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Magnetic Particle Fingerprinting using Arbitrary Waveform Relaxometer

E. Yagiz[1,2,*]· M. Utkur[1,2]· C. B. Top[3]· E. U. Saritas[1,2,4]

[1]Department of Electrical and Electronics Engineering, Bilkent University, Ankara,TurkeyA
[2]National Magnetic Resonance Research Center (UMRAM), Bilkent University, Ankara, Turke
[3]ASELSAN Research Center, Ankara, Turkey
[4]Neuroscience Program, Sabuncu Brain Research Center, Bilkent University, Ankara, Turkey
[*]Corresponding author, email: ecrin@ee.bilkent.edu.tr

Abstract

In magnetic particle imaging (MPI), the information about the local environment, such as its viscosity and temperature, can be inferred via the relaxation behavior of the nanoparticles. As the nanoparticle signal also changes with drive field (DF) parameters, one potential problem for quantitative mapping applications is the optimization of these parameters. In this work, an accelerated framework is proposed for characterizing the unique response of a nanoparticle under different environmental settings. The proposed technique, called magnetic particle fingerprinting (MPF), rapidly sweeps a wide range of DF parameters, mapping the unique τ-fingerprint of a sample. This technique can enable simultaneous mapping of several parameters (e.g., viscosity, temperature, nanoparticle type, etc.) with reduced scan time.

I Introduction

Magnetic particle imaging (MPI) offers promising capability for quantifying viscosity and temperature, and distinguishing different nanoparticle types [1,2]. Recently, we have proposed to estimate the relaxation time constant, τ via a technique called TAURUS (TAU estimation via Recovery of Underlying mirror Symmetry) [3-4]. This technique estimates τ without any calibration or prior information about the nanoparticles, and can be used to distinguish viscosity in the biologically relevant range, or distinguish different types of nanoparticles [3-4].

As the nanoparticle signal changes with drive field (DF) parameters [5], one potential problem for quantitative mapping applications of MPI is the optimization of these parameters. Unlike standard MPI and magnetic particle spectrometer (MPS) systems that operate at a fixed frequency [6], an arbitrary waveform relaxometer (AWR) that can operate at any frequency was recently proposed to enable rapid optimization of DF parameters [7].

In this work, we propose characterization of nanoparticle response by a rapid coverage of the "excitation space", i.e., by rapidly sweeping a wide range of DF parameters. We refer to this technique as "magnetic particle fingerprinting" (MPF), as we map the τ-fingerprint of the nanoparticle in an accelerated framework using an AWR, across a wide range of field strengths/frequencies.

II Material and methods

II.I Theory

The relaxation of nanoparticles is governed by Brownian and Néel relaxation mechanisms, where the former has viscosity and temperature dependence, and the latter has temperature dependence [8]. The overall delay in

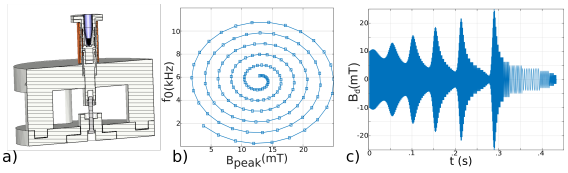

Figure 1: (a) Schematic of the in-house AWR setup. (b) A spiral trajectory in excitation space (B_{peak}-f_0 space). (c) The drive field waveform corresponding to the trajectory in (b). The excitation space is traversed starting from the center of the spiral.

Table 1: Prepared samples at 5 different viscosity levels.

Viscosity (mPa·s)	0.89	1.15	1.54	2.16	3.18	5.04
Glycerol (μL)	0	2	4	6	8	10
DI Water (μL)	10	8	6	4	2	0
Glycerol Volume %	0	10	20	30	40	50

the MPI signal is a combination of these two effects. In x-space MPI, the relaxation effects are modeled as the convolution of the adiabatic signal with the following kernel [9]:

$$r(t) = \frac{1}{\tau} \cdot \exp(-t/\tau) u(t) \tag{1}$$

Here, $u(t)$ is the Heaviside step function. TAURUS technique estimates τ directly from the acquired signal by using the underlying mirror symmetry of the adiabatic signal during back and forth scanning [3, 4],

$$\tau(f) = \frac{S^*_{pos}(f) + S_{neg}(f)}{j2\pi f (S^*_{pos}(f) - S_{neg}(f))} \tag{2}$$

where $S_{pos}(f)$ and $S_{neg}(f)$ are Fourier transforms of the signals from positive and negative scanning directions, respectively.

