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Investigation of impact of tuning coil loading on particle signal harmonics in multi-frequency MPI

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Abstract

In Magnetic Particle Imaging (MPI), suppression of the excitation feedthrough into the receive chain helps towards acquiring the fundamental frequency response of the superparamagnetic iron oxide nanoparticle (SPIONs), which is beneficial for quantitative measurements. As one approach, particularly suited for multi-frequency MPI (mf-MPI), tuning coil loading (TCL) has been shown to effectively reduce the feedthrough at the fundamental frequency way below the levels achievable with e.g. gradiometer coil arrangements alone. In this work, the effect of TCL on higher frequency components is evaluated by capturing the harmonics of a real particle signal, acquired by measurements at different excitation frequencies. A comparison between gradiometer-only and combined gradiometer plus TCL operation is presented. It is shown that TCL does not negatively impact the harmonics, hence provides an effective feedthrough suppression while preserving the higher frequency performance.

I. Introduction

The novel imaging modality Magnetic Particle Imaging (MPI) invented by [1], uses the pronounced saturation effect of SPIONs when exposed to external magnetic fields. A key challenge arises from the strong feedthrough of the excitation signal into the receive chain, masking the weak signal of the SPIONs at the fundamental frequency. In both fixed frequency and mf-MPI, an adjustable gradiometer coil (consisting of measurement (MC) and compensation coils (CC1,2)) can reduce the feedthrough [2].

Tuning coils (TCs) and their loading (TCL) have been introduced in previous work [3], [4], and were shown to considerably reduce the excitation feedthrough. In this work, the effect of TCL on the particle signals' higher harmonics is investigated.

II. Methods and materials

The scanner [2] was extended to create 13.8 mT at 5 kHz and 9 mT at 6 kHz. As depicted in Figure 1, the control of the TCL state (loading active or inactive, i.e., closing or opening switches A-D,) was implemented in the measurement sequences on the control PC [5]. That way, a direct comparison without any in-between manipulation of the scanner is possible. 10 µl perimag® (micromod Partikeltechnologie GmbH) was used as a tracer sample in the center of the field of view.

III. Results and discussion

For both excitation frequencies, the feedthrough of the empty scanner was first minimized by attaching suitable

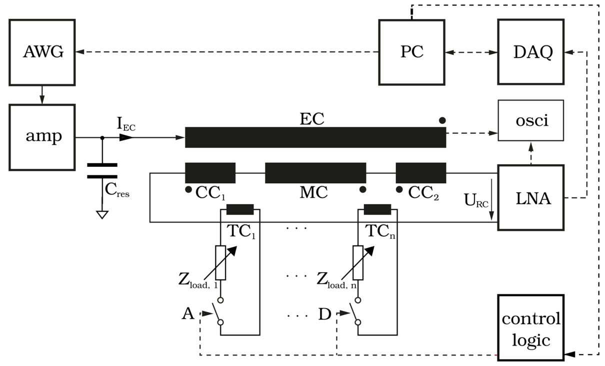

Figure 1: Schematic illustration of the set-up. The drive signal from the frequency generator (AWG) is amplified (amp) and applied to the excitation coil (EC), assisted by a parallel capacitor C_{res} to deliver the required current. A control logic toggles the TCL ($Z_{load,i}$) during measurement sequences. In either situation, the gradiometer coil receive voltage U_{RC} is amplified (LNA) and processed by a data acquisition card (DAQ), controlled by a computer (PC).

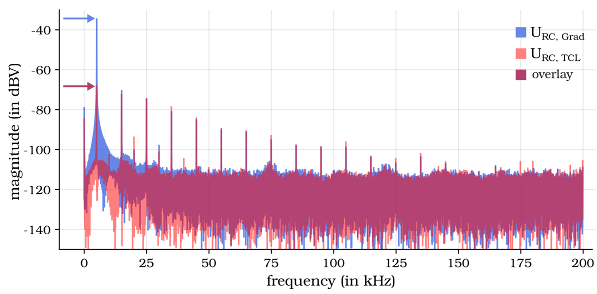

Figure 2: Particle signal spectrum of gradiometer only and TCL measurement at 5 kHz, 13.8 mT. For clarity, the arrows show the respective fundamental magnitudes.

loads to 2 TCs. After inserting the particle sample into the field of view (FOV), the TCL was toggled and the respective measurements were averaged to exclude drifts from impacting the results.

Figure 2 shows the harmonic spectra of the particle signals. $U_{RC,Grad}$ is the reference situation, in which only compensation by the gradiometer receive coil is active. Since no background correction (BGC) is applied, the strong excitation feedthrough at 5 kHz dominates the signal. $U_{RC,TCL}$ denotes the case with TCL, showing reduced excitation feedthrough at fundamental frequency. The remaining signal is expected to be the particle signal. The predominantly odd harmonics are present as before. The frequency range extends to 200 kHz, which corresponds to the 40^{th} harmonic of the applied excitation frequency.

For comparison, the difference in the signal-to-noise ratio (ΔSNR) is determined. In the idealized case where TCL exclusively suppresses the excitation feedthrough, only the 5 kHz component would decrease, while all

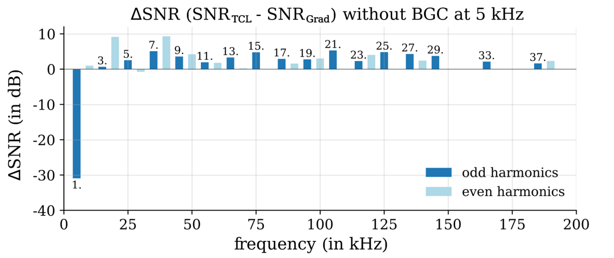

Figure 3: ΔSNR of gradiometer-only and TCL compensation at 5 kHz excitation. Negative ΔSNR values indicate attenuation, whereas positive values indicate improved harmonic SNR.

other components would exhibit a ΔSNR of 0 dB. The results are given in Figure 3, matching the expected behavior in principle.

The 5 kHz signal is, like intended, reduced by over 30 dB. The ΔSNR of the odd harmonics is between 0 and +5 dB, indicating generally preserved harmonic content; the slight increase may be due to reduced noise floor, but will be investigated further. The measurements with an excitation frequency of 6 kHz yield similar results: The ΔSNR of the harmonics is between -2 dB and +2 dB, showing a similar spread and being closer centered around the expected 0 dB.

IV. Conclusion and outlook

TCL was applied at significant field strength, enabling real particle measurements. The harmonics and the SNR of the particle signal do not suffer negative impact by the activation of the TCL. It was demonstrated that, within the measured cases, TCL in general preserves the higher harmonics of the particle signal, while effectively improving the residual feedthrough suppression at different excitation frequencies. In the next steps, the absolute accuracy of the fundamental frequency component of the particle signal will be addressed, to proceed toward quantitative measurements and potentially increased sensitivity.

Acknowledgments

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Author's statement

The Authors have submitted a patent application [6] on the concept of tuning coils with selectable loading.

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