Contribution of brownian rotation and particle assembly polarisation to the particle response in magnetic particle spectrometry

Abstract: The spectrometry of super-paramagnetic iron-oxide nanoparticles is a central tool for characterising particles that are used in Magnetic Particle Imaging. In Magnetic Particle Imaging, nanoparticles are excited by a magnetic field and the particle response is measured. Until now, the influence of the trajectory sequence on the dynamic particle relaxation has not been scoped. With a multi-dimensional Magnetic Particle Spectrometer, analysing the behaviour of different trajectories on the particles becomes possible. In this paper, the contribution of Brownian rotation and assembly polarisation on the particle signal is being analysed.

Keywords: Brownian rotation; polarisation; trajectory.

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1 Introduction

Magnetic Particle Imaging (MPI) is a promising new medical imaging modality, that has been introduced in 2005 by Gleich and Weizenecker [1]. Super-paramagnetic iron oxide nanoparticles (SPIOs) are excited by a magnetic field and the particles will add higher harmonics to the fundamental frequency due to their non-linear magnetisation curve. The characteristics of the SPIOs can be investigated with a Magnetic Particle Spectrometer (MPS) in order to optimise particles that are used in MPI but also to gain knowledge about their behaviour. Until now, the response to one-dimensional excitation could be investigated [2]. Recently, Graeser et al. have developed a multi-dimensional MPS [3] that is capable of applying different trajectories in one and two dimensions on SPIOs. With this setup, the effects of different trajectories on the particle response can be investigated. In this paper, the first steps towards a deeper characterisation of and therefore knowledge about SPIOs used in MPI are taken. Therefore, the influence of Brownian rotation on the particle signal will be discussed. Furthermore, it will be investigated if the polarisation of particle assemblies has an effect on the received signal.

2 Methods

Samples of 0.25 µl undiluted Resovist® have been frozen in a freezer and directly prior to the measurement exposed to liquid nitrogen, additionally. One of the samples has been polarised in x-direction during the freezing process by exposing it to a static magnetic field. The samples are excited before and after the freezing process with a sine signal in the direction of x. The excitation signal has a frequency of \( f_x = 25.25 \text{ kHz} \) and a magnetic field amplitude of 20 mT. In order to perform a two dimensional Lissajous trajectory, a second sine in the y-direction of the frequency \( f_y = 26.04 \text{ kHz} \) is generated (Fig. 1). The 2D Lissajous trajectory has a magnetic field amplitude of 10 mT in both the directions of x and y. For each excitation direction, a receiving signal is acquired [3]. The receiving signals are averaged over 2000 periods according to the excitation frequencies for both one and two dimensional measurements.
3 Results

3.1 1D excitation

The amplitude of the received particle response in time domain is the highest for unfrozen SPIOs. In frequency domain (see Fig. 2), this can be observed as well. The particle response of the third harmonic is several orders higher than for measurements taken with frozen samples, which is caused by a combination of Brownian blocking and lower thermal energy. When comparing the particle responses of the frozen samples, the amplitude of the harmonics is higher for polarised particle assemblies. Up to the 23rd harmonic, a difference in the amplitude of the particle response can be observed. As for the difference between the amplitudes of frozen and unfrozen samples, they can be separated up to the 70th harmonic.

With increasing harmonics, the amplitudes of the harmonics drop. The steepness of this slope indicates the quality of the particles [4, 5]. There is no significant difference in the slope steepness for frozen samples. In comparison to the particle response of the unfrozen sample, however, the slope is much steeper. When calculating the factor between the harmonic amplitudes of frozen and unfrozen samples, it increases up to the 23rd harmonic as well.

3.2 2D excitation

The particle responses in time domain to both unfrozen and frozen samples are displayed in Fig. 3. The two plots are the receiving signals of both the receiving channels. As for the x-channel (upper plot), the signal of the unfrozen sample has an amplitude of about 300 mV. The amplitudes of the frozen samples are in the same order (about 40 mV). The difference of the signal amplitudes is smaller for the y-channel (bottom plot). The unfrozen sample has an amplitude of about 110 mV and the frozen samples of about 60 mV. The particle responses of the frozen samples cannot be separated by signal amplitudes.