II.II In-house AWR Setup

The experiments were performed on an in-house AWR setup, shown in Fig. 1a [10]. This setup consists of a drive coil with 18 turns, with a relatively small 3.1 μH inductance that obviates impedance matching. The receive coil has a three-section gradiometer geometry, with 17, 20, and 5 turns. The shortest section can be adjusted manually via a knob to achieve 80 dB decoupling between drive/receive coils. The bore can fit a 0.2 ml PCR tube. The DF waveform was sent to a power amplifier (AE Techron 7224) through a data acquisition (NI USB-6383) card. The waveform was verified using a current probe (LFR 06/6/300, PEM) before each measurement. The received signal was amplified with a low-noise voltage pre-amplifier (SRS SR560). The entire setup was controlled via MATLAB.

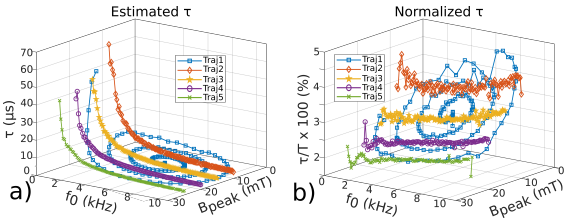

Figure 2: (a) Estimated τ values for 0.89 mPa·s sample, using linear (line-by-line) and spiral trajectories show excellent agreement. (b) τ values normalized by the period (i.e., by $T_0 = 1/f_0$) at each point on the trajectory.

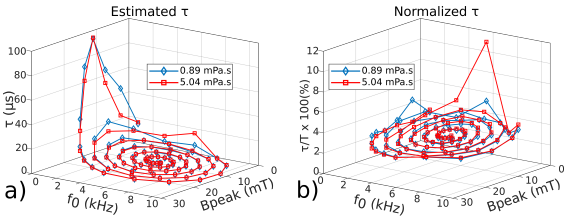

Figure 3: (a) Estimated τ values and (b) normalized τ values for 0.89 and 5.04 mPa·s samples using a spiral trajectory.

II.III Rapid Excitation Space Coverage

The low inductance of the AWR setup obviates impedance matching, enabling rapid coverage of the "excitation space" (i.e., B_{peak}-f_0 parameters of the DF) using a variety of trajectories. Figure 1 shows an example spiral trajectory, together with the corresponding DF waveform. For the first set of experiments, the excitation space was traversed via two different trajectories: linear (line-by-line) and spiral trajectories. Then, TAURUS technique was used to map τ at each (B_{peak}, f_0) point on the trajectory. Next, τ was mapped for samples with different viscosities using a spiral trajectory with 0.6 s duration.

II.IV Sample Preparation

Samples at six different viscosities ranging between 0.89-5.04 mPa·s were prepared [11], as listed in Table 1. Each sample contained 10 μL of Nanomag-MIP nanoparticles (Micromod GmbH, Germany) with 89 mmol Fe/L. Deionized (DI) water and glycerol were added at varying volumes to reach a total volume of 20 μL for each sample. All measurements were performed at room temperature.

III Results and discussion

Figure 2a shows the estimated τ values for 0.89 mPa·s sample for linear (line-by-line) and spiral trajectories. Both trajectories show excellent agreement in the estimated τ values, demonstrating the consistency of the

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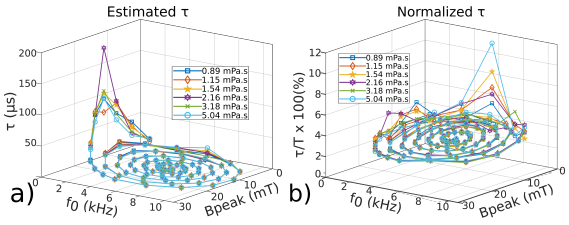

Figure 4: (a) Estimated τ values and (b) normalized τ values for all six samples with different viscosities, using a spiral trajectory. Each sample has a unique τ-fingerprint, especially at low-B_{peak} and low-f_0 regions of the excitation space.

proposed MPF method. Figure 2b shows τ values normalized by the period (i.e., by $T_0 = 1/f_0$) at each point on the trajectory, to better demonstrate the trends. For this sample, τ remains less than 5 % of the period on the covered excitation space, reduces with B_{peak}, and increases with f_0.

Figure 3 shows τ values for 0.89 and 5.04 mPa·s samples. The trends for these two samples are different, especially at low-B_{peak} or low-f_0 regions of the excitation space. Figure 4 shows τ values for all six samples with different viscosities. Each sample has a unique τ-fingerprint, especially at low-B_{peak} and low-f_0 regions of the excitation space.

These results indicate that different viscosities can be distinguished using the proposed MPF technique. We expect to see unique τ trends at different temperatures, as well, enabling simultaneous mapping of viscosity and temperature with the proposed technique.

IV Conclusions

In this work, an accelerated framework is proposed to rapidly cover the excitation space and characterize the unique τ-fingerprint of a nanoparticle under different environmental settings. This technique has a variety of potential applications, including rapid and simultaneous quantification of several parameters (e.g., viscosity, temperature, nanoparticle type, etc.). In addition, it can be used to determine the optimum DF parameters for a given mapping application.

Author's Statement

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