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Temperature-dependent spectrum measurement using a magnetic particle spectrometer

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Abstract

Magnetic particle imaging (MPI) is a novel imaging modality to map the spatial distribution of superparamagnetic iron oxide nanoparticles (SPIONs) with high sensitivity and without ionizing radiation. A magnetic particle spectrometer (MPS) is used to measure the response of SPIONs and acquire the system matrix of the imaging devices. A three-dimensional MPS has been presented lately including a temperature control unit in the sample chamber, which is able to acquire the samples' spectra at different temperatures. In this paper, the spectra of the SPIONs sample measured at different temperatures are presented and compared.

I Introduction

In 2005 Bernhard Gleich and Jürgen Weizenecker introduced magnetic particle imaging (MPI) as a novel imaging technology, it provides sub-millimeter spatial resolution and fast acquisition time for medical imaging [1, 2, 3]. A magnetic particle spectrometer (MPS) can measure the characteristics of superparamagnetic iron oxide nanoparticles (SPIONs) and estimate their usability in different applications [4]. Moreover, it can emulate the magnetic field inside an MPI imaging device for fast acquisition of the system matrix [5, 6].

The SPIONs are sensitive to the temperature [7]; therefore, it is necessary to keep a constant temperature while analyzing the response of the SPIONs. Due to the temperature sensitivity, it is possible to estimate the nanoparticle temperature in vivo [8]. This shows a potential application in magnetic hyperthermia [9], for instance in non-invasively monitoring the temperature during treatment. The ability to discriminate nanoparticles of different temperatures by their spectra shows also the potential application in multi-color MPI, where different colors could be assigned to different nanoparticles by their temperature differences to allow for visualization in a single image [10].

A three-dimensional MPS is introduced in [11], however, the transmit coils and the corresponding hardware have been modified to integrate a temperature control unit in the sample chamber [12], which is able to change and stabilize the sample temperature during measurement.

II Material and methods

II.I Theory

When an external field is applied to the SPIONs, the energy of the applied field trying to align the nanoparticles' orientations and the thermal energy working to randomize them. The static magnetization of the SPIONs can be described by the Langevin function, which exhibits a reduced slop with increasing temperatures. Accordingly,

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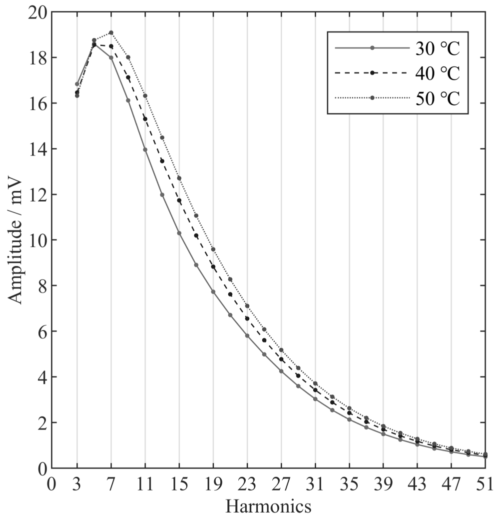

Figure 1: Amplitude spectra of odd harmonics measured at different temperatures. The solid line indicates the spectrum of the nanoparticles measured at 30 °C, the dashed line 40 °C and the dotted line 50 °C.

the spectra of the received signals from the MPS should exhibit a magnitude decrease at higher harmonics.

II.II Methods

A signal generator (DG1022, Rigol, China) and a power amplifier (2105, AE Techron, USA) are used to apply the current on the transmit coils. For the experiment, each channel of the MPS is checked separately. The generated magnetic field is 20 mT at 24.51 kHz, 26.04 kHz, 25.25 kHz for X, Y, Z channel, respectively. The nanoparticle sample used in the experiment is 10 μl Perimag® (micromod Partikeltechnologie, Germany), which has a concentration of 8.5 mg/ml (Fe).

A water phantom is placed in the cancellation unit [11], while the nanoparticle sample is placed in the generation unit. The cancellation unit and the generation unit are built identical to each other. A fiber-optic probe (PRB-100, Osensa Innovations, Canada) is inserted into the water phantom to monitor the temperature. The temperature is sequentially set to 30 °C, 40 °C and 50 °C. The respective nanoparticle signals are recorded by an oscilloscope (HDO 6104-MS, Teledyne LeCroy, USA). One period of measurement time is about 0.1 s. If the measurement is averaged for 500 times, the total measurement time is 50 s. Since the measurement time is short, any heating of the nanoparticle due to the applied fields can be neglected, i.e. the measured temperature of the water phantom is assumed to be the same as the temperature of the nanoparticle sample. An empty measurement is as well recorded and subtracted from the measured nanoparticle signals. MATLAB® is used to analyze the spectra of the nanoparticle signals.

III Results and discussion

Fig. 1 shows the amplitude spectra of the nanoparticles sample at different temperatures (only the odd harmonics are shown). Due to the similar behavior of all three channels, here only the results from the X channel are shown.

As seen in Fig. 1, at the 3rd harmonic, the amplitude spectrum of 30 °C is higher, while at the 5th harmonic, the amplitude spectrum of 50 °C is higher. However, the difference is not clearly distinguishable at 3rd and 5th harmonics. From the 7th harmonics onwards, the difference is more distinct. It shows that the amplitude spectrum of a higher temperature is greater than that of a lower temperature. At 49th harmonic (1.2 Mhz), the spectra are again not distinguishable.

The observations contradict the results described by the Langevin function. The reason is that the static particle model assuming an instantaneous response of the nanoparticles to the external magnetic fields. If considering the particle relaxation effects, both Brownian relaxation and the Néel relaxation are influenced by the temperature. Not only the temperature of the nanoparticles themselves, but also the temperature of the surrounding medium. In Fig. 1, it can be observed that, for the same temperature increment, which is 10 °C, the difference of the amplitude is not the same, i.e. the relation between the amplitude spectrum and the temperature variation is not linear.

IV Conclusions

The results show that the 3D MPS is capable of distinguish the temperature effects of the nanoparticles. To study the temperature dependence of the nanoparticles, a dynamic particle model should be used.

Moreover, the system calibration is in progress to provide a more reliable data. Afterwards, different particles will be measured at smaller temperature steps to understand the effects of temperature variation on the amplitude spectrum, which would be the first step towards hybrid matrices based on the temperature difference.

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Author's Statement

Conflict of interest: Authors state no conflict of interest.

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