André Behrends*, Matthias Graeser, and Thorsten M. Buzug

Introducing a frequency-tunable magnetic particle spectrometer

Abstract: Image quality in the new imaging modality magnetic particle imaging (MPI) heavily relies on the quality of the magnetic nanoparticles in use. Therefore, it is crucial to understand the behaviour of such particles. A common technique to analyze the behaviour of the particles is magnetic particle spectrometry (MPS). However, most spectrometers are limited to measurements at a single or multiple discrete excitation frequencies. This paper introduces a frequency-tunable spectrometer, able to perform measurements in the range of 100 Hz - 24 kHz.

Keywords: magnetic particle imaging; magnetic particle spectroscopy; tunable-frequency; magnetic nanoparticles; particle parameters; image quality

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1 Introduction

In 2005 the upcoming imaging modality magnetic particle imaging (MPI) was presented by Weizenecker and Gleich [1]. Until now, a lot of effort has been made to improve the imaging systems. Sensitivity enhanced systems like field-free line imaging, as well as better signal processing techniques are just two of the many aspects that have been addressed. Nevertheless image quality in MPI not only depends on the quality of the imaging system, but likewise on the quality of the magnetic nanoparticles. The influence of magnetic nanoparticle properties on imaging quality has been discussed for example by Ferguson et al. [2]. A common method to determine the properties of magnetic nanoparticles is magnetic particle spectroscopy (MPS) as presented by Biederer [3]. However, modern MPS systems are only capable of measuring at discrete frequency steps. Most systems are limited to one excitation frequency, others to multiple discrete frequencies [3][4]. The following sections describe a measurement setup which is capable of carrying out MPS measurements with a freely tunable excitation frequency in the range of 100 Hz - 24 kHz. This reveals the possibility to determine different properties of the nanoparticles, such as: the influence of Brownian and Néel rotation on signal quality, the frequency-dependent hysteresis and its related dissipation losses, the hydrodynamic volume of the particles, the temperature of the sample or the viscosity of the medium surrounding the nanoparticles [5][6][7].

2 The basic setup for MPS

The most published signal chain of an MPS system is shown in Figure 1. It consists of a personal computer (PC) which generates the excitation signal. This signal is amplified by a power amplifier (AC Amp), a bandpass-filter (BPF), the transmission (Tx) and send (Rx) coils, a bandstop-filter (BSF) and a low-noise amplifier (LNA). The nanoparticles are depicted as dots between the send and receive coils.

Figure 1: The basic setup of a MPS system adapted from [3]. It consists of a PC for signal generation, controlling and measurement, as well as a power amplifier (AC Amp), a bandpass-filter (BPF), the transmission (Tx) and send (Rx) coils, a bandstop-filter (BSF) and a low-noise amplifier (LNA). The nanoparticles are depicted as dots between the send and receive coils.

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load to the power amplifier’s optimal load. This ensures a high efficiency of the power amplifier. Due to the fact that the excitation field induces a signal orders of magnitude higher than the particle signal, a bandstop-filter has to be used to reduce the excitation signal. The filtered signal is amplified by a low-noise amplifier and finally fed back to the PC for further analysis. This setup is limited to a single excitation frequency due to the bandpass and lowpass filtering stages, which have to be made of passive electrical components to avoid nonlinear effects and prevent the distortion of the particle signal. To overcome this limitation the send and receive chain have to be modified. These modifications are presented in the upcoming section.

3 Modification of the basic MPS setup

To allow a free choice of the excitation frequency in a given frequency range, it is required to get rid of frequency limiting structures like lumped filters and the concept of an ideal impedance matching. The two major issues which have to be addressed are: distribution of the required current in the send coil, which is equal to restraining the power amplifiers load to a specific range and elimination of the excitation signal in the receive chain, allowing the measurement of the particle signal.

3.1 Receive chain modifications

For a frequency-independent elimination of the excitation signal a cancellation technique described by Graeser et al. [8] has been implemented. The idea is to build two identical measurement chambers. During the measurement process, in one of the chambers the particles are inserted and the other one is left empty. The send coils of the chambers are connected in series, providing the same current in the coils and accordingly the same excitation field. The receive coils are connected in series as well, but with subtractive polarity, thus the excitation signal cancels out. As the particle signal is only induced in one receive coil it is unaffected by the cancellation and is the only signal left. The setup is shown in Figure 2. The dots next to the coils depict the same instantaneous polarity. If the send coils produce the same field, the induced signals in the receive coils will cancel out. Since the particle signal is only induced in one chamber, it is not affected by this cancellation. Ideally the particle signal is the only signal left.

