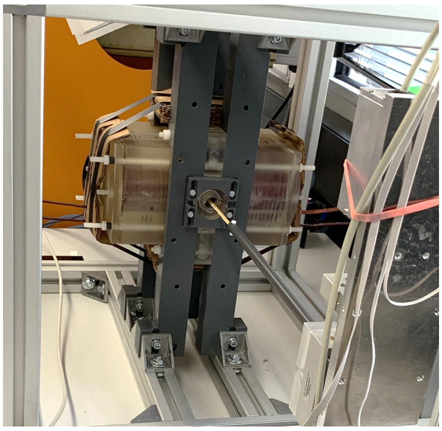

Figure 1: Relaxation MPI coil assembly with selection field generator as well as transmit and receive coils.

time we can easily recover the exponential relaxation signal and thus determine the relaxation time constant of the tracer directly from the signal, whereas in conventional MPI (especially in Fourier-domain treatment of the signals) the relaxation times cannot be inferred easily from the harmonic spectrum. In the past, we have put great efforts in connecting the receive spectrum back to its affecting particle and environmental parameters, such as temperature or viscosity [3-5]. Relaxation MPI will therefore enable multi-color MPI without the need of prior knowledge, calibration or complex models.

II Material and methods

We designed and built a new MPI imaging setup to demonstrate relaxation-based MPI on actual hardware. A photo of the central coil assembly is shows in Fig. 1.

The selection field generator was constructed from NdFeB permanent magnets. It features a field-free-point (FFP) design with a field gradient of 4.9 T/m along the magnet axis and an imaging gradient in the orthogonal plane of approximately 2.0 T/m. The transmit coil along the bore is designed as a low inductance solenoid ($L = 29.8\ \mu H$) and made from a hollow copper pipe, which combines a reasonable effective copper diameter ($Rs = 56\ m\Omega$) and an easy water-based cooling option. The transmit coil (with 35 mm inner diameter and coil constant $K = 0.46$ mT/A) is fed directly from the power amplifier, a Hubert A 1110-16-A 4-quadrant voltage amplifier. No analogue transmit filters are inserted. Still, the square wave obtained by feeding a voltage-preformed signal to the power amplifier and transmit coils provides a transition time of less than 10 µs for a 3.68 mT field step. The differential receive coil (17 mm opening, inserted in the larger Tx coil) along the bore is designed as a solenoid with two center-symmetrical compensation coils. Initial experiments were conducted without a dedicated preamplifier (which is still under construction). The constructed hardware is very cost-effective. Building costs of the coil assembly, with the selection field generator and transmit / receive solenoids as well as shift coils, are around 1000 Euros. The most single expensive component is the power amplifier, which we had available at our lab. However, since linearity is not a major concern, we think that we should be able to use even a digital amplifier in the future. The system is operated in the open lab space without shielding, except for an aluminum layer between transmit and receive coils.

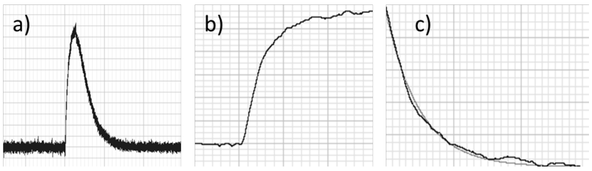

Figure 2: (a) Induced relaxation signal for the perimag® sample, (b) obtained step response of the particles' magnetization and (c) fitted exponential function to estimate time constant.

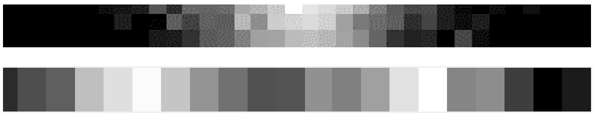

Figure 3: (top) Bottom-half of the 2-dimensional point-spread-function (PSF) of the gridded signal, (bottom) 1-dimensional relaxation MPI image of two point samples (at 10 mm distance). Length of the field-of-view (FOV) is 20 mm in both images.

The imaging sequence consists of a square wave oscillating between ±3.68 mT subjecting the tracer every 20 ms (used for averaging) to a 7.36 mT step-like field transitions. The image is rasterized by moving the sample in the x-/y-plane via a calibration robot. However, the system is equipped to perform the FFP shift in x-/y-direction by superimposing dc offset fields for 2D imaging.

For the initial experiments, we used a sample with undiluted perimag® plain (25 mg/mL) from micromod Partikeltechnologie GmbH (Germany). The phantom geometry is a capillary glass tube with an inner diameter of approximately 1.25 mm diameter and filled with the particles to form a point-like reference sample in the imaging plane.

III Results and discussion

The data shown here are the very first measurement results after provisioning of the system (and before the deadline).

Figure 2 shows the receive voltage signal induced in the detection coils after a field step of 7.36 mT. A 20 kHz digital low-pass filter was used to limit high-frequency noise. The obtained MPI image when gridding the signal onto the imaging plane is depicted in Fig. 3. As a concentration measure, we used the area under the curve (from Fig. 2a) as suggested in [2]. The field step used for excitation leads to approximately 3.68 mm displacement of the FFP, which causes blurring in the excitation direction. Since the full-width-half-maximum (FWHM) of the perimag tracer is around 8.4 mT (estimated from conventional MPS at 100 Hz), which corresponds to 4.2 mm in the 2 T/m gradient used for this study, the observed resolution in Fig. 3 is probably still dominated by the steady-state magnetization curve. No deconvolution or reconstruction has been performed yet, but should be considered, when a more suitable tracer (with narrow PSF) is used.

We also integrated the induction signal over time to obtain the magnetization step response (Fig. 2b). Fitting the curve with an exponential function reveals a relaxation time constant characteristic for the tracer particles used in the experiment (Fig. 2c). In the future, the data can be utilized to derive a functional parameter, such as viscosity or temperature.

IV Conclusions

Relaxation-based Magnetic Particle Imaging is a very interesting and promising concept for recording MPI images. Initial measurements on the newly designed imaging hardware demonstrate that MPI images can be recorded on a reasonably sized sample and without any filters in the transmit or receive sides. The system is directly driven by the power amplifier and at this point we do not even use a proper preamplifier. We think that by optimizing some system components for the relaxation operating mode, the concept can provide a compelling alternative to the conventional MPI with greatly reduced hardware complexity and/or improved flexibility with respect to acquisition sequences and signal evaluation.

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Author's Statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The experiments are not related to any experiments on animals or humans.

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