The spectra of the measurements are shown in Fig. 4. The upper plot accords to the x-channel and the bottom one to the y-channel. Like for 1D-excitation, there is a difference in harmonic amplitudes and slope steepness between the spectra of frozen and unfrozen samples in the x-channel receiving signal. Particle signal can be detected up to 900 kHz and 500 kHz for unfrozen and frozen samples, respectively. Like in time domain, the difference between frozen and unfrozen samples is not as high for the y-channel. The third harmonic amplitude is of the same order for both frozen and unfrozen samples. For higher harmonics, a difference in amplitudes can be observed up to about 500 kHz. The slope is steeper for the frozen samples.

In both the x- and y-receiving signals, the particle responses of the polarised and non-polarised frozen samples cannot be separated. The amplitudes of the harmon-
When polarising a frozen particle assembly in excitation direction, the amplitude of the receiving signal increases, but it does not exceed the signal quality of unfrozen particles as the thermal energy of the particles has been lowered during the freezing process. The easy axes of the particles are aligned in the excitation direction due to the polarisation. Although the particles are blocked for Brownian rotation, they respond to an excitation in the same direction they have been polarised in.

When not being blocked for Brownian rotation, the particles respond to the two dimensional excitation of the Lissajous trajectory. After freezing the particles, a drop in amplitude of the received signal is noticeable. Polarisating the particles in the direction of x has no effect on the particle response. As it is shown in Fig. 1, the Lissajous trajectory does not excite in the direction of x solely. At every time point of the trajectory, an excitation in the direction of y takes place as well. Therefore, the excitation happens mainly diagonal to the direction of x. As a consequence, the detected particle signal of frozen samples does not increase when polarising them in a non-exciting direction.

5 Conclusion

It has been shown, that blocking particles for Brownian rotation has an impact on the particle response. The particle signal decreases and the slope of the harmonic amplitudes becomes steeper. Although the particles are blocked for Brownian rotation, the easy axes of the particles can be adjusted by Neel rotation [7]. Blocking the particles for Brownian rotation, the contribution of Neel rotation can be isolated and investigated further.

After blocking the free rotation of the particles, the receiving signal drops. Polarising the particles in excitation direction, they respond with higher amplitudes than non-polarised ones. As the particle signal does not increase when exciting them diagonal to their polarisation direction, this observation can be confirmed. The contribution of both the polarisation and excitation direction will be explored by applying other 2D trajectories [3, 6] and polarising particle assemblies in different directions during the blocking process. As freezing the particles lowers their thermal energy, other processes to block the particles for Brownian rotation need to be applied.

If SPIOs are applied in vivo, they may be blocked for Brownian rotation due to tissue viscosity. Then, the particle signal drops and the harmonic slope becomes steeper. Due to this, one can expect a lower SNR of those particles. As an excitation in the direction of their easy axes are of the same order and the slope steepness is about the same.

4 Discussion

When freezing particles, the Brownian particle rotation is blocked. The particles cannot rotate freely and adjust their easy axes by particle rotation to the magnetic field that is applied. Therefore, the detected particle signal drops. This effect can both be observed for the one and two dimensional measurements. Additionally, the thermal energy of the particles is decreased during the freezing process. This introduces a drop in the particle signal as well.

The steepness of the harmonics amplitude slope is linked to the image resolution, that can be obtained using the particles [6]. This is because the point-spread-function (PSF) of the particles is determined by their harmonics slope. After blocking the particles for Brownian rotation, the steepness of the slope increases. A broader PSF is to be expected, the resolution of frozen particles in MPI will decrease. As this new PSF would not be known, it cannot be compensated for.

Figure 4: Spectra of 2D particle responses. Unfrozen and frozen samples have been excited by a 2D Lissajous trajectory. The spectra of the received signals of both receiving coils are shown for up to 1 MHz. The harmonic amplitudes of the frozen samples are small compared to the ones of the unfrozen sample. According to the receive channels, a difference in the harmonic amplitudes is detectable for up to 900 kHz and 500 kHz, respectively.
axes increases the particle response, using different excitation trajectories sequentially may improve the detection of small particle assemblies.

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**References**