3.2 Send chain modifications

The limiting factor of an amplifier is its output power. To produce a sufficient current and a desired field strength, an apparent power given by

$$|S| = I^2 \cdot |Z| = \frac{1}{2} |Z|^2 \cdot |\hat{i}|$$

is required. Here $I$ is the root mean square value of the current, $Z$ is the complex load impedance and $\hat{i}$ is the current amplitude. The load of two coils in series is given by the absolute value of the sum of their complex impedances

$$|Z| = |(R_{L1} + R_{L2}) + j\omega (L_1 + L_2)|,$$

where $R_{L1}$ and $R_{L2}$ are the equivalent series resistances $L_1$ and $L_2$ are the inductivities of the two send coils respectively. The frequency $f$ of the signal is related to the angular frequency $\omega$ by $\omega = 2\pi f$. The electrical parameters of the send coils are measured and the required current to produce a magnetic field amplitude of 10 mT is determined by simulation. The values are shown in Table 1. The frequency range is split into four measurement ranges. For one frequency in each of the measurement range the system’s apparent power is minimized by a capacitor in series connection to the coils. The measurement ranges, the frequencies for which the apparent power minimization is done and the corresponding capacitor values are shown.
Table 1: Parameters of the send coils and the required current

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coil 1</th>
<th>Coil 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductivity</td>
<td>37.5 µH</td>
<td>37.5 µH</td>
</tr>
<tr>
<td>Equivalent series resistance</td>
<td>34.5 mΩ</td>
<td>28.7 mΩ</td>
</tr>
<tr>
<td>Required current amplitude</td>
<td>13 A</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: The measurement ranges, as well as the frequencies for which the apparent power minimization is done and the corresponding capacitor values are shown.

<table>
<thead>
<tr>
<th>range</th>
<th>frequencies</th>
<th>minimized frequency</th>
<th>capacitance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100 Hz – 8.5 kHz</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>8.5 kHz – 14 kHz</td>
<td>9160 Hz</td>
<td>4 µF</td>
</tr>
<tr>
<td>3</td>
<td>14 kHz – 19 kHz</td>
<td>14 700 Hz</td>
<td>1.5 µF</td>
</tr>
<tr>
<td>4</td>
<td>19 kHz – 24 kHz</td>
<td>19 875 Hz</td>
<td>0.83 µF</td>
</tr>
</tbody>
</table>

In Table 2. In Figure 3 the logarithmic apparent power of the different setups over the full frequency range is shown and the related measurement ranges are highlighted. As it can be seen the apparent power stays below 500 V A for every measurement range. The minimization frequencies are chosen to low. This is done to ensure the resulting load is inductive for most measured frequencies, because capacitive loads may lead to instabilities in the amplifier’s operation [9]. The power amplifier used to drive the coils is an AE Techron 7224 amplifier with a maximum power output of 1000 W into an optimal load of 8 Ω [10]. It is necessary to oversize the amplifier concerning the power, as the stated load impedance is almost never the optimal load to achieve the maximum output. In addition, the load is reactive for most frequencies, which means the signal from the amplifier is partially reflected back to the amplifier, leading to increased heating of the amplifier and limiting the maximum applicable power to the load.

3.3 Full setup of the spectrometer

The resulting setup of the spectrometer is presented in Figure 4. The capacitors are connected in series right after the power amplifier, each with the possibility to be bypassed with a short connection. The send coils are connected in series as well, whereas the voltage over one coil is measured using a voltage divider. If the voltage differs from the expected value, the excitation voltage is adapted accordingly. The receive coils are connected in a subtractive polarity manner such that the excitation signal cancels out. Then the particle signal is amplified by the SR560 low-noise amplifier and measured by the PC.

Figure 3: The logarithmic apparent power to produce a current of 13 A over the full frequency range is shown for the different measurement setups. The corresponding measurement range for each setup is highlighted.
4 Results

The spectrums of two exemplary particle measurements are shown in Figure 5. The amplitudes have been normalized and plotted against the k-th harmonic of the excitation frequency. Measurements have been carried out for 49 frequencies starting at 100 Hz, 500 Hz and continuing in steps of 500 Hz to 24 kHz. The particle signals have been measured successfully for every frequency and every particle measurement has been corrected by a preceding empty measurement.

5 Conclusion

In conclusion a setup for a frequency-tunable spectrometer in the range of 100 Hz - 24 kHz has been introduced. Based on particle measurements it could be shown that the spectrometer is working as intended and is able to determine the particle spectrums accurately. This allows for further investigations such as: particle performance, relaxation effects or dissipation losses.

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Author’s Statement

Conflict of interest: Authors state no conflict of interest.

Material and Methods: Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use has been compiled with all the relevant national regulations, institutional policies and in accordance the tenets of the Helsinki Declaration, and has been approved by the authors’ institutional review board or equivalent committee.

References
