Investigation of the MPI Signal’s Dependency on Ferrofluid Concentration

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Abstract

LANGEVIN’s single particle model (SPM) yields a linear relation between magnetic particle concentration $c$ and higher harmonic amplitudes in magnetic particle imaging (MPI). In reality, the MPI signal is nonlinearly related to $c$, as demonstrated via simulation and experiment. Depending on the actual field of application, this may have severe impact on MPI.

Inadequacy of paramagnetic theory

The SPM is a well-established ferrofluid magnetization theory in the field of MPI [1]. Due to its paramagnetic nature, it describes noninteracting magnetic particles. Therefore, it is valid only in the limit of particle concentration $c \to 0$. In a real ferrofluid, particles interact magnetically. The smaller the distance between single magnetic moments, the more they support each other in the process of alignment to an external magnetic field $H$. Hence, the magnetization curve $M(H)$ nonlinearly depends on $c$: increasing $c$ leads to a steeper curve; saturation is reached for weaker $H$. This effect is ignored by the SPM. The impact of particle interaction can lead to drastic deviations from the SPM, as visualized in Figure 1.

MPS Simulation

As a consequence of the nonlinear impact of $c$ on $M(H)$, the $n$-th higher harmonic amplitude $A_n$ in magnetic particle spectroscopy (MPS) is nonlinearly dependent on $c$, too. For investigation of $A_n(c)$ by means of simulation, we use a second order modified mean-field theory (MMF2) [2]. MMF2 incorporates magnetic particle coupling and reflects experimental results best of all models tested in [3].

Within the MPS simulation, a monodisperse ferrofluid made of homogeneously distributed magnetite particles at different iron concentrations $c_{Fe}$ is considered. Using MMF2, the relative magnetization response $M_{rel}(c_{Fe})$ is calculated. Its time derivative is analyzed via discrete FOURIER transformation, leading to $A_n(c_{Fe})$. Evaluation of the relative magnetization is equal to analyzing ferrofluids with a constant total amount of magnetic substance (shrinking the ferrofluid volume while increasing its concentration).

Figure 2 shows the result of the simulation. To stress the most important outcome, all $A_n$ are normalized to $A_1$: the ratio $A_n/A_1$ changes with varying $c_{Fe}$. In general, the $A_n$ severely increase due to concentration enhancements. Harmonics with higher $n$ are affected more. As expected, in terms of the SPM, the $A_n$ are independent on concentration changes.

MPS Experiment

$A_n(c_{Fe})$ and $A_0(c_{Fe})$ were investigated in an MPS experiment, for one ferrofluid at five different iron concentrations $c_{Fe}$. The volume of the ferrofluid was kept constant, so that the total amount of substance linearly changes with $c_{Fe}$. Harmonical excitation was done with 8 mT amplitude. The detected response was correlated to the experiment by linear scaling of MMF2 data to experimental setup. This was done using MMF2 and SPM. The result of the simulation was correlated to the experiment by linear scaling of MMF2 data to experimental data.

The experimental and simulated data is shown in Figure 3. The nonlinear $A_n(c_{Fe})$ dependency could be verified. Furthermore, MMF2 is providing a proper description of the magnetization response of dense ferrofluids. The difference between the SPM and MMF2 curves visualizes the inadequacy of the SPM.

Conclusion

It was shown that changes of the higher harmonic amplitudes in MPI are not linearly related to concentration changes, as misleadingly suggested by the SPM. Therefore, current linear image reconstruction schemes are not qualified for quantitative reconstruction of the spatial particle concentration distribution.

For a theoretical description and simulations of the MPI signal, SPM seems to be the first choice.

References


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